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Artificial neural network to predict the weld status in laser welding of copper to aluminum

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Abstract

Laser welding of copper to aluminum is challenging due to the formation of complex intermetallic phases. More Al (~18.5 at. %) can be dissolved in Cu, in contrast to Cu (~2.5 at. %) in Al. Therefore, welding from copper side, large melting of Al can be achieved. However optimum Cu and Al must be melted for a strong joint. Finding the right amount is difficult and time consuming by tradition analysis technique like inspection by weld cross-sections. Considering the speed of the welding process and complexity of analysis involving with metallography cross-sections, alternative rapid method to qualify the welds are necessary. The acoustic emission during laser welding can give proportional information of the Al, Cu melted. With such an approach the weld status can be obtained in real time. In this paper the acoustic welding signal using an airborne sensor in the audible range of 20 Hz to 20 kHz, is correlated to the weld strength and material mixing (Al, Cu melt). Finally, the weld status is predicted by an artificial neural network based on the acquired signal.

Keywords: laser welding; Cu-Al welding; optimum melt; Acoustic emission; weld status; prediction; artificial neural network;

1. Introduction

Laser welding of copper to aluminum is challenging due to the formation of complex intermetallic phases and high reflectivity of copper (Cu) for the near-IR laser beam wavelength of 1030 nm [1]–[3]. High intensity of 10^7 W/cm^2 or lower laser wavelength of 515 nm is essential to penetrate the copper metal to joint with Al [4]. More Al (~18.5 at. %) can be dissolved in Cu, in contrast to Cu (~2.5 at. %) in Al [5]. However the excessive melt of Cu and Al must be avoided for a strong joint [6]–[9]. Laser beam trajectory or oscillation is very useful for joining Al to Cu because of the ability to create a keyhole with a small beam diameter, at the same time to enlarge the weld seam [8]–[10]. The melt information can be obtained from optical analysis by destruction of the welded sample to inspect the weld cross-section and revel the microstructure by chemical etching [11]. This technique is complex, time consuming and cannot be performed rapidly. Real-time automatic identification of good or bad weld based on the laser parameters and sensor data is required. Especially during situation like COVID-19 pandemic a high level of autonomy in production is valuable to limit human interaction and avoid disruption in manufacturing.

Several technique for monitoring the process during the welding exist, like monitoring the optical emission using a photodiode [12], [13], high speed camera [14], high speed temperature measurement using pyrometer and acoustic emission using airborne or structural-borne [15]–[17].

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Typically, the frequency range of signals for airborne sensor is 20 Hz to 20 kHz. For structural borne sensors the typical range of signal frequency measured is in the range of 50 kHz to 200 kHz [18]. Acoustic emission based on the airborne sensor (20 Hz to 20 kHz) is particularly interesting for this study because of the rapid contact less measurement and relatively inexpensive sensor requirement. Similar approach by [19] using airborne sensor in the frequency range of 20 Hz to 20 kHz showed that the evolution of vapor plume displaces the surrounding air and results in generation of sound waves.

The acoustic signal (air-borne sound pressure waves) in the audible range between 20 – 20 kHz is mentioned as acoustic emission in this paper. Very spare literature exists on the analysis of the acoustic signal for Cu-Al welding. During laser welding particularly in keyhole mode at very high intensity (10^7 W/cm^2), vapor/plume of metal and acoustic waves are generated [20][15]. In this research for welding Copper to aluminum, keyhole mode is fundamental to penetrate the copper with 1030 nm laser, which is accompanied by emission of rich acoustic signal. A high intensity acoustic signal is emitted for higher laser power because of melting of Cu and Al metals. Based on this idea, the excessive or insufficient melt of Al and Cu is identified in real time. An optimum melting of Cu and Al is essential i.e., to avoid insufficient or excessive melt. Estimation of the optimum melt is difficult and time consuming by tradition analysis technique like inspection by weld cross-sections. Since the laser welding is fast with speed in the order of about 300 mm/s, real-time weld signal analysis is preferred to qualify the weld. As the acoustic emission (welding signal) give relevant information of the Al, Cu melted, with such an approach the weld information can be obtained in real time. In this paper the acoustic welding signal is correlated to the weld strength and weld bead. Finally, the weld status is predicted based on the acquired signal.

This paper is organized as follows. The welding setup and acquisition of acoustic emission is detailed in section 2. The relation of laser welding power to the tensile shear test is discussed in section 3.1. The acoustic signal emitted during the laser welding for different laser powers and the corresponding weld zone is presented in section 3.2. The relation of the acoustic signal and tensile shear strength of the weld is explained in section 3.3. An artificial neural network model based on the acoustic signal is presented in section 3.4 to predict the weld status.

2. Experimental

2.1. Laser welding setup

Copper (top sheet) and Aluminum (bottom) sheet of dimensions 40 mm x 60 mm with thickness of 0.4 mm each is used for welding in overlap configuration as shown in the Figure 1. The laser welding is performed with disk laser of wavelength 1030 nm and a maximum power of 2000 W.

The laser beam is focused to a diameter of 110 µm and directed on the top of copper sheet. The laser beam trajectory is in the form of spiral [21] (diameter of 5 mm, Figure 1) with the laser beam movement start from the inside to the outside as shown by the red arrow in the schematic. The beam movement from the outside to inside (reverse direction) resulted in excessive heat accumulation at the center of the spiral and results in blow holes. However, with the inside to outside trajectory sound weld is obtained. The effect of preheating of the outer material on the weld seam is low due to the selected spiral dimension of 5 mm. The melting of Cu-Al is influenced by changing the laser power and speed.

The purpose of laser beam movement is to enlarge the weld zone with a small beam diameter (110 µm) and to achieve high intensity leading to keyhole mode of welding for copper.

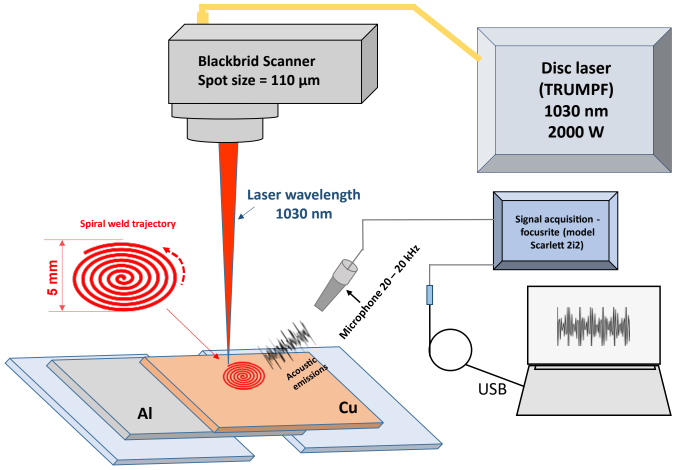

Figure 1 Schematic of the laser welding and acoustic signal acquisition for Cu-Al welding

Table 1 Laser power and velocity used for model the ANN

Laser Power [W]	Velocity [mm/s]
2000 - (100 %)	200, 300, 400, 500
1800 - (90 %)	200, 300, 350, 400, 500
1700 - (85 %)	100, 200, 300, 400, 500
1600 - (80 %)	300
1500 - (75%)	300

The laser power and velocity (reported in Table 1) are selected based on preliminary experiment to include both good and bad welds. For low laser powers of 1500 W, 1600 W the velocity was fixed to 300 mm/s as the higher velocity resulted in no welds. For higher laser powers of 1700 W, 1800 W and 2000 W the speed was changed from 200 to 500 mm/s. The selected parameter in the Table 1 is sufficient to have a wide range of weld conditions. For each power and velocity, five welding experiments (n=5) were performed resulting in a total of 80 welds.

2.2. Acoustic emission

The acoustic emission focused in this research is in the audible range i.e. 20 Hz – 20 kHz at the sampling rate of 100 kHz.

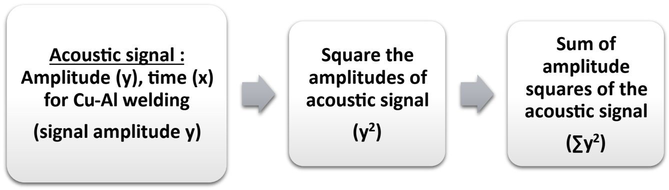

Figure 2 Flow chart showing the signal processing step to obtain the total sum of amplitude square as the acoustic emission value

The airborne acoustic emission is measured very close to the weld zone with a portable Omni-directional microphone, with frequency response of 20 – 20 kHz as depicted in the Figure 1. The signal is acquired with commercially available audio interface from focusrite (model Scarlett 2i2). The acquisition was performed with python interface, in 16 bit depth and sampling rate of 100 kHz.

The acquired signal is the measure of acoustic activity during laser welding process. The signal data comprises of amplitudes of the signal (y) and sample points representing time (x). The acquired signal is transformed to sum of the squared values of the signal amplitudes (Σy^2). The signal processing step to obtain the acoustic emission (Σy^2) is shown in Figure 2. The signal amplitude represents the intensity of the acoustic emission during the welding. The total acoustic emission (sum of amplitude squares) represents the melting activity during the laser welding.

2.3. Tensile shear test

The weld strength of the spiral trajectory is evaluated by tensile shear test performed at a crosshead feed rate of 1.2 mm/min. The welded sample is secured by clamps at each ends. Good or bad weld is determined from the tensile shear test. A force value of over 250 N is defined as a good weld. The tensile shear force of 250 N is selected because the value is about 85 % of base Al (291 N).

3. Result and discussion

3.1. Tensile shear strength of the spiral welds

The tensile shear strength of the welds is shown in Figure 3 for different laser powers at 300 mm/s, with five samples per data point (N=5). At low laser power of 1400 W (70%) there is no weld. Increasing the power to 1500 W (75 %) a mean shear force of 256.3 N is obtained. Increasing the laser power to 1700 W (85 %) the mean shear force value increase to 291.5 N. Further increasing the laser power to 1800 N (90%) the shear force decreases to mean value of 247 N. A maximum laser power of 2000 W (100%) leads to a low shear force value of 157 N.

A strong joint with maximum mean shear force of 291 N is achieved for laser power of 1700 W. From the tensile shear test results optimum welding power is required for a strong joint. In the following sections 3.2 and section 3.3 the relation of the acoustic signal to the laser power and weld shear force is discussed. A model to predict the weld status is explained in section 3.4.

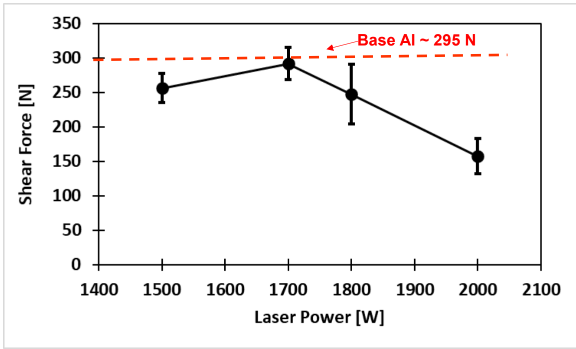

Figure 3 Plot of laser power [W] to tensile shear force [N]

3.2. Acoustic emission during welding of Cu-Al

As explained in the tensile shear test results, the optimum laser power/ melting is very critical for the joint strength. With the acoustic emission monitoring in this study, the total amount of Cu, Al melted is of interest. The sum of amplitude squares (Σy^2) of the signal corresponding to the welded parameter is the focus for welding of Cu and Al. The sum of amplitude squares (Σy^2) is defined as the acoustic emission (Units) in this paper.

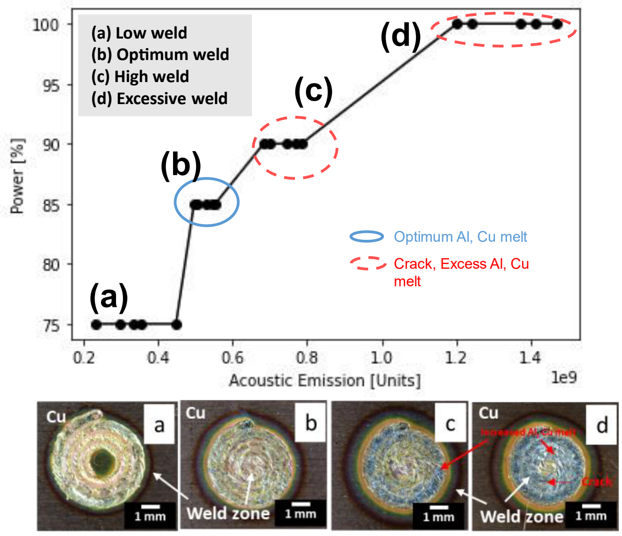

Figure 4 Relation of Laser power [%] and acoustic emission for different level of Al-Cu melt

The acoustic emission during the welding process for different laser power and velocity of 300 mm/s is shown in Figure 4.

For laser power of 75 % (1500 W) the acoustic emission obtained is in the range of 0.2 - 0.5 $\times 10^9$ (case (a)). In this case the melted Al and Cu is very low. Increasing the laser power to 85 % (1700 W) the emission obtained is in the range of 0.5 - 0.6 $\times 10^9$ (case (b)). In this case the melted Cu and Al is sufficient to create a weld zone for the entire spiral area Figure 4 (case (b)). In this condition there is no surface cracks formed in the weld zone. Further increasing the laser power to 90 % (1800 W) the emission obtained is the range of 0.7 - 0.9 $\times 10^9$ (case (c)). Welding with a maximum power of 100 % (2000 W) the emission value is obtained in the range of 1.2 – 1.5 $\times 10^9$ (case (d)).

The weld bead in case (a) has limited mixing of Cu and Al. Increasing the laser power, more Cu and Al is melted. The weld zone in case (b) has the optimum melt of Al and Cu and the weld in this condition is very strong with shear force nearly equal to the base of Al (i.e 295 N). Further increasing the laser power to 90 % and 100 %, even more Al and Cu is melted and the weld zone in this condition has cracks because of excessive Al, Cu mixing. A good proportional relation of the acoustic signal is obtained with respect to the laser power, which is related to the amount of Al and Cu melted to form the weld zone. For a good joint strength, the weld bead/zone as in case (b) is desired. The value of acoustic signal is obtained depending on the melting of Al and Cu. This is used for prediction of sufficient or excessive Al-Cu weld.

3.3. Acoustic emission and shear force

The plot of acoustic signal to the shear force is shown in Figure 5 for different power and velocity. The tensile shear force, acoustic emission depends strongly on the laser power and the velocity. For low value of acoustic emission (~ 0.3 $\times 10^9$) and high velocity (500 mm/s), the weld obtained is weak and is defined as low weld. Depending on the laser power and velocity combination, the acoustic emission in the range of 0.3 $\times 10^9$ – 0.7 $\times 10^9$, resulted in a high shear force value of over 250 N (~ 85 % of Al) and is termed as optimum weld as shown in the Figure 5. The weld is strong, and the failure did not happen in the weld/fusion zone, but in the heat affected zone (HAZ) of Al sheet.

Therefore, the welds of shear force greater than 250 N is accepted as a good weld as they achieve about 85 % strength of the base Al. For the increased acoustic emission, the shear force decreases, and the failure is in the fusion zone. In this zone a large amount of Al is melted and results in formation of cracks in the weld zone (weak weld). Less shear force of about 60 % (~ 175 N) of Al is obtained in the case of excessive weld. The strong joints with strength of at least 85 % of base Al is desired. Therefore, prediction of the weld status, good or a bad weld is performed from the acquired acoustic signal. The weld joints with the shear force greater than 250 N is treated as “1” (good weld, desired) and force value less than 250 N is treated as “0” (bad weld, undesired). Based on this an artificial neural network is modelled (section 3.4) to predict the weld status (“0” or “1”).

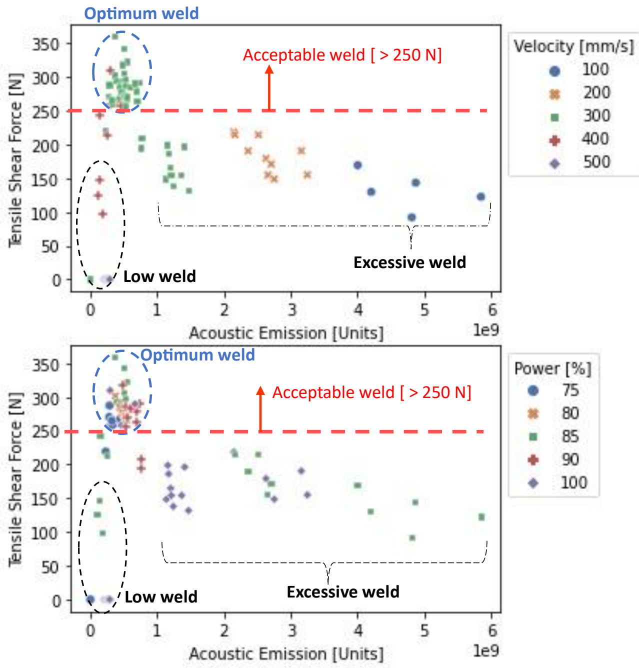

Figure 5 Relation of acoustic emission to tensile shear force of the weld for different laser power and velocity

Layer (type)	Output Shape	Param #
normalization_1	(None, 3)	7
dense (Dense)	(None, 128)	512
dense_1 (Dense)	(None, 128)	16512
dense_2 (Dense)	(None, 128)	16512
dense_3 (Dense)	(None, 128)	16512
dense_4 (Dense)	(None, 128)	16512
dense_5 (Dense)	(None, 128)	16512
dense_6 (Dense)	(None, 128)	16512
dense_7 (Dense)	(None, 128)	16512
dense_8 (Dense)	(None, 2)	258

Total params: 116,361
Trainable params: 116,354
Non-trainable params: 7

Figure 6 Summary of the artificial neural network (ANN) model used for prediction the weld status

3.4. Prediction of weld status from the acoustic signal

As discussed in the previous sessions, lower melt or excessive melt is detrimental for the weld strength. Sufficient melt is necessary for a good weld. The artificial neural network (ANN) architecture is selected for modelling because, different input features like laser power, velocity, measured acoustic emission and its relation to the shear force/weld status can be learnt by the model automatically based on the examples or data.

For the prediction of weld status classification approach is used. The model should identify the optimum weld as “1” and treat insufficient and excessive weld as “0” (undesired/bad weld). The objective is to predict the weld status (output) for different laser power, velocity and measured acoustic emission as the inputs.

The dataset consists of 80 welds with the laser power (W), velocity (mm/s), measured acoustic signal (Units) as the input (features), and weld status (0/1) calculated based on the tensile shear force (N) as the output (label). For modeling, 90 % (72 welds) of the data was used for training of the model and 10 % (8 welds) of the data was used for validation.

A sequential network model [22] [23] (implemented in python programming language [24]) is designed with a normalization layer and nine fully connected layers, each with 128 units and the last layer consist of 2 units to represent weld class i.e. good and bad weld. Rectified linear unit activation function is used for the hidden layers, and the final layer with unit of 2 is activated with softmax function. Adam optimizer and categorical cross entropy as loss function is used to compile the model. The summary of the model is shown in Figure 6 and the metrics of the model is listed in the Table 2.

Table 2 Model accuracy for prediction of the weld status

Metric	Value
Training accuracy	100 %
Training loss	6.35×10^{-8}
Test accuracy	100 %
Test loss	4.76×10^{-8}
Validation accuracy	**91 %**

After training for 500 epochs, the model predicts the weld status with an accuracy of 100% (loss = 6.35×10^{-8}) on the training and test data. Accuracy of about 91 % was obtained on the validation dataset. As the model can predict the weld status for different laser power and velocity based on the acoustic emission, there is high potential to implement the model in production.

To predict the value of shear force, regression approach is used with the model consisting of same configuration and number of layers as the classification approach, but all the layers are activated with “Rectified linear unit” and the “Mean absolute error” is used as the loss function. The mean absolute error is selected for loss function, as a continuous value is expected for the shear force rather than categorial value (0/1) used in classification approach. With the regressing approach in contrast to the classification approach, the model is trained to directly predict the value of shear force (N). The Table 3 summarizes the approach for prediction of weld status and shear force. The plot in Figure 7 shows the actual shear force value and the model prediction for different sample number in the dataset. The model can predict the value of shear force very close to the actual value. The model predicts the shear force value of zero very accurately which correspond to low or weak weld. For the optimum and high welds, the shear force is predicted with an error of about +/- 50 N to the actual value. Considering the complexity of the welding process involving wide range of laser power and velocity used, the proposed model and approach is acceptable. However further tuning the model and improving the size of the dataset is required in the future work. It is important to point out that the model learns the complex relation between the laser process parameter (power, velocity) and the measured acoustic signal (in process information) to predict the weld status or shear force. This can aid in the production process for identification of weld status or anomality in real time for Cu-Al welding.

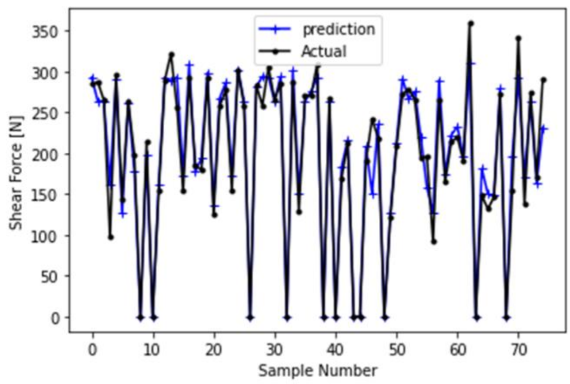

Figure 7 The model prediction vs the actual value of the shear force [N]

Table 3 Summary of classification and regression model for prediction of weld status and shear force

Approach	Inputs	Output	Loss function
Classification	Laser power, Velocity, Acoustic emission	Weld status (0/1)	Categorical cross entropy
Regression	Laser power, Velocity, Acoustic emission	Shear force [N]	Mean absolute error

4. Conclusion

Prediction of a good or a bad weld in real time without destruction of the weld sample is essential for quality assurance in Cu-Al joining. It was shown in this investigation that for welding of Cu to Al optimum melt is desired and, insufficient and excessive melting must be avoided. The acoustic emission during welding was utilized in this research to identify the weld status (sufficient/excessive melt). Higher acoustic emissions are generated during excessive Cu-Al melting and low acoustic emissions are recorded during less Cu-Al melting.

It was shown that optimum melting region, for a good weld can be identified from the acoustic emission. Further an artificial neural network was trained to predict the optimum melt or good weld as status "1", and insufficient or excessive weld as status "0". A good prediction accuracy of about 91 % was obtained on new data set. Further research is required to extend the model with multidimensional data like acoustic emission, monitored laser power, shear force and microscopic image. Further great potential for detection can be unveiled with this multidimensional data approach.

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