Temperature Measurement in Plasma Cutting Through Infra Red Imaging and Comparison with FEM

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Abstract
Measurement of temperature is a basis for carrying out technique and derivative analyses. Therefore, there has arisen the need to understand theoretically and control appropriately metallurgical and mechanical characteristics in heat-affected zone (HAZ), which has a significant influence on the strength and toughness of mild steel plate. Commonly, metallurgical phenomena in HAZ are evaluated based on the highest temperature and the cooling rate. Therefore, in order to control metallurgical and mechanical characteristics in HAZ by means of the plasma cutting conditions, evaluating the temperature distribution and the temperature history near the melted zone is essential. In this study, in order to investigate the temperature distribution and histories during plasma cutting, the Infra Red results were compared with the FEM results. Based on the results, it was expected to control temperature distribution near melted zone by more appropriate heat input characteristics, which is depended on heat source arrangement.

INTRODUCTION

Temperature measurement in today's industrial environment encompasses a wide variety of needs and applications. To meet this wide array of needs the process controls industry has developed a large number of sensors and devices to handle this demand. Temperature is a very critical and widely measured variable for most mechanical engineers. Many processes must have either a monitored or controlled temperature. This can range from the simple monitoring of the water temperature of an engine or load device, or as complex as the temperature of a weld or cut in a laser application. More difficult measurements such as the temperature of smoke stack gas from a power generating station or blast furnace or the exhaust gas of a rocket may need to be monitored. Much more common are the temperatures of fluids in processes or process support applications, or the temperature of solid objects such as metal plates, bearings and shafts in a piece of machinery.

Many methods have been developed for measuring temperature. Most of these rely on measuring some physical property of a working material that varies with temperature. One of the most common devices for measuring temperature is the glass thermometer. Another type of thermometer that is not really used much in practice, but is important from a theoretical standpoint, is the gas thermometer. Other important devices for measuring temperature include:

- thermocouples,
- thermistors,
- resistance temperature detector (RTD),
- pyrometer,
- langmuir probes (for electron temperature of a plasma),
- infrared.

Thermocouples consist essentially of two strips or wires made of different metals and joined at one end. Changes in the temperature at that juncture induce a change in electromotive force (emf) between the other ends. As temperature goes up, this output emf of the thermocouple rises, though not necessarily linearly.

The thermistor is a device that changes its electrical resistance with temperature. These devices exhibit a negative temperature coefficient, meaning that as the temperature increases the resistance of the element decreases. These have extremely good accuracy, ranging around 0.1° to 0.2°C working over a range of 0 to 100°C. These are still the most accurate transducers manufactured for temperature measurement; however thermistors are non-linear in response.

Resistive temperature devices capitalize on the fact that the electrical resistance of a material changes as its temperature changes. As their name indicates, RTDs rely on resistance change in a metal, with the resistance rising more or less linearly with temperature.

A pyrometer is a type of thermometer used to measure high temperatures. It is a non-contacting device that intercepts and measures thermal radiation, a process known as pyrometry. The thermal radiation can be used to determine the temperature of an object’s surface.

A Langmuir probe is a device named after Nobel Prize winning physicist Irving Langmuir, used to determine the electron temperature, electron density, and electric potential of plasma. It works by inserting one or more electrodes into plasma, with a constant or time-varying electric potential between the various electrodes or between them and the surrounding vessel. The measured currents and potentials in this system allow the determination of the physical properties of the plasma.

Infrared sensors are noncontacting devices. They infer temperature by measuring the thermal radiation emitted by a material.

P.V. Ananthapadmanabhan et.al [1] formed the nano-sized alumina by in-flight oxidation of aluminium powder in a thermal
plasma reactor. Nano-sized aluminium oxide powder had been synthesized in a thermal plasma reactor by in-flight oxidation of aluminium metal. The particle size of alumina formed ranges from a few nanometers to 30 nm. They also developed a theoretical model for in-flight oxidation of aluminium.

H.K.Kang [2] examined the thermal properties of plasma sprayed tungsten deposits by spraying tungsten powder on a graphite substrate and studied the microstructures, porosities, and thermal conductivities of tungsten deposits. He had found that tungsten was partially oxidized to tungsten oxide (WO3) after plasma spraying. Most pores were found in the vicinity of lamellar layers in association with oxidation. It was revealed that both tungsten oxide and the lamellar structure with pores have a significant influence on the electrical and thermal conductivity.

Zahir Salhi et.al [3] developed Very Low-Pressure Plasma Spray and used for deposition of copper powder coating on stainless steel substrate. Also studied the volatilization of the injected powder in supersonic plasma by using optical emission spectroscopy. It was shown that the plasma expansion with decreasing chamber pressure increases the volatilization of particles and allows obtaining a very dense coating with crystalline structures and avoids oxygen, due to the preheating of the substrate with plasma.

S. Kumar et.al [5] used a non-transferred DC plasma torch to produce aluminium macro powders. The powders produced were doughnut shaped. The macro particle size was estimated theoretically and compared with experimental results. The pressure inside the particle was estimated. The pressure gradient develops the indentation on the powder surface which seems to be doughnut.

Masaya Shigeta et.al [6] conducted a numerical analysis for the titanium-based boride and silicide nanoparticle synthesis using induction thermal plasma including the material evaporation process and the nanoparticle growth process with nucleation and co-condensation. Both systems presented the nanoscaled particle size distributions. Ti–B system showed the smaller particle diameter, sharper distribution, larger particle number density, and wider range of the composition than Ti–Si system. Ti–Si system provided a narrower range of the silicon content due to the simultaneous co-condensation of titanium and silicon. The precursor particle trajectory and temperature history were examined by Lagrangian approach taking into account the rarefied gas effects.

Emel Taban [7] conducted an experiment to join duplex stainless steel with a thickness of 6.8mm by plasma arc, Tungsten Inert Gas (TIG), and plasma arc-TIG welding processes. And he carried out Impact toughness testing and also examined fractographs by Scanning Electron Microscopy (SEM). Microstructural analysis, ferrite content, and hardness survey of the weld zones were done while the variation in chemical composition was investigated with energy dispersive X-ray spectroscopy (EDX).

Qing Yu Hou et.al [8] deposited Nickel-based alloys powders with and without nano-Al2O3 on low carbon steel using plasma transferred arc welding machine. And they studied microstructures of the two deposited coatings by optical microscopy, scanning electron microscopy, X-ray diffraction and transmission electron microscope. They also conducted Wear resistance experiment on one sliding wear machine to value the deposited coatings and concluded that the typical hypoeutectic microstructure and the component segregation exist in the Al2O3-free coating.

Genyu Chen et.al [10] carried out spectroscopic measurements of electron temperature and electron density of the keyhole plasma and plasma plume in deep penetration laser welding conditions. They developed an Optical Multi-channel Analyser to receive spectra from several points separately and simultaneously. They also calculated the temperature with the spectral relative intensity method. The spectra collected were processed with Abel inversion method to obtain the temperature fields of keyhole plasma and plasma plume.

Chuanbao Jia et.al [11] conducted experiments in air and under water (0.4 m depth) and collected the spectrum signals. They found that the width of the weld under water was about two-thirds of the width in air and suggested that the arc plasma was compressed by the water environment. They analyzed and identified a unique peak at 656.2793 nm in the underwater spectrum, consistent with H atomic transitions, suggested that H atoms become involved, although without affecting the overall spectral similarity of the two environments. In either environment the arc plasma was mainly composed of self-shielding gas and evaporated metals, with only minor effects stemming from the interaction with water.

Yan Li et.al [12] developed a three dimensional numerical model to investigate the plasma arc welding (PAW) process, featured by the compound volumetric heat source movement and heat transfer with phase change in the weld pool, where fluid flow is driven by a combination of surface tension, electromagnetic and buoyancy forces. They proposed a modified heat source model to involve the key-holing effect of PAW. It was composed of a double-ellipsoidal volumetric heat source at the upper and a conical volumetric heat source at the lower. They proved that the modified heat source model as well as fluid flow consideration can improve the PAW simulation. They concluded that high plasma arc power or/and low welding speed is beneficial to complete joint penetration, but optimum process parameters are good choice to ensure both the high weld quality and complete joint penetration.

Liming Liu et.al [13] investigated effect of laser pulse on the recovery delay of arc plasma during pulsed laser–arc hybrid welding of Mg alloy based on the dynamic behavior of Mg atoms. High-speed camera and spectograph were employed to monitor the behaviors of Mg atom in the arc plasma and to characterize the effect of laser pulse on the arc plasma, respectively. It was found that the arc plasma cannot recover to its original state immediately after laser pulse action and it takes 0–5 ms for the excessive Mg atoms to escape from the arc plasma depending on the given parameters.

C.S. Wu et.al [14] introduced the basic principles of plasma arc welding (PAW). The PAW process was compared to gas tungsten arc welding, its process characteristics were listed, the classification was made, and two modes of operation in PAW, i.e., melt-in and keyhole, were explained. The keyhole mechanism and its influencing factors were introduced. The sensing and control methodologies of the PAW process were reviewed. The coupled behaviors of weld pool and keyhole, the heat transfer and fluid flow as well as three-dimensional modeling and simulation in PAW were discussed. And a novel PAW process variant, the controlled pulse key holing process and the corresponding experimental system were introduced.

Weicheng Xie et.al [15] used the fiber spectograph for collecting the spectral distribution of the Ar plasma-arc. Then they analyzed the influences of the electric current and air current on the spectral distribution. It was found that electric current below 100 A, air current below 10 A/min is good for spectral analysis, while two different wavelengths of 696.5 nm and 763.5 nm are suitable for temperature field testing and analyzing.
EXPERIMENTS

For temperature measurement machined mild steel (MS) plates of dimensions: 150 mm x 100 mm x 16 mm were used. The machined MS plates were well cleaned to ensure no surface variations and a uniform surface finish. The plates were cut by Plasma Cutting process. All the cuttings were made using a FLAMINGO Portable Shape Cutting machine of Hypertherm Powermax 45 made by ESAB INDIA Ltd. This machine has a current range of 20-45 Amps and a maximum voltage of 275 V. Arc currents of 45-55 Amp and arc voltages of 127-138 V DC were used. Cutting was carried out in the vertical position with cutting speed of 320 mm/min.

Thermal imaging was carried out using an infrared camera (RayCam C.A.1886) with operating temperature of -15 °C to 50 °C and operating humidity of 10-95 % HR.

The infrared camera was used to capture thermal image manually from a distance of about 1.0 m from the MS plate and suitably focused so that the entire workpiece could be seen immediately after cutting (Fig. 1). This made it possible to observe the temperature distribution in the MS plate. The images were initially recorded using the data card. The images were subsequently displayed back and analyzed.

![Figure 1 Thermogram produced by thermal imaging camera](image1)

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.

Finite difference equation: Finite difference equation is a powerful and very modern technique to find the temperature in any point in a body. It works in following steps:[9]

1. we divided whole body or surface in symmetric mesh,
2. every mesh has some nodes according to the shape of finite element (here we consider square finite element),
3. we balance energy for each node and find linear equation,
4. after solving linear equations we find temperature at any node.

The temperature gradients may in turn be expressed as a function of the nodal temperatures. That is,

\[
T_{m,n+1} + T_{m,n-1} + T_{m+1,n} + T_{m-1,n} - 4T_{m,n} = 0
\]

(1)

Above equation is fundamental equation to find out temperature at any point in surface with square finite element subjected to two dimensional steady state conduction.

Now we apply this equation on our problem. It was done by writing 42 linear equations. Then a matrix was made and the data was entered in Microsoft Office Excel. The matrix was solved by using Microsoft Office Excel. For this the Array was used for finding the inverse of the Matrix and doing multiplication of matrices.

![Figure 2 Nodal network](image2)

Set of temperatures at all the nodes were calculated by using Finite Element Method and the obtained temperatures were compared with FEM.

RESULTS AND DISCUSSION

The whole area of MS plate was equally divided into 96 squares of 12.5 mm side. The intersection points are called nodes which were numbered from 1 to 42. The temperature was calculated at these nodes by using Finite Element Method.

![Figure 3 Meshing of surface with square finite element Method](image3)

![Figure 4 Temperature distribution along line 4-4 by FEM (axis x: points, axis y: temperature [°C])](image4)
A graph showing temperatures vs. points (Fig. 4) was plotted for the temperatures along a vertical line 4-4. The curve is smooth but it could not give the exact temperatures at various points.

A thermogram was captured using Thermal Imaging Camera in which maximum and minimum temperatures were shown (Fig. 5). Software was used to draw the graph along the line L1 which is shown in figure 6. This curve is not as smooth as figure 4. But this gives exact temperatures at various points.

**Figure 5** Heat affected zone for 16 mm mild steel plate

**Figure 6** Temperature distribution along line L1 by infrared analysis

**CONCLUSION AND FUTURE DIRECTION OF RESEARCH**

It is clear from the above that temperature can be measured by using several methods. FEM involves a lot of calculation which takes more time and also it cannot give exact results. On the other hand, Infra Red Imaging technique is faster and gives exact results. But the set up cost of Thermal Imaging Camera is high. So if the numbers of observations are more then we should use Infra Red Imaging technique.

**REFERENCES**


**LIST OF USED SYMBOLS**

HAZ – Heat affected zone

FEM – Finite Elements Method

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