A Guide to Using Thermal Cameras in Welding/Metal AM R&D

Inspection Solutions with Vision

Background

Heat measuring sensors have been applied to metal joining and fabrication processes for many years. Most of the equipment used in past would not allow for proper temperature measurement and characterization because only a single point was being measured at a time. Operators using pyrometers can never be fully sure if they are aimed at the correct point for measuring, often causing unstable readings with poorly understood random variations.

A better solution is a thermal camera sensitive to the temperatures of phase transformations in metals and their melting points at the same time, which is anywhere from about 350-1800 °C. A thermal camera can provide a 2D image of a surface and allow the operators to see where in the process the temperature measurements are being made, providing much more consistent and predictable temperature readings.

A camera such as the Xiris XIR-1800 thermal camera is sensitive to Short Wave Infra-Red (SWIR) radiation and generates a High Dynamic Range (HDR) image. The combination of these two features provides some of the best possible conditions for measuring a broad range of temperatures such as what is seen in welding and Metal Additive Manufacturing (Metal AM).

Xiris XIR-1800 Thermal Camera

Such a thermal camera can have a variety of applications for the development of Welding and Metal AM processes. Below, we identify several main areas that can be used to help develop your process to achieve better process control and quality assurance.

Temperature Measurements

In welding and Metal AM, temperature distribution, cooling, and heating rates play a significant role in the process and affect the mechanical properties of a weld joint, or a structure built with Metal AM. Thermal cycles are usually the cause of most distortions in welding and Metal AM processes.

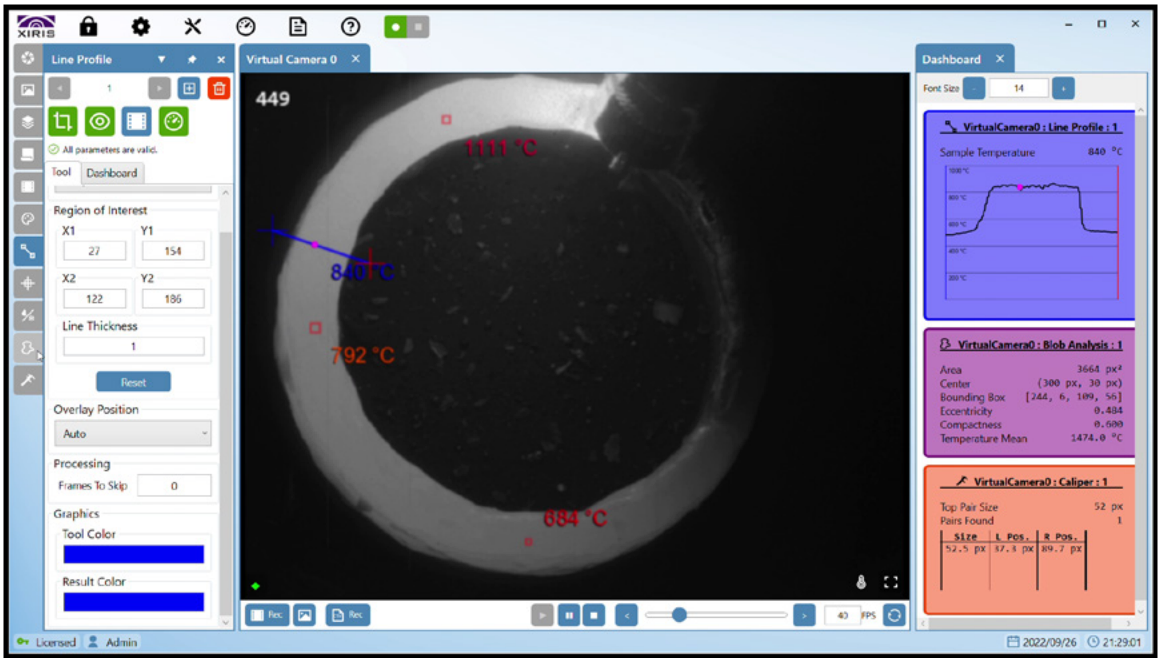
Microstructural transformations occur during thermal cycling in the weld and the heat affected zone (HAZ). The final microstructure of the weld determines its mechanical strength. The distribution of different phases in the joint will depend on the peak temperature and the cooling rate reached at each location. For some alloys, the heating rate has also been found to affect phase transformations.

1. **Cooling Rate Analysis**

   A major concern of anyone performing a metal joining process is the strength of the weld. Many factors can contribute to the strength of the weld, such as: the metallurgy of the wire and base material, the chemical composition of the shielding gas or the amount of fusion of the weld bead to the base metal. However, perhaps the greatest factor of concern is the cooling rate of the weld bead and its adjacent heat affected zone – how long does it take to cool through the interval where the most significant microstructural changes occur?

   In steels, this factor is known as $\mathbf{t_{8/5}}$ – the time in seconds for a material to cool down from 800 °C to 500 °C. If the time is too short, the resulting weld bead could become brittle due to martensite formation; if the time is too long, softer phases could form in the weld, and the resulting weld bead may not meet its hardness or strength requirements.

Trying to measure this with a point-based temperature sensor is very difficult without the visual feedback of what the operator is looking at. Using a thermal camera such as the Xiris XIR-1800 is far more accurate and precise, as temperature reading points can be placed anywhere in the image and the feedback to the operator is intuitive and immediate. The result is temperature readings that can be directly correlated to the $\mathbf{t}_{8/5}$ time.



A video of a GMAW process laying down weld bead in spiral formation

The above video shows a GMAW process where the weld bead is put down in a spiral formation. Several temperature point readers have been placed where key temperature milestones should be achieved. Here, the cooling rate of interest is the $\mathbf{t}_{8/5}$. By placing individual temperature readers in the right place in the video image, operators can easily determine if the process is cooling at the right speed.

2. **Peak Temperature Measurements**

   The first stage in the microstructural evolution of the base metal is heating. In steels, iron atoms can regroup into different combinations in the crystal lattice, called microstructures or phases. When heated above a certain temperature, the present phases transform into austenite. If such a temperature has not been reached, a partial austenitizing may occur. During cooling, austenite and other phases will transform again depending on the cooling rate. Other metals, such as titanium, often have microstructural transformations with a similar mechanism.

   In welding, depending on what temperature is reached at a particular location at or near the weld, an initial change in the local microstructure will occur. This will affect the phase transformation during the cooling part of the thermal cycle. For example, the maximum temperature reached at a point some distance from the weld will define whether that location will remain unaffected or will fall into the heat affected zone (see Figure 1 on next page).

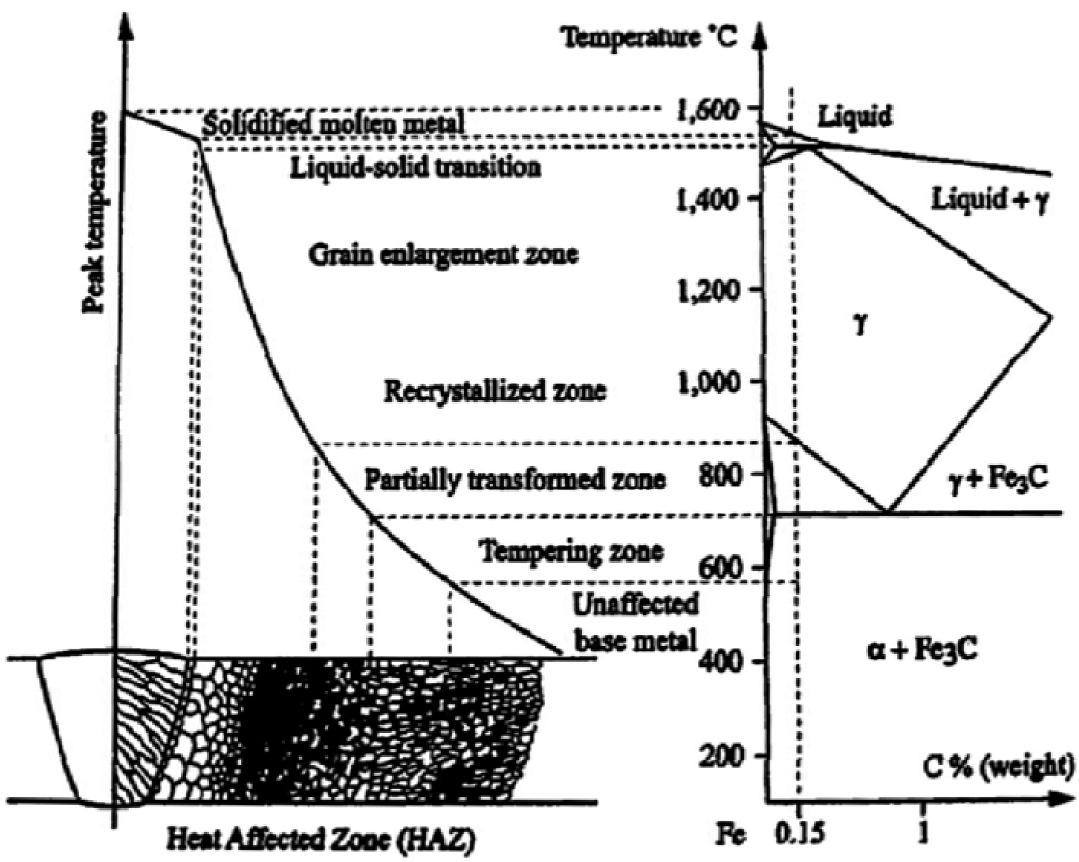


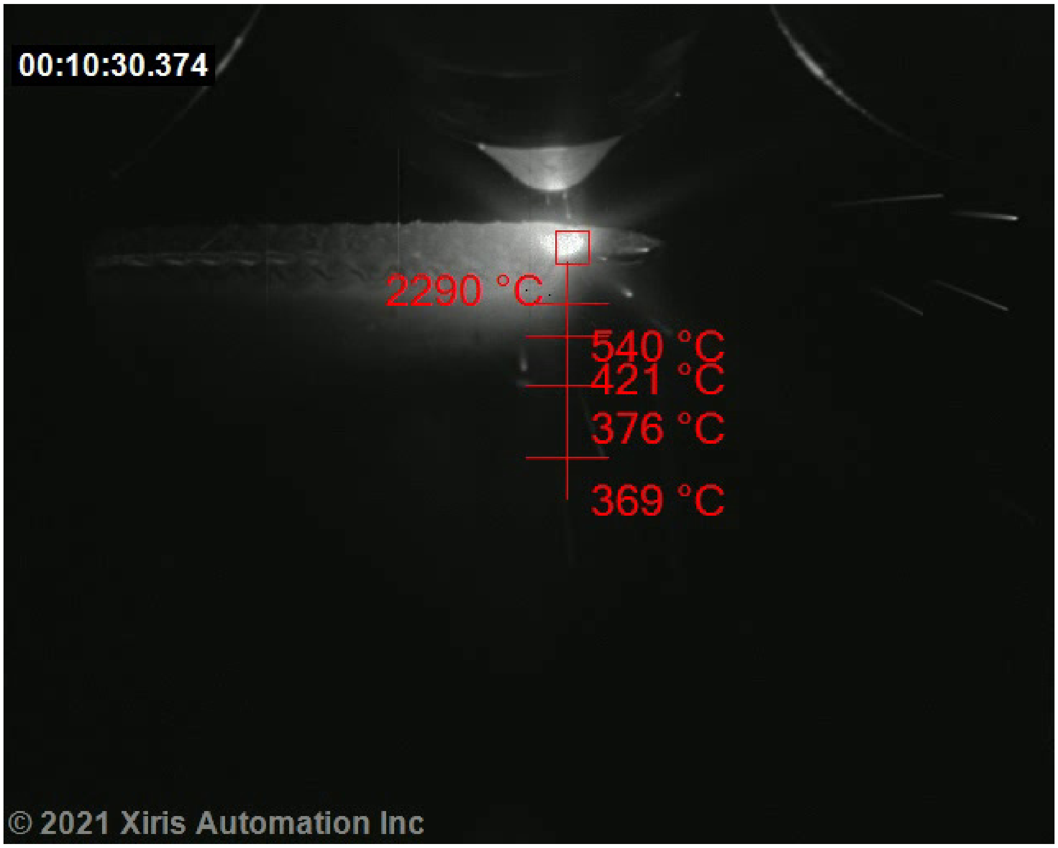
Figure 1- Effect of peak temperature on microstructural changes in weld metal and heat affected zone. Reprinted from Esterling, Introduction to the physical metallurgy of welding, 1992.)

A thermal camera with a high dynamic range such as the XIR-1800 can produce thermal maps of both the weld zone and the HAZ. Such detailed temperature distribution maps can be particularly useful in cases of parts with complex geometry, or materials sensitive to thermal cycles such a high-strength steels, etc.

3. **Monitoring Inter-pass Temperatures Between Weld Passes or AM Layers**

   In any type of multi-pass deposition process such as narrow gap multi-pass welding or Direct Energy Deposition (DED) Additive Manufacturing, the temperature of a previous pass of deposited material is of great concern to operators running the process. The previous layer's temperature, or inter-pass temperature, is important for mechanical and microstructural properties of the weld. Inter-pass temperature plays the same role as the preheat temperature for the previous weld pass.

   High inter-pass temperatures tend to reduce the strength of the weld metal. For this reason, it may be important to impose control over the inter-pass temperature when a particular mechanical strength is required. For some sensitive base metals, it may be necessary to control the minimum inter-pass temperature as well, to avoid hot cracking.



A video of a multi-pass deposition process showing inter-pass temperature readings

These general rules are just as important, if not more so, for Metal AM. Real-time temperature measurements are critical to ensure that the heat input of the most recent deposited layer does not exceed the heat dissipation rate. The Xiris XIR-1800 thermal camera makes it much easier to acquire reliable real-time data of the temperature distribution in the deposited material while being able to adjust the heat input according to the situation and to reach steady-state inter-pass temperatures as required.

4. **Bead Temperature Profiling**

By measuring multiple points along a weld bead, a temperature profile of the entire weld bead can be achieved to help to characterize how the weld bead is cooling and determine the location of various features of the weld bead. An example of how real-time thermal imaging analysis can be implemented in Gas Metal Arc Welding (GMAW) with a thermal imaging camera is shown in the video below:

A video of a GMAW welding process with Line Profile and Pixel Reader measurement tools

In this video, the melt pool, the electrode tip, droplet formations, and the cooling weld bead are all clearly visible. The brightness of each pixel can be calibrated to be associated with a particular temperature value. The surface emissivity adjustments allow for fine tuning of the measurements based on localized emissivity values to match the true temperature.

To perform precision bead temperature profiling, various software measurement tools within Xiris WeldStudio™ 3 Pro can be used:

A. A **line profile tool** shows the temperature distribution along the chosen line (seen in the video above in the graph in the top right corner). In the graph, the temperature is increasing from left to right approaching the weld arc. By placing a line profile tool along the cooling weld bead, useful process data can be obtained about the melt pool, including:

    i. The location of the liquidus/solidus interface between the melt pool and the solidifying weld bead. This can be seen by finding the location of a local maximum temperature of precisely the melting point of the metal.

    ii. Points inside the melt pool are seen to be a different temperature because of the changes in emissivity. Portions of the melt pool that are shiny will have different emissivity (and therefore measured temperature) compared to those with rougher texture such as silicates or impurities. The changing emissivity causes the sudden drop and random variations in the temperatures measured inside the melt pool. This effect can help clearly identify and separate the melt pool from the solidified bead material.

    iii. The cooling profile through the solidification area can be monitored and plotted to determine if the process is working correctly. If the camera is moving with the weld torch, the line profile along the weld bead can be interpreted as the welding thermal cycle. Since the welding speed is constant, the graph of temperature distribution along the weld can easily be recalculated as the temperature changes during the weld cycle for each point in the profile.

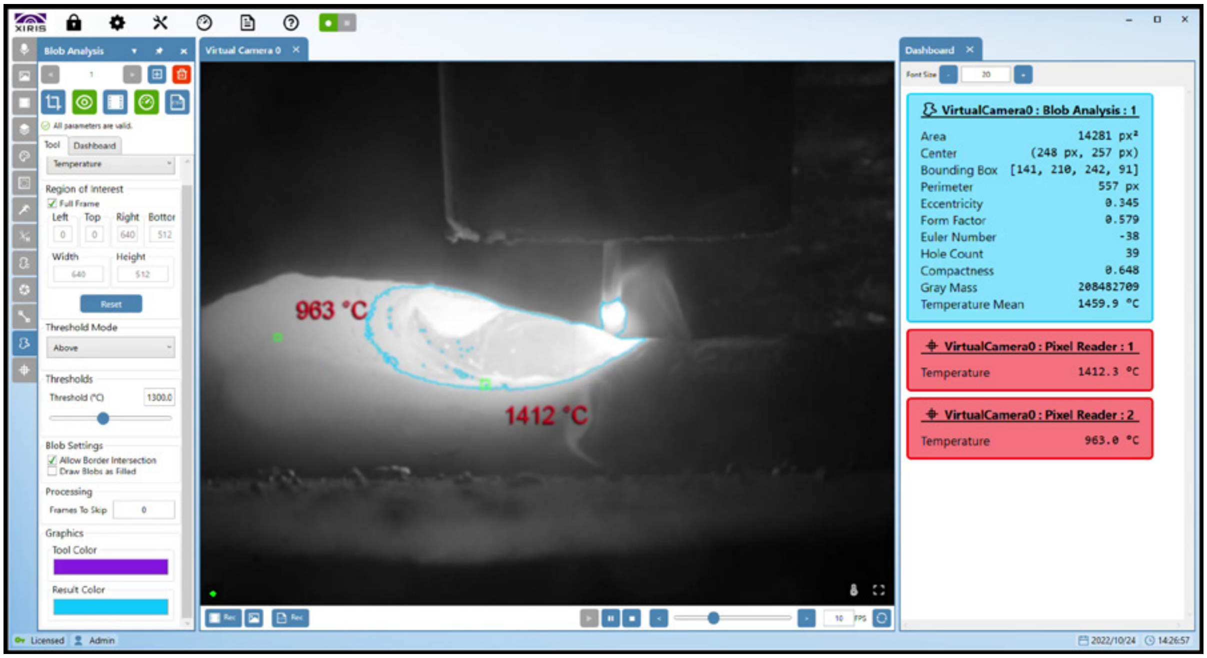
B. Individual **pixel reader tools** can be placed at specific points along the weld bead to show the temperatures of those chosen points. Data from those points can then be processed using 3rd party software to provide detailed thermal history to perform microstructural and mechanical property prediction.

C. The hot spot on the tip of the wire electrode can be automatically detected using a **local maxima tool**. This tool can be used to establish a datum from which all other process measurements can be made in software. The maximum temperature location can be automatically recalculated for each frame providing immediate positional updates that can be used to more precisely adjust the position of other measurement tools for better process control.

A photo of GTAW welding process with the Pixel Reader measurement tool

Imaging Applications

Apart from being a reliable temperature measurement instrument, the XIR-1800 is also a very capable imaging camera. Due to its Short-Wave Infrared (SWIR) spectral range, the camera is also highly suitable as a visual monitoring camera. SWIR has proven to potentially be the best spectral sub-band for monitoring of Metal AM and welding, as it is much closer to visible light compared to Mid-Wave or Long-Wave Infrared (MWIR and LWIR) that are used in traditional thermal cameras. The result is that a SWIR image appears just like a regular visible monochrome image. One thing is different, however: the weld pool and weld bead are much more distinguishable from the background in a SWIR image, providing excellent quality images for operators to better see what is going on in the weld process.



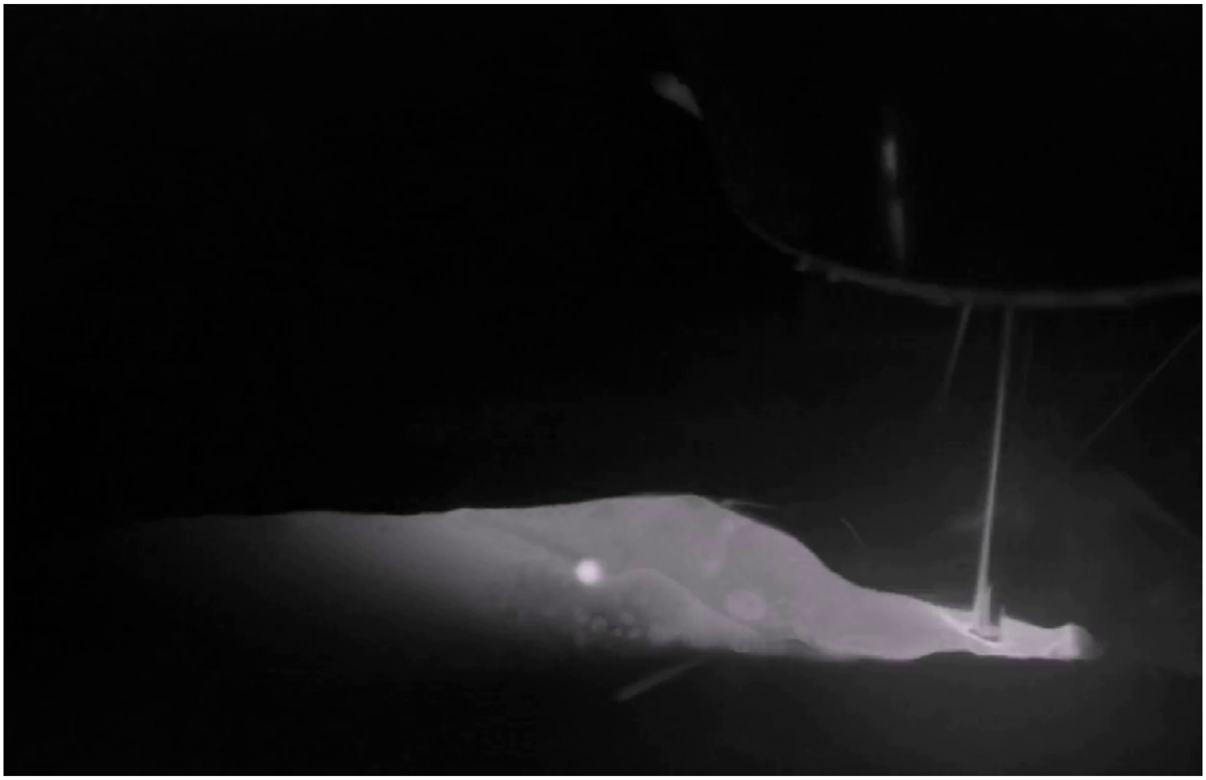
A video of Thermal Segmentation of a Melt Pool

5. **Robust Melt Pool Segmentation**

Perhaps the most important way to use a thermal camera for welding or metal AM process characterization is to accurately segment the melt pool from the background. The melt pool contains a great deal of information about the weld process, such as whether there is too much or too little power being applied, where impurities or contamination may exist in the weld pool, or if any other irregularities form during the solidification process. By being able to provide a robust thermal image of the melt pool, it can then be segmented from its background, and its size and shape can be easily measured using standard machine vision techniques.

6. **High Speed Monitoring**

As discussed above, the XIR-1800 is a unique thermal camera that can perform temperature measurements in welding without getting saturated by the arc. However, not many know that this camera also has a hidden high-speed capability. With its regular frame rate of 180 frames per second, it can achieve up to 700 fps with a short exposure time and reduced resolution. Frame rates of 500-700 fps are often sufficient to monitor phenomena such as powder flow in Laser DED or metal transfer in GMAW. For example, short circuit process are reported in the literature to have droplet detachment frequency of the order of 75-200 Hz. With such a frame rate on the XIR-1800, each cycle will be recorded with a decent level of detail using equipment that costs a fraction of the price of a high-speed camera.



A video showing metal transfer in a Pulsed GMAW Process

Summary

Advances in electronics and camera design have now made precision temperature measurement of metals in their transition phases a reality. With the ability to measure between about 350 – 1800 °C, such thermal cameras can provide valuable temperature measurements and visibly meaningful images of welding and relating processes. The result is a powerful tool for use in process research and product development of welding and additive manufacturing processes that can help develop solutions for process control and quality assurance.

Video Link Summary

1. *A video of a GMAW process laying down weld bead in spiral formation*, Page 5: https://youtu.be/-reGls3UaWc
2. *A video of a multi-pass deposition process showing inter-pass temperature readings*, Page 9: https://youtu.be/zgsnLfPRtPQ
3. *A video of a GMAW welding process with Line Profile and Pixel Reader measurement tools*, Page 10: https://youtu.be/QO62R2Es-HA
4. *A video of Thermal Segmentation of a Melt Pool*, Page 14: https://youtu.be/NV48rHkgMNU
5. *A video showing metal transfer in a Pulsed GMAW Process*, Page 15: https://youtu.be/8-DBIjdLdo0

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