Paper II

Non-contact Temperature Measurements using an Infrared Camera in Aerospace Welding Applications

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Abstract

This paper describes the application of infrared (IR) thermal imaging and temperature measurements in welding applications, both on single plane plates and on an aero engine turbine component with complex geometry. Temperature profiles were measured on the plates using thermocouples (T/C) in combination with an IR camera system, and the results were compared. The IR camera was used both in line scan mode (270 Hz scan frequency) and in full frame mode (1 Hz frame rate). Different methods of surface treatments have been tested to handle the problem of the surface emissivity variations due to oxidation during welding. Results from measurements using thermocouples and IR camera is presented in the paper as well as temperature measurements using the IR camera on a turbine exhaust case (TEC) engine component.

1 Introduction

Experimental temperature data is required in welding research and development, and for validation of numerical simulations of the welding process (Ref. 1). Temperature measurements near or in the weld pool are of special interest, and this is a challenge in selection and application of measurement methods and for assessment of measurement quality.

1.1 Thermocouple Measurement in Welding.

Temperature measurements using T/C type K (NiCr-NiAl) is commonly used in welding research. They are relatively inexpensive and can be used at the high temperatures near the weld pool. There are however some issues that need to be addressed concerning measurement quality when using T/C Type K in welding applications (Ref. 2). Measurement response time is critical, especially when the T/C is installed close to the weld. Generally, it is not possible to state the response time for a single T/C in this situation, since it is the whole measurement system response time that is measured. The T/C wire diameter is an important parameter to consider when discussing response time, but also the attachment method is an important factor, which effects the response time. Another issue is measurement system calibration (including T/C wire), which must be performed over the whole measurement range. Measurement inaccuracy needs to be addressed when using T/C Type K at high temperatures in the range 1250 °C - 1372 °C, which is above the
recommended range of use. There are however other T/C types that can be considered to be used in welding experiments, for example T/C type B (Pt-30%Rh-Pt-6%Rh) which can be used at higher temperatures, but can be more difficult to install.

1.2 Infrared Radiation Measurement in Welding.

Infrared radiation measurement of temperature has several advantages compared to T/C measurement. Using a pyrometer, non-contact temperature measurement can be done on a single point on the object (Ref. 3). A scanning mirror IR-camera with a photon detector is an attractive device in welding research and applications. It allows both full field temperature measurement, as well as high speed measurement using line scanning. The use of IR cameras for quantitative temperature measurements in TIG (GTAW) welding is in many cases limited by the difficulties to handle the surface emissivity variations and the reflected radiation from the electrode during welding. When performing spectral radiance temperature measurements, the spectral radiance temperature measured is not only depending on the object emissivity, but also on the wavelength spectral band used for the measurement (Ref. 4). The emissivity used in the measurement must then be spectral emissivity used for the detection device. A number of issues must be addressed when performing IR radiation temperature measurements in the weld pool. One important factor is the uncertainty in the surface emissivity in the melt at the measurement wavelength, and the contribution from electrode background reflection (Ref. 5). Another factor to consider is the occurrence of slag in the melt (Ref. 6). The melted steel and the slag have different radiance due to their emissivity, which are different. Slag has in general higher emissivity than steel and it appears hotter compared to the melted steel at the same temperature. There is also an uncertainty in the IR measurement due to the change in surface emissivity during material solidification and the effect of the surface oxidation in the cooling phase. The surface emissivity is assumed to increase during cooling and oxidation, but it is difficult to measure actual emissivity during the cooling phase (Ref. 7). A well known fact in radiation measurements is that when there are uncertainties in the emittance of a surface it is general best to do measurement at as short wavelength as possible. This is due to that the spectral radiance as a function of temperature increases very rapidly towards shorter wavelengths. A given uncertainty in emissivity then leads to smaller uncertainties in temperatures at shorter wavelength.

2 Instrumentation

2.1 Thermocouple Instrumentation on Plates.

Type K thermocouples were used in all experiments on plates. Six T/C were positioned perpendicular to the welding direction. The first gauge was positioned as close to melted zone as possible at a distance of 4 mm from the center of the weld. The rest of the T/C were positioned at 4.5, 5, 6, 7 and 8 mm from the center of the weld. The T/C were coupled to a signal conditioning unit and the T/C signals were amplified to give a calibrated and linearised output from 0 to 5 volt. A PC based data acquisition system was
used for sampling of the T/C signals, and the measurements were presented on-line on the PC monitor and measurement data was written to disk. The complete measurement system (including T/C wire) was calibrated over the whole measurement range. The T/C used in the test had a wire diameter of 0.11 mm and surrounded by ceramic cement and Inconel protection for lead out. The T/C wires were attached to the plate using spot welding.

2.2 Infrared Camera.

The IR camera used is a Varioscan 3021-ST high resolution 16 bit Stirling cooled camera from Jenoptik GmbH, Germany. The camera uses scanning mirrors to image the measurement object on a point detector. The camera resolution is 360(h)x240(v) pixels, and the operating wavelength range is 8 μm - 12 μm. The camera detector is of MCT type (HgCdTe). The camera has four filters for different calibrated temperature ranges, and at the highest measurement range, the system is calibrated in the temperature interval from 200 °C - 1700 °C. For higher temperatures linear extrapolation of the Planck black body radiator is used. The camera was used both in line scan mode with a horizontal line scanning frequency of 270 Hz, as well as in full frame mode with a frequency of 1 Hz. The measurements and analysis of the IR tests were made using the IRBIS Plus software from Jenoptik.

2.3 Surface Preparation.

Different techniques of surface treatment have been tested to handle the problem with surface emissivity variation on the metallic surface due to oxidation outside the weld joint. The surface treatment should ideally have a low emissivity variation over a wide temperature range and should be insensitive to emissivity variations due to oxidation during welding. Diffuse black high temperature paint for engine exhaust pipes was tested. Initial tests showed that the paint could be used up to about 650 °C. In order to find a surface treatment that could be used at higher temperatures, different kind of soot deposition techniques were tested. From the experiments it was found that by using an acetylene/oxygen flame, a thin high temperature resistant soot layer could be produced. The optimal gas mixing is reached by starting from a pure acetylene flame, and then gradually increase the oxygen gas until no soot is visible in the flame. An emissivity value of 0.96 has is reported in Ref. 8 for soot applied to a solid in the range 50-1000 °C.

3 Experimental Setup

TIG (GTAW) welding was performed using an in-house robotised welding cell. The torch used is from Binzel AB and is linked to a six-axis robot from ABB, IRB1400. The power source is a TIG Commander 400 AC/DC from Migatronic AB. Throughout all experiments thoriated tungsten electrodes were used. A special fixture designed to avoid distortion has been used during the welding of the plates. The aero-engine component,
a part of a V2500 engine turbine exhaust case (TEC) from Volvo Aero Corporation, was TIG welded using the robotised welding cell. A segment of 1/13 was cut out of the TEC, which originally consists of an inner and outer ring and 13 vanes, see figure 1. The TEC is made of Greek Ascoloy with a vane thickness of 1.25 mm. The vane was spot welded between the outer and inner ring.

![Image of aero engine component and IR-camera setup](image)

**Figure 1:** *Overview of the aero engine component and the IR-camera setup.*

### 4 Measurements

Welding experiments were performed on both plane plates and on the turbine component. The purpose of the T/C measurements was to get reference data against which the IR measurements could be calibrated. Initial test measurements were performed on T/C instrumented stainless steel plates. For comparison of the IR measurements against T/C measurements, the acetylene/oxygen sooting technique was used on the plates. Using this technique, all but the weld joint remained sooted during and after the weld experiment. This allowed quantitative temperature measurement on the outside the weld joint using the IR camera. In fig. 2 the TEC component is shown after a weld test. In the experiments, the Greek Ascoloy plates and the TEC vane had a thickness of 1.25 mm. The stainless steel plate thickness was 2.0 mm. To avoid oxidation on the backside during welding, Argon gas was used as root gas in all weld trials. The types of welds performed were bead on plates, and no filler material was used.

#### 4.1 Measurement on Plates.

Figure 3 are showing temperature measurements on a Greek Ascoloy plate with 6 T/C installed.
The T/C were spot welded to the plate and positioned in radial direction to the weld. The first T/C was mounted as close as possible to the weld (fig. 4). The position of the T/C was measured in a microscope after welding. These T/C positions were later used in the analysis of the IR line scan temperature images, for which the corresponding pixels were selected and used for comparison of temperatures.

When using the IR-camera in line scan mode, two different acquisition modes can be used. In one mode, 5600 lines are scanned continuos at a rate of 270 lines/s and then the data is saved to disk. The scanning time and the readout time is both 21 s, which means that only a part of the whole temperature cycle will be measured, and this can be seen in fig. 16. In the other line scan acquisition mode, images like those in fig. 5 are captured, with an image size of 360(h)x240(v) pixels. After a camera readout time of approx. 0.1 s, which is indicated in the fig. 5 by the white field, another line scan image is taken, and so on until the end of the weld test. During the IR camera measurements a macro lens was used with a working distance of 100 mm to the plate, see figure 15. Due to the viewing angle, only a small section of the plate will be in focus. In the camera software, a camera line perpendicular to the welding direction (see fig. 4) is selected at the focused position on the plate and scanned at 270 Hz. The optical magnification in the IR camera system gives a spatial resolution of 7 pixels/mm on the object during line scan. Care has been taken to select the correct pixel in IR scan lines that correspond to the T/C position on the plate. In fig. 6 radial temperature profiles representing different line scans have been plotted.

As can be seen from fig. 6, the radial temperature profile for the sooted stainless steel plate has three peaks. For the curve going through the maximum temperature in the weld pool, the soot is probably attached to the surface outside the weld pool for temperatures until the curve drops on each side of the weld. For comparison, temperatures measured with T/C positioned at 4, 5 and 6 mm from the center of the weld are also plotted in figure 6. The agreement between IR- and T/C measurements is good in this region, as can be seen.
in figure 6. Over the melting temperature, the soot layer has disappeared and the surface emissivity changes instantly. This can be seen as a sudden temperature drop at the edge of the weld pool. At the center of the weld, the high temperature peak is due to reflection of radiation from the electrode, and this is explained from the results in figure 14 and 15. The line plotted 6.7 s after the maximum temperature profile shows that the temperature wave has propagated far out on the plate, and that temperature in the center of the weld is in the same range as at the edge of the weld (where the soot is still attached). The lower temperature seen at the weld joint is due to a different surface emissivity compared to outside the weld. The surface emissivity of the weld is changing (increasing) over time due to material solidification and surface oxidation. During the IR camera measurements, a constant emissivity value of $\varepsilon = 0.99$ was used at every pixel in the image.
4.2 Measurements on the Aero-Engine Component.

Several welding experiments were performed on the component and temperatures were measured using the IR camera at 1 Hz full frame rate and the 270 Hz line scan mode. No thermocouples were used in the experiments on the TEC component. In fig. 7 is shown a full frame (1 Hz) IR temperature measurement during welding on the sooted TEC (compare the weld path and the component set-up in fig. 2 and fig. 1). In this experiment the filter range was up to 800 °C, therefore temperatures higher than 800 °C are shown in black in the image. On the outer ring of the component, there are two rigid supports (which can be seen in fig. 1), and the cooling effect of these supports can be clearly seen in fig. 7.

Line scan temperature measurements were also performed during the weld test, and a contour plot of the temperature distribution of the middle section is seen in fig. 8. The cooling effect of the support is clearly also in this graph.

Figure 9 shows line scanned temperature profiles on the front part of the vane. All profiles are measured to the right side of the weld as seen in fig. 7 and in the contour plot in fig. 8. The temperature profiles in figure 9 correspond to the radial positions for which the T/C were instrumented on the weld tests on the Greek-Ascoloy plane plates. Figure 10 shows four temperature profiles from the middle part of the TEC. The highest temperature in this part of the component is much lower compared to the front and back part due to the big heat sink on the outer ring support. The measured IR line scan temperature profiles for the back part of the TEC is shown in figure 11. Here the wall thickness in the vane and the outer ring can be assumed to be homogenous, like the front part.
Figure 6: IR line temperature profiles and T/C measurements in radial direction from the weld for a stainless steel plate.

Figure 7: Full frame thermal image of turbine component showing the heat propagation in the range 100-800 °C
Figure 8: Temperature contour plot of the middle section of the turbine exhaust case (TEC) measured using line scanning.

Figure 9: Infrared line scan temperature profiles measured on the front part of the TEC.
Figure 10: Infrared line scan temperature profiles measured on the middle part of the TEC.

Figure 11: Cross section of a welded plate.
5 Discussion

5.1 Thermocouple Measurements.

Close to the weld, the temperature gradient is very high and the spot welded T/C installation will effect the transient response of the T/C, and this may cause a significant error in the measurement. Comparison of T/C and IR measurements indicates that there may be a significant difference in peak temperature between the T/C temperature measurement and the IR measurement near the weld joint. The spot-welded T/C had a diameter about 0.7 mm on the plate. Measurements were done to study the effect in transient response and measured peak temperature, using a smaller spot weld diameter, approx. 0.56 mm. In order to study the potential lag effects of different spot sizes, four T/C were installed in pairs on two plates, see fig. 4. One plate had T/C separated at the radial distance 3.8 mm (C1 and C2) and 4.3 mm (D1, D2) from the center of the weld. The T/C pairs at the same radial distance were separated 3 mm in the axial direction. The other plate had the T/C separated at the radial distances of 4.3 mm (A1, A2) and 4.8 mm (B1, B2). The two plates were welded with different welding currents. The reason for this is that at the first plate, the first T/C pair was at the very edge of the weld seam. On the other plate the welding current was lowered so the T/C should be about 1-1.5 mm away from the edge of the weld pool. The two measurements have been plotted in the same graph, see fig. 12. Experiments were also done with smaller spot weld sizes, but these did not survive the weld test.

![Graph showing temperature vs. time for different T/C spot weld sizes and radial positions.]

Figure 12: Comparison of T/C peak temperature difference at the thermal gradient near the weld for different T/C spot weld sizes and radial positions.

As can be seen, the T/C pair (C1, C2) closest to the weld, and at a distance of 3.8 mm from the center of the weld, is showing a relatively large difference in peak temperature. The T/C pair (D1, D2) at a distance of 4.3 mm shows a smaller difference in peak temperature. In the second test, the weld width was smaller, and the T/C pairs (A1, A2) and (B1, B2) was positioned 4.3 and 4.8 mm from the center of the weld. As can be seen in fig. 12,
there is a small peak temperature difference for T/C pair (A1, A2), but for T/C pair (B1, B2) the two different spot weld sizes shows identical temperatures. During the passing of the TIG weld temperature transient, no difference in transient response time due to the different spot weld sizes could be measured during the test, only a difference in peak response temperature. The peak T/C temperature difference due to surface attachment size is significant only very close to the weld. Using a non-contact fast response IR detector in this region, it can be expected to give even higher peak temperatures (if the surface emissivity and the background reflection are known).

5.2 Infrared Image Data Processing.

In order to generate temperature profiles at different radial distances from the weld, the center of the weld has to be defined in the IR image. Two different methods based on pixel averaging and peak temperature detection have been used to accomplish this, and both have been found to give the same result, within \( \pm \) one pixel. In fig. 13 a temperature contour plot from a weld test on a sooted stainless steel plate is shown. In fig. 14 the high temperature region of fig. 13 is contoured.

![Figure 13: IR line scan temperature contour plot from a weld test on a sooted stainless steel plate.](image)

By counting the number of lines between the two high temperature peaks in figure 14, and using the line sampling frequency, \( f =270 \) Hz, together with the welding speed \( (v=2.5 \text{ mm/s}) \), gives that the weld torch has traveled the distance of 3.22 mm between the two peaks. Using the electrode to plate distance 1.5 mm gives the angle \( =25^\circ \) in figure 15, which is close to the viewing angle during the experiments.

In fig. 16, temperature measurements using T/C and IR are shown from a welding experiment on a sooted Greek-Ascoloy plate. The measurement position is just at the edge of the weld, 4 mm in radial direction from the center of the weld. The explanation for the high IR temperatures up to 500 \( ^\circ \text{C} \) in the beginning of the heat transient is due to the weld torch that comes into the field of view of the camera. The next part of the curves shows
Figure 14: Temperature contour plot showing the peaks where the electrode position is right above the measurement position (line 1844) and the peak due to reflection of electrode radiation (line 2192).

Figure 15: Optical and geometrical calculation gives torch positions of maximum reflected radiation in the IR-image.

The temperature peak response. It is seen that the IR measurement reach a higher peak value (TIR=1418 °C) compared to the T/C measurement (TT/C=1243 °C), and this can also be seen in the measurements in fig. 6 for stainless steel. From the T/C response tests, it was stated that an IR measurement is expected to reach a higher peak temperature very close to the weld, compared to a T/C measurement. In all experiments, the T/C position and the IR scan line is not taken at the same position on the plate, see fig. 4, but are a separated by a few millimeters. Due to process variations, the IR measurement position may be inside the melt, explaining the sudden drop in temperature as a result of a sudden emissivity variation. As can be seen in figure 17, during the cooling phase, the IR and T/C temperature curves show good agreement. This means that surface emissivity is close to the value set in camera, $\varepsilon = 0.99$, indicating that the surface oxidation during the cooling phase results in a high emissivity. It should be pointed out that the agreement between the T/C and IR measurements increases with the radial distance from the weld, and this can be seen in fig. 17.
Figure 16: Comparison of T/C and IR line scan temperatures on a sooted Greek-Ascloy plate at 4 mm from the weld line.

An example of this is shown in figure 17 for a stainless steel plate, showing good agreement between T/C and IR measurements at 6 mm and 7 mm from the weld line.

Figure 17: T/C and IR temperatures on a sooted stainless steel plate 6 mm and 7 mm from the weld line.

6 Summary and Conclusion

Temperature measurements have been successfully performed on an aero engine turbine component using an infrared camera system. Both full field temperature images and time resolved line scan profiles have been measured and analyzed. By deposition of a soot layer on the metal surfaces to be welded, a surface with high emissivity was produced that made it possible to handle the emissivity variation due to surface oxidation outside
the weld joint, and to suppress reflected radiation. Thermocouple- and infrared measure-
ments have been performed on plane plates made of stainless steel and Greek Ascoloy,
and comparative analysis has been made of the results. Infrared radiation temperature
measurements has also been made in the weld pool and during solidification and the cool-
ing phase, and the results have been analyzed and problem areas have been identified that
promote further work in this field.

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