# Complete In-Process Monitoring of Cold Spray with High-Speed Multispectral Infrared Imaging

Cold spray technology has attracted considerable attention in recent years as it has fully evolved from a conceptual theory to a practical application in industry. There are still many challenges with optimizing cold spray methodologies, but high-speed infrared imaging cameras offer rich information which is valuable to this process. Telops worked with the Canadian National Research Center (NRC) to test the capabilities of Telops' multispectral cameras in monitoring multiple key processes during cold spray depositions. As opposed to previous cold spray measurements which only probed the temperature and speed of particles in flight, the NRC team seek to monitor the emissivity change of deposited layers on the substrate during the cold spray process. Time-resolved multispectral imaging illustrates the benefits of spectral information obtained at a high frame rate when facing dynamic situations such as this. The Telops MSM3K camera was used to fulfill these demanding requirements. In this note we present measurements demonstrating the possibility of performing complete in-process monitoring of the cold spray technique.

## Introduction

Cold spray technology has developed rapidly over the last three decades with applications in fields including aerospace, additive manufacturing, biomedical instruments, energy, and electronics. Cold spray is especially amenable to process metals and inter-metallic compounds that must avoid oxidation and high thermal stress during manufacture, nanomaterials that commonly have grain issues when heated, and amorphous materials that easily crystallize [1, 2]. Cold spray systems are still in the early stages of industrial implementation, but they have already demonstrated great potential in improving performance and efficiency while reducing costs. Proper understanding of the thermo-mechanical processes happening during cold spray depositions is key to optimizing this promising technology and allowing its wide-spread use in industry.

Particle impact velocity and temperature are two key factors which describe the bonding behaviour. Measuring these physical quantities experimentally is essential to optimizing the cold spray process and the final product. Previous Telops work focused solely on the temperature and speed measurements of in-flight particles in the cold spray jet and the post-processing deconvolution required to obtain the true particle temperature [3]. This application note gives an overview of the potential for complete monitoring of all parameters in a cold spray process including spectrally resolved emissivity change, in-flight particle speed and temperature, and thermal profiles of additive manufacturing-like structures.

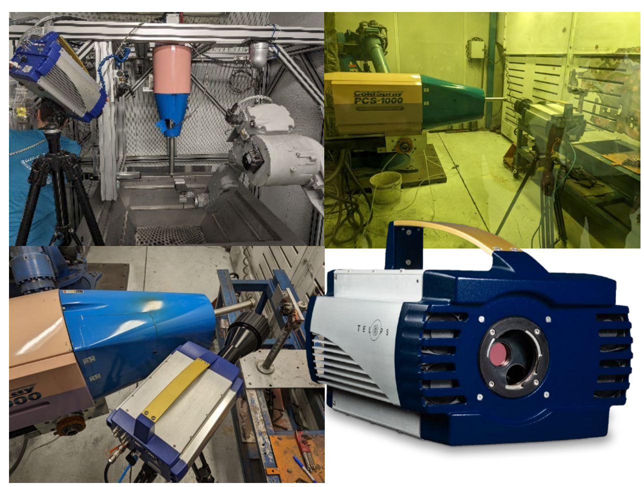

**Figure 1 Telops MSM3K multispectral camera mounted in various positions for cold spray monitoring**

## Experimental Information

The cold spray application involves multiple types of observations requiring good temporal and spectral resolution. Thus, the Telops MSM3K is a perfect candidate. The camera has an extended infrared midwave range of 1.5-5.4 µm and uses a 320×256 pixel cooled InSb focal plane array (FPA) detector. All Telops cameras benefit from the real-time radiometric and non-uniformity correction features using the Telops patented calibration method [4].

A Telops-designed G1X microscope lens with a 29 cm fixed distance and 9.6 mm field of view of was used to catch the in-flight particles and the magnified structure growth edge. For high-speed imaging of the jet, the integration times were set to either 3, 5 or 7 µs at a frame rate of 3000 Hz and a narrowed window size of 320x64 pixels. The structure growth observations done with the G1X and 50 mm lenses were accomplished with a lower frame rate of 100 Hz and automatic exposure time (AEC). All experiments were conducted indoors at an ambient temperature of about 20 °C. The MSM3K camera was maintained at a safe distance from the jet as the highest risk of damage was from the structure growth measurements due to particle ricochets. The jet gun was angled at $\sim 20$° from normal to the substate (Figure 1, bottom left) to minimize the number of particles bouncing back to the camera.

To provide spectral information for the substrate scene (Figure 1, top left), the 8 multispectral channels of the MSM3K were used to observe the variation in radiance as a function of wavelength during a deposition. Channels #1 had no filter and #2 was equipped with an OD-1.0 neutral density filter, such that the associated frames in those channels are representative of broadband images. The other 6 channels had various narrow band spectral filters. Image acquisitions for the substrate were carried out using the full FPA window with the AEC adjusted exposure times ranging from 14 to 110 µs depending on the channel in multispectral mode. The filter wheel rotation speed was set to its maximum speed of 6000 rpm leading to an effective frame rate of 100 Hz/channel. The camera was installed at various distances from the targets depending on the scene observed and the lens used, as shown in Figure 1. A circular 50 mm Janos Varia lens was used for the substrate multispectral data acquisition and structure growth measurements.

# Results and Discussion

## In-Flight Velocity and Temperature

With the G1X lens, clear images of the microparticles ranging in diameter from 40-50 µm were obtained while they moved at supersonic speed which allowed calculating their temperatures and velocities. The expected "smearing effect" is demonstrated in Figure 2 where a particle's radiance is spread over a range of pixels at a longer exposure time.

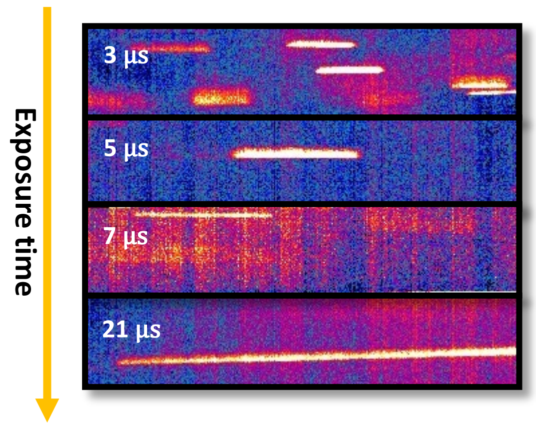


**Figure 2. NUC images of Cold Spray particles in flight showing a stronger smearing effect at increasing exposure time.**

The particle velocity calculated from the horizontal smear using Particle Streak Velocimetry (PSV) was well within the uncertainty of the expected velocity (slightly above 600 m/s) based on the test parameters. The particle temperature was calculated by accumulating the radiance of the entire smear and using a semi-empirical law (Equation 1) to express the signal detected by the infrared camera [5].

$$W_{tot} = \varepsilon_{\lambda,T_p} \frac{R}{exp\left(\frac{B}{T_p}\right) - F} + \left(1 - \varepsilon_{\lambda,T_p}\right) \frac{R}{exp\left(\frac{B}{T_{ref}}\right) - F} \qquad (1)$$

Here, $\varepsilon_{l,Tp}$ represents the particle emissivity, $T_p$ is the particle temperature, $T_{ref}$ is the temperature of the surroundings, $R$ is a function of exposure time and wavelength band, $B$ is a function of wavelength, and $F$ is a positive value close to 1. The emissivity has to be assumed to be a constant for the calculation.

Details of the modeling and larger scale testing can be found in the application note mentioned earlier [3]. The results here are similar to the previous study with the recorded in-flight temperature being slightly greater than the simulated temperature. A major influencing factor is that most of the observed radiance comes from particle reflection (due to a low ε value) and a portion of the signal comes from the hot nozzle in the scene as expected.

## Thermal Monitoring of Structure Growth

Figure 3 shows a recording of structure growth accomplished by cold spray of copper particles. The sturdy 2 cm tall copper structure took 10 s to grow. The hot spot of the cold spray within the elevating crater followed by rapid cooling of the bottom layer of the structure were observed. The measurements with the G1X lens (Figure 5, bottom left) enabled imaging of the rough surface edge of the structure which transferred heat to the substrate. The focal plane was very narrow due to the angle of the camera, but the position of the plane was observed to gradually move left as the copper accumulated on the surface.

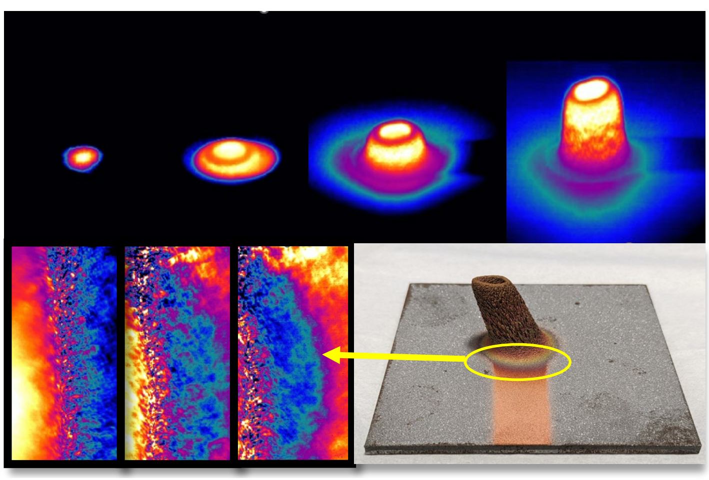

**Figure 3. Thermal Imaging of structure growth through cold spray deposition. Bottom left, imaging with G1X lens done to observe the temperature behaviour at the edge of the deposited structure. Plane of focus moving towards the left as the material was deposited from that side. Bottom right, the copper structure grown following the angle of the cold spray gun.**

The temperature profile of the structure is shown in Figure 4. Initially, an emissivity of 1.0 for a blackbody is assumed but the profile is later corrected in post-

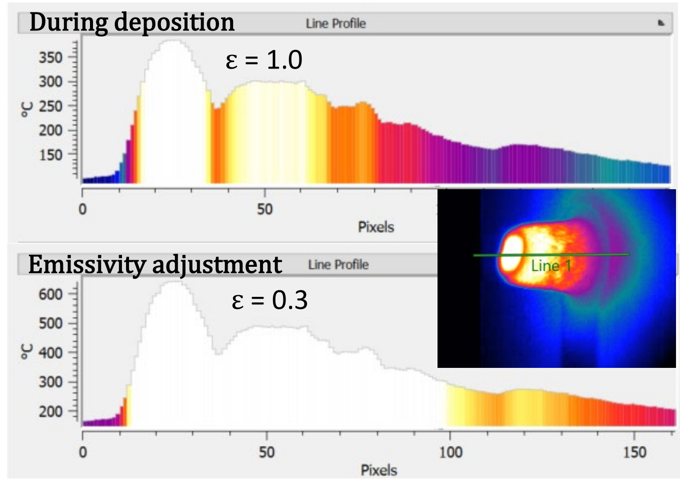


**Figure 4. Temperature profile of the structure during the deposition. Live temperature is significantly lower than the real temperature due to Telops camera assuming the scene is a black body. The low emissivity value of copper can be incorporated to adjust the data in post-processing.**

processing within the RevealIR software using an emissivity of 0.3. This ε value is a rough estimate for copper which does not account for the wavelength dependence of the emissivity and the very rough surface of the structure. Nevertheless, the corrected temperature profile is much closer to the real temperature of the particles bonding on the substrate. While more testing and optimization is required to determine the material's emissivity behaviour during the cold spray process, this work illustrates that thermal monitoring in such an additive manufacturing process using a high-speed infrared camera works extremely well.

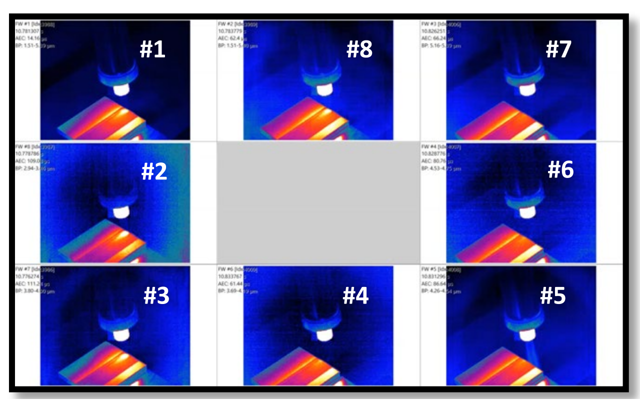


**Figure 5 Top view multispectral acquisition of the substrate during the Cold Spray deposition process. The 8 channels images are in NUC mode. Difference in the spectral windows show a variation in radiation detected, information used to determine the change in emissivity after deposition.**

### Future Work: Emissivity change on substrate

As shown in Figure 5, the radiance level observed in the midwave infrared range varies depending on the spectral window of each filter channel. Performing a multispectral emissivity measurement for metallic layer deposition can be quite challenging. Indeed, the observed temperature of the deposited copper layer is lower than the steel substrate even though the copper layer temperature should be the same or higher than the steel.

Emissivity depends on the material composition, thickness, roughness, and oxidation of the deposited layers. Radiometric calibration of a multispectral camera involves characterizing the response of the detector and full optical train in all channels against known radiance produced by a blackbody reference. The real temperature of a selected target can be estimated according to its spectral emissivity within the range of each filter. Additionally, a challenge in trying to accurately monitor particle temperature in the cold spray process is that the particle emissivity is predicted by the NRC team to dynamically change during deposition. The tests described here were not performed with a multispectral camera optimized for such dynamic emissivity conditions. Ideally, the filter wheel should be configured with multiple narrow band filters which have very close but not overlapping spectral properties to generate an emissivity curve as a function of wavelength. The results nevertheless show that it is possible to distinguish the radiance emitted in selected spectral windows and to observe the emissivity differences with good temporal and spatial resolution. In Figure 3, cold spray is observed in some channels (#5 in particular) is visible while not in others. This indicates that filters within specific spectral windows would facilitate monitoring the emissivity change on the substrate without extraneous signal from the “hot” gas in the spray. This is equivalent to using a through-flame filter in combustion applications [6].

## Conclusion

The combination of Telops high-speed thermal imaging and permanent calibration permits complete in-process monitoring of cold spray processes. In addition, spectrally resolved multispectral imaging offers the potential for monitoring changes in particle emissivity during particle-substrate bonding. These capabilities can be invaluable for refining the bonding models for new materials and for improving the cold spray manufacturing methodology.

We invite readers to visit the Telops’ YouTube channel to see this data in action in the video obtained on this topic.

## References

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