



High-Speed Videography of Welding — Part 3: Natural Radiation Lighting

A comprehensive discussion of natural radiation lighting techniques and the equipment needed, including detailed descriptions of appropriate setups

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Abstract

This paper is the third of a three-part series covering the field of high-speed videography in welding in depth. This third part provides a comprehensive discussion of natural radiation lighting. The effect of optical filters is discussed in detail, with the beneficial use of long-wavelength edge filters around the near-infrared range. Building on Part 1, detailed descriptions of appropriate setups are provided with examples of published practical implementations. Welding processes addressed include gas metal arc welding, gas tungsten arc welding, flux-cored arc welding, submerged arc welding, electroslag welding, and laser cladding. Advantages and disadvantages are explored thoroughly. Natural radiation lighting is especially useful because of the simplicity of the equipment involved, information about the morphology and temperature of the surface of the molten metal, and information about the arc, such as the presence of metal vapors. Modern digital cameras typically have the necessary high dynamic range that enables the use of this technique. The implementations of natural radiation lighting reviewed in this paper, together with those for front and back lighting in Part 2, and the fundamental concepts and resulting quantitative guidelines in Part 1 provide welding researchers with a previously inexistent compilation of criteria to select proper equipment, accessories, and parameters for high-speed imaging of a vast variety of phenomena in welding, laser welding, and associated processes such as additive manufacturing or cutting.

Keywords

- Videography
- Lenses
- Filters
- Camera
- Wavelength
- High-Speed
- Illumination

Introduction

Part 1 of this work established the scientific and technological foundations of high-speed videography of welding operations, including considerations of time scales, emissions of light from the welding operation, and considerations of sensors, lenses, filters, and software. The concepts, terminology, and acronyms used in this paper were also explained in detail in Part 1.

Part 2 of this work focused on how those fundamental concepts are applied in concrete welding applications using backlighting and front lighting techniques. In this paper, natural radiation lighting techniques in the literature are surveyed exhaustively and discussed in detail. Typical setups are described, and image examples are presented, sourced from both literature and the authors.

Natural Radiation Lighting

Natural radiation imaging techniques collect radiation from the plasma arc, molten weld pool, and metal droplets. The technique relies solely on the high-speed camera sensor and filters without additional illumination. Similar to front lighting, natural radiation videography can image weld pool and silicate/slag movements on the weld pool surface.

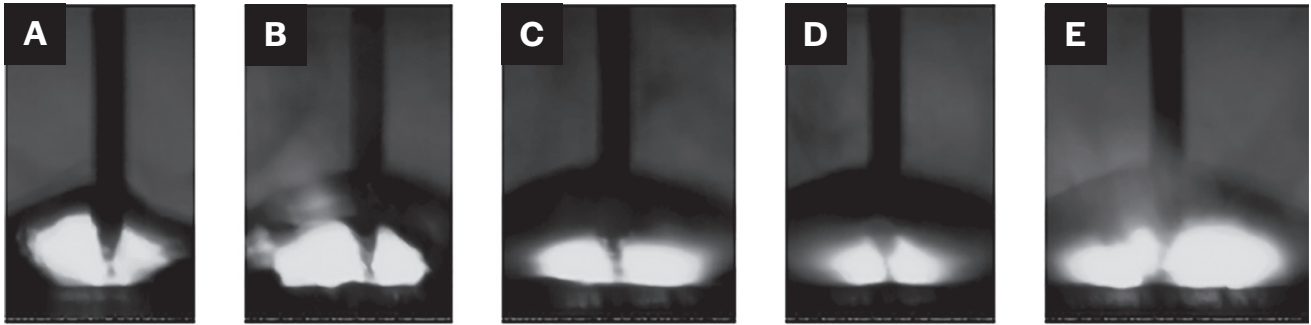


Fig. 1 — Natural radiation lighting with a shade #5 welding glass of pulsed GMAW of steel in Ar-18%CO₂ (Ref. 18).

This technique relies on the very different wavelengths that characterize the arc and the hot metal emissions by filtering away the arc emissions in short wavelengths, while capturing the longer wavelength (near IR) of thermal emissions and their reflections. Natural radiation lighting techniques for digital high-speed cameras were made possible only recently, with sensors with large enough dynamic range.

The natural radiation lighting technique presents challenges with the lack of separate illumination. The intensity of the arc is generally brighter than the molten droplets and the weld pool, especially in the visible light range. If the damping of the filters is not strong enough to suppress the arc light, proper imaging of the weld pool may lead to an overexposed arc region. Natural radiation lighting places greater dynamic range demands on the camera sensor so that it does not saturate in the brighter regions while maintaining acceptably low noise images in the darker regions. Short-circuit and pulsed free-flight metal transfer modes can potentially oversaturate the camera sensor during the periods of high arc current. Reducing the exposure times to compensate for the increased arc intensity may darken the weld pool so that fluid and slag flows cannot be observed. Using an LWP filter to suppress the visual light region reduces the arc light, while being sensitive to hot metal emissions; however, a camera sensitive to the near IR is required. While most camera sensors are naturally sensitive to the near IR, most commercial cameras (especially color cameras) have on-sensor filters that block IR radiation; the cut-off wavelength of these filters may vary depending on the camera make and model.

The absence of additional light to the welding region presents some advantages for analytical and quantitative measurements, such as characterizing the ionized metal vapors and shielding gas spectral lines within the arc column (Refs. 1–6). This technique utilizes NBP filters centered on the spectral peak of interest, such as Fe at 365 nm or 538.1 nm, or Ar at 696.5 nm or 811 nm. In addition to ionized metal vapor spatial distribution characterization, the temperature of the arc and molten metal can be estimated approximately from their radiation emissions (Refs. 7–10).

Setup for Natural Radiation Lighting

The equipment required for natural radiation videography is perhaps the simplest of the lighting scenarios outlined in this set of publications. The incoming light can be unfiltered

or filtered with various filter options. Because no external light source of clearly defined wavelength exists, many possible filters can be used in natural radiation lighting videography for different purposes. Neutral density, edge, and band pass filters are commonly used to visualize the arc and metal transfer. In this technique, it is convenient to have a small collection of filters and experiment with them for each case.

The cost of individual filters can vary considerably depending on the construction material, size, and transmittance profiles. Neutral density filters are often the least expensive option and are useful to decrease the emitted light intensity to avoid sensor saturation. Edge and band pass filters cost approximately the same for equivalent materials and sizes. Narrow band pass filters, especially those with a narrow transmittance profile (e.g., FWHM around 1 nm), cost considerably more than ND, edge, and NBP filters. Tailored filters with very specific wavelength profiles can exceed \$1000 per filter. A collection of filters can be purchased for less than \$2000, providing flexibility to image spectral peaks or nearly eliminating the arc to study metal transfer and weld pool fluid flows. A useful set should contain NBF with 400–1100 nm in 25 nm steps, LWP with a cut-off wavelength between 700–900 nm in 50 nm steps, and ND filters.

Examples of Welding Imaging Using Natural Radiation Lighting

Imaging without a filter may oversaturate the camera sensor, even with the fastest exposure times and the smallest aperture possible. Adding a neutral density filter or welding glass (like those found in welder's helmets) can reduce the intensity of the arc and metal emissions, but result in underexposed regions in the metal.

An important difference exists between welding glass and neutral density filters. Welding glass partially attenuates the bright light in the visible spectrum but effectively eliminates wavelengths outside the visible spectrum to avoid damage to the human eye. Welding glass is specifically designed to block UV (< 40 nm) and near-IR (> 700 nm) light, preventing damage to the retina and reducing welder fatigue. Neutral density filters, in contrast, even when designed for the visible light spectrum, often transmit in the UV and near-IR wavelengths. The exact transmittance outside the visible range might vary from their transmittance in the visible.

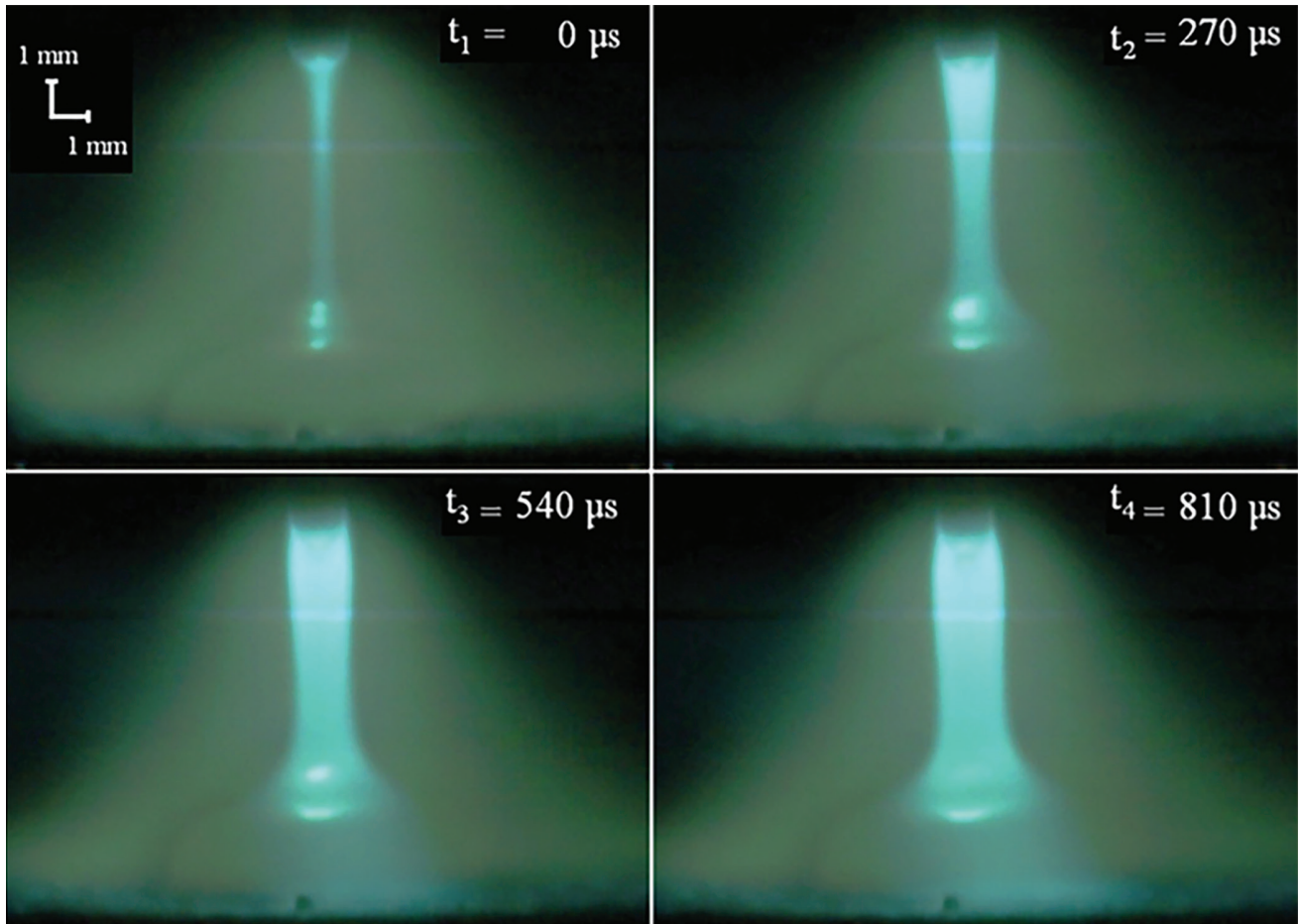


Fig. 2 — Natural radiation lighting with an ND filter of pulsed GMAW of steel (Ref. 21).

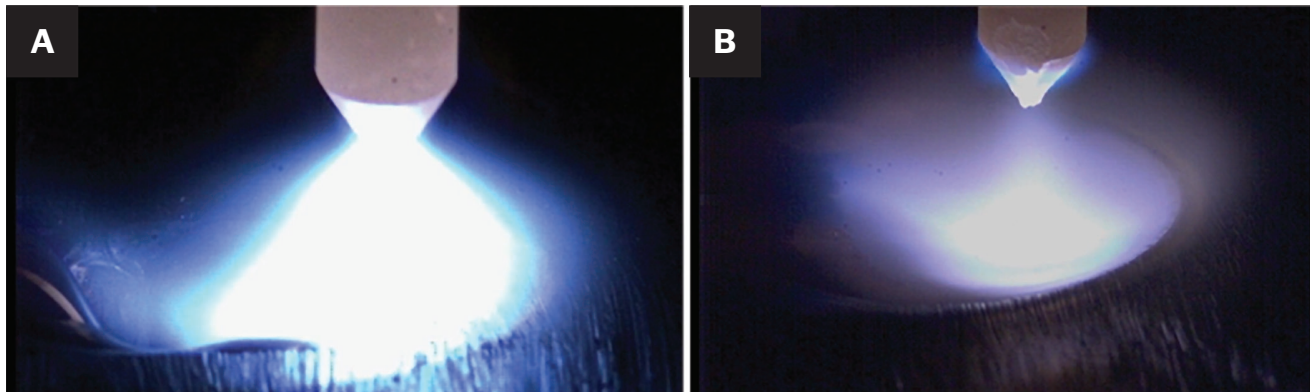


Fig. 3 — Natural radiation lighting with an ND filter of autogenous pulsed GTAW of steel in: A — Pure argon; B — pure helium. Images taken with the same exposure times during the 300 A pulse.

Imaging using natural radiation lighting without a filter includes the work on gas metal arc welding (GMAW) of aluminum by Zhu et al. and by Liu et al. (Refs. 11, 12), the work on GMAW of steel and laser-GMAW hybrid welding by Liyan et al, Fan et al., and Liu et al. (Refs. 13–15), and the work on arc interactions between a gas tungsten arc welding (GTAW) and CuSi3 GMAW electrode by Wang et al. (Ref. 16). Taka-

toshi et al. made high-speed videos of electrical resistance welding (ERW) of steel pipe, also without a filter (Ref. 17); in this case, the absence of an arc resulted in clear images of the weld region as the only emitted light was that of the hot metal and its reflections.

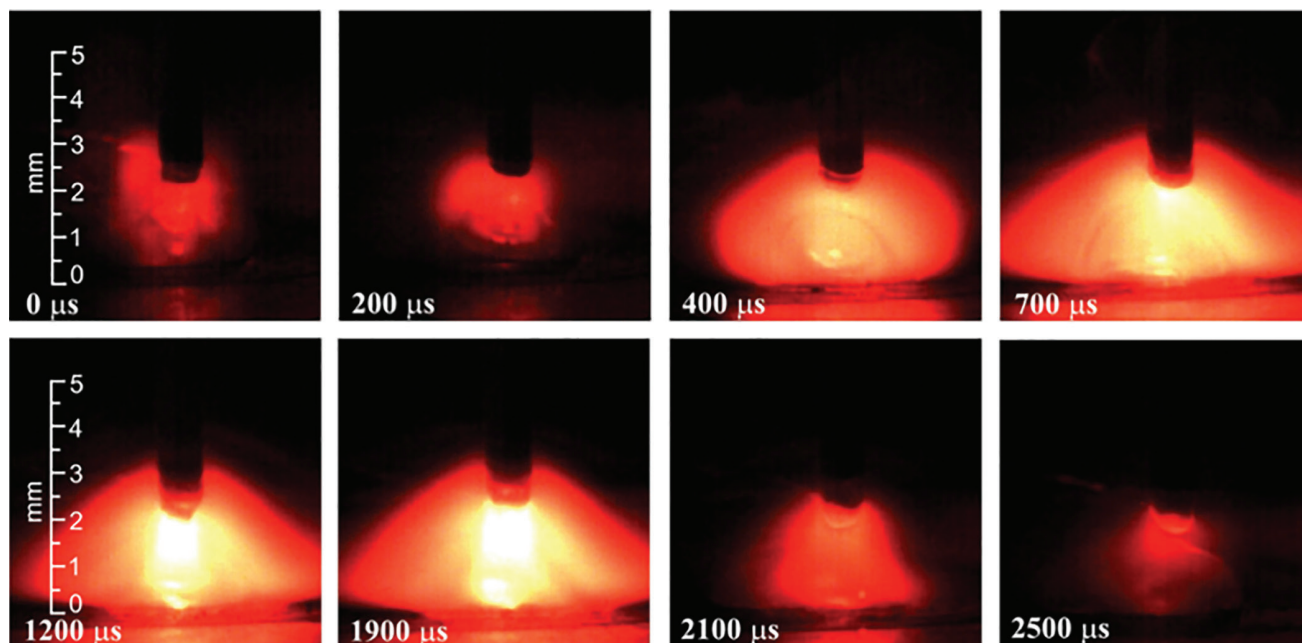


Fig. 4 — Natural radiation lighting with an NBP filter (650–700 nm) of controlled short-circuit GMAW (Fronius CMT) in Ar-8%O₂ (Ref. 2).

Natural Radiation Lighting Using ND Filters

Ghosh et al. used a shade #5 welding glass to study arc shape during pulsed GMAW of mild steel (Ref. 18). Figure 1 shows the poor edge definition obtained with this technique. Ghosh et al. also used this technique to characterize the pulsed arc and metal transfer using stainless steel and aluminum filler wires (Refs. 19, 20). A successful application by Rouffet et al. of ND filters to pulsed steel GMAW in pure argon shielding gas is shown in Fig. 2 (Ref. 21).

The effect of shielding gas composition on welding videography with ND filters is demonstrated in Figure 3, which compares images of autogenous pulsed GTAW on steel with pure argon (Ar) and pure helium (He) shielding. Both images correspond to similar 300 A pulse peaks with the same ND filter and the same exposure. The disparity between the arc intensities is readily apparent, wherein the Ar-shielded image is overexposed. This is a consequence of the difference in arc spectra of Ar and He, as well as the camera sensor's spectral sensitivity.

Natural Radiation Lighting Using BP Filters

Tailored NBP filters can help determine the presence and distribution of ionized elements throughout the arc column. Wilhelm et al. studied the effect of shielding gas on controlled short-circuit mild steel GMAW transfer (Ref. 2). Sample images of this work can be seen in Fig. 4, where the arc reignition phase was documented with a 650–700 nm band pass filter. Using pure iron (Fe) wire, Siewert et al. used a 700–900 nm BP filter to study the argon spectral lines in pure Ar shielded pulsed GMAW (Ref. 22). Wu and Liu used a CCD camera with an NBP filter of central wavelength of 655

nm, FWHM of 40 nm, and an ND filter to analyze full-penetration keyholing in PAW (Ref. 23).

Narrow-band pass filters are a popular method of analyzing and characterizing the arc and metal transfer phenomenon. Kim et al. studied the effect of the arc spectrum on welding imaging and the advantages of selecting an NBP filter between spectral peaks to improve visualization of the weld pool in GTAW (Ref. 24). Ma et al. studied the effect of pulsed GTAW on the Ar I spectral lines during arc ignition with a 794.8 nm NBP filter (Ref. 25). Zhang and Zhang used a 514.9 ± 6 nm NBP filter to characterize the effect of active fluxes on the evaporation of magnesium (Mg) (which has a spectral peak at 516.73 nm (Ref. 26)) during alternating current (AC) GTAW of AZ31B magnesium plate with pure argon, as shown in Fig. 8 (Ref. 27). Siewert et al. studied the distribution of metal vapors and ionized argon in the arc column of pulsed GMAW using 400 nm, 656 nm, and 700–900 nm NBP and BP filters (Ref. 22). Bachmann et al. used a 650 ± 10 nm NBP filter in pure Ar shielded steel GMAW to determine the surface tension and viscosity of free-flight metal droplets from the droplet oscillations (Ref. 28). In a multi-angle tomographic setup, Nomura et al. used a 697.3 ± 0.7 nm NBP filter using various tilt angles to obtain a wavelength shift to reach the targeted wavelength of 696.5 nm for Ar in Ar-shielded steel GMAW (Ref. 29). The authors used a 537.8 ± 0.5 nm filter to capture the Fe I lines at various tilt angles (see Fig. 5).

Dos Santos used 515 ± 10 nm and 900 ± 10 nm BP filters to study arc phenomena of the different regions of the electric arc in pulsed GMAW (Ref. 30). The 515 ± 10 nm filter picks up the features of the arc core and the peak iron line at 516.74 nm, while the 900 ± 10 nm filter captures the outer arc cone, droplet formation, and weld pool dynamics. With the right exposure settings, the 900 ± 10 nm filter allowed

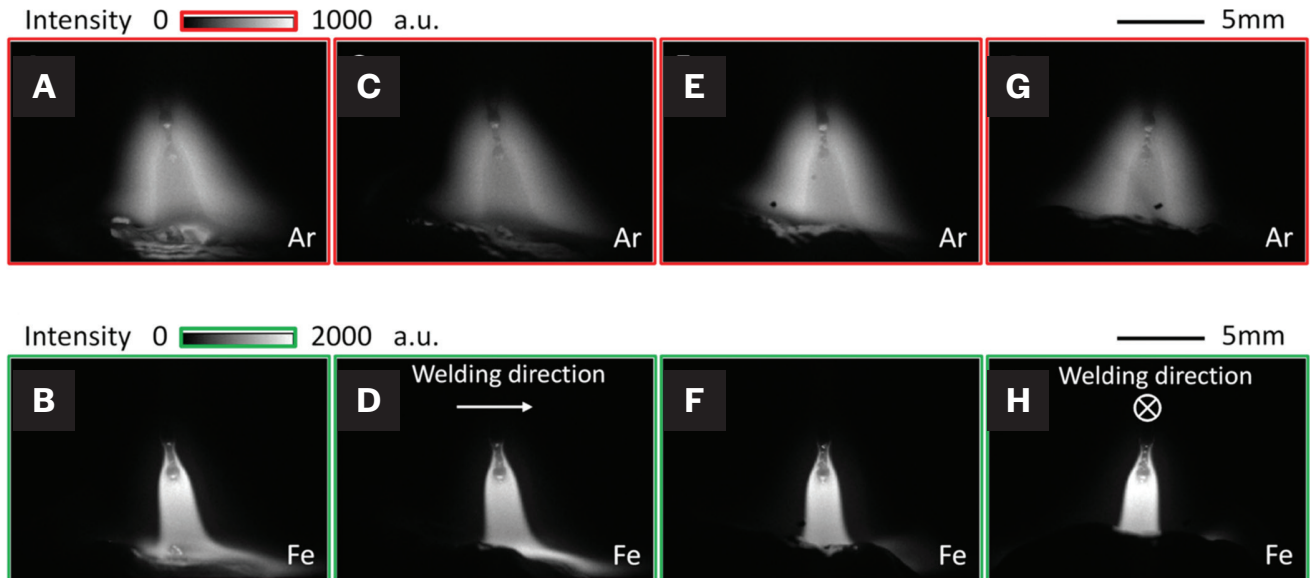


Fig. 5 – Natural radiation lighting of GMAW in globular transfer from 4 angles with two different NBP filters: A – 696.5 nm for Ar I; B – 538.1 nm for Fe (Ref. 29).

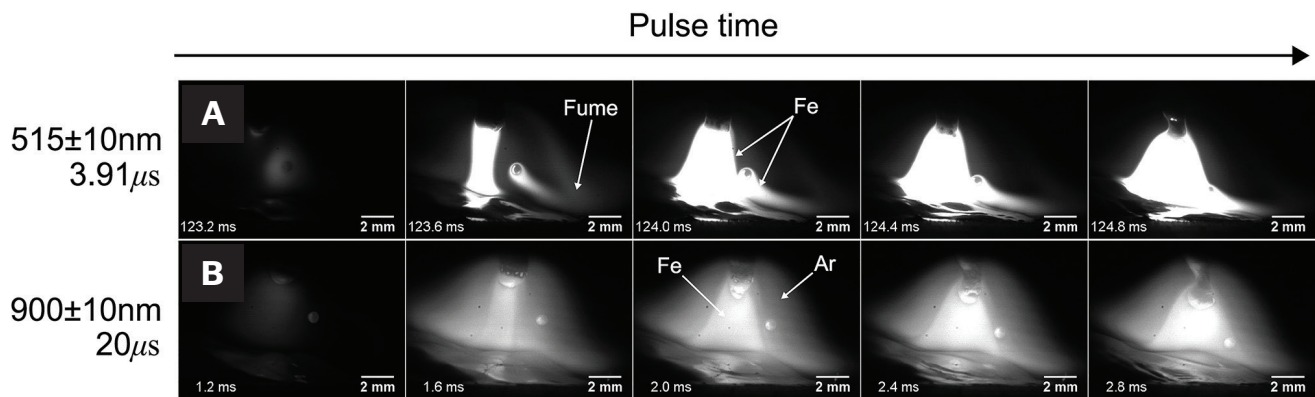


Fig. 6 – Natural radiation lighting of GMAW using two different NBP filters: A – 515 ± 10 nm for Fe I; B – 900 ± 10 nm for Ar I, showing both Fe and Ar emissions (Ref. 30)

imaging of both the iron-rich inner core and the outer cone of the ionized Ar (see Fig. 6).

Other applications of NBP filters include the work of Huang et al. and Shao et al. using an 808 nm NBP filter to study metal transfer of laser-assisted GMAW (Refs. 31–33); the laser used in this study was a 1 kW diode with a wavelength of 808 nm, providing additional light to the weld droplet surfaces and enhanced energy for droplet detachment. Gött et al. used a high-speed camera with an NBP filter to validate an innovative spectroscopic feedback system to optimize GMAW pulsing parameters, resulting in lower fume generation (Ref. 34). Zhao et al. used a narrow band pass filter to characterize the weld pool flow of keyhole laser-GMAW hybrid welding (Ref. 35). Valensi et al. used a 468.8 ± 3 nm NBP filter to study the plasma shape of pure-Ar shielded GMAW spray transfer, shown in Fig. 7 (Ref. 36).

Figure 7 illustrates how the filter choice has a big impact on characterizing an arc. Both images show the same welding arc and should look the same, but each image focuses on a

different part of the plasma. The left side (A) highlights the central part dominated by metal vapor and shows the Ar shape with only a weak glow, while the left side (B) ignores the metal vapor and only shows the Ar part of the arc. Different filters can reveal the unmixed presence of the metal and shielding gas.

Narrow-band pass filters with natural radiation lighting are useful beyond the characterization of element lines present in the arc. Fujita et al. used a 1064 nm NBP filter to avoid the bright Ar spectral lines in GTAW for automation vision systems (Ref. 38), obtaining a clear view of the weld pool surface and electrode tip shown in Fig. 9.

Ogawa (Refs. 39, 40), reviewed the effect of BP filter wavelength during He-shielded GTAW, as shown in Fig. 10. In this figure, a systematic testing of BP filters is carried out, with center wavelengths ranging from 340 nm to 694 nm and FWHM of 10 nm in all cases.

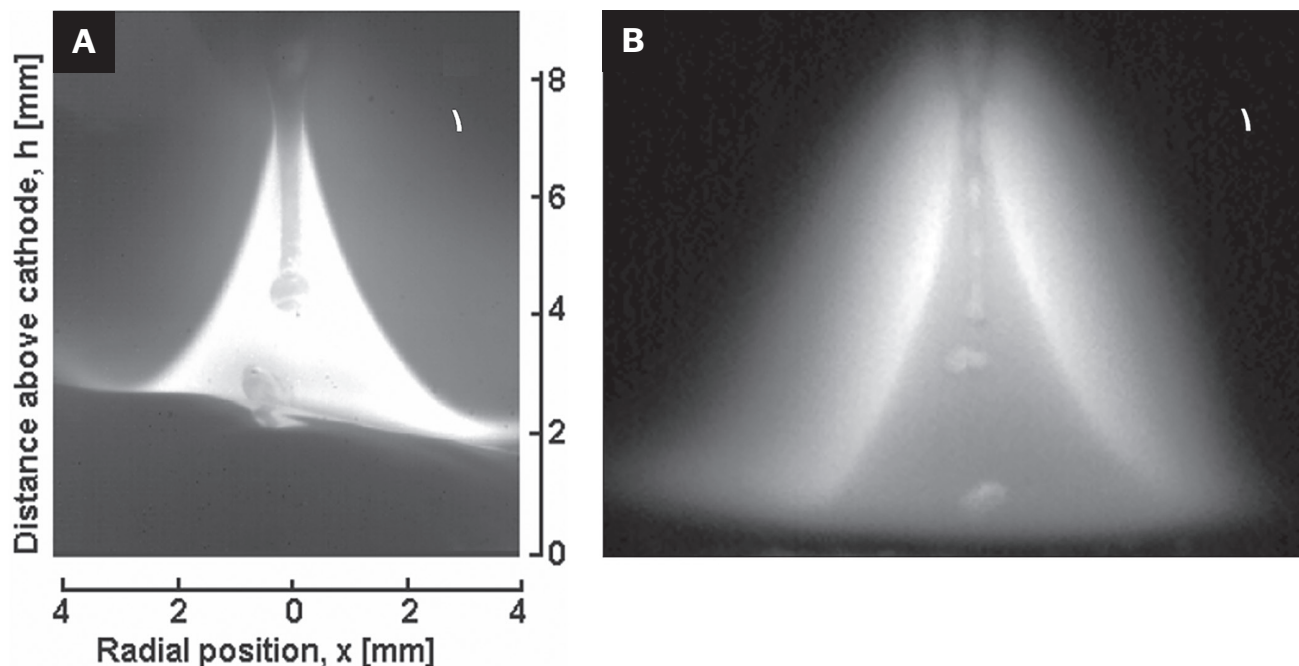


Fig. 7 — Natural radiation lighting of spray transfer in GMAW in pure argon: A — 468.8 ± 3 nm NBP filter highlighting metal vapors (Ref. 36); B — 696 ± 2 nm NBP filter highlighting argon (Ref. 37).

	Positive wave of AC arc			Negative wave of AC arc		
Normal wire						
AFM01 flux coated wire						

Fig. 8 — Natural radiation lighting with a 514.9 ± 6 nm NBP filter of AC GTAW on magnesium AZ31B in pure Ar. The filter was selected to capture the 516.7 nm emission peak of Mg (Ref. 27).

Even with the exact profiles for each filter being unspecified by the author, the side-by-side comparison in Fig. 10 allows several observations: in K) He I is visible, which has a spectral peak at 667.8 nm. The captured image at this filtered range of wavelengths is significantly different from H), where there is no He line, but where metal lines tend to be. Based on this observation, it is possible to deduce that I), which captures the He I spectral peak at 587.6 nm, and

K), which captures the He I spectral peak at 667.8 nm, show the He part of that arc. This observation also demonstrates that the He part of the arc is dim, as the shape is not recognizable in the full spectrum as represented by A). Given the spectra captured, B) – H) are likely characterized by metal vapor lines. Notice that F) and G) look like a mixture of H) and K), which indicates that He spectral peaks are included, probably He I peaks at 501.6 nm in f) and 504.8 nm in G).

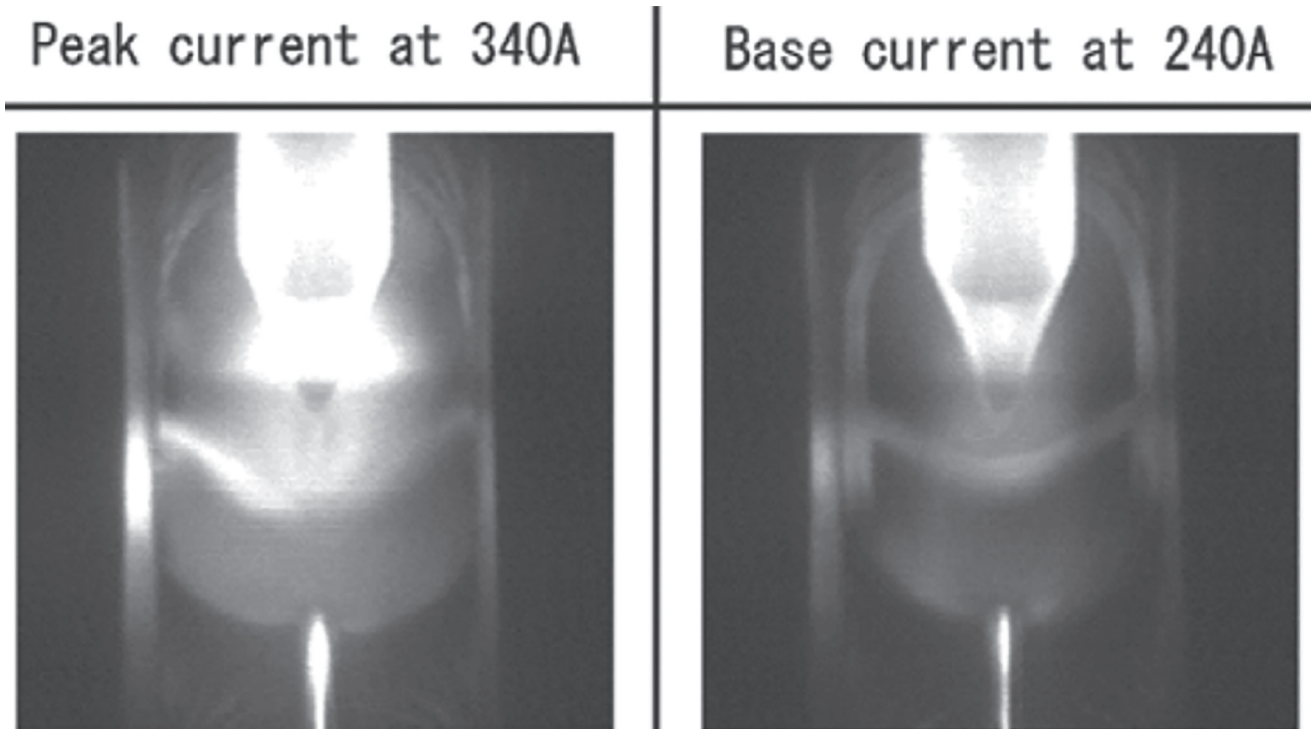


Fig. 9 — Natural radiation lighting with 1064 nm NBP and ND filters of pulsed GTAW in orbital pipeline v-groove welding (Ref. 38).

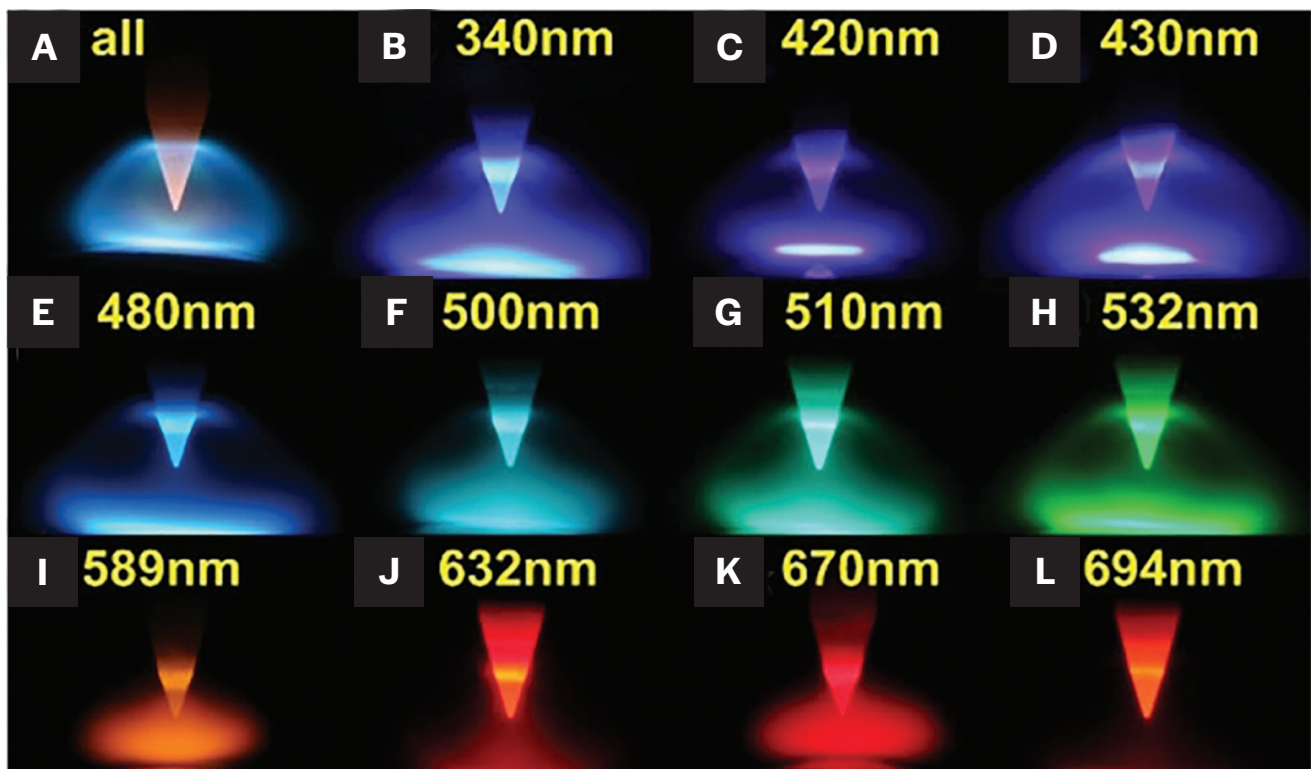


Fig. 10 — Natural radiation lighting with different NBP filters of GTAW of 304 stainless steel in pure He. FWHM of all filters was 10 nm (Ref. 40).

Natural Radiation Lighting Using Edge Filters

Edge filters, in contrast to NBP filters, allow relatively large ranges of wavelengths to pass through. The utilization of edge filters in research applications is limited; however, our experience is that they are very successful for natural radiation lighting applications. Ribic et al. used an SWP edge filter and an ND filter to locate the keyhole in a laser-GMAW hybrid welding system (Ref. 41). Guest et al. used an 850 nm LWP filter to characterize the tungsten carbide non-wetting phenomenon on the weld pool surface when using GMAW with tubular Ni-WC hardfacing consumables (Ref. 42).

The authors have compiled a collection of edge filter images across a variety of welding processes and welding parameters. Figure 11 compares a BP and LWP filter during pure-Ar shielded flux-cored arc welding (FCAW) using a Phantom V210 high-speed camera. The slag flows and molten droplets are clearly observed using the 850 nm LWP filter, whereas the weld pool and slag are difficult to observe with the 700–800 nm BP filter. This is because the camera's color sensor has low spectral sensitivity in the 700–800 nm range, limiting the amount of light collected from the weld pool.

To display colors similar to those perceived by the human eye, the blue filter in the Bayer filter of the Phantom V210 camera is also slightly transparent in the infrared at around 1050 nm (see Fig. 4 in Part 1). Light gathered through this

window of transparency in the Bayer filter is interpreted by the camera as blue, hence the image appears with a purple-blue tint when the 850 nm LWP is used, even though no blue component passes through the 850 nm filter.

Natural Radiation Lighting of Pulsed and Short-Circuit Processes

Imaging dynamic current processes, such as pulsed GTAW/GMAW or short-circuit GMAW, is difficult when relying on natural radiation produced from the welding process. The large intensity differences observed during the background and peak current levels can exceed the dynamic range of camera sensors, and filter selection becomes crucial.

Figure 12 demonstrates the use of an 850 nm LWP filter during pulsed GMAW of Al 4043. In this series of images, the peak current pulse nearly saturates the camera sensor, while the background droplet formation period image is slightly underexposed. The large intensity difference during short-circuit and controlled short-circuit GMAW transfer can be demonstrated by Fig. 13, corresponding to short-circuit metal transfer of controlled short-circuit (Lincoln STT) steel GMAW in Ar-15% CO₂ shielding gas, imaged at 10,000 fps with an 850 nm LWP filter. In this figure, the 300 A peak current of the arc reignition phase nearly saturates the camera sensor, and the molten droplet on the electrode tip and the weld pool

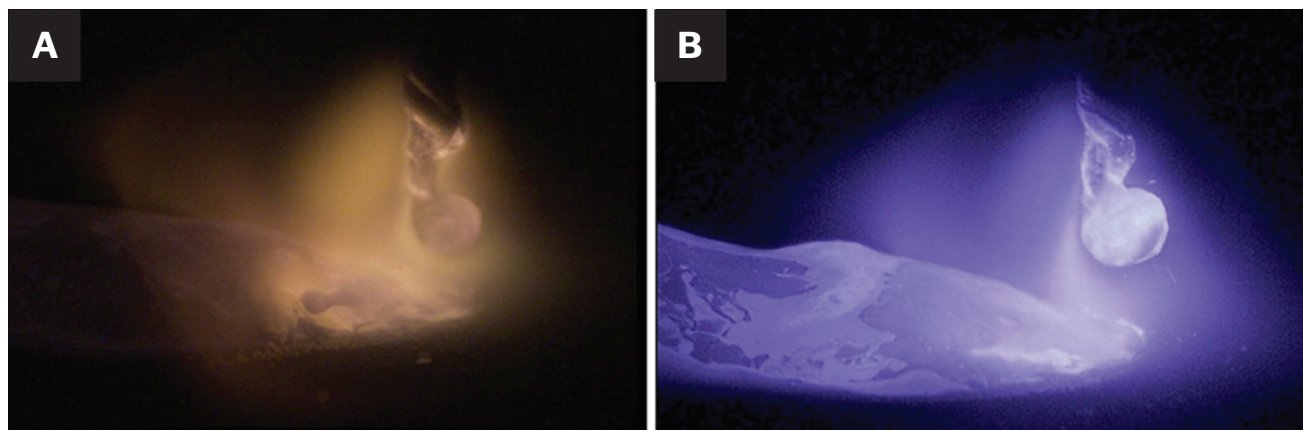


Fig. 11 — Natural radiation lighting of FCAW of E71T-1 in pure argon using two filters: A — 700–800 nm BP; B — 850 nm LWP.



Fig. 12 — Natural radiation lighting with an 850 nm LWP filter of pulsed GMAW of 4043 aluminum in pure Ar: A — Peak current; B — downslope after peak; C — droplet formation during background current.

surface under the arc are barely discernible. A high-speed camera with a lower dynamic range would have most likely been unable to properly image the wide intensity difference of the arc reignition and short-circuit periods.

Natural Radiation Lighting of Processes Under Slag

A special case for which edge filters have been used successfully is the imaging of submerged arc welding (SAW) with

natural radiation lighting, as shown by Sengupta et al. (Refs. 43–46), Reisgen et al. (Ref. 47), and Gött et al. (Ref. 48). In this case, a quartz tube, quartz screen, or thin metal tunnel is used to create an opening in the flux bed and capture the arc and metal transfer process (see Fig. 14). The resulting images are shown in Fig. 15 for the metal tunnel, and Fig. 16 for a quartz screen (1) and quartz tube (2).

A recent adaptation of this technique is Ogino et al., who used a similar setup to observe the flow of molten metal and

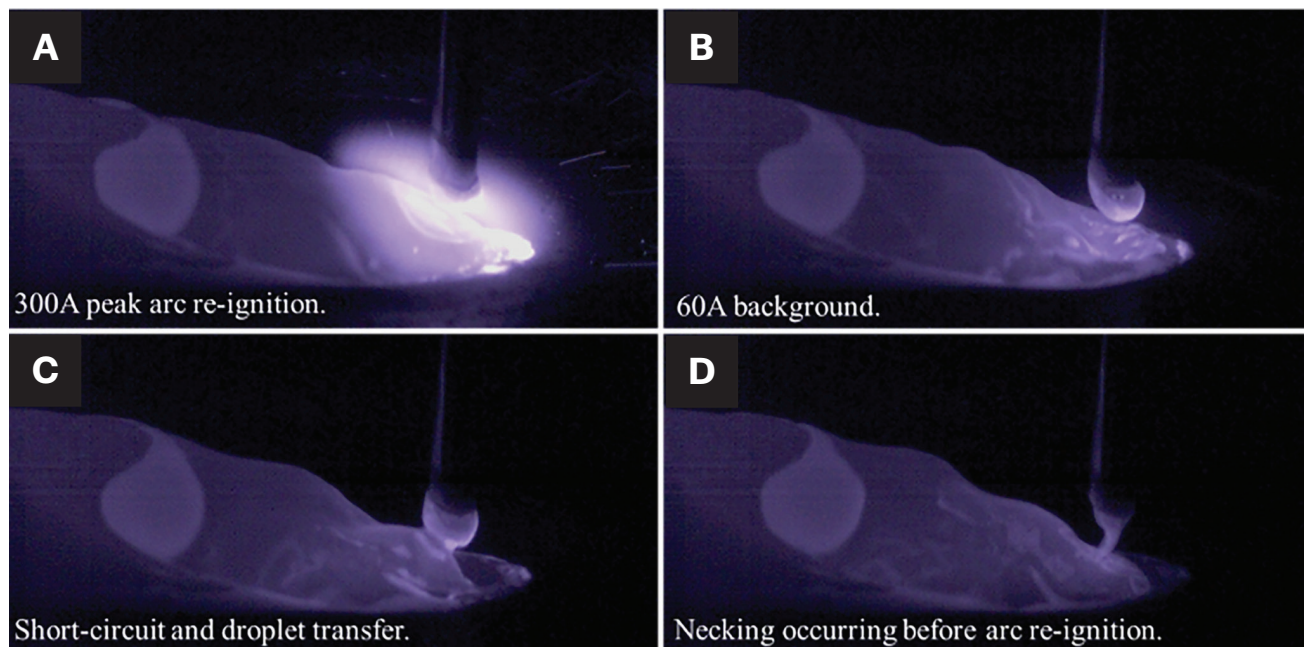


Fig. 13 — Natural radiation lighting with an 850 nm LWP filter of GMAW in short-circuit (Lincoln STT) of steel GMAW with Ar-15%CO₂. Frame rate was 10,000 fps.

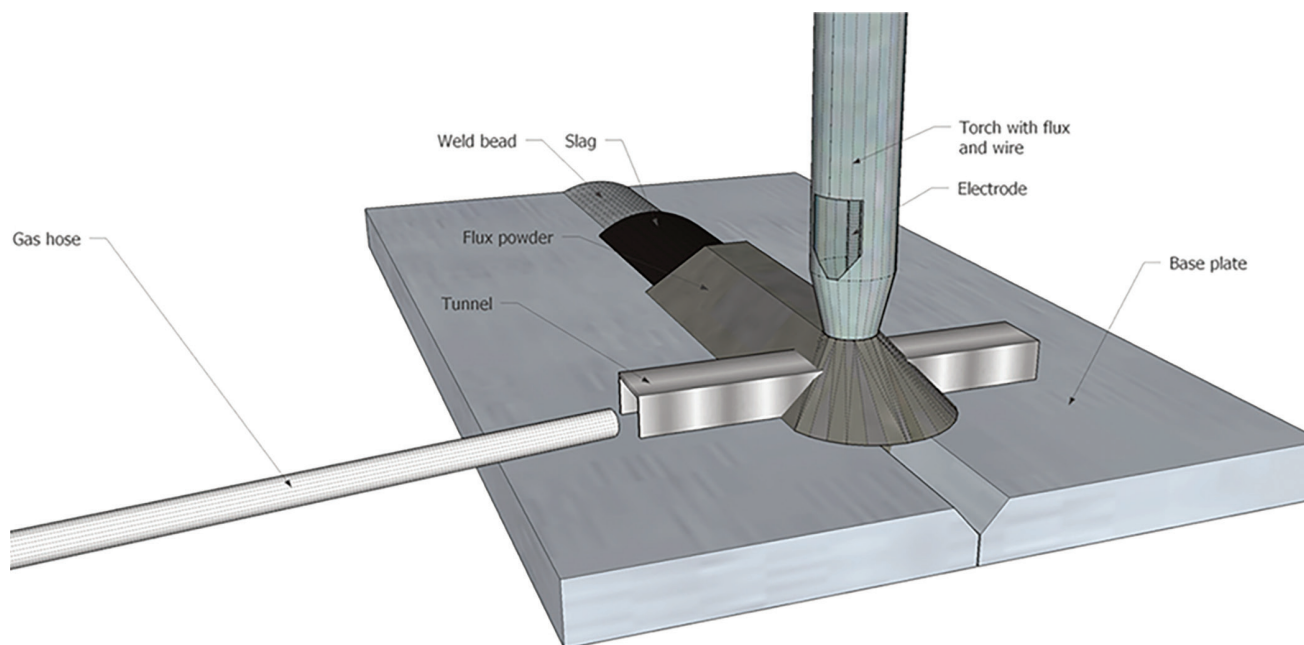


Fig. 14 — Experimental setup for imaging metal transfer in SAW (Ref. 44).

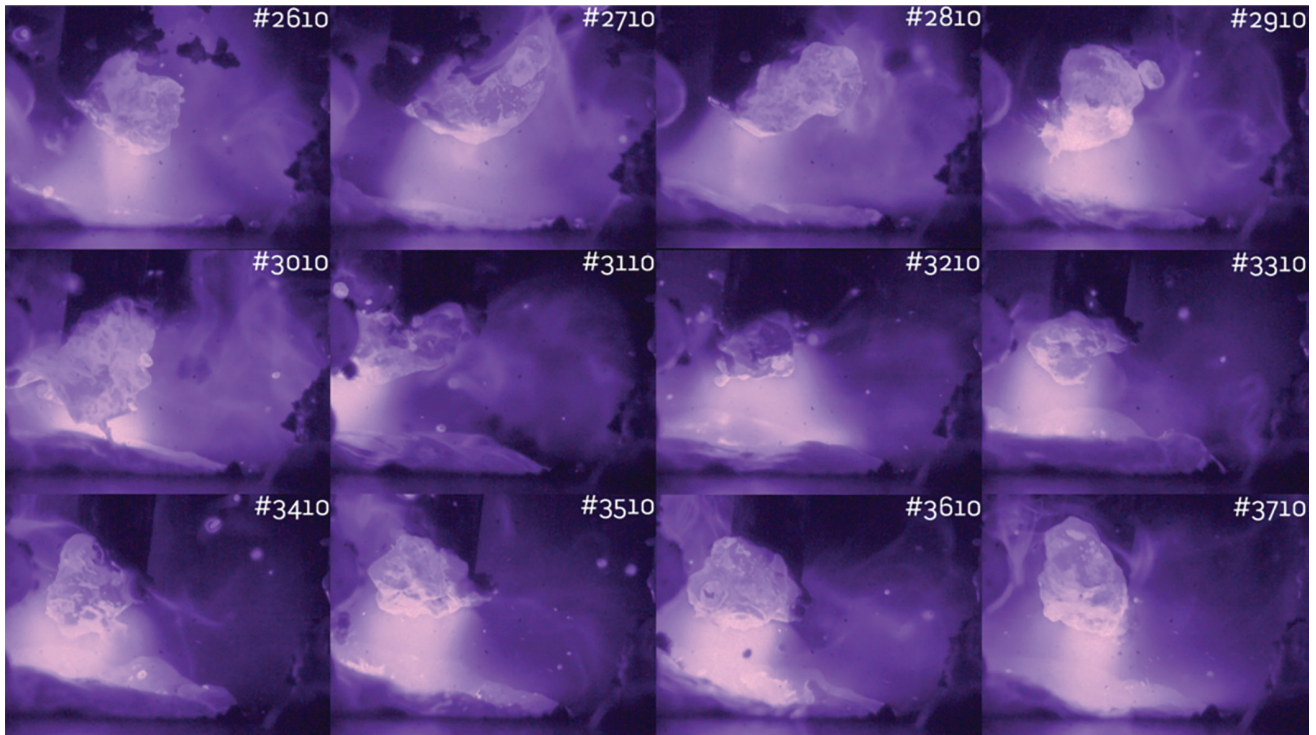


Fig. 15 — Natural radiation lighting of metal transfer in SAW using an 850 nm LWP filter and a thin metal tunnel. Welding parameters were 500 A DCEP and 30 V, and the frame rate was 10,000 fps (Ref. 44).

slag in electro slag welding (ESW). They created a modified Hele-Shaw setup with a viewing window and used a high-speed camera (see Fig. 17). They did not specify a filter. Still, the yellow-orange coloration of the image suggests a filter in the range around 590 nm (Ref. 49).

Natural Radiation Lighting of Laser Processes

Edge filters can also be applied to non-arc welding processes, such as laser welding and cladding. Figure 18 illustrates laser cladding with a 4 kW CO₂ laser with a wavelength of 10.6 μ m of Inconel 625 (A, C) and Ni-WC wear-resistant powders (B, D) with a coaxial feeder. Natural radiation lighting with an 850 nm LWP filter (C, D) limits the large contrasts caused by temperature gradients. This produces clear images of powders preheated under the beam and powder impinging on the weld pool's free surface. Cold powders emitting little IR radiation are not visible in this case. For comparison, the same processes are imaged with a halogen sidelight (A, B), which reveals the powders above the weld pool, but overexposes the weld pool.

Natural radiation lighting imaging of diode or Nd:YAG fiber laser welding, with a wavelength of 1064 nm, can present a challenge for researchers. The camera sensor may be sensitive to the laser light and saturate very quickly due to the high intensity of the reflected light. In this case, using a blocking notch filter for 1064 nm with an optical density of 6 is advantageous, since it blocks the reflected laser light and allows the combination of other filters. Alternatively, a 1000 nm SWP filter could be used.

High-Speed Temperature Measurements Using Natural Radiation

Natural radiation emissions can also be used to measure the metal and the arc temperature. Arc temperature measurements are outside the scope of this review because they involve specific techniques often requiring dedicated spectrometers. For metal temperatures below visible glowing (600°C–800°C), emission outside the IR range is negligible, and dedicated infrared SWIR and LWIR cameras are needed. For higher temperatures, radiation in the visible spectrum allows visible-light sensors (also sensitive in the NIR range) to perform temperature measurements.

Dedicated IR cameras operate with similar principles to those for visible light, but sensor materials are different. Temperature estimation is based on the intensity of radiation arriving at each pixel. One significant limitation of this technique in welding is the damage the welding arc can cause to the non-refrigerated thermographic sensors. Common sensors are often made of vanadium oxide or amorphous silicon whose resistance changes when radiation impinges on the sensor pixels. Welding applications require sensors made of indium antimonide (InSb) and actively cooled (e.g., by a Stirling cooler), and work by counting the photons of energy in a specific waveband. These sensors are significantly more expensive but can be exposed to arc emissions without damage and calibrated beyond 2500°C (depending on the camera, this may require an ND filter). Some high-end thermal cameras can also do high-speed imaging (e.g., 4175 fps for FLIR A6751SC when using windowing).

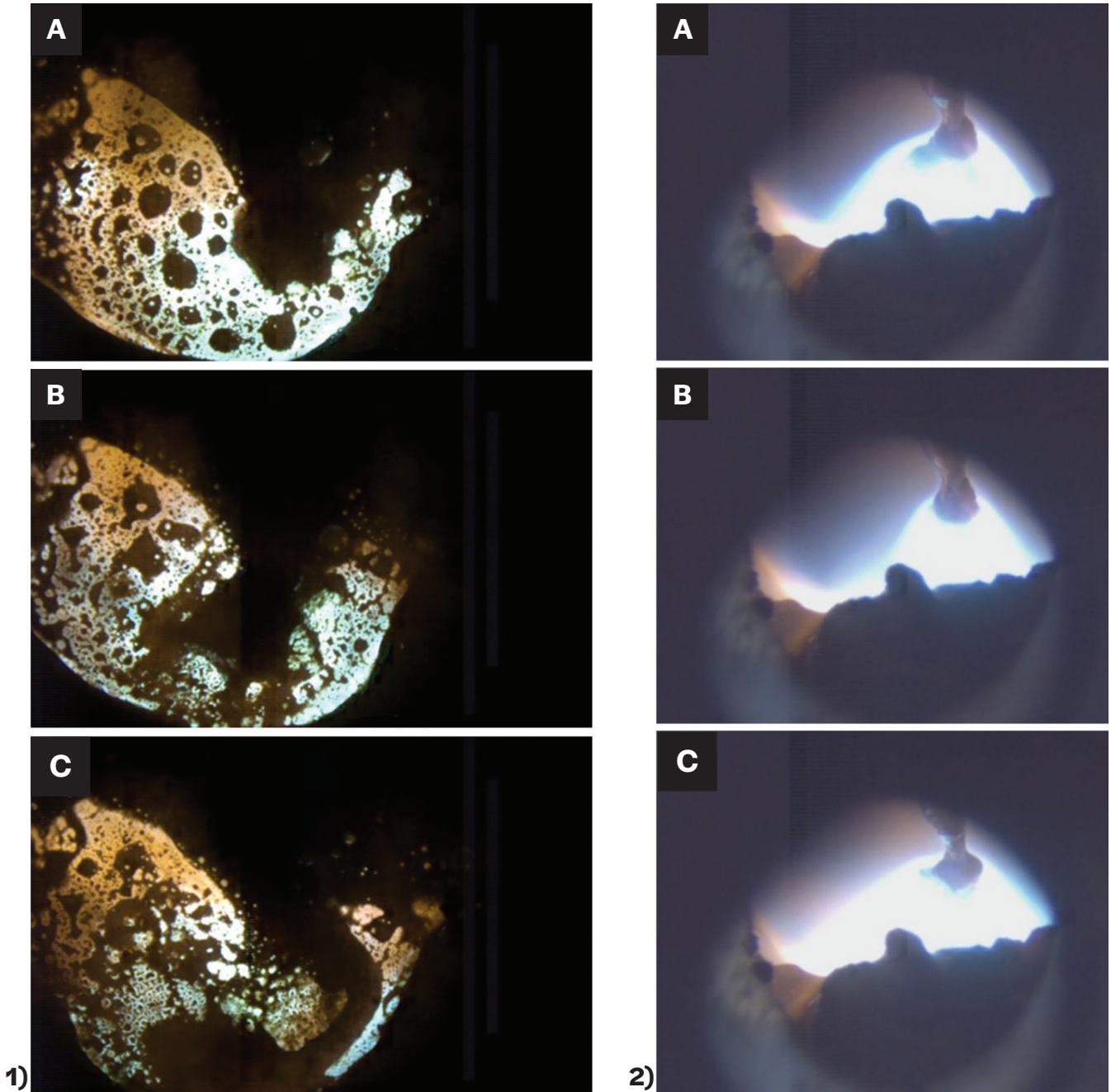


Fig. 16 — Natural radiation lighting of metal transfer in SAW. Welding parameters were 435 A DCEP and 28 V, and the frame rate was 20,000 fps: 1 — A quartz screen was placed parallel to the travel direction; 2 — a quartz tube was placed parallel to the travel direction (Ref. 47).

A challenge of thermal imaging based on intensity is that temperature estimation depends on the emissivity of the surface, about which there is typically a large uncertainty, varying with different materials, wavelengths, and angles towards the camera. Environmental disturbances can also be measured, such as temperature and gas composition between the emitter and the camera.

Visible light high-speed cameras are applicable at high temperatures, such as those of molten metal. They can infer emissivity pixelwise by using more than one wavelength, thus conferring advantages over standard thermal cameras,

which use a single unknown emissivity for the whole image. The multiple wavelengths can be obtained, for example, by filtering light through two NBP filters, or by splitting the optical path behind a lens into two synchronous images, each with a spectral NBP filter of a distinct narrow spectrum range.

There are four main techniques for splitting the optical path into multiple wavelengths. First, a monochrome sensor separates the optical path into two or more images (Refs. 9, 37, 51–54). Second, an RGB color sensor reads the three output signals separately (Refs. 7, 55, 56). Third, using a camera with a beam splitter and separate sensors (Ref. 57).

Fourth, using a pyrocam with a custom sensor that filters two wavelengths (Refs. 51, 58). A bifurcation setup has the advantage of comparing two wavelengths that ideally are relatively far apart and thus can use Planck's law to determine a temperature irrespective of emissivity (Refs. 9, 51).

While using multiple wavelengths eliminates the need for calibration based on emissivity, the angle of observation still needs to be considered, as in metals, the directional emissivity is higher at shallow observation angles (Ref. 59). As Siewert et al. point out, this results in a higher temperature estimation at shallow angles (Ref. 22).

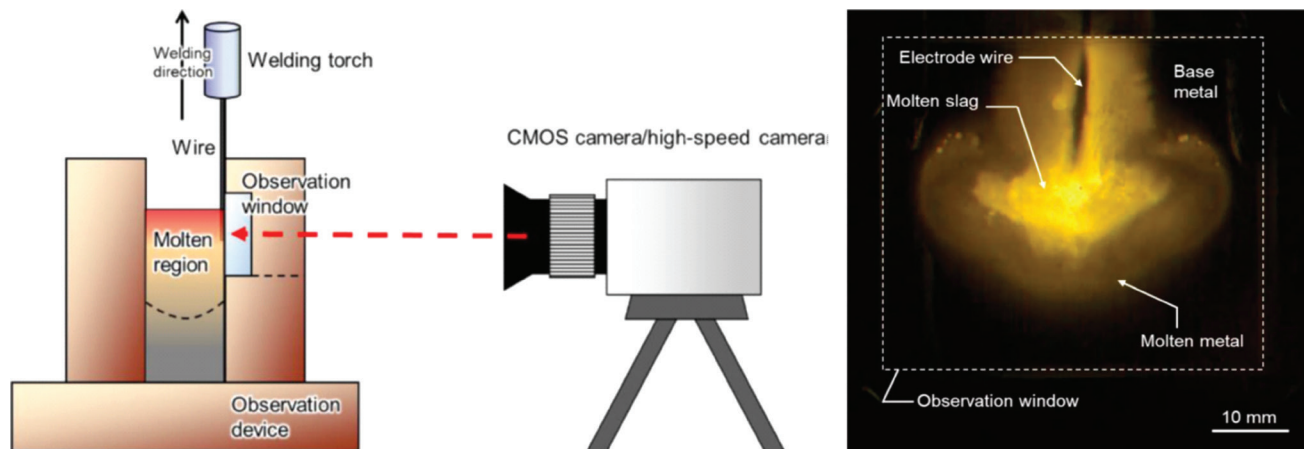


Fig. 17 — Natural radiation lighting of molten metal and slag flow in ESW using an observation window that functions as a Hele-shaw cell (Ref. 49).

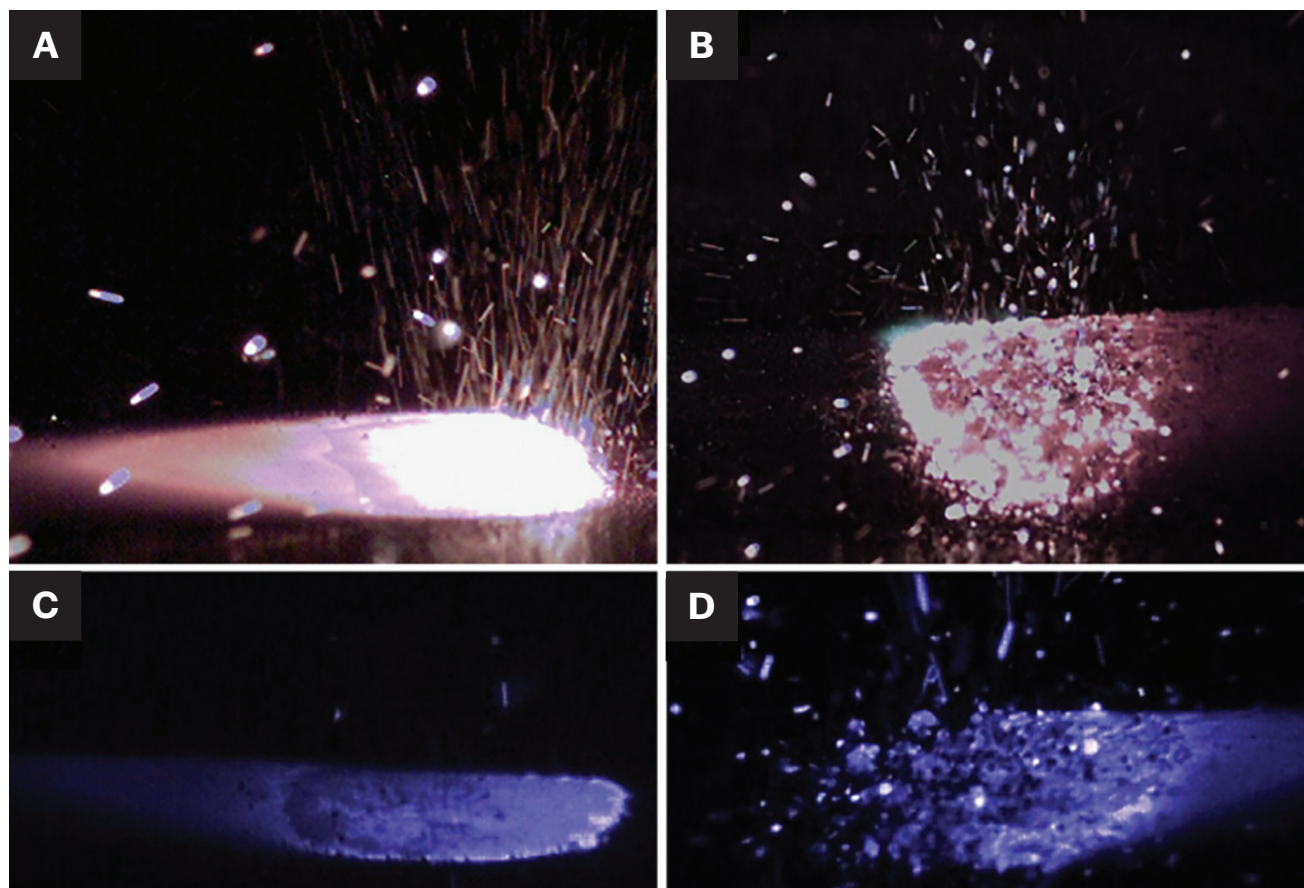


Fig. 18 — Front lighting with a halogen light and no filters (A, B) and natural radiation lighting with an 850 nm LWP filter (C, D) of laser cladding with a 4 kW CO₂ laser of Inconel 625 (A, C), and Ni-WC (B, D) (Ref. 50).(TH4.1)

Summary of Advantages and Disadvantages

Disadvantages of natural radiation lighting include the challenge of imaging processes of high dynamic range, such as short-circuit metal transfer in GMAW. Typically, cameras with high dynamic ranges are needed; however, this is not a problem for modern digital cameras. Features of the welding process that emit little radiation are often unseen, such as the electrode extension in GMAW. Another challenge of natural radiation lighting is that selecting filters and camera settings is more difficult than other lighting techniques because the camera receives the full light emitted by the metal and the arc without assistance from an external source.

Conclusions

The technique of natural radiation lighting of high-speed imaging of welding and its combinations with other lighting techniques are reviewed in depth. Detailed descriptions of appropriate setups and examples of published practical implementations are provided. Welding and related processes addressed include GMAW, GTAW, FCAW, SAW, ESW, and laser cladding.

Natural radiation lighting is especially useful because of the simplicity of the equipment involved and because it offers information about the surface of the molten metal, including a sense of surface temperature, even when using cameras that capture only visible and near IR radiation. Natural radiation lighting also offers information about the arc, such as the presence of metal vapors. Features of the welding process that emit little radiation are often unseen, such as the electrode extension in GMAW. The selection of filters is critical in this technique and requires knowledge and patience.

The practical implementations reviewed in this paper, together with the fundamentals described in Part 1 and the techniques of back lighting and front lighting described in Part 2, should enable welding researchers to select proper equipment, accessories, and parameters for high-speed imaging of a vast variety of phenomena in arc welding, laser welding, and associated processes such as additive manufacturing or cutting.

Appendix

Acronyms

BP	Band pass
CCD	Charge coupled device
fps	Frames per second
FWHM	Full width half maximum
IR	Infrared
LWIR	Long wavelength IR
LWP	Long-wave pass
NBP	Narrow band pass

ND	Neutral density
RGB	Red, green, and blue color channels
SWIR	Short wavelength IR
SWP	Short wave pass
UV	Ultraviolet

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