Effect of Shielding Gasses on Heat Transfer in Pulsed Gas Metal Arc Welding

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Approval

It is certified that the contents and form of the thesis entitled “Effect of Shielding Gasses on Heat Transfer in Pulsed Gas Metal Arc Welding” submitted by Ahmed Afzal Butt have been found satisfactory for the requirement of the Masters in Design and Manufacturing.

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Executive Summary

Welding is a major joining technique employed in industries like in nuclear, aerospace, submarine and ship building and pressure vessel applications for the manufacturing engineering structures. In recent years great developments are being made in this area to optimize and improve the process with higher efficiencies and more production rates.

The objective of this research is to find an improved non-intrusive method to study the effects of different shielding gasses used in pulsed GMAW in heat transfer.

Heat affected Zones and Heat fusion zones are developed during the welding process and later cooling of the molten weld pool associated to that heating process have considerable effect on mechanical properties and physical properties of the engineered product.

Optical Image analysis using high speed imagining devices is used to determine arc heat temperatures that are produced during the welding process .We utilize the high speed image processing method based on Abel Inversion and Fowler Milne method to study the behavior of how different shielding gasses create heat distribution inside the welding arc. In the last we discuss the results and future work recommendations are stated.

Keywords: Pulsed Gas Metal Arc Welding, Heat Transfer , optical image analysis , Abel Inversion , Fowler Milne Method.

Thesis Outline

The dissertation is organized into four chapters and the contribution of each chapter can be summarized as follow:

Chapter 1 give the introduction about the topic brief on the current work that has been done in the area of optical spectroscopy and image analysis. Defines the scope and objective of the work that is done.

Chapter 2 provides insight about the Gas Metal Welding Process , types of Metal transfers in welding , Advantages , benefits and limitations of P-GMAW process and forms the foundation of scope and motivation. Spectroscopic Image Analysis Method ,Abel Inversion and Fowler Milne Method.

Chapter 3 explains the methodology used to achieve the objectives that were defined. How Matrix based Abel inversion is used to calculate the emissivity and Fowler Milne method is used to obtain temperatures.

Chapter 4 concludes the work by providing the comparison on the results and recommendations for the future work.

Chapter 1

Introduction

Welding is a fundamental part of engineering and manufacturing processes. Welding is considered one of the most commonly used manufacturing processes which involve a large number of variables contributing towards the quality of the final product. Ability to produce strong and durable joints between different materials it would have been impossible to produce a variety of products we all rely on in our daily lives. Welding is extensively used in the fabrication of various products ranging from industrial applications, Buildings, pipeline fabrication, trains and bridges, medical implants and electronic devices to high-precision engineering applications in aerospace, marine applications. Welding has reduced the cost involved in manufacturing and Production time considerably. Welding offers significant advantages in material joining compared to other mechanical joining methods which include flexibility in design, material utilization, improved structural integrity and weight and cost savings (1) (2)

The distortions in the welding are something which cannot be avoided but however with careful utilization and optimization of the welding process they can be minimized to significant level. Pulsed GMAW is widely used in the industry due to its superior properties and lower heat input.

The temperature distribution inside the electric arc is of great consideration in order to understand and evaluate the degree of impact of heat produced during the process. Different methods are used to evaluate local plasma temperature, like Thomson scattering effect or Langmuir electric probe measurements, but these techniques have direct influence on temperature being measured to a greater extent and add error to the data being recorded (3). Non-intrusive methods are better suited to accomplish this goal with minimum possible interference in contrast to the actual results. Optical emission spectroscopy (OES) is the commonly used method in the analysis of thermal plasmas for temperature determination. Optical Image analysis using high speed imagining devices is used to determine arc heat temperatures that are produced during the welding process. Arc temperature greatly influences the metal spray transfer, heat transfer to the work piece and resulting fusion zone and heat affected zones. This method has advantage over it's older counterpart spectroscopic for lesser computational effort and shorter experimental runs.

1.1 Motivation & Scope of Research

Considering the importance of welding as a joining technique in the in manufacturing industry enormous efforts have been made to explore in the past, the different welding processes and their effect on weldment individually at various prestigious academic and research centers around the globe. Considering the low per unit weld cost and effective working capability of Pulsed GMAW there is big gap present in process optimization. A very little material is present on shielding gases on arc central minimum temperature effect on welding heat transfer much of that has been carried out using optical spectroscopy which is a very long and repetitive process. Monochromatic Image Analysis method is used in our work to study the effect of different shielding gasses in Pulsed Gas Metal Arc Welding.

1.2 Objective

The objective of research is to develop an image analysis technique to study how arc central minimum temperature is affected by different shielding gases composition using Abel Inversion based on Matrix Based inversion to evaluate emission coefficient that can be later utilized in generating arc temperature distribution using Fowler Milne method.

In our research work Pulsed GMAW will be used with different shielding gasses and temperature profile of the arc temperatures will be used to analyze heat transfer from base current value to peak.

Chapter 2

2.1 Gas Metal Arc Welding

The GMAW process is an important joining process in the Manufacturing industry. Large number of research and development continue to provide improvements in this welding process, and the results have been promising in determining temperature.

GMAW process, is an arc welding process in which metals are heated by providing them with an electric arc between a continuously fed filler metal wire as an electrode and the work. Shielding gases is provided by an externally supplied gas cylinder connected to welding plant to protect the molten weld pool from oxidation and controlled cooling (7).

The GMAW process can be used to weld a wide range of both steel and alloyed material. The GMAW process can be easily modified for use with semiautomatic and complete automatic robotic automation welding applications. (8)

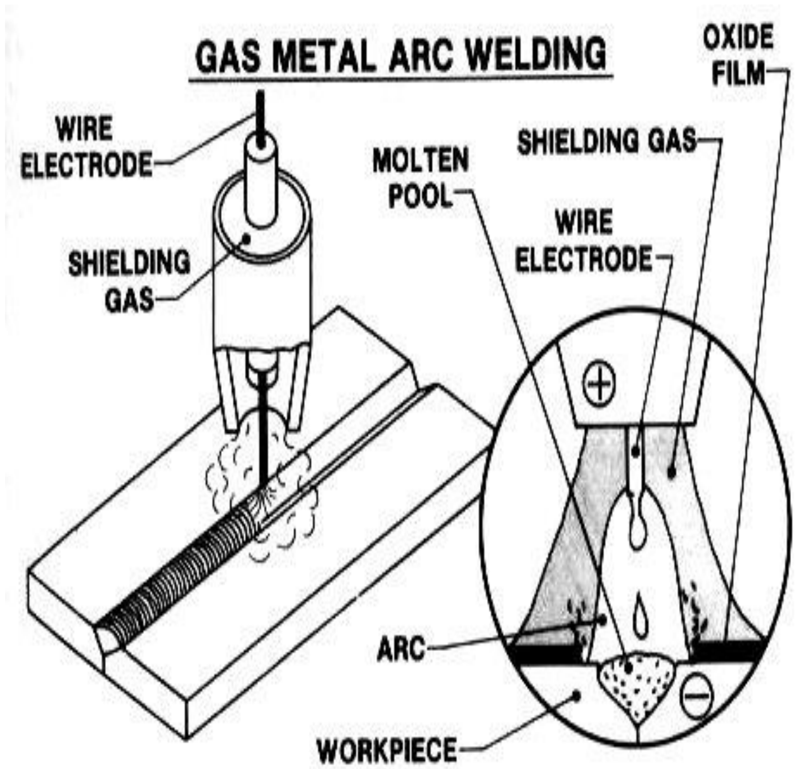


Fig.1 Gas Metal Arc Welding Process

Advantages	Benefits	Limitations
• Ability to join wider range of materials. • Enhanced mobility due to simple equipment. • Beautiful weld bead appearance. • Lesser welding fumes making the process quicker. • Easy automation process. • Higher process efficiency.	• Lower cost of weld per unit length. • Effectively handles poor fit-ups reducing chances of NDT failures. • Minimum post weld clean up required as compared flux cored arc welding or submerged arc welding.	• Excessive heat input in axial spray transfer welding mode limits the use to thicker materials. • Excessive heat input limits the use to flat position only.

2.2 Modes of metal Transfer

2.2.1 Short Circuit Transfer

Short-circuit metal transfer is the mode of metal transfer by repetitive electrical short-circuits. The transfer of molten metal droplet of electrode occurs during the short circuiting of the filler metal electrode and workpiece. when the Physical contact of the electrode occurs with the molten weld pool, in form of spray and the frequency of the short-circuiting frequency can 200-300 times every second . (8) (9)

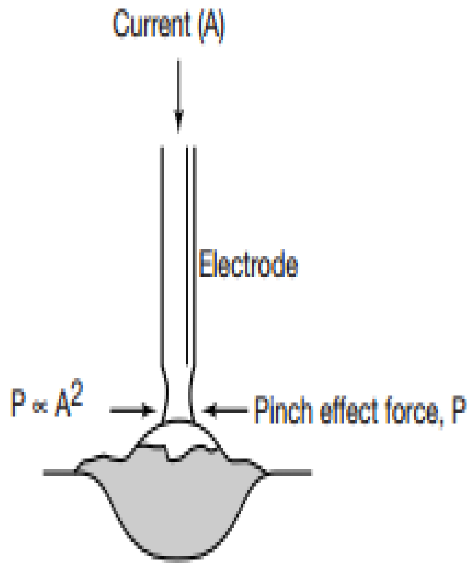


Fig.2 short circuit Heat Transfer

2.2.2 Globular Transfer

Globular metal transfer is transfer mode in welding, in which molten metal is deposited in dual combination of, short-circuits and gravity-assisted large droplets formations. The larger droplets are irregularly shaped and at very high current level is difficult to control the formation of drops of molten metal, and spatter is too much leading to difficulty in controlling the welding process. Gravity assistance is main transfer method of the large molten droplets, with a high frequency of short circuiting. (8) (9)

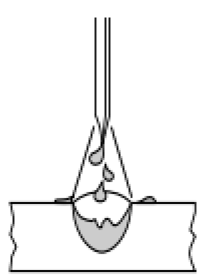


Fig.3 Globular Metal

2.2.3 Spray Transfer

Spray/Projected metal transfer the molten metal is deposited in form of stream of small droplets replicating a dense spray normally the size of the droplet equals the wire size. This method is applied to thicker thickness material by using fillets weld and for use in multiple type weld joints (8) (9).

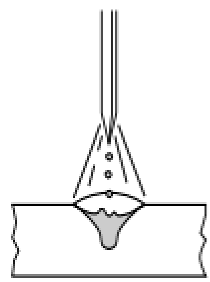


Fig. 4 Axial Spray Transfer

2.2.4 Pulsed Gas Metal Spray Transfer

This type of welding process applies waveform signal produced by electronic card to produce a very precise controlled electric arc with wide variable filler metal wire feed speed range. With the precision control of electric arc dynamics, GMAW-P can be used as fast welding process at high travel speeds, with larger deposition rates. (8).

Pulsed gas metal arc welding, is variant mixture of Projected/spray molten metal transfer and Globular metal Transfer, in which the welding current is cycled between base and peak values. Metal transfer from wire to the work piece occurs during the high energy peak current in the form of a single regular shaped molten droplet. Pulsed Gas metal arc welding process has following advantages: control of weld spatter and the minimized incomplete fusion defects that are part of the basic globular and short-circuiting transfer (8).

The pulse metal transfer produces metal spray that has the characteristic of both globular and short circuiting transfer. Because the arc is very stable and has lower heat input is involved than either of the spray or globular transfer, it allows out-of-position welding. Major benefits of this process include: better arc development characteristics, greatly reduced spatter and minimum fume generation as no flux is involved, incomplete fusion resulting from the short circuiting transfer and lower heat input than spray transfer at a given wire feed speed (8).

The pulsing transfers small amount molten metal droplets directly through the arc to the workpiece, one droplet during each pulse. As the wire is advanced, the current pulses and transfers the next molten droplet (8).

2.3 Shielding Gases used in Gas Metal Arc welding

Different shielding gases respond in different ways when temperature is applied to them. The current flow through the electric arc, its magnitude, has a great influence on the behavior of the molten droplet formation and heat transfer to the workpiece (8). Three basic criteria important in understanding the properties of shielding gas:

- Ionization potential
- **Thermal conductivity.**
- The chemical reactivity of the shielding gas with the molten weld filler and base metal.

The thermal conductivity of the gas enables it to transfer thermal energy or heat, is the most important consideration for selecting a shielding gas. The thermal conductivity also affects the shape of the electric arc and the temperature distribution inside the electric arc region as well as the metal penetration, formation of the weld pool and heat affected zones and defects in the weld are also closely related to the shielding gasses. In some cases, a given shielding gas will favor one type of the transfer mode, but will be incapable of meeting the requirements of another it can be clearly judged that shielding gasses play an important role in heat transfer and metal transfer during the welding.

2.4 Spectroscopic Analysis

Optic emission spectroscopic analysis is carried out using a narrow bandwidth filters, image resonator, mono-chromator and silicon intensified target detectors or optical fibers connected to a data processing system. The detector measures spectrally dispelled light based on measuring pattern program (6)

Multiple series of tracks are scanned based upon the size of the filter. The data is recorded and multiple set of experiments are conducted to obtain intensity from the series of tracked blocks. Maximum values in data set for individual tracks are filtered out and averaged resulting in intensity distribution profile across the arc. The intensity is later processed using Abel Inversion to give the emissivity and this is later processed out to give the temperature distribution across the arc.

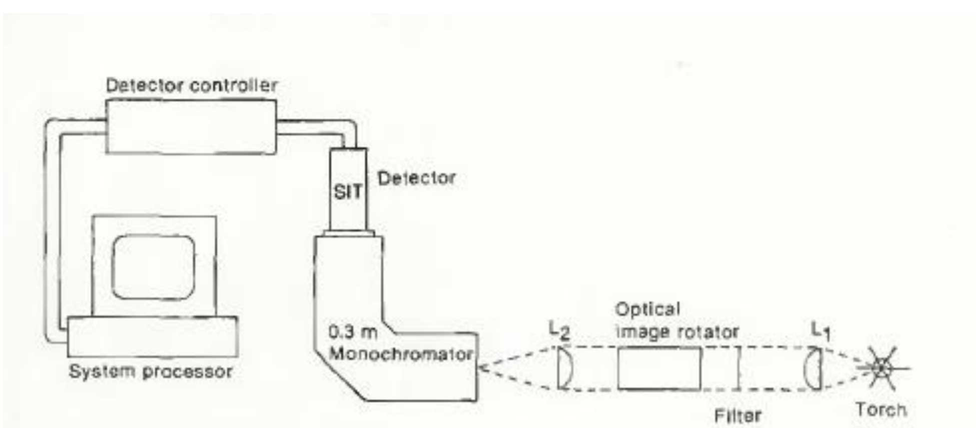


Fig. 6 Experimental Layout of the Apparatus used for optical image Spectroscopy.

2.5 Abel Inversion

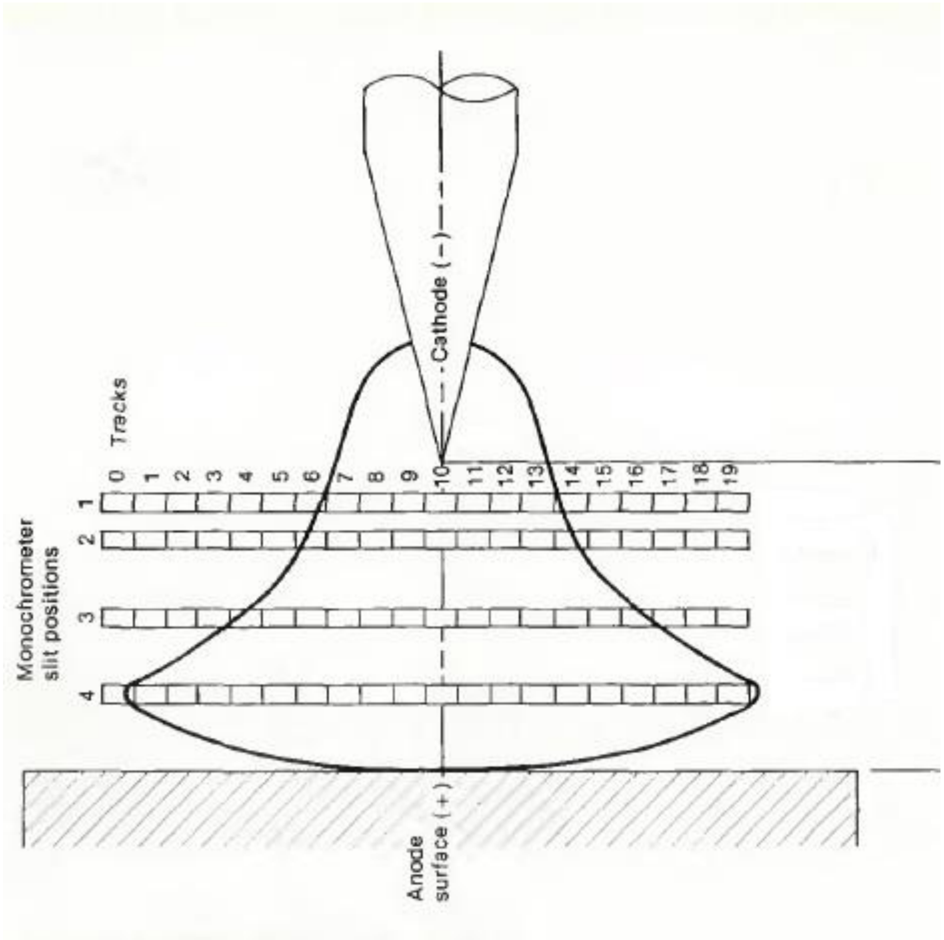


Fig. 7 Scan Pattern at different heights from the electrode.

This can be analyzed though the process is pretty simple but yet a very monotonous and repetitive. The instruments have to be calibrated every time and a little out positioning of the sensor can lead a wrong data set of values. Time to complete the experiments is very much and thus making this process very unfavorable.

2.5 Abel Inversion

In applications of plasma physics and mechanical design engineering, such as astronomy, plasma diagnostics and flame studies, the parameters in the inner part of the study object are almost impossible to be measured directly without actually affecting the quality of the data being measured. In many cases, only the line-of-sight of the projected intensities from the radiating source can be collected (10) (11).A cylindrically symmetric source, for example arc plasma with the optically thin assumption with LTE , the Projected intensity is directly related to the emissivity and reconstruction of the of the emissivity distribution from the projected data is known as Abel inversion (11).

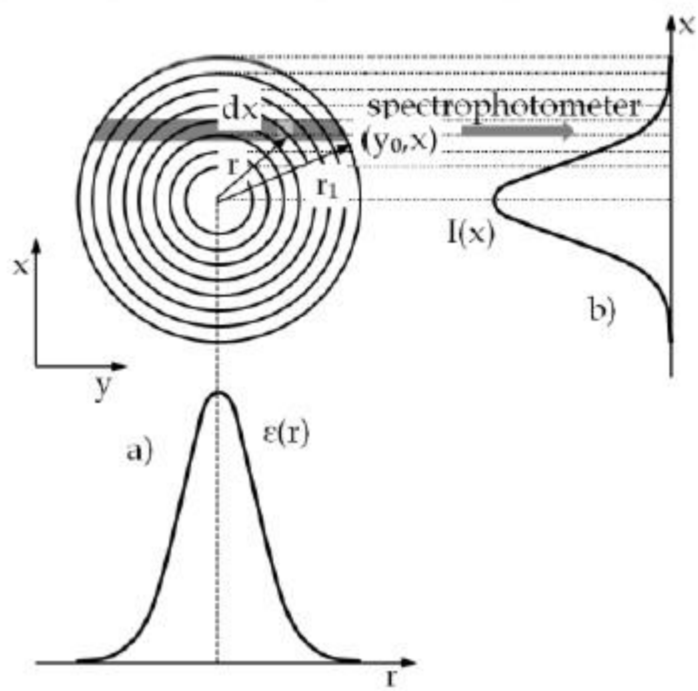


Fig. 8 Abel Inversion Schematic

$$I(x) = \int_x^r \frac{\varepsilon(r) r \, dr}{\sqrt{r^2 - x^2}} \quad \Longrightarrow \quad \varepsilon(r) = -1/\pi \int_r^R \frac{\left(\frac{dI}{dx}\right) dx}{\sqrt{x^2 - r^2}}$$

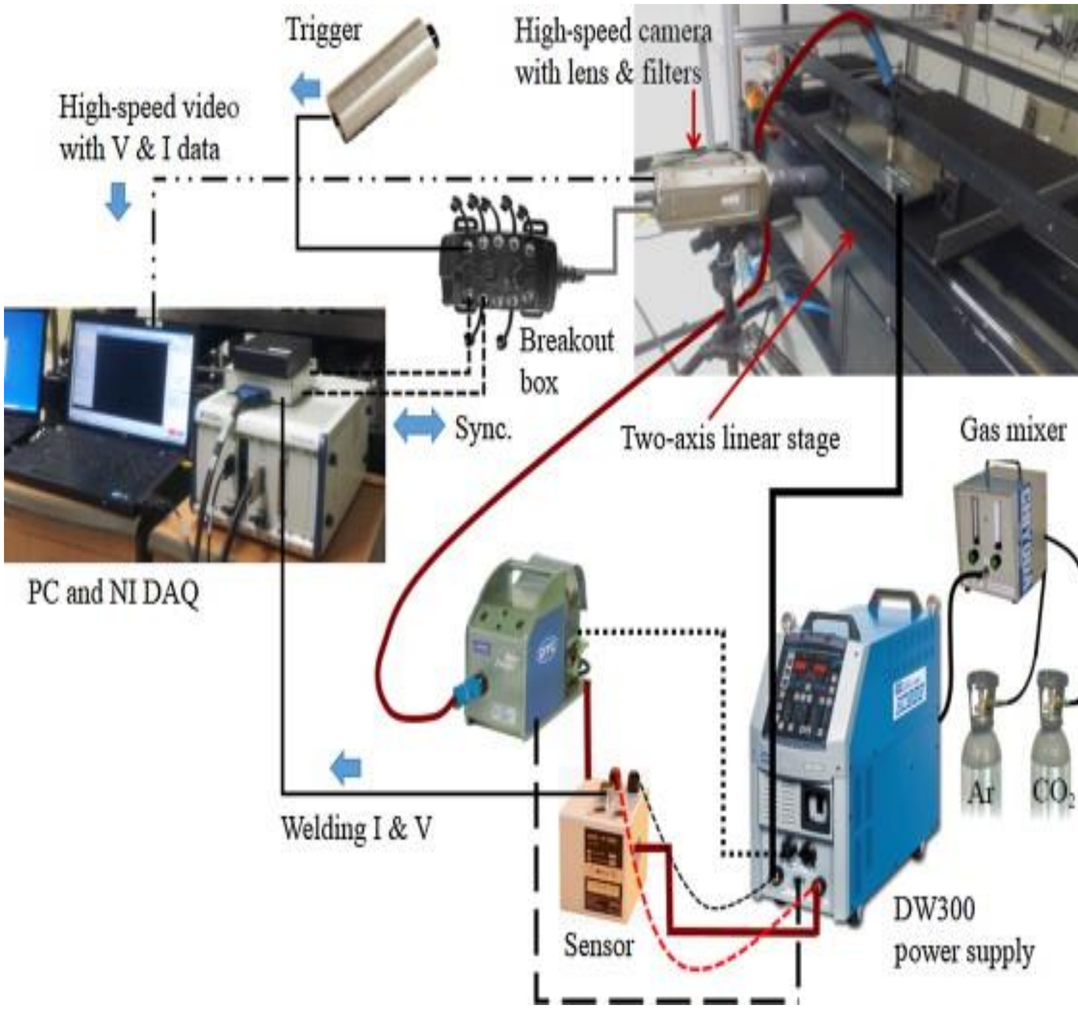
Bockasten et al. (10) Used the third degree of polynomials for experimental data fitting and Maldonado *et al* used Fourier expansion for the integration of Abel inversion (6). Elder et al found the generalized Abel equation for optically thick plasma (12), Wang et al . developed the method by Gauss numerical integral (GNI) (13) (14). Deutsch and Beniaminy used the piecewise cubic spline for experimental data (14)and Haidar used Bessel functions for data fitting to decrease the inversion errors (15).

The most commonly used method of Abel inversion for a circularly symmetric radiation source is the Fourier–Hankel technique, which could not be applied to the other condition (16). The polynomial least squares fitting method was first introduced by Freeman and Katz (17); they fitted all the data with a polynomial of fixed order. But the inverted results are very poor, especially near the edges of the fitted interval (18) (19).

Chapter 3

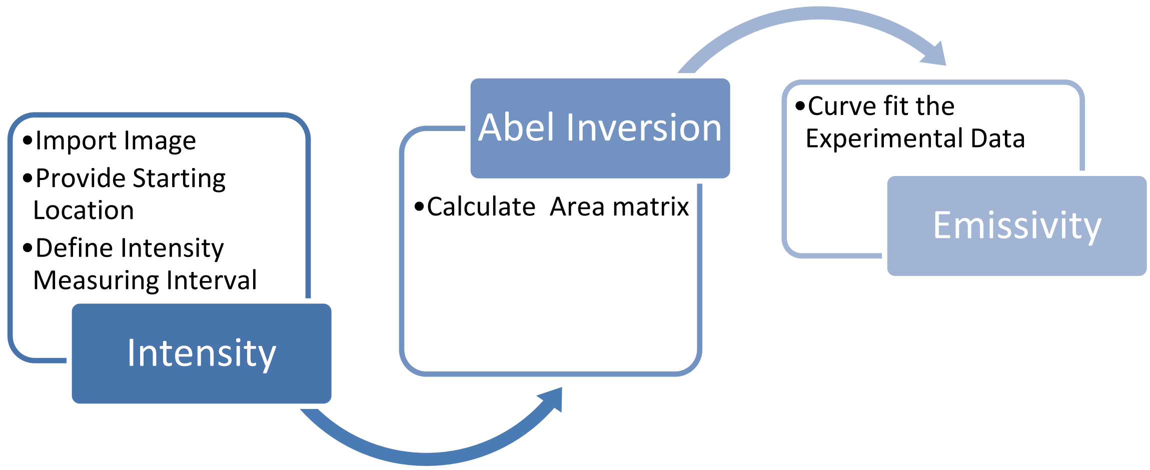
3.1 Methodology

The arc spectrum high-speed imaging experimental system consists of welding system and optical acquisition system. The welding system consists of the pulsed Gas Metal Arc Welding System. Optical system includes a high speed imaging camera, neutral filters, interference filter of large bandwidth and Camera lenses. Detailed Description of the experimental setup is as following:



Process Flow Chart ABEL Inversion

Fig. 9 Experimental Setup of Image Acquisition



3.2 Matrix Based Abel Inversion Method

The integrated sum of emission per unit volume is the intensity of the emitted radiation in the direction of the line of observation. For cylindrical plasma source, which is assumed to be optically thin, along the line of the measurement direction the projected intensity is related to the emissivity by a determined function. Reconstruction of the emissivity distribution from intensity of the projected data is known as Abel inversion. Abel inversion method developed by cho and na et al (27)for calculations of emissions from circular and elliptical profiles of plasma radiation sources. Matrix based Abel inversion process provides quick and reliable conversion of intensity into emissivity Figure 10 shows a disk of cylindrically symmetric plasma for Abel Inversion.

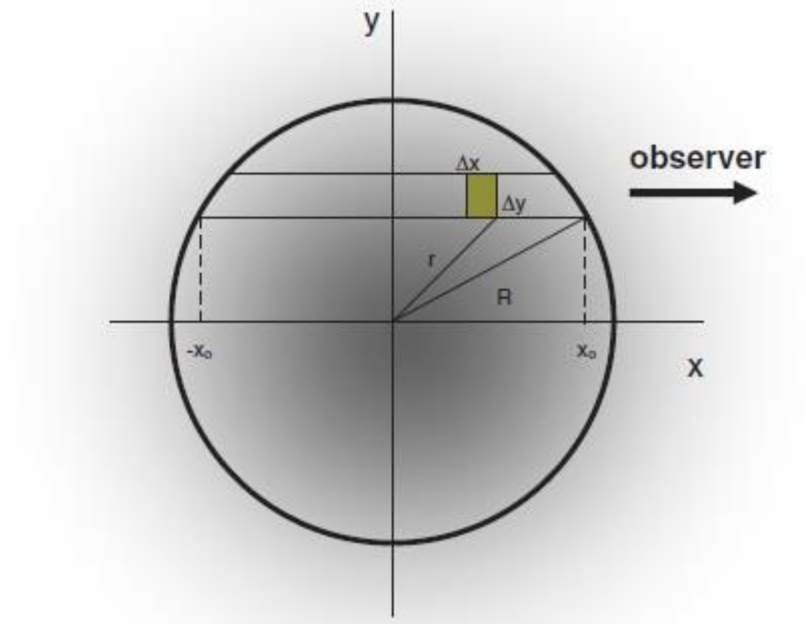


Fig. 10 Coordinate system for Abel Inversion

The plasma is assumed and treated as optically thin radiation in local thermodynamic equilibrium (27), that there is no self-absorption in the plasma, and then the measured intensity of radiation is related as follows:

$$I(y)\Delta y\Delta z = \sum_{x0}^{xn} \varepsilon(r)\Delta x\Delta y\Delta z \qquad \text{Eq. 1}$$

Where I(y) denote the intensity, ε(r) is the emissivity in the radial direction, Z denotes the symmetric axis of the arc and observer is observing in the direction parallel to x-axis. Rearranging the equation 1 into integral form will give us:

$$\text{I(y)} = \int_{x}^{r} \frac{\varepsilon(r) r\, dr}{\sqrt{r^2 - y^2}} \qquad \text{Eq. 2}$$

The intensity of radiation from the emitted source multiplied by its local area of measurement is the same as the summation of all the emissivity multiplied by the local volume having the same local thickness (27) resulting in the simplification of equation 1:

$$I(y)\Delta y = \sum_{x0}^{xn} \varepsilon(r)\Delta x\Delta y \qquad \text{Eq. 3}$$

In equation the left hand side of the equation is the measured intensity multiplied by the measuring interval of the intensity and the right hand side of the equation represents the emissivity multiplied by the local area refer to figure 10.

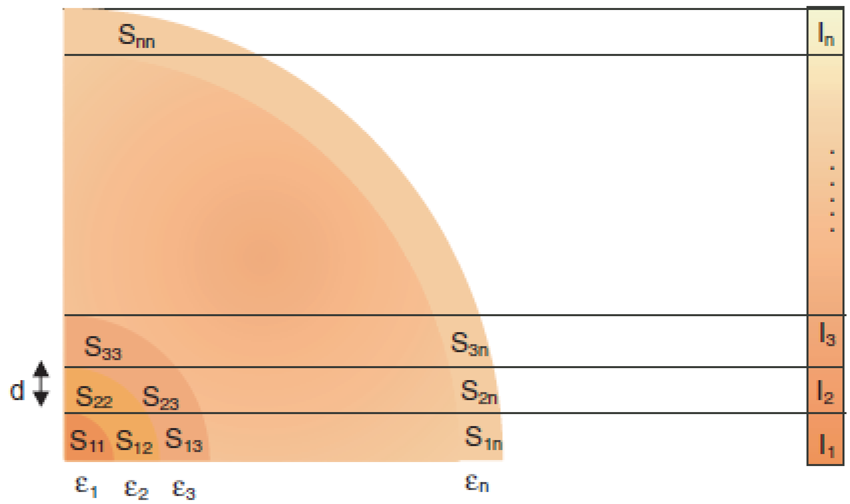


Fig. 11 Geometric Relationship for Abel

From the above figure we can conclude that measured intensity is the sum of the product local emissivity multiplied the local area. Using the geometric relationship we can obtain the below equations.

$$I_1 = 2(S_{11}\varepsilon_1 + S_{12}\,\varepsilon_2 + \ldots\ldots + S_{1n}\,\varepsilon_n)/d$$

$$I_2 = 2(S_{22}\,\varepsilon\,2 + S_{23}\,\varepsilon_3 + \ldots\ldots + S_{2n}\,\varepsilon_n)/d$$

$$I_n = 2(S_{nn}\,\varepsilon_n)/d$$

Eq. 4

The n sets of above equation can be formed into matrix form for solving them for emissivity as follow:

$$\begin{pmatrix} S_{11} & S_{12} & S_{13}\ldots\ldots\ldots\ldots S_{1n} \\ 0 & S_{22} & S_{23}\ldots\ldots\ldots\ldots S_{2n} \\ 0 & 0 & S_{33}\ldots\ldots\ldots\ldots S_{3n} \end{pmatrix} \begin{pmatrix} \varepsilon_1 \\ \\ \varepsilon_3 \end{pmatrix} = \frac{d}{2} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

Eq. 5

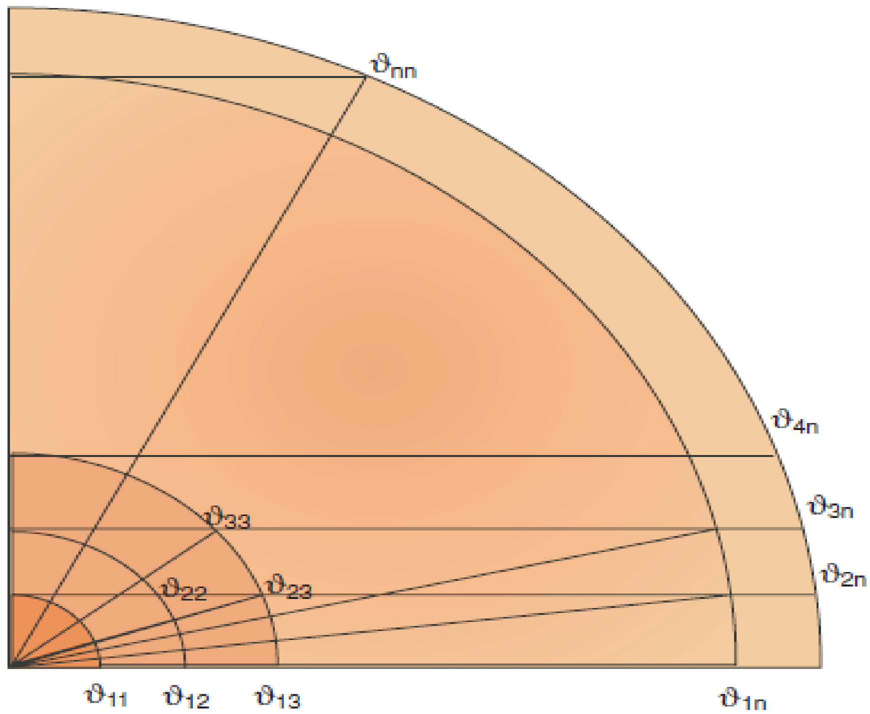


Fig. 12 Area Matrix

In order to calculate the area matrix S, ϑij is introduced and θij as the angle between the y axis and ϑij from origin defined by user for the axis that define the center point of the arc (27). Following equations can be obtained :

$$\theta ij = \cos^{-1}\left(\frac{(i-1)}{j}\right) \text{ for } i \leq j$$

Eq. 6

$$\theta ij = 0 \text{ for } i \geq j$$

Pij is the cross sectional area between the outside of the ith line in the observing direction of the radiation and the inside of the jth line in the radial direction. Then, the area matrix Sij can be expressed as follows:

$$Pij = \frac{1}{2}(jd)^2\theta ij - \frac{1}{2}\big((i-1)d\big)^2 \tan(\theta ij) \quad \text{for } i \leq j$$
$$Pij = 0 \quad \text{for } i \geq j$$
Eq. 7

$$Sij = (Pij - Pi + 1j) - (Pi(j-1) - P(i+1)(j-1)) \quad \text{for } i \leq j$$
$$Sij = 0 \quad \text{for } i \geq j$$
Eq. 8

Once the local area is obtained the emissivity can be obtained by solving the matrix equation 5.

$$\varepsilon = (d/2) \left[S \right]^{-1} \left[I \right]^{-1}$$
Eq. 9

To solve the matrix matlab code developed based on the logic of matrix inversion method (28).

3.3 Fowler Milne Method for Temperature Determination

Different methodologies have been developed and used by different authors to study physical, thermal and electrical properties of welding arc plasma radiation sources. Some developed numerical models to investigate free burning arcs. Lowke et al. (1997) simulated the arc temperatures in mixtures of argon and hydrogen as shielding gasses, Murphy (1994a)predicted the dominant demixing gas process in a mixture of nitrogen and argon arc plasma, and Murphy et al. (2009) investigated the influence of adding helium, hydrogen and nitrogen to the argon shielding gas. These numerical models were based on strong assumption and approximation, and the calculated results often required validation by experimental study. Other scholars carried out experiments measuring temperature and gas composition in multi-element arc plasmas. Song (1990) used absolute intensity of Ar I and He line to determine temperature and gas composition of argon-hydrogen arc plasma, while Li et al. (1993) used Ar I and N I line to determine temperature and gas composition of argon-nitrogen arc plasma.

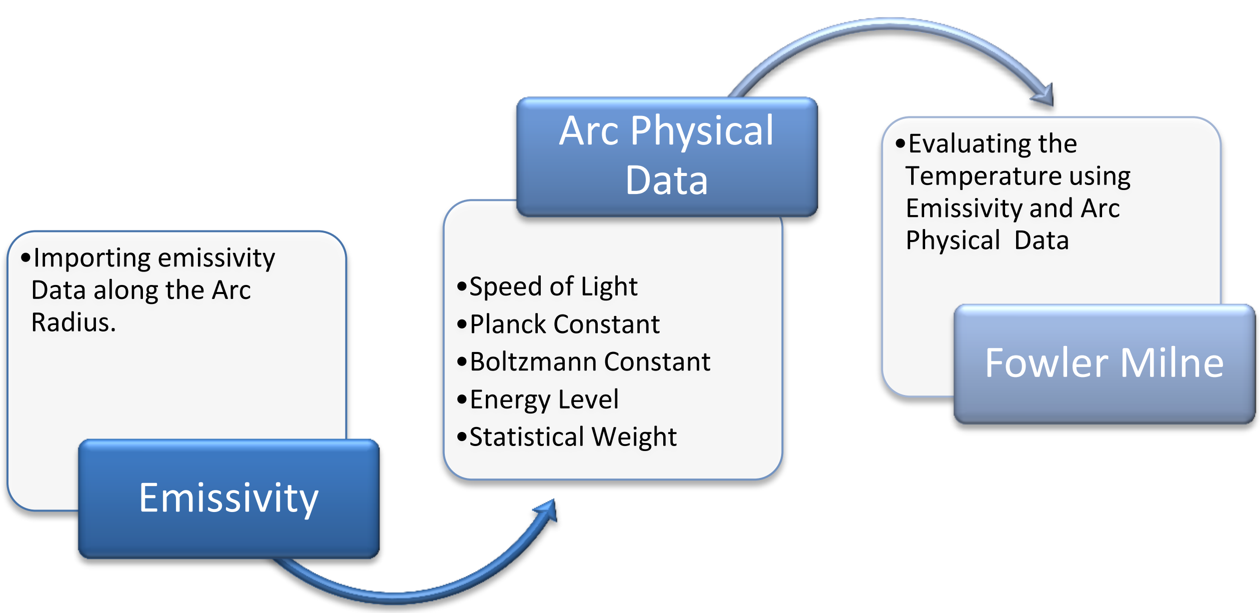
Apart from the Numerical model which mostly relied on the spectroscopic method new method that were much more convenient and less time consuming were developed alongside. This method was based on high speed imaging method and later processing the image on the same principal of abel inversion and later temperature determination using fowler milne method.

Tashiro et al (2010) studied the temperature generation in the arc using pulsed Tungsten Inert Gas Wielding using pure argon as shielding gas.

Wang et al. (2013) studied the effect of shielding gasses on arc temperature with current variation. Their main area was to study how a small variation in current affected the arc temperature and heat generated.

Na et al(2005,2013) used fowler Milne method on GTAW and Pulsed GTAW to study effect of shielding gasses and their mixtures on the arc physical properties. Using matrix based Abel Inversion as discussed earlier they calculated the arc temperature distribution, forces involved in the arc generation process and the effect of arc on heat transferred to the work piece.

Xiao et al (2014) used GTAW welding using argon-I, argon-II and helium mixtures to study the arc temperatures generated. Based on Olsen-Richter diagram calculated the intensity and later emissivity and using the fowler Milne method temperatures are carried out.



3.4 Line and Continuum Radiation

Line Radiation is defined as the radiation that is emitted by the change in state of neutral atom . Continuum radiation is the radiation that is emitted by the combination of electron to ion and ion into an atom.

The combined line radiation and continuum radiation produce the effect of total emitted radiation however the effect of the continuum radiation can be ignored as reported by the literature (13) (15).

The Ratio of Electron number density and partition function can be taken unity. (28)and the values of constant were taken from the previous work done (28).

$$\varepsilon = \frac{hc}{4\pi\lambda}\, gm\, Anm \frac{nj}{uj} e^{\left(-\frac{Em}{KT}\right)}$$

Relation between line radiation and Temperature

Eq. 10

h = plank's Constant
c = Speed of Light
Em= Energy of Upper Level
gm = Statistical weight of upper level
Anm = Transitional Probability

nj = number Density
Uj = Partition function
K = Boltzmann constant

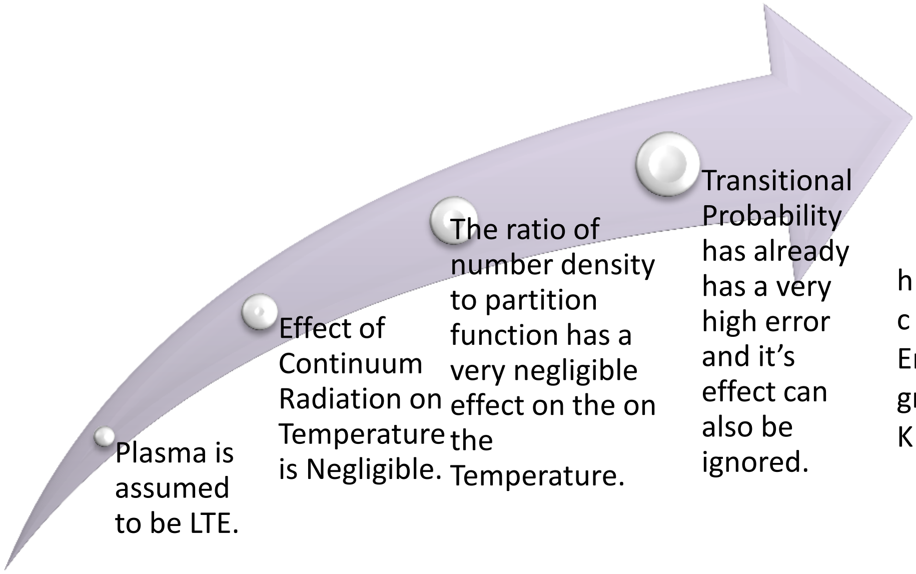
$$\varepsilon c = Cei \frac{ne}{(\sqrt{Te})\lambda^2} \Sigma ni Zi^2 \xi i \ (\lambda, T)$$

Eq. 11

Relation between Continuum radiation and Temperature

ne = electron density
Ni = ion density
Zi = change of ion

Te = Electron Temperature
ξi = Biermann constant
Cei = Electron –Ion Combination Constant



$$\varepsilon = \frac{hc}{4\pi\lambda}\, gm\, e^{\left(-\frac{Em}{KT}\right)}$$

h = plank's Constant
c = Speed of Light
Em= Energy of Upper Level
gm = Statistical weight of upper level
K = Boltzman constant

Chapter 4 Results

4.1 Results Pure Argon 140 AMP CURRENT

Pure Argon as a shielding gas was used with the welding current of 140 Amps and flat position was used for welding.

4.2 Results Pure Argon 260 Amps Current

Pure Argon as a shielding gas was used with the welding current of 260 Amps and flat position was used for welding.

4.3 Results Argon-8% CO_2

Argon with 8% carbon dioxide as a shielding gas was used with the welding and flat position was used for welding.

4.4 Results Argon-10% CO_2

Argon with 10% carbon dioxide as a shielding gas was used with the welding and flat position was used for welding.

4.5.Conclusions and Results Discussion

The arc central minimum temperature phenomena is a negative phenomenon while using Pure Argon as the shielding gas the central minimum temperature cannot be avoided as the value of the welding current increases the effect gets more prominent.

Metal vapor concentration in the plasma results in central minimum temperature reason being that iron ions are more radiative than any other element present in the plasma. Likewise high metal concentration produces high cathode jets due to constriction. In order to counter the problem CO2 reactive shielding gas is added to the mixture.

Addition of CO2 not only reduces the metal vapor concentration but helps in increasing the arc temperature in Fig. 18 when using 8% of co2 prominent arc central minimum temperature exists from intermediate to peak stage however with 10% of CO2 in the mixture the peak temperature observed are more and also the central minimum temperature are avoided.

For same value of welding current increase in percentage of carbon dioxide results in higher temperatures this gives us the advantage that using a smaller current rating welding plant we can welding thicker sections of materials saving energy.

Using excessive carbon dioxide greater than 10 % will negatively affect the joint quality as the gas is reactive and oxygen can oxidize the surface metal and also it can result in porosity and spattering.

Concentration of metal vapor in the plasma results in the phenomena of Dip as the radiative heat transfer is more by high concentration of metal plasma and this result in arc center minimum temperature.

Pulsed GMAW with high percentage of CO2 gas mixture can be used to weld thick material while using the pure argon thinner materials can be welded using the advantage of pulsed current which results in minimum heating of Workpiece for same current Range.

Electrical Conductivity of pure Argon is more as compared to mixture so change in conductivity results in the change Heat input and thus Penetration as the resistance from the mixture will be more so will be the initiating current and peak current and thus more penetration can be achieved.

The Cathode spot size greatly varied with the concentration of carbon dioxide as the percentage increased the size of the spot increased resulting in higher arc central temperatures this can be clearly seen during the arc development stages as the result of the increase in the size of the cathode spot the center of the arc showed a variation.

Applying this technique on different welding joint Configuration Arc Heat Input can be varied as per Requirement.

Same working Technique can be applied to AC-GMAW Process to effectively implement a single welding technique to thin sheets as well as thick plates welding

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