Technique Note

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Welding Imaging: Using a Pulse Laser & Bandpass Filter to Visualize High-speed Melt Pool Dynamics

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Abstract. In this technique note, discussed is an imaging method for characterizing melt-pool dynamics during highly luminous welding events. To achieve high-quality video of welding events, there are generally two key challenges to overcome: (1) deployment of an imaging system capable of capturing the temporal dynamics of the weld, and (2) mitigation of the intense emission from the welding site to have clear visibility into the melt-pool. In this short technique note, we discuss the characterization of a welding event by integrating a Phantom VEO-1310 camera, a 1 kW 808 nm Firebird Pulse laser from Oxford Lasers, and the use of an 810 nm +/- 5 nm bandpass filter.

Introduction. Traditionally, to attain visual insight into welding behavior, whether by eye or a digital camera, a neutral density (ND) filter is introduced. The purpose of the ND filter is to purely attenuate emitted photons (evenly across the visible range), with the goal to pull the emitted signal below the upper bound of an image sensor's dynamic range (DR) to avoid pixel saturation. To date, the DR of some of the best scientific *high-speed* CMOS sensors range between ~50-70 dB, while welds in some cases can demand approximate DRs of >140 dB (10^7:1) for proper characterization. While adding an ND filter indeed helps to decrease the emitted light from the weld, it also simultaneously decreases the scattered light emanating from the surrounding areas (sometimes referred to as the shadows or cold areas). This approach generally results in images with a single hot spot surrounded by a dark noisy background, which is not ideal for scientific characterization and analysis.

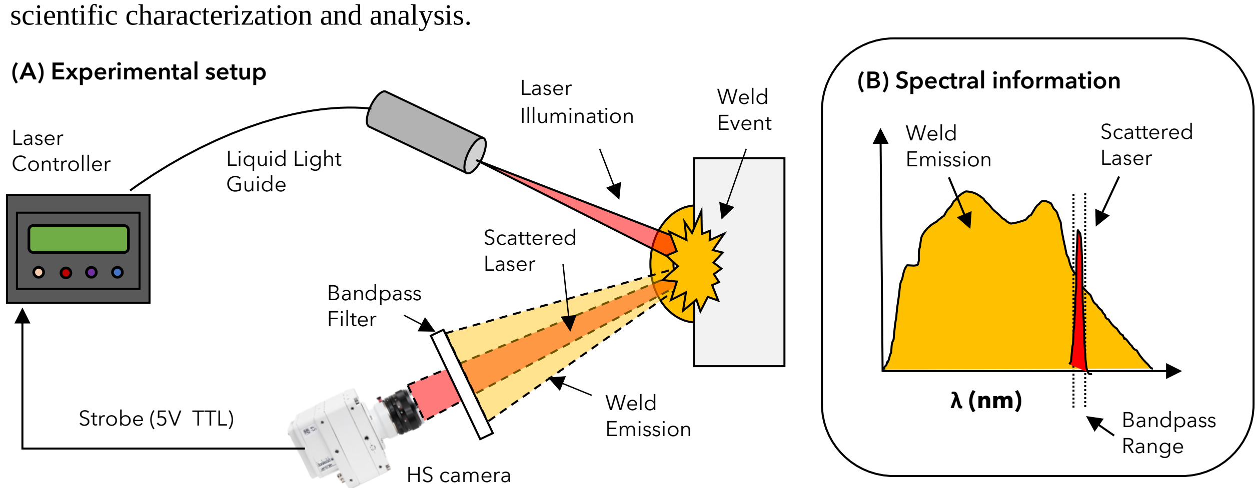


Figure 1. (A) High-speed imaging and pulse laser configuration illustrating the concept where a high-power pulse laser is used to illuminate the weld event (i.e., melt pool, spatter, etc.). The phantom VEO1310 captures high-speed images synchronously with the laser pulse emission via common 5 V TTL signal. (B) Spectral plot illustrating that the weld event emits intense light across the visible region, but where the band pass filter only permits a small band around 810 nm to enter the camera, matching the spectral band of the laser illumination.

To brighten up that background, sometimes a series of strong LED lights are used to illuminate the welding area. This will improve the result, but where the emission from the melt-pool generally still leads to strong oversaturation, leaving little to no insight into the melt-pool dynamics. It is possible that as LED technology progresses in terms of light intensity, it may become viable in this scenario.

Mechanism. An established method used to overcome these challenges involves the coupling of a high-speed camera with a TTL controllable pulse laser (> 400 W) together with a bandpass filter centered near the wavelength of the laser (808 nm), see **Figure 1** for labelled illustration and **Figure 2** for real-world setup. Essentially, this imaging technique blocks emitted photons from the welding event (due to the presence of the narrow band pass filter) while permitting scattered photons from the pulse laser illumination to enter the camera and form an image. Inevitably, welding events will also produce light matching the wavelength of the illumination laser, however, the amount emitted, relative to laser-scattered photons, is generally negligible and undetectable. In the end, this will result in a monochrome video with clear insights into the welding event, see **Figure 3** for a comparison of with and without the presence of the bandpass filter, resulting in pixel saturation and clear insights into the melt pool, respectively.

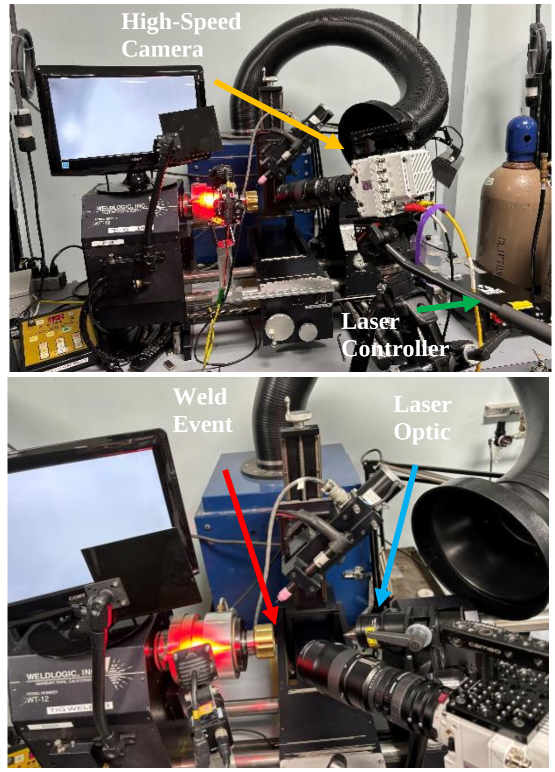


Figure 2. Two photographs showing the experimental setup highlighting the position of the camera, laser optic, and weld event ROI.

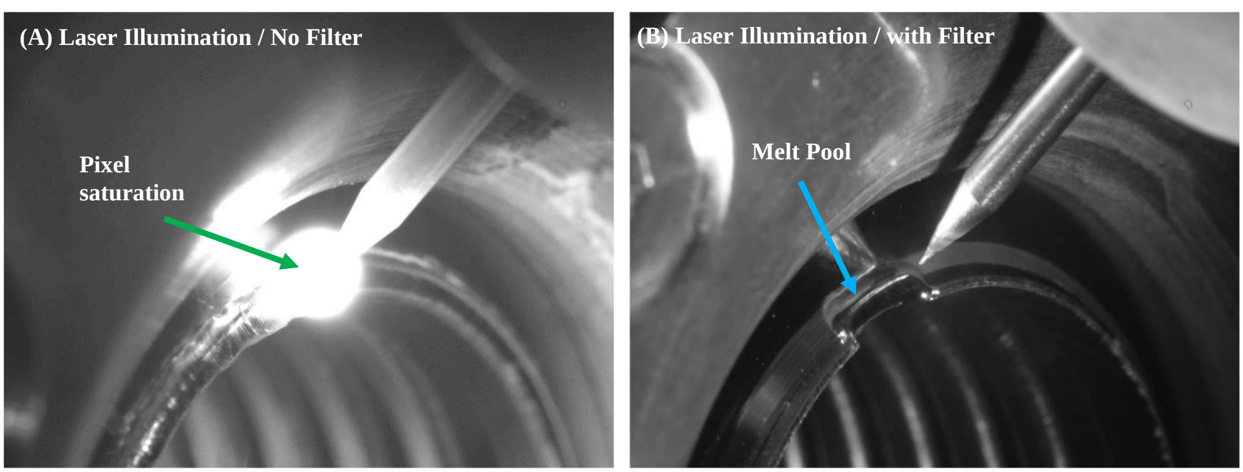
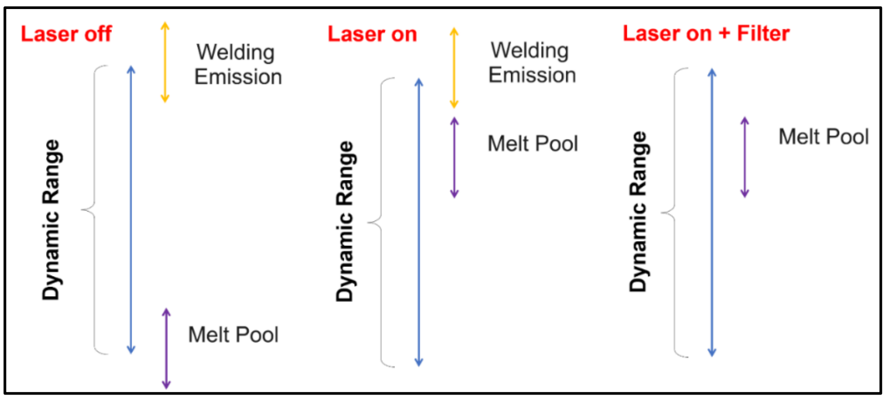


Figure 3. (A) This is the welding event when the laser is illuminating the subject but where the camera is without a band pass filter, leaving the region of interest (i.e., the melt pool) saturated. (B) This is the welding event when the laser is illuminating the subject and with the use of a band pass filter, leaving the region of interest well characterized (filter 810 +/- 5 nm).

Hardware Configuration. The setup consisted of a monochrome VEO1310 high-speed camera (72 GB RAM) equipped with a 100 mm Makro Zeiss with a series of extension tubes (Nikon F-mount). Threaded to the lens via step down rings (from K&F concept) was an 810 nm band pass filter, and both +/- 5 nm and +/- 10 nm bands were tested. The welding event was illuminated with an Oxford Laser pulse laser (Firebird, 1 kW at 808 nm) equipped with a liquid light guide and a diffusing optic to adjust the spot size of the laser. The laser controller was placed on a lab bench while the laser head was mounted on a tripod. To configure the camera with the pulse laser, the camera's output signal called "strobe" was utilized. The strobe signal is a 5V TTL signal where the falling edge represents the start of frame exposure, and the rising edge represents the end of exposure. Therefore, the laser controller was set to 'falling' or 'negative' edge, enabling the firing of a laser pulse per every negative edge sent by the camera (or start of image exposure). The connection was made via 1 m 50 Ω BNC cable, female-female. The pulse width and exposure time of the camera was set to 1 µs. The phantoms programmable IO was used to optimize the phase of the laser pulse train and frame exposures (shift until brightest images achieved). A liquid light guide was connected to the laser head of the Oxford laser, and a diffusing optic was used to have an adjustable projection. A laser circle of ~ 1 inch was used for the ~1/4 inch event area. The laser's diffusing optic was positioned by a Manfrotto variable friction arm and super clamps. An Edmund optics laser detection card was used during the setup to ensure proper illumination. The complete setup is shown in **Figure 2**.



Discussion. To understand complex imaging techniques, it is sometimes best to illustrate them as simply as possible. As a best attempt at that, drawn is a schematic that shows the dynamic range of the sensor against the weld emission and melt-pool scattering during the laser on/off and filtering. In the leftmost depiction, we have 'Laser off', where the only thing the camera detects is the bright welding emission that will produce a signal beyond the dynamic range of the sensor (in general, under nominal settings). In the middle depiction, when the laser is turned on, the intense laser scattering will lift the brightness of the surroundings and become visible to the camera, however, the weld emission still goes well-beyond the dynamic range of the sensor (under nominal settings). Finally, with laser on and bandpass installed, we eliminate the emission from the welding event while permitting the scattered laser-photons to enter the camera and produce images with well-illuminated surroundings, melt-pools, spattering, etc.

Concluding remarks: The integration of the camera with a pulse laser and band-pass filter serves as the powerful methodology to visualize and characterize welding events. This method should not be limited to only welding, as it is certainly amenable to any ultra bright or ultra emissive scenario like those found in ballistics and range scenarios (ballistic impacts, explosives, fuse work, arcing, etc). It should also be noted that the Firebird is a Class IV laser, and thus is very dangerous to operate. The proper protection equipment and facilities should be utilized when operating the laser.

While using a laser and bandpass filter serves as an optimal solution for welding imaging, there are other methods that can be employed to mitigate bright events including the use of extreme dynamic range (EDR), dual-slope mode (DSM), high-dynamic range (HDR), utilization of high-intensity LEDs, and dynamic exposure control.