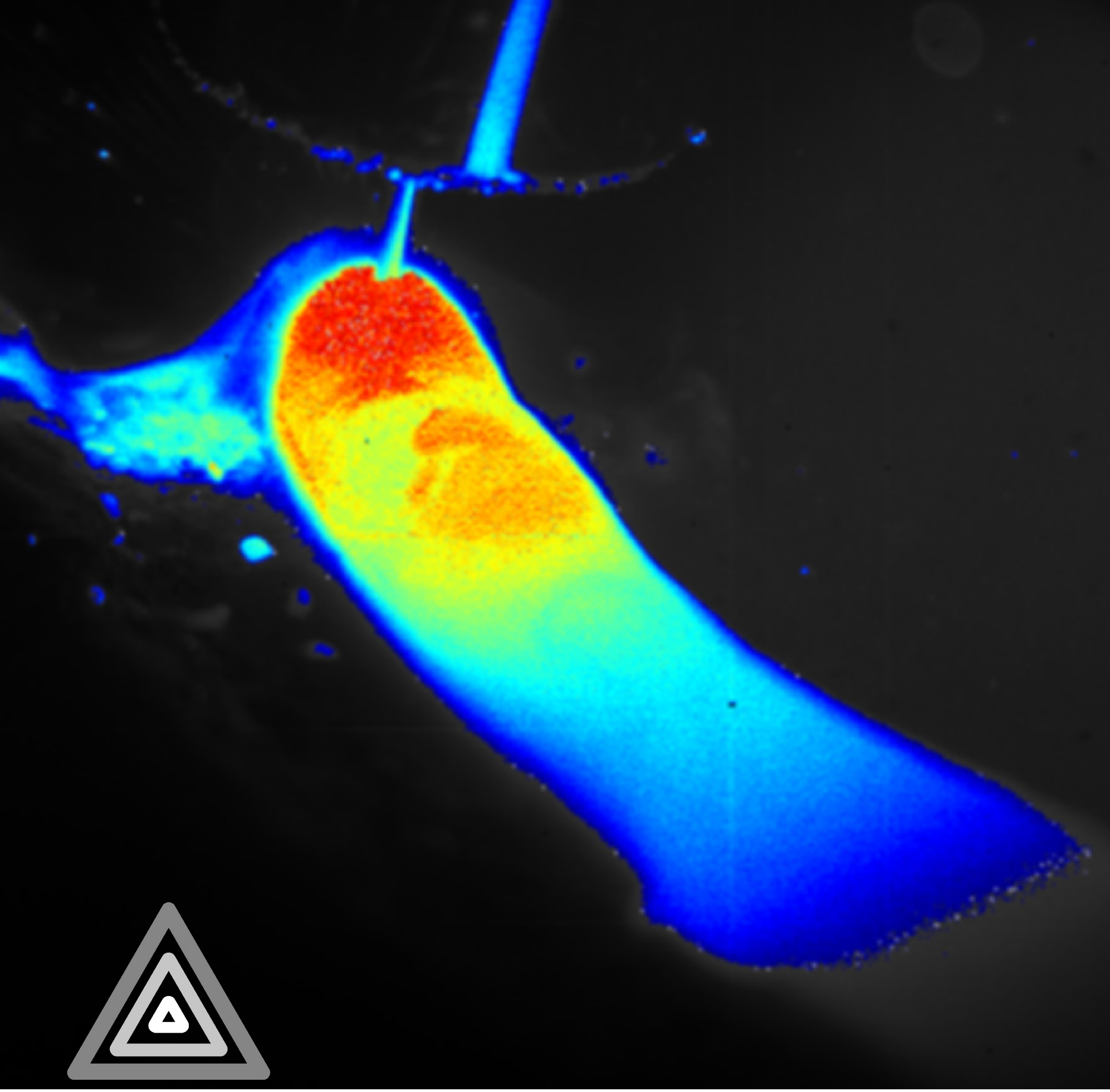


SWIR Thermal Imaging for Metal Additive Manufacturing

XIRIS
Inspection Solutions with Vision

Background

Metal Additive Manufacturing (MAM) is a new technology that produces 3D parts, layer by layer, from a powder or wire based material. It includes a variety of different process technologies used to build up a part, currently being commercialized by various companies, most of which have a proprietary variant of the category of technology they employ, as seen below:

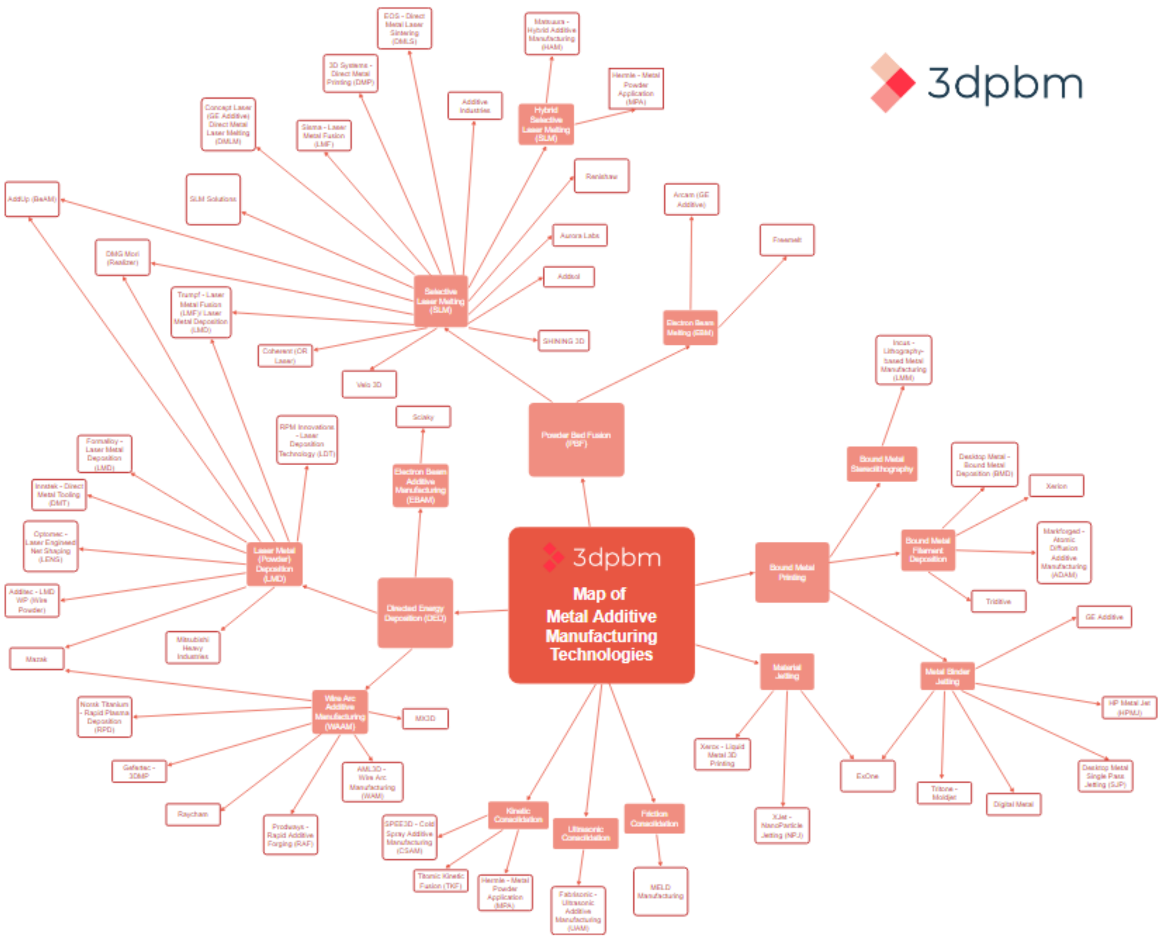


Figure 1 - Map of Additive Manufacturing Technologies (Source: 3dpbm Complete Map Here)

Metals involved in MAM are typically stainless steel, steel, aluminum, titanium, cobalt or nickel either in pure form or as an alloy. The choice of MAM process technology used is a function of different parameters including part complexity, part size and volume to be produced.

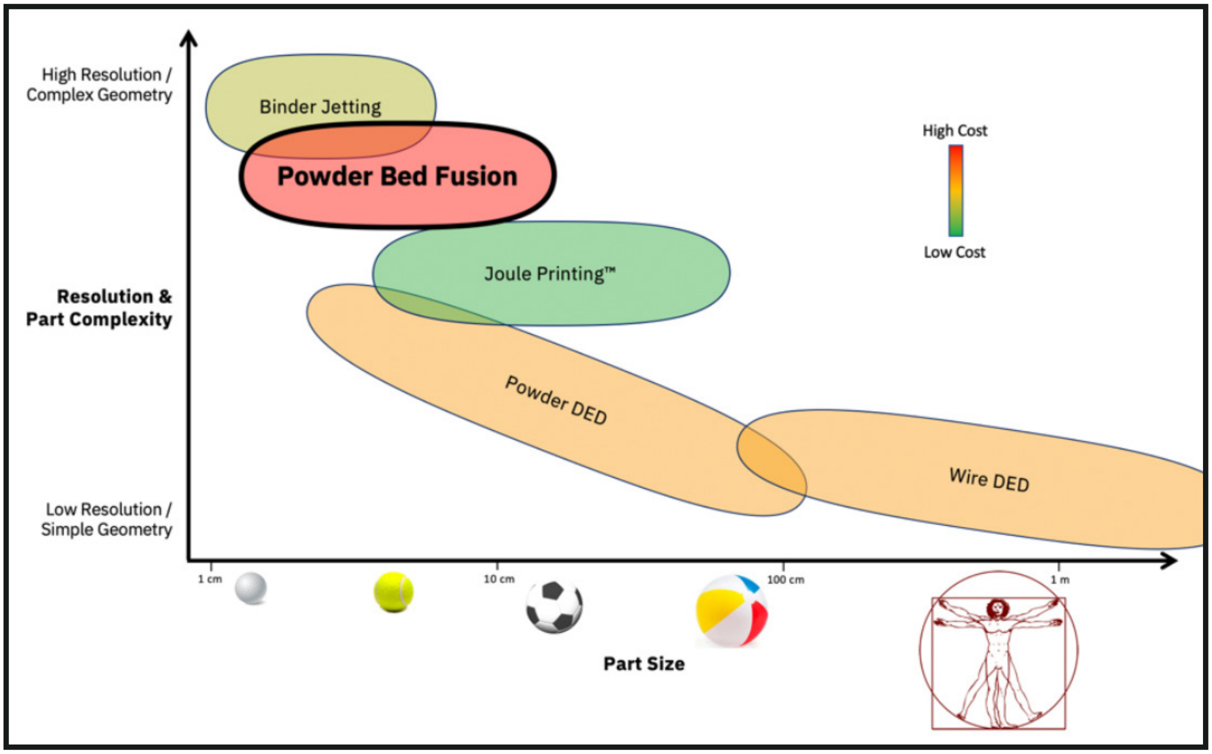


Figure 2 - Metal AM Process Technology Applications (Source: Digitalloys)

MAM is a fast growing industry that is able to offer the promises of lowering the production cost, shortening development and manufacturing times, improving part performance (incorporating part weight or internal shapes that are not possible when using any other manufacturing technology), or even the ability to repeatedly repair highly complex parts made out of expensive exotic metal materials.

Manufacturers of precision parts are attracted to using metal AM instead of other traditional powder processes (e.g. Hot Isostatic Pressing - HIP, Metal Injection Molding - MIM, Press and Sintering) or traditional metal machining processes because it allows for the production of intricate, free-form components directly from CAD—making the production of these parts more feasible than with conventional machining. In addition, Metal AM parts often end up being lighter and stronger than parts made with traditional subtractive machining processes and are made with a lower environmental impact.

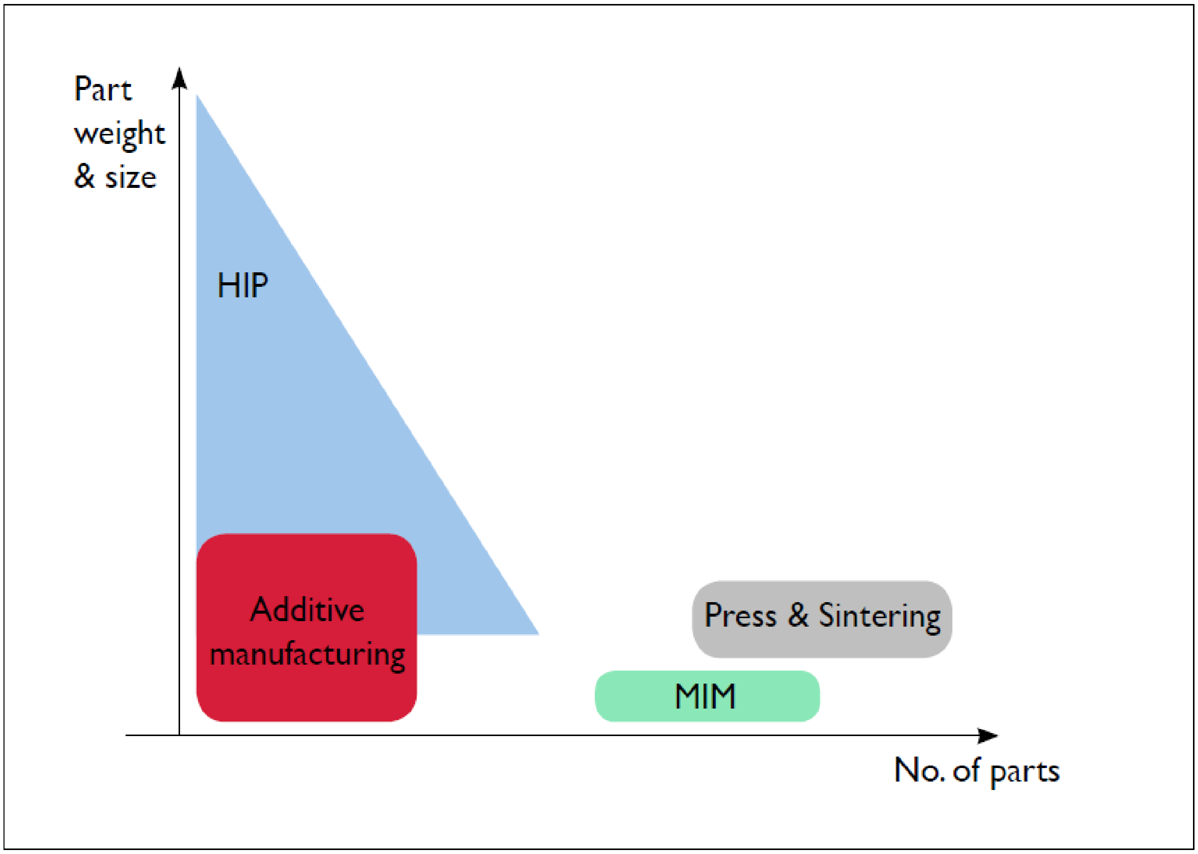


Figure 3 - Powder Base Additive Manufacturing positioning (Source: EMPA)

However to make those objectives a reality, many process and quality control challenges that arise due to the complexity of the MAM-produced parts must be resolved. In particular, the difficulty of precisely controlling the deposition process and the demanding qualification procedures required of parts destined to industries such as aerospace, automotive, medical, power generation, and some consumer goods are often obstacles to a successful process implementation.

Traditionally, process and quality control has been achieved on MAM processes through direct (and often limited-view) observation of the deposition process or statistical non-destructive and destructive post-process testing of a large number of completed parts. This method of quality control is often not feasible because of its cost—a problem that increases with the complexity and size of the batch of parts.

Fabricators implementing Metal Additive Manufacturing in industries such as aerospace, defense, and healthcare have no room for error in their manufacturing processes. They must ensure that the resulting parts are geometrically and metallurgically sound. This is critical to the success of the process and requires using all available information and developed algorithms to be able to monitor and adjust the process in real time. Parameters such as the base material and melt pool temperature and appearance or the melt pool/weld bead cooling rates can be very useful important information to control the process.

To monitor these process inputs, use of non-contact temperature measurement sensors is needed, so many fabricators are considering the use of pyrometers or thermal imaging/thermography cameras. However, when monitoring specialty metals with high melting points, using a sensor with the wrong thermal technology can lead to unreliable and unusable measurements for quality or process control.

With the right tools, operators should be able to see and detect defects in the deposition process, correcting them prior to completion of the product build.

The Challenges of Using Thermal Cameras to Detect Defects in MAM

There are a number of issues related to the detection of defects during the deposition process in MAM, including:

1. **High Contrast Scenes**

   Direct Energy Deposition (DED) is a form of Metal Additive Manufacturing where the power source (typically an open arc welding torch such as TIG, plasma or laser) travels with the material to be deposited (typically in the form of a wire or powder), melting the material as soon as it has been fed. The bright arc (in Wire Arc Additive Manufacturing, or WAAM) or the laser spot (in Laser Cladding applications) can saturate a traditional thermal camera in the weld arc or melt pool region, resulting in a poor image with no potential for meaningful measurement capabilities.

2. **Fast Illumination Changes**

   DED is a fast and dynamic process that requires high speed data capture needing a global shutter with short exposure times. Process measurements, complex analys and results need to be in real-time, with low latency to be able to enable precise control. Some applications require the complete process to be recorded without the loss of a single frame and that video to be stored for many years as backup.

3. **Emissivity Changes**

   The emissivity of a metal (or the measure of the metal's ability to emit infrared energy and therefore indicate the temperature of the object) can change significantly based on the texture and metallurgical composition of the surface of the metal. Molten metal (such as aluminum, stainless steel, titanium, etc.) that has a very shiny, mirror-like surface has very low emissivity that can change significantly with small changes in surface texture. Such emissivity changes can lead to large measurement errors of the temperature of the metal.

4. **Harsh Environment**

   The operating environment of a DED process is typically very harsh, with high ambient temperatures, smoke, fumes and spatter. Sometimes in the DED process, ambient particulates such as smoke and fumes can block the view of the process when using visible light imaging systems.

5. **Size and Weight**

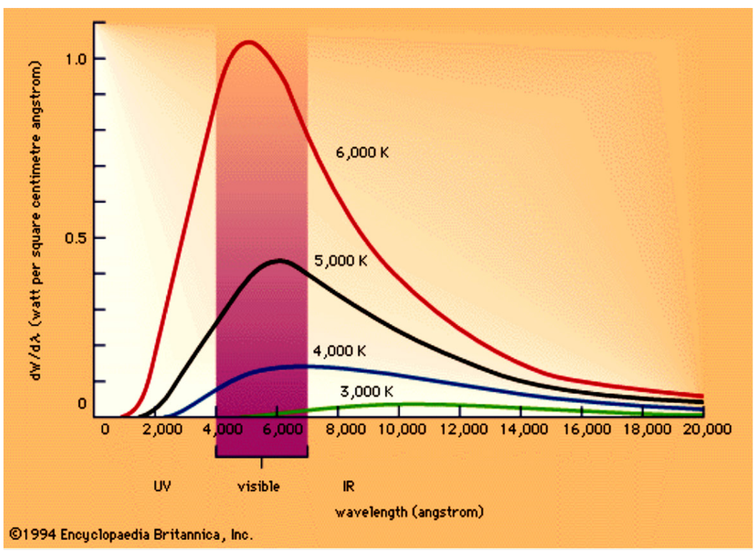
   The nature of a DED process is such that a robotic arm or gantry system is used to carry the power source (such as a welding torch), a material delivery system (such as a powder nozzle or wire feeder), and various sensors to collect as much information as possible about the process. As a result, space and weight on the robot arm are a challenge.

6. **Changing Scene Temperatures**

   One of the greatest challenges with Metal Additive Manufacturing is that there are a significant number of interrelated process parameters used that need to be controlled very precisely to make good parts. Particularly critical is the melt pool size and shape and the rate of cooling of the deposited material as it solidifies into its near net shape because this determines the materials properties.

In certain metal deposition processes that use a high energy power source such as a laser, very high melting temperatures of the metal materials involved are present.

This requires a thermal imaging/thermography camera capable of measuring an extremely large range of temperatures without saturating the image detector. Additionally, due to the rapid thermal conductivity in metals, a suitable thermal camera needs to have very short detector integration times in order to capture rapidly changing temperatures.



Planck Curves emission of black bodies

Gas Welding (2 500-3 200°C)

- ❑ Neutral flame 3 250°C
- ❑ Oxidising Flame 3 350°C
- ❑ Carbonizing Flame 3 050°C

Arc Welding (5 000 – 6 000°C)

Resistance Welding (2 500°C)

Thermit Welding (1 260 -2 500°C)

Laser Cladding ~1900-2400°C

Figure 4- Plank's law vs wavelength and temperature range for processes (Source: INNOVIDEA)

The Solution – SWIR Thermal Imaging

Traditionally, some DED manufacturers have implemented single point temperature measurement sensors, such as pyrometers, only to find out that they do not obtain sufficient data about the process to be reliable sources of measurement.

Attempts have also been made using Long Wave Infrared (LWIR) thermography cameras to visualize welding and additive manufacturing processes, but their dynamic range is extremely limited resulting in saturated images in regions of high intensity. Moreover, in LWIR cameras, the precision of temperature measurement is inadequate as explained below.

In recent years, imaging detectors using InGaAs 2D arrays have been commercialized allowing cameras to be developed with sensitivity in the Short Wave Infrared (SWIR) region (900nm-1700nm). SWIR imaging offers similar image capability and perception to the human eye due to the dual capability of sensitivity to both reflective and emissive infrared radiation over ~250°C. Indeed, SWIR images are usually monochrome with many grey levels providing high contrast images that allow a perception of shade and depth of field by the user. When adequately calibrated, they can offer a precise thermography capability for high temperatures typically found near the melting point of most metals used in MAM.

Benefits of SWIR Imaging Technology in Metal AM

1. **Ability to See Through Particulates and Glass**

   Various measurements that are difficult or impossible to perform using visible light in a metal AM process are possible using SWIR. When imaging an AM process using the Xiris XIR-1800 Thermal Camera with SWIR imaging, particulates such as water vapor, smoke and fumes are transparent to the camera. Additionally, metallic greyish hues often associated with AM processes that appear almost indistinguishable in the visible spectrum may be easily differentiated using a Xiris XIR-1800 SWIR camera with high dynamic range (HDR) capability.

Figure 5- Comparative images showing the same welding process in visible and in SWIR using a XIR-1800 Thermal Camera (Source: Xiris)

SWIR wavelength imaging is compatible with using standard glass optical lenses and filters. This provides a much more robust imaging solution that can survive the harsh environments often found in Additive Manufacturing processes.

This is important because it allows the glass optics to be protected with lower cost, more durable protective windows. In dirty AM environments, this can be especially useful if the protective window needs to be changed regularly due to weld spatter and contamination. There are a number of different glass objective lens options available to allow the camera to be used in almost any MAM imaging application. Glass lenses are significantly lower cost than lenses used on longer wave thermal cameras (LWIR, MWIR) that are made from exotic materials such as germanium or chacolgenide glass. Using standard glass objective lenses provides additional functionality such as inclusion of an adjustable aperture. Using a small aperture with a SWIR camera can provide a greater depth of field so that objects will appear in focus with clear sharp features across a greater range of distance from the camera. This can reduce image processing and offer more reliable measurement results.

2. **Human-like Vision**

Unlike Mid-Wave Infrared (MWIR) or Long-Wave Infrared (LWIR) light, which is emitted from the object itself, SWIR light is similar to visible light in that photons are reflected or absorbed by an object, providing the strong contrast needed for high resolution imaging. Therefore, SWIR imaging provides a much better tool for Additive Manufacturing to be able to clearly see the boundaries of key components in the vicinity of molten metal.

SWIR imaging produces images that are recognized by the human brain – they look similar in shape and size to a visual image so that humans can see, recognize and validate the components present in a SWIR image of a welding process and are able to confirm if the measuring tools used on the resulting images are working correctly. Typical examples of this include measuring the correct points on a melt pool or finding the correct boundary between the melt pool and the parent material.

3. **Thermography Capability**

SWIR cameras also provide the best capability for imaging hot metal as they can image heated metal in the range of 250 -~1800 °C. Being able to acquire 2D images with such a wide temperature range across important transition temperatures is key to achieving reliable and real-time measurements for process control of Additive Manufacturing processes.

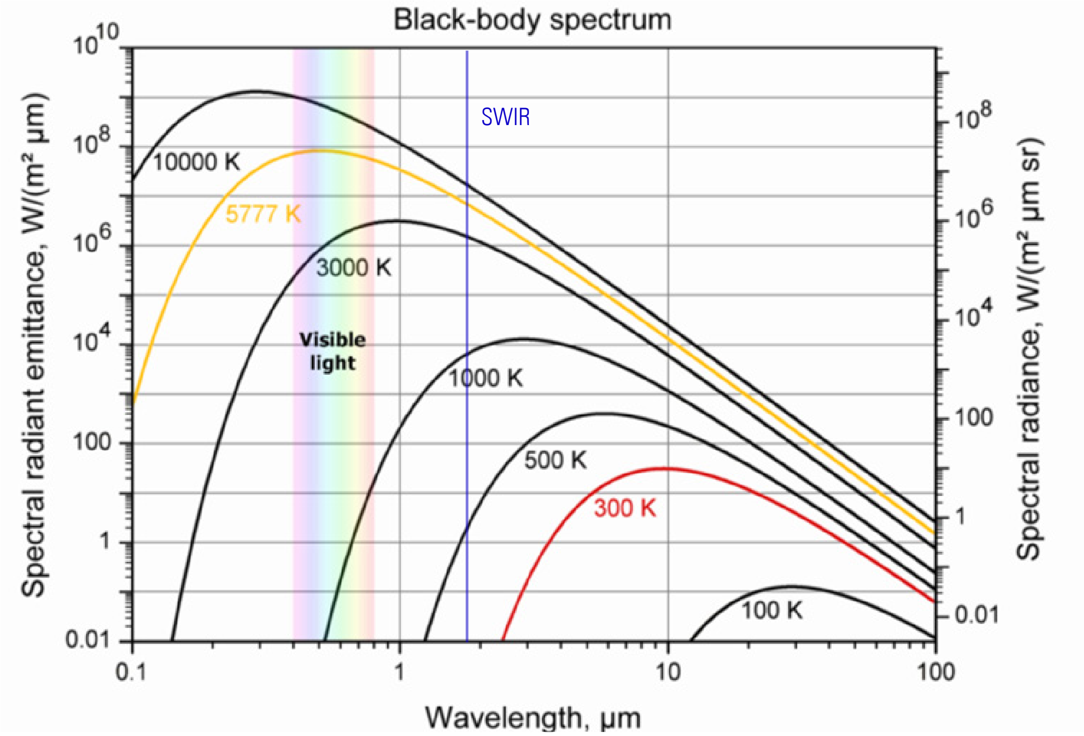


Figure 6- SWIR Band Chart (Source: Wikimedia Commons user Sch, adapted by Sun.org)

In Figure 6 above, the wavelength of the peak amount of radiation emitted from a black body shifts with increasing temperature towards a shorter wavelength. This means that using SWIR imaging for high temperature monitoring uses a stronger signal in the SWIR range than longer wavelengths used by MWIR and LWIR, making SWIR more robust and reliable for metal thermograpghy.

4. **Higher Measurement Accuracy**

SWIR imaging is much less sensitive than LWIR or MWIR imaging to emissivity changes of a metal. This is important when imaging Additive Manufacturing processes because the emissivity of the melt pool can change considerably as the metal cools, moving through a wide temperature range as it changes from a liquid to solid state. The shorter the wavelength, the less sensitive to emissivity changes on the sensor. Hence SWIR imaging is much less sensitive to changes in emissivity compared to LWIR or MWIR imaging as shown in Figure 7 below.

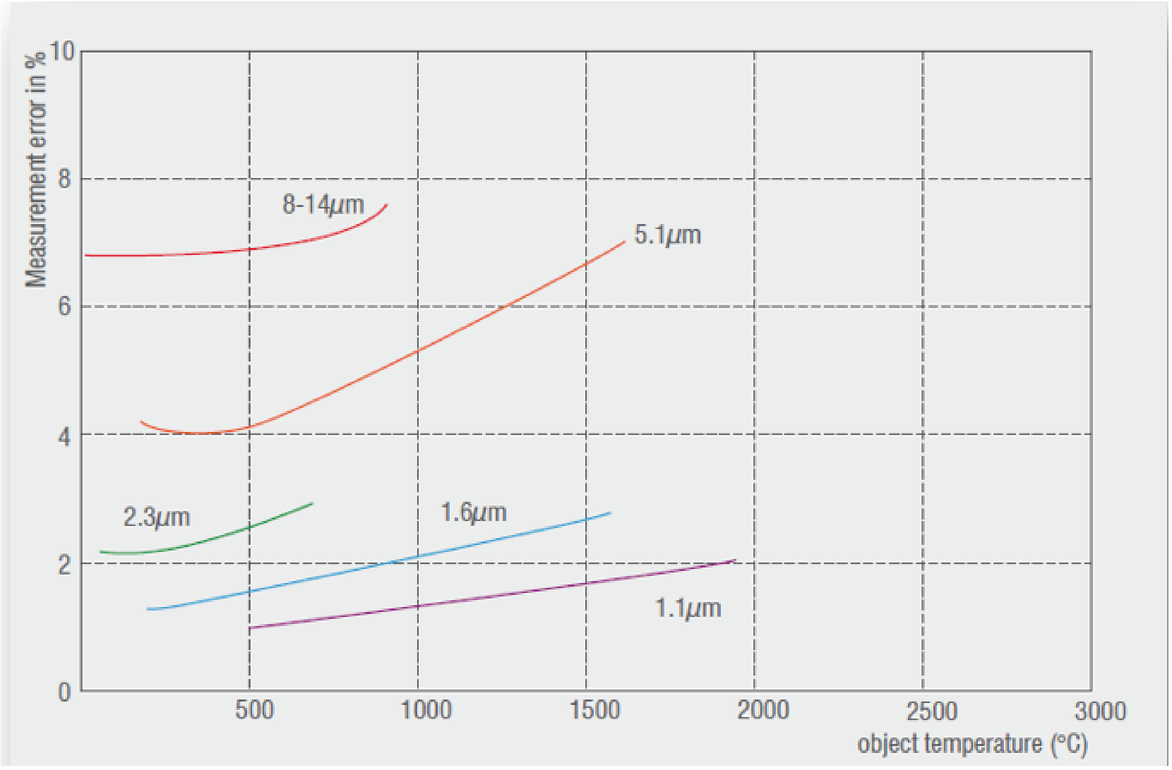


Figure 7- Target Temperature (C) with Emissivity Assumed to be 10% and Ambient Temperature Lower than Target. (Source: R&C Instrumentation)

5. **See features when no welding is present**

   Since SWIR imaging is more sensitive to wavelengths less than 1100 nm than other types of IR imaging, it can be used to see cooler objects when no welding arc is present. This can be particularly useful during the set up of a welding process before an arc has been struck, or after the welding process to monitor the cooling rate of the weld bead. Illuminating the weld area with Near Infrared (NIR) LEDs during set up is easily done, as the NIR end of SWIR wavelength (i.e. <1100 nm) is sensitive to reflected radiation.

6. **SWIR imaging works with "Eye Safe" Lighting**

   SWIR imaging can see light in the wavelength spectrum up to about 1700nm. As such, "eye safe" lasers that have a wavelength greater than about 1400nm can be used with SWIR imaging cameras. This opens up the possibility of using powerful laser sources triangulated with a SWIR camera to better detect and measure key features of the weld process such as seam presence and alignment, melt pool or weld bead geometry without the need for Laser enclosures.

Why Choose the Xiris XIR-1800 SWIR Camera?

Figure 9- The Xiris XIR-1800 SWIR camera

1. **An Outstanding Dynamic Range**

   The Xiris XIR-1800 Thermal Camera has an HDR (+120dB) in 14-bit pixel resolution that is able to provide high contrast visualization of the complete metal deposition process, including the brightest open arc power source or laser, AND its immediate background such as the parent material, wire/powder feed, and melt pool/bead.

2. **High Speed**

   With a full frame rate of up to 200 fps and a global shutter, the XIR-1800 Thermal Camera can provide real-time images of the metal deposition process with minimal image distortion due to variations in power source arc intensity commonly seen with pulsed power supplies such as MIG, TIG or laser. Higher frame rates up to 1000 fps are also possible by using a reduced Area of Interest.

3. **Low Exposure Time with Triggering**

   The XIR-1800 provides short exposure times down to 100 micro seconds (0.0001s), allowing the capture of very high-speed processes without image blur. This is much faster than cameras based on LWIR imaging technology, which are generally limited to 60 - 120fps. In addition, the camera is equipped with an external trigger signal, that can provide the ability to acquire images at exactly the same point in the metal transfer cycle, making image measurements as consistent as possible.

4. **Compact and Robust**

   The XIR-1800 is a fully digital camera that connects to an external PC via Gigabit Ethernet ensuring no loss of image quality up to 100m away from the weld process. The relatively small form factor of the camera and its ability to use a huge variety of optics means it is suitable for most applications and supported with a suite of mounting and cooling accessories.

5. **User Friendly and Versatile GUI Supported by Xiris' Standard Software Tools, Including:**

   i. Xiris WeldStudio™ software utility provides a common platform to connect any of Xiris' cameras (visible or thermal), providing everything needed to set up, control, display and record videos from any Xiris camera.

Multiple cameras can be connected to the same WeldStudio™ program, allowing for multiple Xiris weld cameras and XIR-1800 SWIR cameras to connect and appear on the same screen. WeldStudio™ autodetects any connected Xiris cameras and provides an intuitive ability to set up, control and show each camera video feed in real-time in its own window, with a full feature set of camera controls. In addition, standard and infrared-specific machine vision tools are included in WeldStudio™ for evaluation and reporting including:

- Custom Pseudo Color maps
- Thermal Line and Spot Profiling
- Hot and cold spot detectors
- Blob Analysis
- Edge Detection
- Pattern Matching
- Graphical Overlay Tools, including Cross-hairs and Reticle
- Recording and Playback of Video and RAW images
- Temperature Calibration File Management (Available Q3 2021)

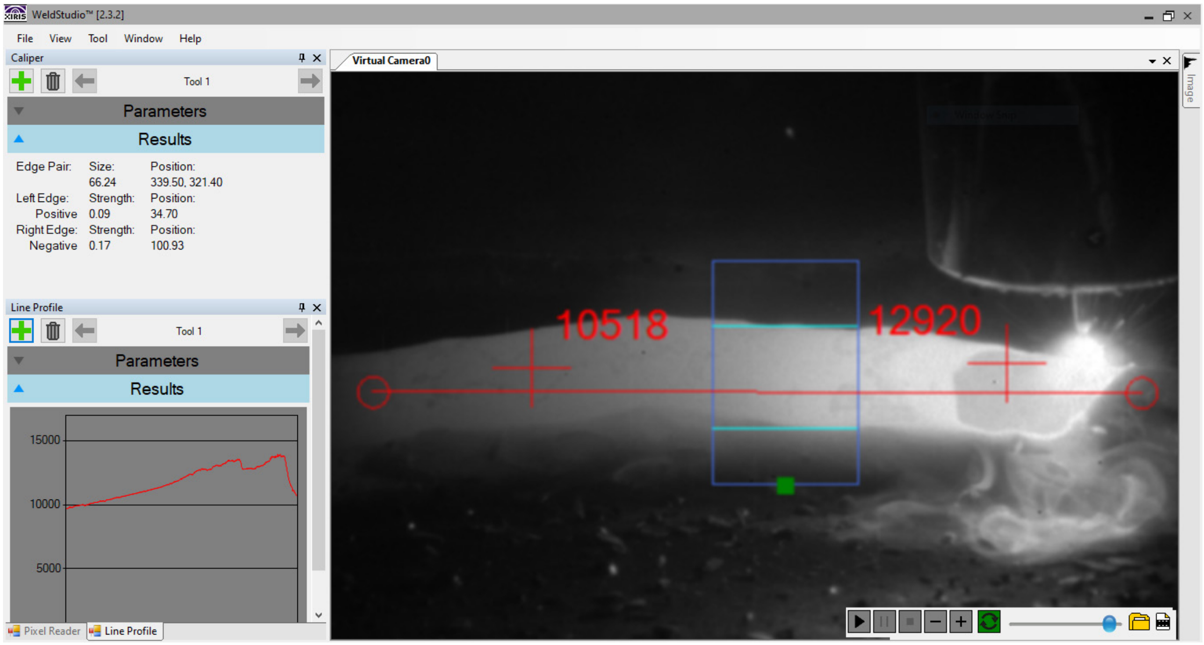


Figure 10 - Machine Vision Tools within the WeldStudio™ Software Utility

ii. Xiris WeldSDK™ is a software development kit that enables OEMs to control and interface directly with a Xiris XIR-1800 Thermal Camera in real-time to create custom image processing and display applications using powerful infrared specific machine vision tools to provide real-time process control. The kit includes all the necessary camera, thermal and machine vision tools, supporting documents and sample code to create an embedded imaging system that uses the XIR-1800 Thermal Camera. Xiris WeldSDK supports Windows or Linux operating systems.

Conclusion

The Xiris XIR-1800 Thermal Camera can significantly improve the quality of deposition in an Additive Manufacturing process in four ways:

1. When integrated as a sensory feedback tool in a closed loop control, it can continuously make adjustments to the process so that the process stays "in control." Detecting and correcting any potential defects early in the AM deposition saves significant cost and time before additional value-added processes have occurred.

2. Dramatically reduce the setup time required to make the First Article to be manufactured on a DED machine by providing images and thermal data of the process to the operator for faster process validation and acceptance.

3. Perform in-situ process monitoring and quality assurance when integrated with the Xiris WeldSDK during production of AM parts. The WeldSDK allows OEMs (and advanced end users) to obtain valuable material deposition information that can be used to monitor and control the DED process in real-time.

4. Used in production to create a record of the thermal characteristics of the process for traceability, off-line review and possible process troubleshooting should any issues arise.

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