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# Thermography for Online Detection of Incomplete Penetration and Penetration Depth Estimation

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**Abstract**

Conventionally, the quality of the weld is ascertained only after the welding has been completed through the use of NDT techniques. A lot of time, material and manpower is wasted before one comes to know about the soundness of the weld. These limitations can be overcome if the weld is continuously monitored in real time for the assessment of defects using appropriate NDE sensors.

This paper highlights the application of thermal imaging sensors for detection of defects such as lack of penetration and estimation of depth of penetration during Tungsten Inert Gas (TIG) welding. Analysis of the results confirms that IR technique can detect lack of penetration and depth of penetration online. A linear relationship could be established between the surface thermal profile and the depth of penetration.

**Keywords:** Welding, Infrared Thermal Imaging, Incomplete Penetration, Depth of Penetration

## 1.0 Introduction

Welding is one of the most widely used methods for joining of metals. In spite of the numerous advances in the art and science of welding, failures do occur and welds continue to be considered as a weak link. Conventionally, the quality of a weld is ascertained through the use of Non-destructive test techniques such as ultrasonics or radiography. However these techniques are applied after the entire welding is completed. Thus, a lot of time and manpower is spent before one comes to know about the soundness of the weld. This inherent limitation can be overcome if the weld is continuously monitored in real time for the detection of defects and their automatic elimination by on-line control of the welding parameters. Such online monitoring would also enable repair of defective welds immediately. Potential non-destructive testing (NDT) sensors, for on-line monitoring include optical, X-ray and Infrared (IR). Of the three, welding being a thermal processing method, using IR sensors has been a natural choice for sensing and weld process monitoring. The basis for the use of thermal / IR sensors for weld monitoring is that the perturbations that arise due to variations in arc positioning, heat input and due to presence of contaminants distinctly manifest as differences in the spatial and temporal surface temperature distributions.

Literature survey reveals that extensive work has been done primarily in the area of IR imaging for seam tracking (commercial systems are available), and development of strategies and parameters for control of weld bead and joint depth penetration [1-15]. Recently, point IR sensors have been used for measurement of penetration depth [16-18]. However, except for the initial works by Chin et.al [1], Mansoor et.al[2] not much work has been reported in the area of online detection of defects.

This paper focuses on the application of IR imaging for online detection of defects. The choice of the defects for evaluation by IR imaging is based on their severity levels, frequency of occurrence and also ability of the welder to introduce the same during the welding process. Lack of penetration is incomplete penetration of the weld through the thickness of the joint. In some circumstance, LP acts as a surface notch and is a severe defect. LP is considered in general to be a serious defect. Codes such as ASME do not permit any LP in welds. Hence, this defect was chosen for the study. The paper also highlights the methodology adopted for quantitative estimation of weld penetration depth.

## 2.0 Experiment

For defect detection studies machined AISI type 316 stainless steel (SS) plates of dimensions - 200mm x 150mm x 8mm were used. The machined SS plates were well cleaned and emeried to ensure no surface variations and a uniform surface finish. Weld edge preparation was carried out carefully (figure 1). A land of 2mm was provided and a bevel angle of 30° was maintained. The plates were butted together to form a single 'V' groove with a weld angle of 60°. A root gap of 2mm was maintained.

The plates were butt welded by manual arc welding process. All the welds were made using a Triodyn K 320 arc-welding machine of Advani Orelikon make. This machine has a current range of 35-320 Amps and a maximum voltage of 90V. Arc currents of 60-155 Amp and arc voltages of 18 to 32 V DC were used. The electrodes used were E 308L – 16 of diameter 2.5mm and length 200mm for the root pass and 3.15 mm for the subsequent passes. Welding was carried out in the 1G and 3 G positions. For the study on determination of depth of penetration, AISI type 316 LN plates with dimensions 125 mm x 50 mm were used.

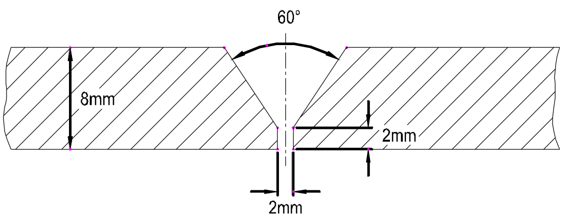



*Figure1:* Typical weld joint design

For joint depth penetration studies, plates with two different thickness of 3 mm and 5 mm was used in which varying penetration depths ranging from 2 mm – 5 mm were introduced. TIG welding was carried out in 1G position using tungsten electrodes with 2 % thorium. No filler wire was used. The shielding gas used was argon (purity - 99.9%) with a flow rate of 10 lit/min. The welding speed was 12 cm/min. The current and voltage used for 100 % penetration is given in Table – 1.

*Table 1: Welding current and voltage used for joint depth penetration studies*

| Plate thickness (mm) | Current (A) | Voltage (V) | Penetration (%) |
|---|---|---|---|
| 3 | 120 | 15 | 100 |
| 5 | 220 | 19 | 100 |

Figure 2 gives the schematic experimental set up. Thermal imaging was carried out using a focal plane array based infrared camera with a thermal sensitivity of 0.1K, spectral sensitivity in the range of 3-5 μm and frame rate of 30 fps, which is sufficient for viewing the welding process online.

The infrared scanner was fixed at a distance of about 1.0 m from the weld pad and suitably focused so that the entire weld pad could be seen during welding. This made it possible to observe the temperature distribution in the weld pool and its vicinity. A combination of appropriate level, ranges and apertures were selected depending on the temperatures being monitored (i.e. during welding, cooling etc). The images were initially recorded using the flash disk. The images were subsequently played back and analysed.

Line profiling, isothermal contouring and thermal chopping were some of the image analysis functions that were used in visualizing the temperature distributions, surface gradients, anomalies and variations. The experimental conditions were carefully maintained to minimize errors.

**3.0 Results and Discussions**

**3.1 Incomplete Penetration [19]**

The incomplete penetration formed during welding is a defect that could be unambiguously identified online since it occurs during the root pass and at the centre of the weld.

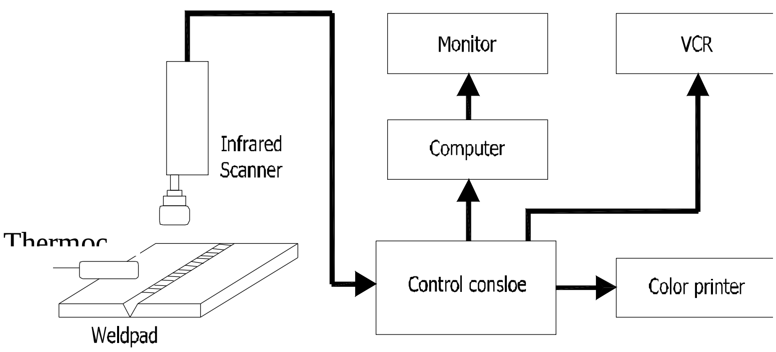



*Figure 2:* Schematic of the experimental set up for online weld monitoring studies

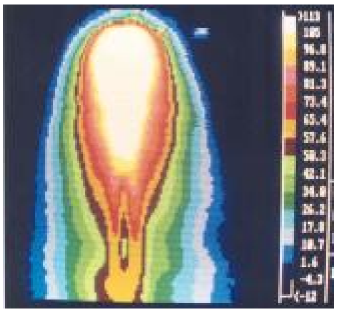


*Figure 3*: Isothermal profiles of lack of penetration formed during root pass

Isothermal profiles of incomplete penetration or Lack of Penetration is shown in figure 3. Lack of material (basically air gap in the root region) appears on the thermal image as a cold spot at the centre of the weld. More than 7 K difference is observed between the defective isotherm and the adjacent isotherm. LP was observed with the scanner being positioned in the front i.e. facing the weld arc and also with the scanner positioned at the rear. It is observed that in both the cases, LP could be detected. However, the thermal contrasts are observed to be better in the latter case due to reduced thermal scatter and absence of interference from the arc.

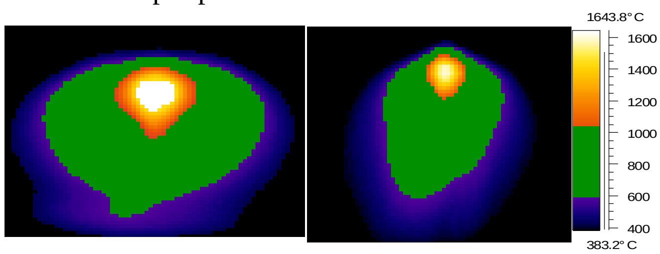
### 3.2 Depth of Penetration [20]

The effect of depth of penetration on the surface temperature distribution was investigated by welding pads of different thickness, in the range of 2-5mm, with different current. Figure 4 is the corresponding temperature distributions displayed as isothermal maps of three welds with 100 %, 80 % and 60 % penetration depths. Figure 4 clearly reveals that there are pronounced and identifiable changes in the three isothermal maps.

Figure 5 is a line profile of temperature distribution across the weld for the three different penetration depths. It can be observed from Figure 5 that as the depth of penetration increases, the peak temperature attained and the width and area under the temperature distribution curve also increases. This is quite understandable since the depth of penetration of the weld primarily depends on the heat input and the distribution of the heat energy.

The integrated area under the temperature distribution curve is a measure of the amount of heat input to the weld, with all other conditions (such as heat losses) remaining constant.

The temperature distribution curve is fitted by regression analysis using a Gaussian function. The area under the curve is determined using the ORIGIN® software. Figure 6 is a plot of the peak area and the input power. It can be observed from figure 6 that the peak area has a linear relationship with the input power.




100% of Penetration 60% of Penetration

*Figure 4:* Isothermal patterns for different penetration depth

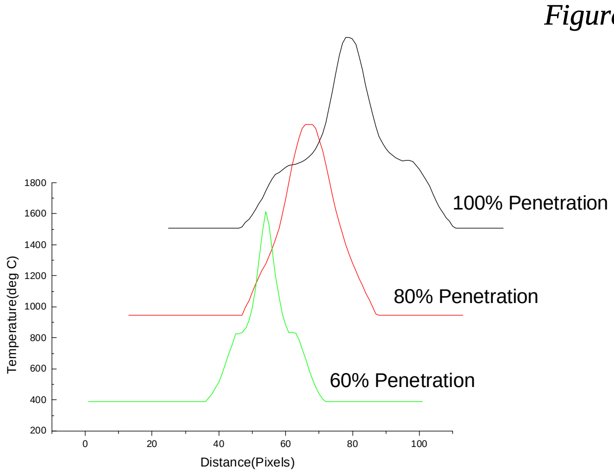



*Figure.5:* Plot of line profile for three different penetration depths

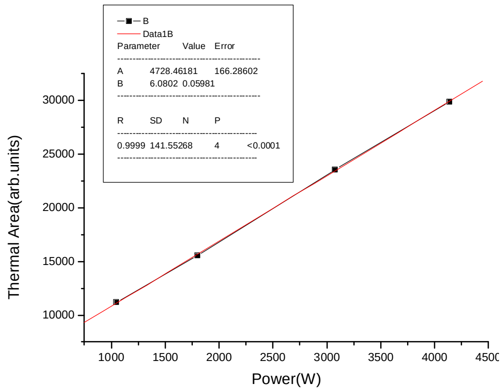



*Figure 6:* A plot of thermal area Vs input power of the welding machine

Measurement of the penetration depth was carried out using standardised metallographic techniques. Sections were cut from the weld, which corresponds to the point of the weld where the line scans are taken. The metallographic samples are polished and then electrolytically etched using 10 % oxalic acid to measure depth of penetration. Figure 7 is a typical cross sectional view of partial (40 %) and full penetration weld. Figure 8 indicates a linear relationship between the depth of penetration and thermal area.

*Figure. 7:* Cross section view of partial and full penetration weld.

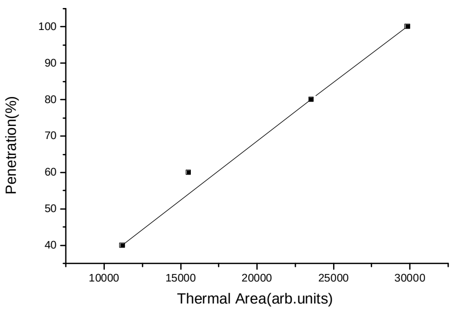



*Figure 8:* Thermal area Vs depth of penetration.

One of the important parameters that affect temperature measurements in IR is emissivity. It is well known that emissivity is a function of surface condition, viewing angle and temperature of the object. Since the objective was detection of the anomalies based on thermal asymmetries, a rigorous temperature measurement of the thermal distributions was not attempted. However it was ensured that the plates had a uniform surface finish and the techniques used for the analysis use relative differences in infrared measurements, the effects of emissivity variations had not been considered.

## 4 .0 Conclusions

It is clear from above that surface temperature distributions are sensitive indicators of weld quality. The experimental investigations clearly reveal that thermal imaging can detect lack of penetration and estimate depth of penetration. Analysis of the surface temperature distributions as a function of various degrees of penetration clearly indicates that the thermal profile across the weld pool and the integrated area under the thermal distribution curve have a linear relationship and this can be used as a sensitive indicator of the depth of penetration. Since the area under the thermal curve is directly related to the weld input power, this parameter can be used for feedback and control.

## 5.0 Acknowledgements

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