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# *In situ* monitoring of Cu/Al laser welding using Laser Induced Fluorescence

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**Abstract**

Laser-induced fluorescence (LIF) is used to investigate laser spot welding of 200 µm thick Cu and Al foils. The key to strong Cu/Al welds is limited intermetallic compound formation through controlled molten metal interaction time. For laser lap welds, Cu in the vapor plume is indicative of the degree of Cu melting. LIF sensitively detects individual elements and is used to interrogate the vapor plume for the earliest presence of Cu atoms. We perform welds across a wide range of laser power (3 kW – 8 kW) for a pulse duration of 2 ms. We qualitatively determine weld strength by mechanically pulling apart the samples. Temporally resolved LIF signals, along with backscattered laser light monitoring, demonstrate Cu detection immediately upon Al penetration. We find that LIF can detect Cu even under laser power conditions too weak to create a strong weld, which suggests that LIF may be sensitive enough for real-time, *in situ* monitoring of Cu/Al laser welding.



*Keywords:* spot welding; dissimilar metals; copper; aluminum; battery manufacturing

## 1. Introduction

Laser welding of dissimilar metals is often difficult due to incompatibilities of optical and thermophysical properties. However, in modern devices the need to join dissimilar metals is imperative to realize increasingly complex components for the electronic, medical, and aerospace industries. One example is the joining of Al cathodes to Cu anodes encountered in lithium-ion battery manufacturing [1–3]. These joints need to be mechanically robust and highly electrically conductive. However, large mixtures of Al and Cu result in a brittle intermetallic phase (IMP) that is weak and highly resistive [4]. In practice, the solution is to control the time that both Cu and Al are molten to limit the amount of IMP formation. This has resulted in a very narrow process parameter window that is difficult to repeatably achieve in production due to the instability and irregularity inherent to laser welding of Al and Cu. As a result, manufacturers currently rely on various other methods for joining even though a laser welding solution is desired due to its potential for precision, versatility, and high throughput [2,5].

In order to realize the benefits of laser welding, a fast and sensitive method of process monitoring is needed. Typically, laser welding of Cu to Al foils is achieved in a lap weld configuration with light incident to the Al as it is slightly more absorptive. Since the goal is to form a bond while limiting IMP formation, the time that the underlying Cu is molten is key. Therefore, detection of Cu atoms in the vapor plume could be a useful indicator of IMP formation. The use of optical emission spectroscopy (OES) has been investigated previously for this purpose but its limited sensitivity could only determine whether or not the laser was incident to an Al or Cu surface [6]. Instead, we apply laser induced fluorescence (LIF), which was previously demonstrated to be 4 orders of magnitude more sensitive than OES [7] and can be time-resolved [8].

In this work, we perform basic investigations of LIF to determine its feasibility as a real-time process monitor during laser welding of Cu/Al foils. The goal here is to determine the following: 1) Can LIF detect Cu in the vapor phase under lap


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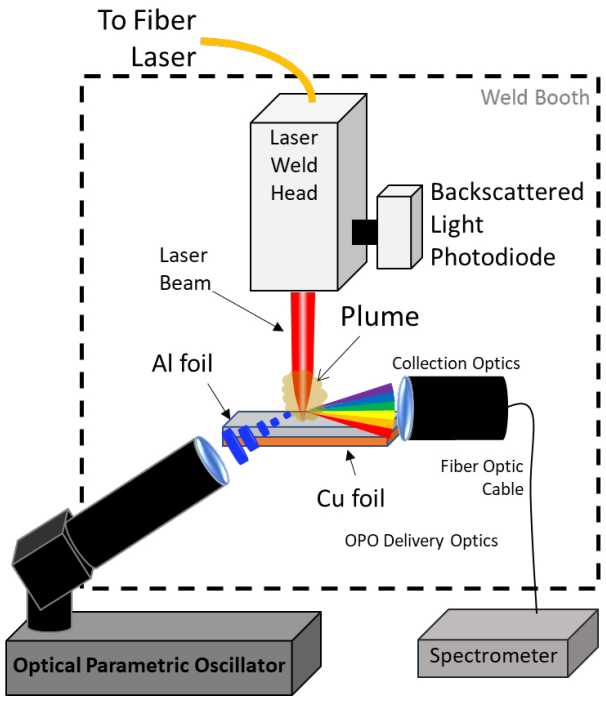


Fig. 1. A sketch of the experimental system. The laser welding and LIF experiment are contained within a commercial laser welding enclosure. See text for other experimental details.

weld conditions realistic to the industrial process? 2) If so, is the sensitivity of LIF enough that the Cu signal could potentially be used as an indicator of weld quality?

## 2. Experiment

Fig. 1 shows the experimental system used to make the LIF measurements, which is similar to that used in [7]. A high-power laser beam is focused to the surface of an Al/Cu foil stack. Spot welds are performed using a continuous-wave fiber laser at 1070 nm wavelength and a beam diameter of 600 µm that is round with a roughly flat-topped profile. The laser beam is delivered through a commercial laser weld head with a 200 mm focusing lens. All spot welds in this work are from a 2 ms long laser weld pulse. A photodiode with a 1070 nm bandpass filter is attached to the weld head to collect directly backscattered laser light. Unless otherwise stated, a $N_2$ shield gas was used during the laser welding process.

The foils are prepared by cleaning the surfaces with acetone and drying with clean, dry air. Each foil layer is 200 µm thick and are wrapped around a 100 mm diameter mandrel (not shown in Fig. 1) so that they can be rotated with the top surface always at the focal plane of the weld laser. The mandrel has a milled channel so that the bottom of the Cu foil is not in contact where the spot welding occurred.

The LIF signal is excited with an optical parametric oscillator that provides a 5 ns laser pulse at a 10 Hz repetition rate. This beam is delivered free-space into the weld booth with a series of mirrors in enclosed tubes and converges in the weld plume through a 50.8 mm diameter lens with a 100 mm focal length. The wavelength of the OPO is tuned to 324.75 nm which excites Cu atoms in the $3d^{10}4s^2S_{1/2}$ ground state to the $3d^{10}4p^3P^0_{3/2}$ state [9]. From this excited state, collisional

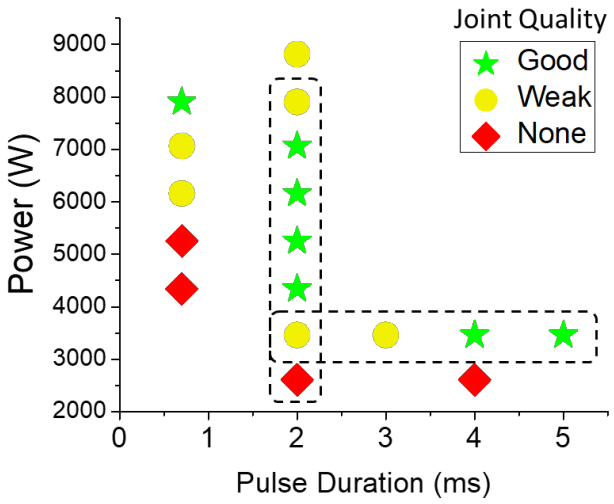


Fig. 2. Laser weld parameter space indicating and the qualitative assessment of the joint quality. The dashed lines indicate the parameter tested with LIF.

processes transfer atoms to the $3d^{10}4p^3P^0_{1/2}$ state. Then, relaxation to the ground state emits photons at 327.4 nm.

The fluorescent emission is collected by a pair of uncoated, planoconvex, lenses (f = 100 mm) that focus the collected light onto a 1 mm core diameter fiber optic cable. This cable delivers the light to a Czerny-Turner style spectrometer with a fixed 1800 line/mm grating, a slit width of 10 µm, and a resolution of approximately 0.1 nm. The detector in the spectrometer is a complementary metal-oxide-semiconductor (CMOS) array of 4096 pixels. An integration time of 100 µs was used for all acquired spectra.

The LIF spectral signal occurs only at the point in time where the OPO pump pulse excites the Cu atom and lasts only briefly, with delay times on the order of 100 ns. Therefore, time-dependent LIF spectra were obtained by controlling the time delay between the OPO laser pulse and the initiation of the weld laser plume. A full description of this process can be found in [8]. In this work, the reported intensity at every point in time is a result of 10 averaged spectra.

The goal here was to investigate the feasibility of LIF for *in situ* monitoring of the Cu/Al spot weld process and thus a broad range of spot weld conditions were sought. Fig. 2 shows a process diagram of laser power versus pulse duration. The general joint quality was assessed based on whether or not the foils remained intact after handling (good), initially stuck together but fell apart (weak), or none if no mechanical joint was formed. This is a very qualitative assessment that allowed for broad identification of laser weld process parameters that should be used to evaluate LIF while covering a wide range of conditions. Future efforts will include quantitative measurements [10] over a more refined set of laser processing parameters. The parameters used in this work are shown with the black dashed boxes in Fig. 2.

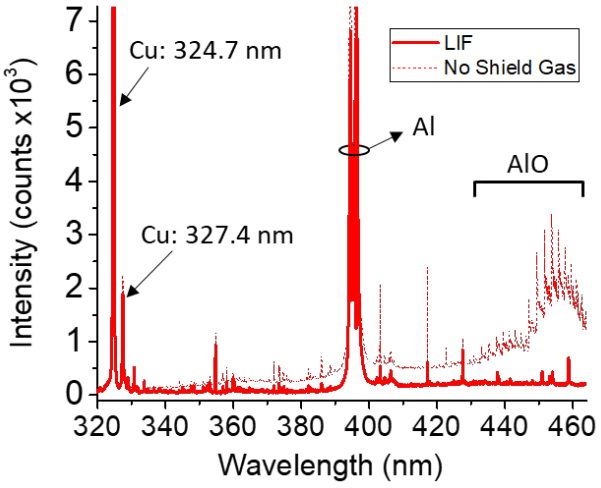


Fig. 3. LIF spectra with excitation at 324.7 nm and Cu fluorescence at 327.4 nm. Other spectral features are background emission due to non-resonant excitation of elements (for instance, Al) in the vapor plume. The dashed curve was obtained without a shield gas and shows optical emission (OES) from aluminium monoxide (AlO).

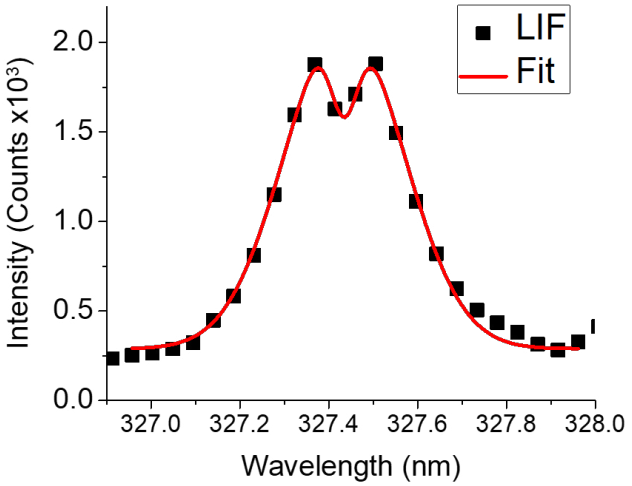


Fig. 4. Cu fluorescence peak at 327.4 nm. The spectral shape is a result of self-absorption, which the fit curve (red line) considers as described in the

$$G_{0,SA}(\lambda) = I_{0,SA}\, e^{-(\lambda-\lambda_c)^2 / (2s_{0,SA}{}^2)} \quad (1)$$

Therefore, a total of 5 fit parameters per spectral line are needed with $\lambda_c$ the peak centroid and $s_{0,SA}$ a width parameter. More sophisticated functions exist for fitting this phenomenon (see, for instance, [11]), but at the expense of significantly more fitting parameters. Figure 4 shows an example fit result using this method. The emission intensity is then determined by integrating $G_0(\lambda)$.

## 3. Results and Analysis

### 3.1. Spectra and Fitting

Fig. 3 shows representative LIF spectra obtained at 1.6 ms delay following the rising edge of a 2.0 ms weld laser pulse. Two peaks associated with Cu are at 324.7 nm and 327.4 nm. The first is substantially more intense as this is the wavelength at which the OPO is pumping, making unambiguous analysis of the peak difficult. The peak at 327.4 nm is due to the atomic transition previously described in the previous section, which is only visible when the OPO is tuned to exactly 324.7 nm. Also identified are a pair of peaks associated with Al [11,12]. Although Al atoms are not optically pumped like Cu, they appear in the spectrum due to their large abundance in the vapor plume in a naturally occurring excited state. These peaks are visible without the OPO pulse whereas the Cu peaks are not. Also shown in Fig. 3 is a spectrum obtained in air that shows a broad background and a series of peaks appearing above 430 nm. These are due to AlO [12–14] and demonstrate the necessity of an inert shield gas for spectral measurements.

The intensity of these peaks is proportional to the amount of Cu or Al present in the vapor plume. However, due to the effect of self-absorption the analysis is slightly more complicated than simple peak integration [15]. Self-absorption occurs because light emitted by energetic atoms at the vapor plume interior is partially absorbed by relatively cooler atoms near the plume periphery. This effect leads to a reduction of the measured peak intensity with a peak inversion possible. An example of this is shown in Fig. 4 for a Cu peak at 327.4 nm.

In order to approximate the true spectral intensity as a function of wavelength, $I(\lambda)$, the peaks are fit by a summation of Gaussian functions as $I(\lambda) = G_0(\lambda) - G_{SA}(\lambda)$. The emission spectrum of the plume interior is $G_0$ and the effect of self-absorption given by $G_{SA}$. These are defined as

### 3.2. Laser Power Dependence

The time-dependent detection of Cu in the vapor plume is of particular interest for the use of LIF for *in situ* process monitoring during Cu/Al welding. Fig. 5a shows the integrated intensity of the Cu peak at 327.4 nm for a 2 ms weld pulse for laser powers between 3460 W and 7910 W. The intensity is determined as described above by equation (1) with all curves normalized to one. These data show a steep onset of Cu signal occurring at progressively sooner times with increased weld laser power. In a previous work, Simonds et al. found a similar feature for Fe emission from stainless steel that correlated with keyhole formation [8]. The important result of these data is that the lowest laser power (3460 W), which was too low a power to result in a strong mechanical bond, still had enough Cu in the vapor plume for detection by LIF. This suggests that the LIF signal for Cu could be used to determine the appropriate laser pulse duration for creating a strong laser spot weld.

It is also possible to compare the intensity of the Cu peak with that of the OES signal of Al near 395 nm. These are doublet peaks that are also affected by self-absorption and so the same fitting function is used for them as described earlier for Cu. Here we analyze the Al peak at 394.4 nm. The ratio of the integrated intensity of Al signal versus Cu is shown in Fig. 5b for the spot weld performed at 4340 W. These data show

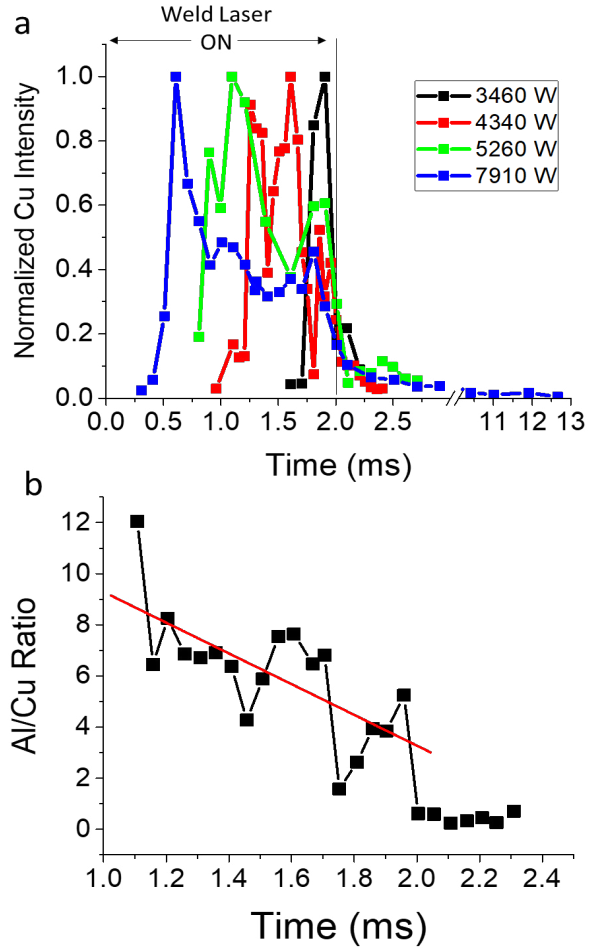


Fig. 5. Normalized integrated intensity of the Cu LIF emission as a function of time for all laser powers investigated is shown in (a). The ratio of the Al signal to Cu signal for the spot weld performed at 4340 W is given in (b).

that the relative signal intensity of Al steadily decreases in the vapor plume until the end of the 2.0 ms laser pulse. This data is consistent with the physical interpretation that the laser first melts through the Al foil until it reaches and melts the Cu foil below.

Direct, backscattered weld laser light was also collected during the spot weld as it is relatively simple to obtain and gives a second independent dataset. An example of these time-resolved signals is shown in Fig. 6 for weld performed at 5260 W. The black curves are from ten repeated welds with the solid red line the average (left ordinate). This is not a calibrated signal; thus, it represents the relative change in scattered light from the weld melt pool. Also shown is the integrated Cu LIF intensity as a function of time (right ordinate) for the same laser weld conditions.

There are several shared features in the backscattered signal, which suggests that there is a common physical origin. First is an initial spike that is readily interpreted as a large initial reflection due to the high reflectivity of the unperturbed Al foil surface. This is then followed by a steady decrease in backscattered light before a peak at 0.6 ms. The end of this peak coincides with the first detection of Cu in the vapor plume by LIF around 0.7 ms. Therefore, this suggests that the backscattered laser light peak at 0.6 ms is attributable to the laser weld depth fully penetrating the Al foil and the weld laser

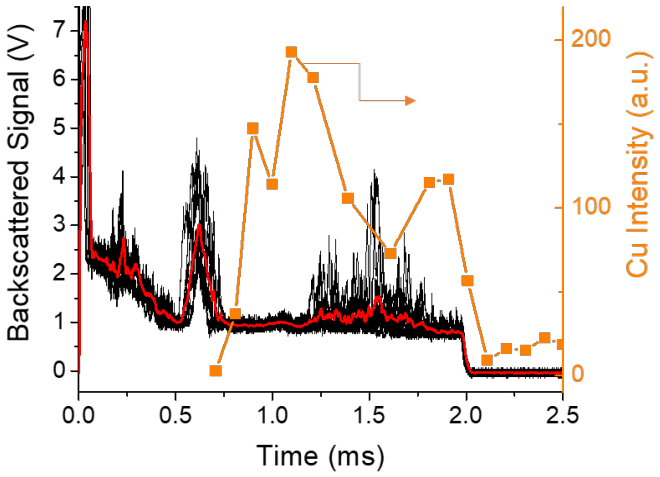


Fig. 6. The left ordinate shows the backscattered weld laser light signal as a function of time. The red curve is the average of the ten data sets obtained under identical conditions (2.0 ms at 5260 W) shown in black. The right ordinate shows the integrated intensity of the Cu LIF peak versus time for the same laser weld conditions.

illuminating the solid Cu foil surface. One would expect an increase in scattered laser light from a solid Cu surface as solid Cu is also highly reflective. Further physical interpretation of the backscattered laser light requires additional experimentation and is beyond the scope of this work.

### *3.3. Pulse Duration Dependence*

The effects of laser pulse duration are investigated from 2 ms to 5 ms, which spans the “weak” to “good” weld conditions (see Fig. 2). The integrated intensity of the Cu LIF peak for these conditions is shown in Fig. 7. The detection of Cu in the vapor plume occurs at nearly the same point for all conditions around 1.5 ms. For all weld pulse durations, the Cu signal is strong until the end of the laser weld pulse, and beyond. For the 5 ms laser pulse, the signal persists for almost 3 times as long. As depicted in Fig. 2, 2 ms and 3 ms pulse durations result in weak joints, whereas welds with 4 ms and 5 ms pulse durations were strong. The fact that LIF was able to detect Cu in the vapor plume before sufficient laser light exposure again suggests that

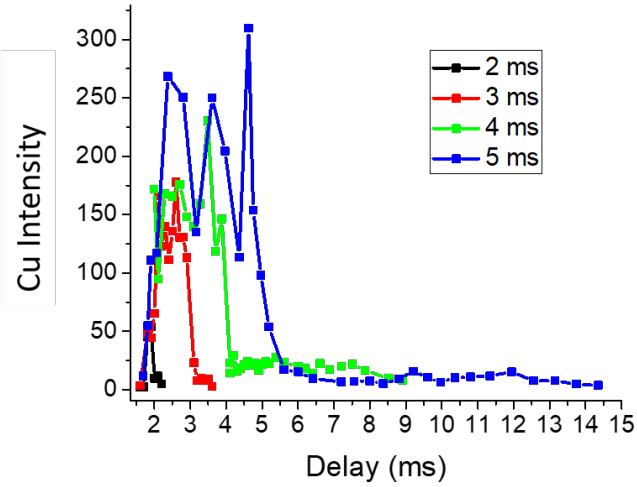


Fig. 7. Cu LIF intensity is plotted versus time for different pulse durations with a laser power of 4340 W.

LIF could be used as an *in situ* metric for determining Cu/Al spot weld optimization.

## 4. Conclusions

This work explores the potential of using LIF for *in situ* monitoring during laser lap welding of Cu and Al foils. We found that the increased sensitivity of LIF enables detection of Cu atoms in the vapor plume before sufficient laser energy was deposited to form strong mechanical joints. This represents a marked advantage over previous spectroscopic monitoring attempts, which could only detect Cu when the laser was directly incident to the Cu surface when Al was not present.

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