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Numerical Study of Tungsten Cathode Characteristics During TIG Welding

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Abstract: Tungsten Inert Gas (TIG) is widely utilized across various industries. The understanding of tungsten electrode behavior, key component in this process, is vital for optimizing processes and enhancing weld quality. The shape of the electrode tip, influenced by its operational characteristics, significantly impacts the behavior of the electric arc and, consequently, the quality of the welded assembly. This study aims to analyze the influence of current intensity on the thermal and electrical characteristics of the cathode tip during TIG welding, using numerical simulations conducted with Comsol software. The analyses are carried out by applying Direct Current (DC) welding on an aluminum alloy sheet. The results show a similar evolution in the operational characteristics of the electrode as its tip angle varies. In contrast, the current intensity affects only the temperature, which increases with a higher tip angle, while the current density depends solely on the geometry of the electrode tip. The appropriate selection of welding parameters is imperative to preserve the electrode shape and ensure an efficient welding process.

Keywords: Cathode, TIG welding, Operating characteristics, Current density

Introduction

Electric arc welding has long been a cornerstone of industrial processes, continuously evolving and advancing over the decades. Despite its widespread application and technological progress, a thorough understanding of the underlying mechanisms and the development of predictive simulation models remain vital. Such models are essential for improving process efficiency, optimizing outcomes, and minimizing the costs associated with experimental trials. In the specific context of Gas Tungsten Arc Welding (GTAW), also known as TIG welding, the properties and performance of refractory cathodes are critical to the welding process (Sun et al., 2017; Liao et al., 2018; Chen et al., 2017; Botticher & Botticher, 2000). These cathodes are instrumental in maintaining arc stability, regulating heat distribution, and influencing overall weld quality. However, the complex interplay between factory-controlled welding parameters and the operational characteristics of these cathodes hasnot been fully explored.

The advent of modern high-speed computing has made it possible to predict the properties of electric arcs in detail,

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based on the fundamental properties of materials, particularly for those using thermionically emitting cathodes. Nevertheless, most previous studies have relied on assumptions regarding cathode conditions, especially current density, as input parameters (Benilov et al., 2016; Baeva, 2017; Lowke et al., 1995; Uhrlandth et al., 2015; Askri & Minoo, 2008). The calculated maximum arc temperature varies depending on the initially assumed current density.

This study addresses this gap by using predictive numerical simulations to establish a direct correlation between welding parameters and the operational characteristics of the refractory cathode. By employing finite element analysis (FEA), this research aims to clarify the effect of the electrode tip shape and input current intensity on the evolution of current density and temperature distribution. A comprehensive understanding of these relationships is crucial for optimizing welding conditions, extending cathode lifespan, and ultimately enhancing the reliability and efficiency of GTAW operations in industrial environments. This paper presents the methodology employed for numerical simulations, outlines the expected contributions to the field, and discusses the implications for future research and industrial applications.

Physical Phenomena and Mathematical Formulation in TIG Welding

The arc plasma flow is modeled under an axi-symmetrical assumption at atmospheric pressure. The 2D geometry used in our model is illustrated in Figure 1. The cathode is considered to be made of pure tungsten with a diameter of 3.2 mm. The distance between the frontal tip of the cathode and the anode surface is 5 mm. Pure argon is used as the shielding gas.

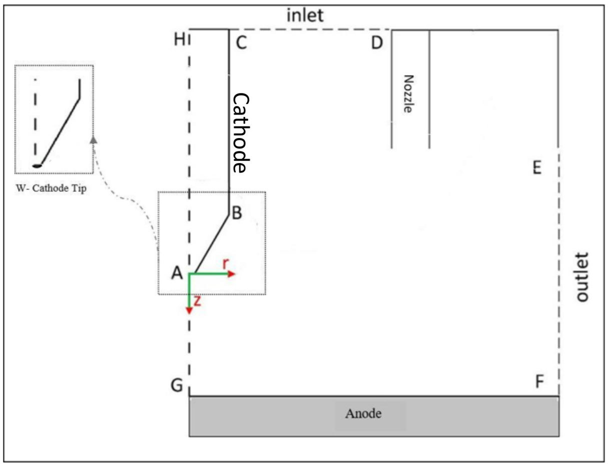

Figure 1. Geometric configuration of the computational area

In TIG welding, the temperature distribution and current density at the cathode are governed by several interrelated physical phenomena

1- **Joule Heating**: When current passes through the cathode, it generates heat due to the resistance of the material, described by Joule's law. It can be expressed as:

$$Q = J^2 \rho \tag{1}$$

Where:

- J: Current density;
- ρ: Electrical resistivity of tungsten.

2- **Thermal Conduction:** Heat generated at the cathode is conducted away through the material. The temperature distribution is influenced by the thermal conductivity of the cathode.

For steady-state conditions, it is given by:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \tag{2}$$

Where:

- ρ: Density of the cathode material (kg/m³);
- c_p: Specific heat capacity (J/kg·K);
- T: Temperature (K);
- k: Thermal conductivity (W/m·K);
- Q: Volumetric heat generation rate (W/m³), which includes Joule heating and other heat sources.

For steady-state conditions ($\frac{\partial T}{\partial t} = 0$), the equation simplifies to:

$$\nabla \cdot (k\nabla T) + Q = 0 \tag{3}$$

Where:

- k: Thermal conductivity of tungsten;
- T: Temperature;
- Q: Volumetric heat generation term (including Joule heating and other heat sources).

3- **Current density**: The total current density at the surface of the cathode, is given by:

$$J_s = J_i + J_{bd} - J_{em} \tag{4}$$

Where:

- J_{em} denotes the current density resulting from thermionic emission,
- J_i signifies the current density caused by ion collisions,
- J_{bd} represents the current density due to the back-diffusion of plasma electrons. The detailed formulas for each component of the current density are provided in [10].

The dominant component of current density, J_{em}, is calculated using the Richardson–Schottky formula and is expressed as follows:

$$j_{em} = e\, A_j\, T_{ca}^2 \exp\left(-\frac{A-\Delta A}{k_B\, T_{ca}}\right) \tag{5}$$

Where:

- e: Electron;
- A_j: Richardson constan;
- T_{ca} : Cathode Temperature;
- A : Work function of the electrode material;
- ΔA: Schottky correction to work function;
- k_B : Boltzmann's constant.

To streamline the mathematical modeling, an axisymmetric coordinate system was employed, as shown in figure. Boundary conditions were established to simulate the current density and temperature distribution at the electrode tip interface during the TIG welding process.

Numerical Results

The figures below present the results for various cathode tip shapes and input currents. These include electrode tips with truncation angles of 30° and 60°, and input currents of 80 A and 110 A.

Temperature Distribution

In TIG welding, understanding temperature distribution is crucial for analyzing the thermal behavior of the tungsten cathode. The high welding temperatures lead to significant heat transfer through the cathode, impacting its lifespan and performance. Figures 2 to 5 show numerical results for two variables studied: tip angle and current intensity. The temperature distribution at the cathode tip is not uniform. The maximum temperature is typically found at the tip's extremity, and it decreases gradually from this point, with a more pronounced reduction along the vertical axis (the body) compared to the periphery. This variation is influenced by the thermal diffusion of tungsten.

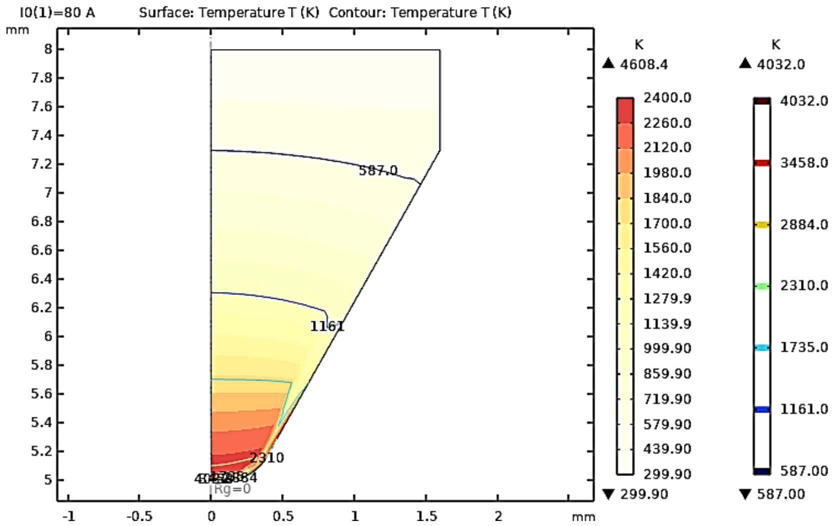

Figure 2. Temperature distribution at cathode tip

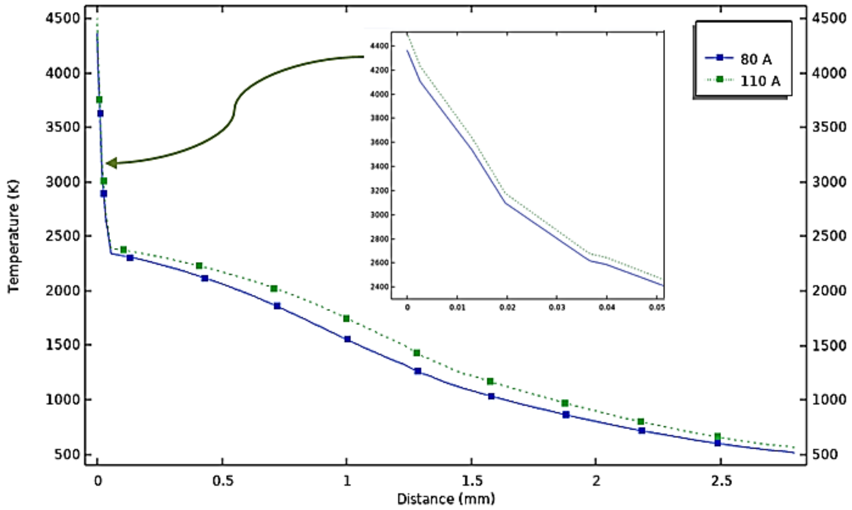

Figure 3. Temperature distribution along the electrode tip from its end for two different current intensities

Figure 4 presents a close-up view of the electrode tip, highlighting the specific areas where peak temperatures are reached with an applied current intensity of 80 A. This comparison examines two electrode angles, 30° and 60°, to emphasize the differences in thermal distribution associated with each angle. Figure 5 illustrates the maximum temperatures for the various cases studied, thereby enhancing our understanding of how electrode geometry impacts temperature behavior during the TIG welding process.

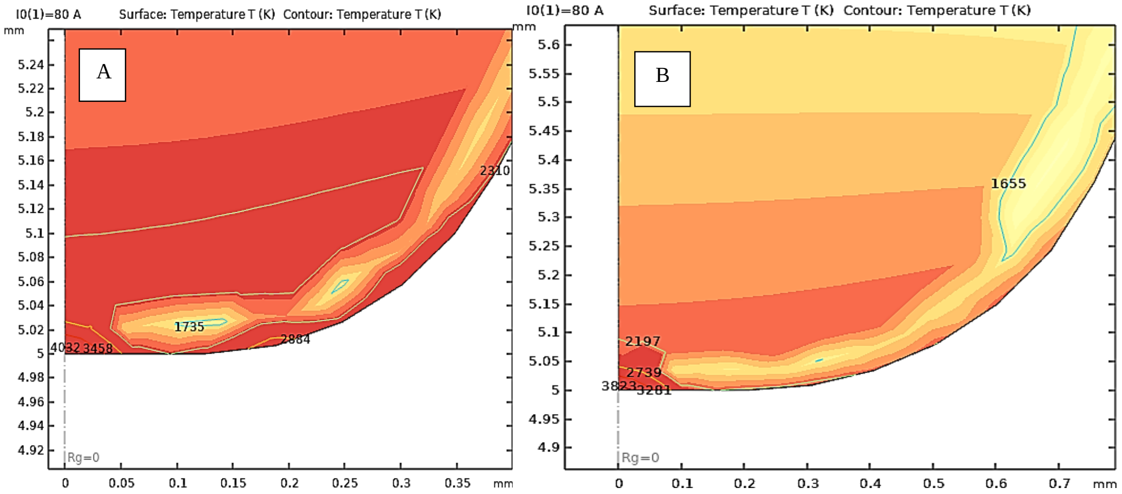

Figure 4. Zoom on the temperature distribution at the cathode tip under a current of 80 A: (A) 30°; (B) 60°

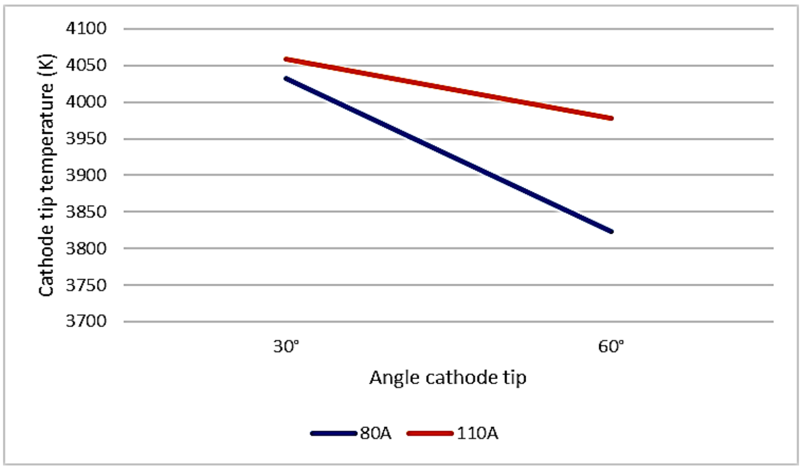

Figure 5. Effect of tip angle on cathode temperature for 80 A and 110 A currents

Current Density Distribution

The distribution of current density in the tungsten cathode is another essential aspect (see Figure 6), influencing the stability of the welding arc and the overall quality of the weld. Current density is affected by the electrode geometry and, to a lesser extent, by the applied current, as illustrated in figure 6 &figure 7.

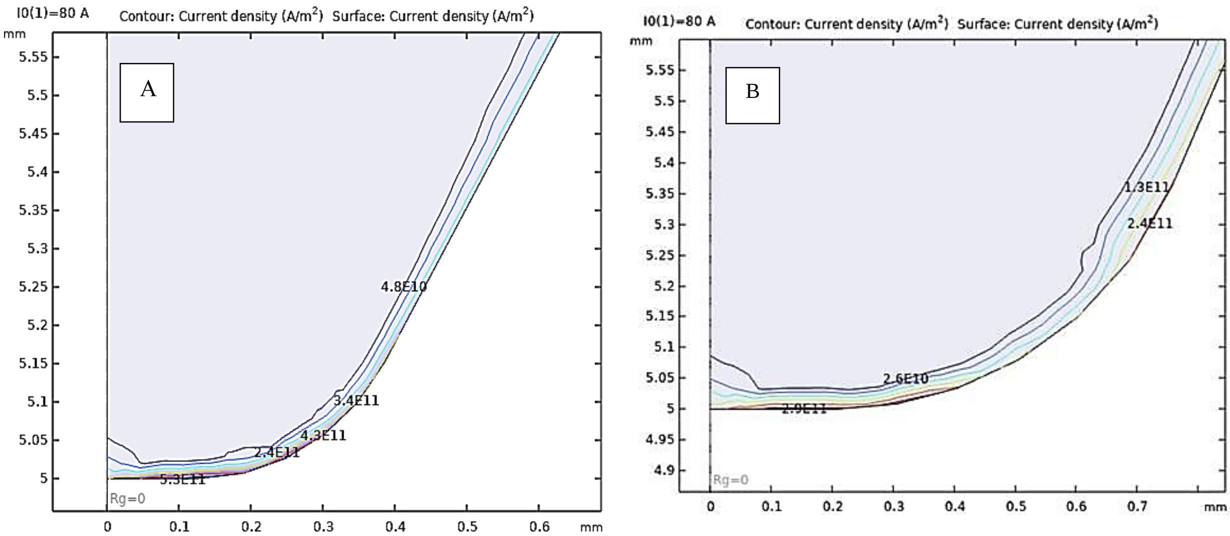

Figure 6. Current density distribution at the cathode tip under a current of 80 A: (A) 30°; (B) 60°

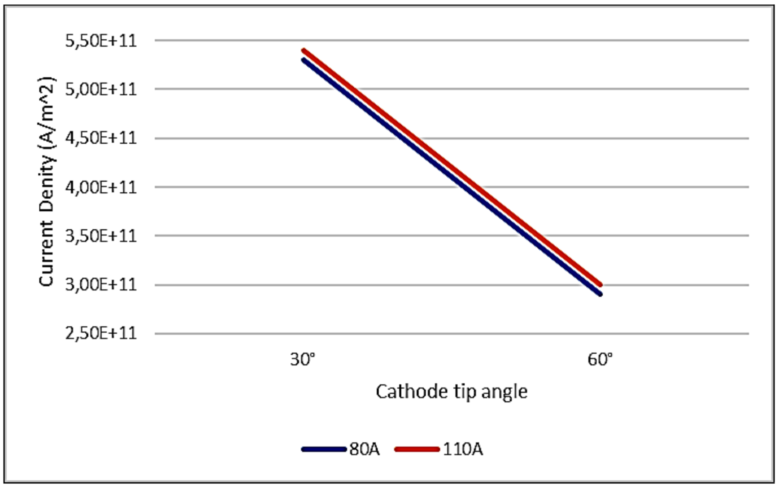

Figure 7. Evolution of current density as function of angle tip cathode and intensity

Discussion

Influence of Angle Tip of the Electrode

An electrode tip with a sharp angle means that the contact surface of the tip is smaller. When electrical current passes through this tip, the current density (current per unit area) becomes higher due to the small surface. The increased current density leads to a greater concentration of heat at the tip. This concentrated heat can cause a significant rise in the local temperature. Conversely, if the angle of the electrode tip is more obtuse, the contact surface is larger. The same amount of current will then be spread over a larger surface, thereby reducing the current density and, consequently, the concentration of heat. The local temperature at the electrode tip will therefore be lower compared to a sharper tip.

Influence of Current Intensity

When the current intensity increases, the total amount of heat generated by the Joule effect (thermal dissipation due to electrical resistance) also increases. In the case of a sharp tip, this increased heat is even more concentrated due to the small surface area, which can lead to extremely high temperatures, potentially reaching the melting point of the electrode material. While, a tip with a more obtuse angle, although also experiencing a temperature rise with the increase in current, spreads this heat over a larger surface area, thereby mitigating the local temperature increase.

Practical Consequences

A higher temperature at the tip can be desirable for operations requiring high precision or deep penetration, such as in certain welding processes where localized melting is necessary. However, this can also lead to faster electrode wear or uncontrolled melting risks. A wider angle is useful for operations that require uniform heat distribution, such as heating larger surfaces or preventing rapid electrode wear. This allows for better thermal management, reducing the risk of premature electrode degradation. From figure 8, it can be observed that the temperature is simultaneously affected by both the shape of the electrode tip and the current intensity, whereas the current density is governed solely by the shape of the tip.

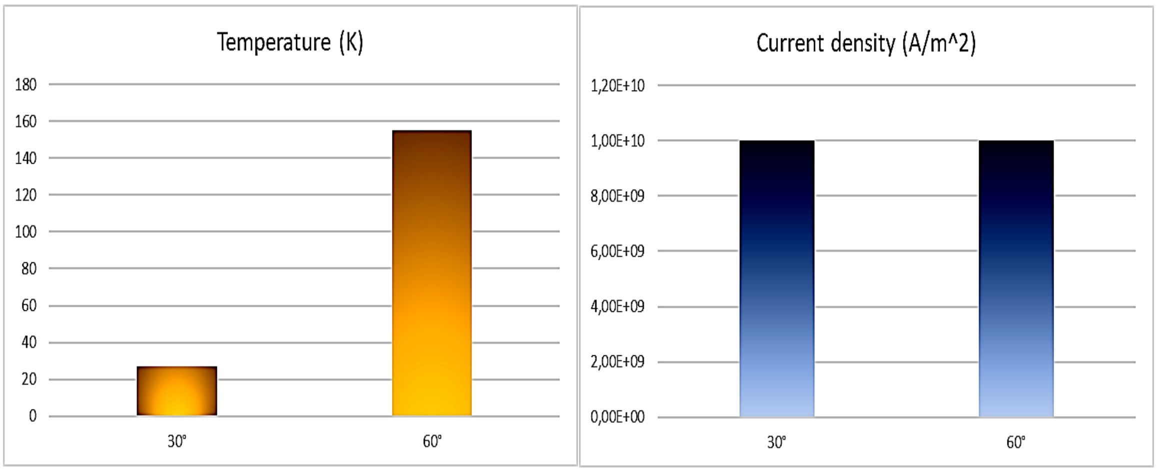

Figure 8. Differences in temperature and current density between measurements at 80 A and 110 A

Conclusion

The angle of the electrode tip plays a crucial role in how heat is distributed, as it directly influences the current density. A sharp angle increases the current density, concentrating the heat and raising the local temperature. In contrast, a blunt angle reduces the current density, spreading the heat over a larger surface and thereby lowering the local temperature. These effects become particularly pronounced at high current intensities, where effective thermal management is essential for the performance and durability of the ongoing process.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors..

Acknowledgements or Notes

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