ASSESSMENT OF ARC STABILITY CHARACTERISTICS IN GAS METAL ARC WELDING AND RELATED WELD QUALITY

BY

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A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF THE MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING OF KYAMBOGO UNIVERSITY

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DECLARATION

I, Eliachu David, declare that the content presented in this dissertation is the result of my original research and scholarly work. This work has not been previously submitted, in part or in whole, to Kyambogo University or any university or higher institution of learning for any academic award. I affirm that all sources used in this thesis are appropriately acknowledged and cited. I understand the academic integrity standards upheld by Kyambogo University and have adhered to them throughout the research and composition of this thesis.

Signature ………………………………….. Date ………………………………………

APPROVAL

This attests that this dissertation has been conducted under rigorous supervision, verifying that this dissertation is an authentic representation of the author's independent work. It is hereby endorsed for submission to the Directorate of Research and Graduate Training of Kyambogo University. This submission fulfills a partial requirement for the attainment of a Master of Science degree in Advanced Manufacturing Systems Engineering. The content of this dissertation adheres to the academic standards and guidelines established by Kyambogo University, reflecting the culmination of scholarly effort and research in the field.

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LIST OF ACRONYMS

% : Percentage

A : Amperage

AC : Alternating Current

API : American Petroleum Institute

Ar : Argon

ASME : American Society of Mechanical Engineers

ASTM : American Society for Test Materials

CC : Constant Current

Cm : centimeters

CO_2 : Carbon dioxide

CTWD : Contact Tip-to-Workpiece Distance

CV : Constant Voltage

DC : Direct Current

GMAW: Gas Metal Arc Welding

GTAW : Gas Tungsten Arc Welding

HAZ : Heat Affected Zone

He : Helium

HRC : Hardness Rockwell; C-scale

ISO : International Standards Organization

Kg : kilogram

MAG : Metal Active Gas

MDPP : Multiple Drops per Pulse

MIG : Metal Inert Gas Welding

Min : minute

mm. :Millimeters

NDT : Non-Destructive Testing

NITAL : Nitric Acid-Alcohol Solution

NPA : National Planning Authority

ODMP : One Drop Multiple Pulses

ODPP : One Drop per Pulse

UIRI : Uganda Industrial Research Institute

UNDP : Uganda National Development Plan

V : Voltage

WPS : Welding Procedure Specifications

ABSTRACT

Gas Metal Arc Welding (GMAW) is a widely employed welding process, and the stability of the welding arc serves as a crucial indicator influencing the overall efficiency of the welding procedure. Arc stability is intricately linked to various quality metrics such as spattering, weld formation, and penetration. While numerous studies have explored arc stability, few have delved into its direct correlation with weld quality. This research addressed this gap by examining how welding parameters, particularly protective gas combinations specifically carbon dioxide and argon affect arc stability. The study involved measuring arc voltage, arc length, and determining arc behaviour under different protective gas combinations. The obtained values were meticulously compared using plotted graphs, offering insights into the behaviour of arc stability in Gas Metal Arc Welding of mild steel. To substantiate the findings, samples generated from experiments utilizing distinct protective gas combinations were subjected to visual inspection, mechanical property testing, and metallographic examination. This comprehensive analysis aimed at elucidating the effects of varied gas combinations on weld quality. The visual, mechanical, and metallographic results were correlated to draw meaningful conclusions regarding arc stability. The 100% argon shielding gas yielded the most stable welding process at a speed of 40 mm/minute, amperage of 150A and voltage of 25v. These parameters hold great significance for future applications in welding machine design and manufacturing. This research contributes to the existing body of knowledge by bridging the gap between arc stability and weld quality, offering practical insights that can inform welding practices and equipment design. The methodologies employed and conclusions drawn from this study serve as a foundation for future advancements in the optimization of weld quality through a comprehensive understanding of arc stability in GMAW processes.

Key words: GMAW, Welding Arc Stability; Penetration; Weld quality; Shielding Gas; Mild Steel.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Arc welding, the third-largest employment category in the metal fabrication industry, is an essential procedure in industrial manufacturing (Desineni, 2003). Only assembly and machining come before it. Arc welding's accuracy and adaptability are crucial to the fabrication and assembly of numerous metal components. Nonetheless, the expertise and experience of the welder play a major role in the success of industrial welding. To achieve the best outcomes, welders must possess the necessary skills and artistry. Gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) are the two main arc welding techniques that are most frequently used in the manufacturing sector (Kumar, 2014).

The Gas Metal Arc Welding (GMAW) process, also known as Metal Inert Gas (MIG) or Metal Active Gas (MAG) welding is commonly used to join both ferrous and non-ferrous materials. GMAW involves feeding a consumable wire electrode continuously through an electrode gun to create an arc between the electrode and the workpiece (Desineni, 2003). This arc produces enough heat to melt the wire electrode and the workpiece, creating a strong bond. Additionally, a continuous supply of either an inert gas (such as argon) or active gas (such as carbon dioxide) is used to shield the weld from atmospheric contamination. One of the main benefits of GMAW is its high welding speed, which makes it an efficient process for completing welding tasks promptly. Furthermore, GMAW provides high weld efficiency, producing high-quality welds with minimal spatter and fumes. Another advantage is the lack of slag formation on the work piece, reducing the need for post-weld cleaning and minimizing material waste. Moreover, GMAW can weld materials with different thicknesses, offering versatility in manufacturing and fabrication processes. The versatility and cost-effectiveness of Gas Metal Arc Welding (GMAW) have led to its widespread use in the industry for creating high-quality welds, making it a preferred choice for various welding applications. (Kah, 2014)

Gas Metal Arc Welding (GMAW) holds significant importance in various industries, including shipbuilding, aircraft, aerospace, building construction, pipeline systems, and the automotive industry. This is attributed to its ability to produce strong joints, high productivity, and the incorporation of automation such as robotic welding (Kaewsakul, 2015) which makes GMAW a more cost-effective option than other welding processes (Kumar. M. K., 2019a). Advancements in the welding industry have necessitated the optimization, productivity, and data-driven innovation. The Laser-GMAW hybrid welding process is a prominent joining technology in various industries whose performance benefits is attributed to the synergistic advantages derived from the integration of the two processes (Acherjee, 2018). The arc behavior during arc welding influences weld prediction, quality, cost, and production cycle time; therefore, understanding and controlling the arc behavior remains a critical factor in all arc welding processes (Kah., 2014). Arc stability is a pivotal factor in assessing the efficiency of GMAW operations, with direct implications for weld quality indicators such as spattering and weld formation; and achieving high-quality welds with minimal spatter loss remains a significant challenge, particularly attributable to the stability of the welding arc. (Paul., 2022). The concept of welding process stability lacks a universally accepted formulation, with various researchers providing different arc stability indicators; for instance, in the context of GMAW, arc stability is taken as the absence of variations in arc length and the maintenance of a consistent contact tip-to-work piece distance (CTWD) (Addamani, 2021). Moreover, ensuring a stable arc in the GMAW welding process necessitates meeting at least two conditions namely; the wire feed speed being aligned with the wire burn rate, and the molten metal transfer from the wire to the weld pool occurring with minimal disruption to the operation.

In the evolving landscape of welding applications in industry, advanced welding processes are increasingly employing real-time control and prediction, which demands comprehensive knowledge of welding arc characteristics. Developments in power sources of GMAW welding systems have enabled digitalization which supports gas regulation and wire feed (Kah., 2014); and selection of input parameters and gas protection type which directly impacts the weld quality (D. Chaudhari, 2014). By optimizing welding parameters, it becomes possible to minimize weld material, enhance properties, and boost process productivity (Öberg, 2017). Within the realm of GMAW, Arc stability in GMAW is a pivotal indicator that is intimately linked to welding quality parameters such as spattering, weld formation, and penetration especially in joining of thin and heat-sensitive materials. Furthermore, automation of the welding process and enhancement of overall welding efficiency necessitate optimization of factors such as shielding gas mixtures, current intensities, flow rates, and welding speed (Kumar. M. S., 2014); and commercial adaptive intelligent welding systems with image processing-based control systems have been developed (Kumar. M. K., 2019b). Despite the advancements in GMAW systems, attempts to improve GMAW weld quality requires an understanding of welding arc characteristics; and some studies have established the significance of sensor applications in detecting specific weld states, each with its unique proficiency within defined limitations (Zhou, 2019).

This research employs a combination of theoretical analysis and practical investigations to conduct a comprehensive study of arc stability characteristics and qualitative weldability factors in the context of specific Gas Metal Arc Welding (GMAW) parameters. The primary objective of this study is to provide a detailed description of arc stability in GMAW while elucidating the intricate interrelationships between the stability of the GMAW process and the overall quality of the resultant weld.

1.2 Problem Statement

The increasing demand for welding of dissimilar steels (Abioye, 2017), driven by the pursuit of enhanced transportation safety, weight reduction for improved fuel consumption, and the need for lightweight solutions in construction and bridge building, has become prominent in recent decades. However, Challenges often occur close to the fusion line and the heat-affected zone, resulting in failures. Gas Metal Arc Welding (GMAW) has demonstrated potential in addressing these challenges by enhancing microstructure formation and minimizing the initiation and spread of cracks (Liu, 2021). In the context of diverse materials and welding processes, a comprehensive understanding of process requirements is essential. This understanding is particularly crucial in GMAW, where advanced analysis, monitoring, quality control, and improvement measures are vital for achieving both efficiency and high-quality welds. The integration of visual-based control systems and optimization techniques is becoming increasingly relevant, aiming to identify optimal welding combinations for specific processes, ensuring safety, environmental friendliness, and economic viability. The central issue lies in the selection of protective gases and parameter fine-tuning, crucial for controlling arc stability and meeting quality standards. Addressing these complexities is imperative for advancing GMAW processes and achieving efficiency, sustainability and economic viability in high-quality weld production.

1.3 Objectives of the study

1.3.1 General Objective

The main objective of this study is to examine the arc stability characteristics in selected GMAW process conditions in conjunction with the quality of welds produced.

1.3.2 Specific Objectives

The specific objectives of the study are:

(i) To evaluate the dynamic characteristics of the welding arc in Gas Metal Arc Welding (GMAW).

(ii) To investigate the influence of the welding process parameters on mild steel weld quality under selected GMAW process conditions.

(iii) To determine the effects of welding parameters on the arc stability in GMAW of mild steel.

(iv) To identify the optimal shielding gas conditions for stable GMAW welding of mild steel.

1.4 Research Questions

The research questions guiding this study are:

(i) What are the characteristics that define the arc dynamics in Gas Metal Arc Welding (GMAW)?

(ii) How welding process parameters influence the mild steel weld quality under selected GMAW process conditions?

(iii) What is the effect of welding parameters on the arc stability in GMAW of mild steel?

(iv) What are the optimal shielding gas conditions for stable GMAW welding of mild steel?

1.5 Justification of the study

This study provides valuable insights for improving the Gas Metal Arc Welding (GMAW) process and developing competence in Gas Metal Arc Welding practice. The study is aligned to Uganda's agenda for industrial development as outlined in "Uganda Vision 2040" which requires competence in manufacturing engineering. (NPA., 2020). This research's primary focus on enhancing the Gas Metal Arc Welding (GMAW) process aligns seamlessly with the Uganda's emphasis on industrial development as a catalyst for economic growth. Moreover, the thriving construction sector and the budding oil and gas sector in Uganda, as pivotal players in the nation's economic landscape. This underscores the need of (NPA., 2020) or development of experts with GMAW welding competence to ensure structural integrity of physical infrastructure in key installation in the fundamental growth sectors of the economy such as the energy, transportation like ferries and boats, agro-processing industries, oil and gas industry, construction, steel manufacturing, etc. As the construction, energy and industrial sectors are expanding in Uganda, advancements in welding competence in the country is crucial for maintaining high standards of structural integrity of infrastructure.

1.6 Contribution of the study

This study provides an insightful expansion of knowledge on GMAW arc stability characteristics with practical implications that leads to advancements in the GMAW welding process control for enhanced weld quality across diverse industrial applications. The specific contribution of this study on GMAW arc stability characteristics is the development of an understanding of the factors influencing arc stability in GMAW which enables appropriate welding process control leading to achievement of high-quality welds in various industrial applications. Therefore, the findings of this research can improve the development of welding machine designs and their consumables that are tailored for the construction and manufacturing sectors in Uganda. This will contribute to identifying the optimal welding parameter combinations that produce a stable arc and acceptable weld quality demanded in specific applications. More so, the elaborative analysis of the relationship between the characteristics of arc stability and weld quality can provide a base for establishing welding process control systems and quality assurance protocols that are specific to Ugandan context.

Additionally, the knowledge on the effects of GMAW welding parameters on arc stability and weld quality generated in this study will be useful in improving the welding training curriculum for welding specialists' workforce with improved GMAW welding competence. The knowledge on arc stability in GMAW welding enables optimization of the GMAW process and serves as a valuable reference for industry practitioners, researchers, and educators, fostering continuous learning and improvement of welding practices. A thorough examination of the connections between arc stability traits and weld quality can offer a technical basis for the creation of welding process control systems and quality assurance procedures in GMAW welding.

1.7 Conceptual framework

In this study, the conceptual framework, as depicted in Figure 1.1, offers a comprehensive exploration of arc stability characteristics within specific Gas Metal Arc Welding (GMAW) process conditions. The primary focus is to gain a deep understanding of the complexities associated with arc behavior in the short circuit GMAW process, with the aim of obtaining valuable insights into the dynamic interactions of welding parameters. The welding parameters under analysis encompass arc voltage, current, and length. Additionally, the study delves into the impact of various shielding gas compositions on arc stability within the short circuit GMAW process, particularly in the context of mild steel welding. The goal is to examine how these different shielding gas compositions influence the qualitative aspects of weldability.

By integrating both arc stability characteristics and qualitative weldability outcomes, the study establishes a conceptual framework that enables systematic exploration of the dynamic interactions within the GMAW process. This conceptual framework also incorporates considerations for welding procedures specification, weld quality and welding process control. Understanding the interplay between arc stability, weldability and the underlying influence of the welding process parameters is crucial for developing robust and reliable welding procedures, ensuring consistent weld quality, and optimizing the overall welding process control. The dynamic interplay between shielding gas compositions, arc stability and the resulting weld quality is an important consideration in process control for the production of superior welded joints. The holistic comprehensive approach of this study contributes to development of a deeper understanding of the complexities involved in GMAW, and can facilitate advancements in GMAW welding practice by providing insights that address the stability, qualitative, and procedural aspects of the GMAW process in practical applications in real-world welding scenarios.

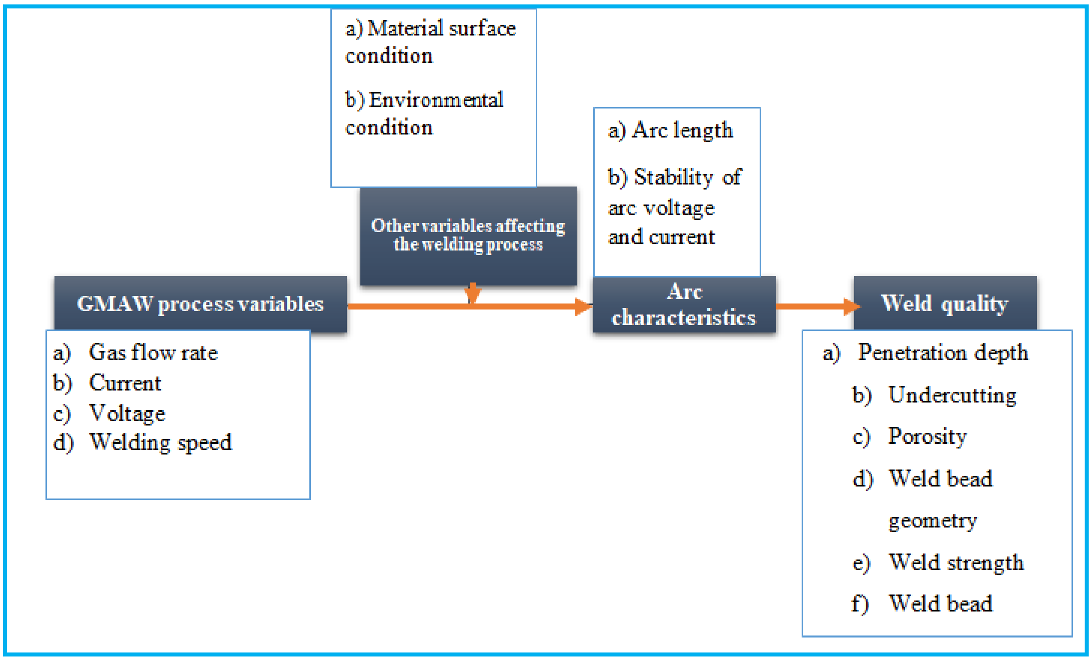


Figure 1.1:Conceptual Framework

1.8 Scope of the study

This research project is dedicated to conducting a comprehensive and in-depth analysis of the factors influencing arc stability in the context of short-circuited Gas Metal Arc Welding (GMAW) of mild steel materials. The primary objective is to assess the effects of different shielding gas compositions and gas combinations on the stability of the arc during the short-circuited GMAW process. The study places particular emphasis on elucidating the impact of varying protective gas environments on arc stability, with the ultimate aim of garnering valuable insights into how these variables shape the overall quality of the welds produced. Through this investigation, the overarching goal is to acquire a profound understanding of the intricate interplay between shielding gas parameters, arc stability, and the resultant weldability and quality attributes. Optimizing the arc stability is recognized as a critical factor in ensuring consistent and high-quality welds, particularly in the short-circuited GMAW process. As such, the study examines both the arc stability characteristics and the qualitative weldability aspects such as visual appearance of the weld, porosity, and other key weld quality indicators.

1.9 Limitations of the Study

The study utilized a semi-automated welding process with the available GMAW equipment to study the defined process parameters, allowing for meaningful experimentation despite the equipment constraints, particularly in a context the unavailability of advanced GMAW technology. This limitation underscored the need to interpret the results within the context of available technology, and to acknowledge that advancements or variations in welding equipment and techniques might provide varied output. Additionally, there are limitations related to environmental factors and industry representation, as study did not exhaust various GMAW conditions and their outcomes. Limited exploration of environmental conditions, such as temperature and humidity, limited the study's ability to comprehensively examine their broader influences on the welding outcomes. Therefore, the study acknowledges that its findings might not have fully represented the diverse requirements of all industries utilizing Gas Metal Arc Welding (GMAW), potentially limiting the generalizability of results across different industrial settings. Despite the highlighted limitations, the study provides valuable insights within the defined GMAW welding parameters studied so the findings are meaningful and applicable to the given context.

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview of Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding (GMAW), also known as Metal Inert Gas welding (MIG) or Metal Active Gas welding (MAG), stands as a versatile arc welding technique employed for joining both ferrous and non-ferrous components (Kah., 2014). In recent times, the double-wire technique has gained increasing popularity as a highly efficient Gas Metal Arc Welding (GMAW) method. It is being utilized in various scenarios to achieve weld beads of superior quality and enhanced efficiency in comparison to the conventional single-wire GMAW process. With over six decades of application, GMAW has demonstrated its adaptability in welding materials such as steel, stainless steel, and aluminium alloys. In the GMAW process presented in figure 2.1, a continuous feed of wire electrode passes through an electrode gun, creating an arc between the electrode and the workpiece (Jiang, 2019).

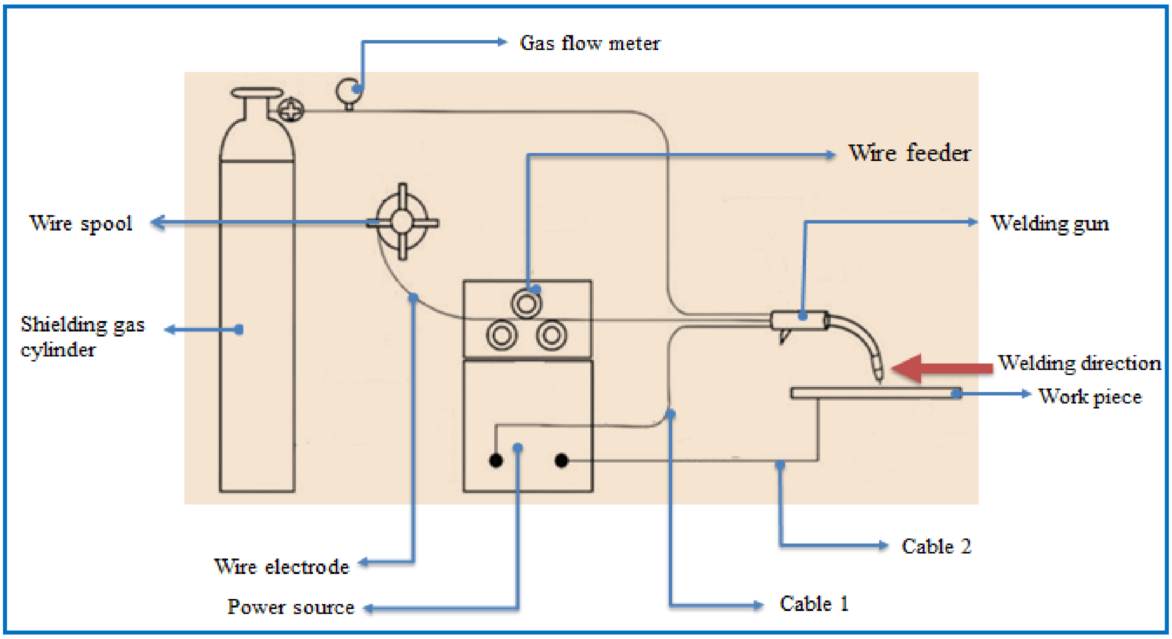


Figure 2.1: Arrangement of components in a Gas Metal Arc Welding (GMAW) system

Gas Metal Arc Welding (GMAW) involves the generation of an electric arc that simultaneously melts the electrode and the work piece. This process is shielded by a continuous flow of either an inert or active gas (Kah., 2014). GMAW offers numerous advantages, including rapid welding speed, high overall weld efficiency, absence of slag on the workpiece, and the capability to weld various materials with different thicknesses. This makes it ideal for assembling components that require a high load capacity. Furthermore, its cost-effectiveness has contributed to its widespread adoption in the welding industry for producing high-quality welds. The quality, productivity, and cost of the welding joint are significantly affected by the parameters utilized in GMAW. Attaining a perfect arc, hinges on properly setting all welding parameters, such as welding current, arc voltage, welding speed, torch angle, free wire length, nozzle distance, welding position, direction, and gas flow rate (Dean, 2023). The study of the relationship between bead geometry and process parameters traces back to the mid-1900s. In 1987, the regression analysis that was introduced to research on welding geometry. Optimal welding conditions are established by considering factors such as the types of base metal, the shape of the welded parts, and the welding process (Ghazvinloo., 2021). Additionally, the diameter of the electrode greatly influences the performance of the welding process.

The maintenance of arc stability is a paramount concern in welding, particularly when pursuing high-quality welds with minimal spatter loss. It plays a crucial role in the efficiency of gas metal arc welding (GMAW) and is closely linked to other quality measures such as spatter and weld formation. At present, there is no universally accepted definition for welding process stability, and different researchers interpret and utilize various stability indicators. In simple terms, arc stability refers to the consistent arc length and maintaining a constant contact tip-to-workpiece distance (CTWD). Achieving a stable arc involves fulfilling at least two conditions: aligning the wire feed speed with the wire burn rate and ensuring the smooth transfer of molten metal from the wire to the weld pool with minimal disruption. The wire burn rate signifies the rate at which the filler metal is consumed by the welding arc's thermal energy, while the feed rate denotes how quickly the wire filler metal is introduced into the weld. Both these factors play pivotal roles in ensuring effective GMAW. (Kumar, 2014).

GMAW, also known MIG welding, is recognized for its reliability and suitability for automation. This extremely versatile welding technique allows for welding in various positions and with a wide range of metal types when properly adjusted. One of the notable features of GMAW is its ability to transfer metal in different ways based on the current and voltage levels. This process involves creating an electric arc between a continuously fed wire electrode and the part being welded to generate the necessary heat for fusion as depicted in figure 2.2. Additionally, the welding torch delivers a gas shroud that protects the weld zone, molten weld metal, and consumable electrode from the surrounding atmosphere. (Jiang, 2019) GMAW is widely utilized in industrial production, and a significant emphasis is placed on selecting the right procedures to ensure high-quality results. Furthermore, the control of process stability is a crucial area of study due to its direct impact on the quality of GMAW welds. Studies and efforts are continuously being made to refine and optimize the GMAW process to meet the highest quality standards in industrial applications (Alfaro, 2021a).

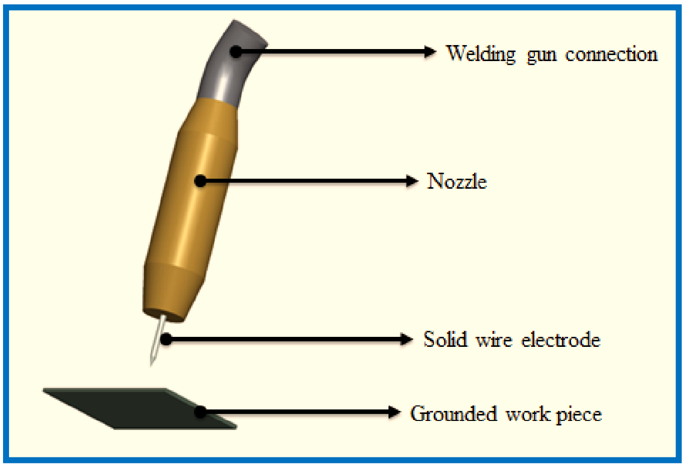


Figure 2.2: Illustration of a layout of GMAW welding grounded work piece, bare electrode, gas nozzle and welding gun connection.

2.1.1 Advantages of GMAW Welding

GMAW offers several benefits that include the following.

(a) ***Enhanced deposition rate:*** With its continuous wire feed mechanism, GMAW facilitates a faster deposition rate compared to alternative arc welding techniques. This translates to expedited welding speeds and heightened productivity. In addition, GMAW is known for its user-friendly operation, making it accessible to welders across skill levels, from beginners to seasoned professionals.

(b) ***Adaptability:*** GMAW's flexibility allows it to be tailored to various welding positions, materials, and project specifications, rendering it suitable for diverse industrial applications. In addition, GMAW lends itself well to automation, particularly in settings requiring high-volume production. This automation capability ensures consistent weld quality and increased operational efficiency.

(c) ***Effective for diverse material thicknesses:*** GMAW can effectively weld materials spanning a broad spectrum of thicknesses, ranging from thin sheets to thick plates, through adjustment of welding parameters.

2.1.2 Application of GMAW

GMAW finds extensive application across various industries:

(a) ***Automotive Sector:*** GMAW is heavily utilized in crafting automobile bodies, frames, and structural components. It excels in welding thin to medium-thickness steels and aluminium alloys, which are increasingly prevalent in modern vehicle construction to enhance fuel efficiency. Automated GMAW systems are commonplace in high-volume automotive production, ensuring uniform weld quality and heightened output. (Alfaro, 2021a)

(b) ***Aerospace and Aviation:*** GMAW is favoured in aerospace for joining aluminium, stainless steel, and specialized alloys crucial for aircraft structures and components. Its capacity to weld diverse material thicknesses, produce high-quality welds, and facilitate automation is invaluable in aircraft and spacecraft manufacturing, as well as in maintenance and repairs demanding precise welding control. (Alfaro., 2021b)

(c) ***Shipbuilding and Marine Applications:*** GMAW plays a pivotal role in constructing and maintaining ships, boats, and marine vessels, especially for welding steel and aluminium structures. Its versatility across welding positions suits the intricate geometries in shipbuilding, while its shielding gas protection ensures weld durability amidst harsh marine conditions. (Alfaro, 2021a)

(d) ***Construction and Structural Fabrication:*** GMAW is a popular choice in welding steel structures like bridges, buildings, and towers, thanks to its high deposition rates and adaptability to various material thicknesses. Automated GMAW systems streamline prefabrication processes, maintaining consistent quality and minimizing on-site welding needs. (Alfaro., 2021b)

(e) ***General Fabrication and Repair***: GMAW is ubiquitous in crafting diverse metal products and in equipment repair due to its versatility and ease of use. Its ability to adapt to different welding positions and metals contributes to its widespread adoption across general fabrication and repair industries. (Alfaro, 2021a)

GMAW has wide-ranging applications in industries such as shipbuilding, automotive manufacture, aerospace engineering, steel structure construction, and industrial equipment fabrication. Because the method may yield welds that are dependable, strong, and affordable, it is commonly used in various industries. All things considered, the GMAW process is a basic and extensively used welding method that provides a blend of productivity, versatility, and weld quality, making it a vital instrument in a variety of manufacturing and fabrication industries. The versatility, efficiency, and quality of GMAW underscore its significance across multiple sectors. As manufacturers seek reliable welding solutions, GMAW's importance is poised to endure and potentially expand further in the future. (Alfaro., 2021b)

2.2 Arc Stability in Gas Metal Arc Welding (GMAW)

Arc stability plays a pivotal role in Gas Metal Arc Welding (GMAW) as it directly influences weld quality and consistency. It refers to the ability of the welding arc to maintain a steady behaviour throughout the process, without significant fluctuations.

2.2.1 Importance of Arc Stability in GMAW

Arc stability is important in GMAW in the following ways:

(a) ***Weld appearance and integrity***: A stable arc ensures uniform weld beads with minimal spatter and smooth surfaces, promoting proper fusion between base and filler metals for strong, defect-free welds (Sakari, 2019).

(b) ***Penetration and weld profile***: Consistent arc stability enable control over weld pool size and shape, ensuring optimal penetration and desired weld profiles crucial for structural integrity. (Dean, 2023)

(c) ***Minimizing defects***: Arc instability can lead to weld defects like porosity, slag inclusions, undercutting, and lack of fusion, compromising weld strength and durability. (Kumar R. S., 2018)

2.2.2 Challenges in Maintaining Arc Stability in GMAW

The following challenges are encountered in maintaining the arc in GMAW welding:

(a) ***Short-circuiting mode***: In this mode, the arc is periodically extinguished and re-established, posing challenges in maintaining stability due to rapid changes in electrical characteristics. (Jia Y. Z., 2019)

(b) ***Welding parameter interactions***: Achieving stable arcs requires balancing wire feed speed, welding current, arc voltage, and shielding gas composition, particularly challenging in short-circuiting mode.

(c) ***Material and joint characteristics***: Base metal properties, surface conditions, and joint geometries can affect arc stability, complicating the process.

(d) ***Environmental factors***: External factors like wind, humidity and temperature can disrupt shielding gas coverage, introducing instability.

2.2.3 Strategies to Overcome Challenges in Sustaining Arc Stability in GMAW

The strategies presented in this section that have been employed to overcome the challenges of sustaining arc stability, include: precise parameter control, innovative arc sensing and control systems, advanced shielding gas management, specialized welding wire, and comprehensive welder training.

(a) **Precise parameter control**: Fine-tuning welding parameters like wire feed speed, current, voltage, and shielding gas flow rate is vital. Advanced welding power sources equipped with dynamic control algorithms can swiftly adapt these parameters to counter rapid electrical changes during short-circuiting, ensuring a stable arc.

(b) **Innovative arc sensing and control systems**: Employing sophisticated arc sensing technologies such as voltage monitoring, current feedback, and arc length detection provides real-time insights into arc behaviour. Advanced control systems leverage this data to autonomously adjust welding parameters, ensuring stability even amidst fluctuations in material properties, joint configurations, and environmental factors.

(c) **Advanced shielding gas management**: Optimizing shielding gas composition and delivery mechanisms is crucial. Utilizing advanced gas mixtures and delivery systems enhances arc characteristics and stability, particularly in short-circuiting mode, while ensuring consistent gas coverage and weld pool protection (Paul., 2022).

(d) **Specialized welding wire**: Tailoring welding wire composition and geometry contributes to improved arc stability. Specialized wire formulations incorporating additives or alloying elements, along with unique wire geometries like cored or tubular wires, enhance metal transfer and arc behaviour, fostering stable welding conditions.

(e) **Comprehensive welder training**: Equipping welders with proper training and skill development is essential. Understanding arc physics, parameter adjustments, and troubleshooting techniques enables welders to identify and rectify arc instability effectively. Hands-on training, simulations, and ongoing education empower welders to maintain consistent weld quality and productivity.

By integrating these strategies, manufacturers and welding professionals can effectively tackle the challenges of maintaining arc stability in short-circuited GMAW, ensuring the consistent production of high-quality, defect-free welds that meet industry standards (Paul., 2022).

2.3 Shielding gas composition on GMAW

The selection of the shielding gas composition plays a crucial role in the Gas Metal Arc Welding (GMAW) process. This choice significantly influences the behavior of the arc, the depth of weld penetration, and the overall quality of the weld (Tukahirwa, 2023). Numerous studies have delved deeply into the effects of different gas compositions on GMAW. In GMAW, the shielding gas serves to protect the molten weld and its surrounding area from atmospheric pollutants such as oxygen and nitrogen, preventing the formation of defects like porosity and embrittlement. Moreover, the shielding gas also governs the characteristics of the welding arc, the amount of heat transferred, and the way in which the metal is transferred, all of which have a direct impact on both the quality and productivity of the welding process.

Considerations for gas metal arc welding (GMAW) include material thickness, joint design, surface condition, mode of metal transfer, welding position, fit-up conditions, desired penetration profile, final weld bead appearance, cost, and the mechanical properties of the deposited weld metal and wire electrode alloy (Tukahirwa, 2023). Additionally, understanding the properties of shielding gases involves evaluating ionization potential, thermal conductivity, and chemical reactivity with the molten weld puddle. These factors play a crucial role in determining the quality and integrity of the weld. For instance, argon is often chosen for non-ferrous metals due to its inert nature, while carbon dioxide (CO_2) finds application in carbon steel welding. Helium, blended with argon, enhances heat transfer. Argon-CO_2 mixtures and tri-mix gases provide tailored solutions for specific applications, balancing arc stability, penetration and other desirable characteristics. The careful consideration of these criteria ensures that the selected shielding gas aligns with the welding requirements, contributing to the production of high-quality welds with the desired properties and appearance (Tusek, 2019).

2.3.1 Inert Shielding Gases

In GMAW, the use of inert shielding gases is fundamental in ensuring the integrity of the welding process (Tusek, 2019). These gases, such as argon and helium, serve the critical function of shielding the weld pool from impurities in the atmosphere and preventing oxidation. (Kumar. M. S., 2014). Argon, being the most commonly used inert gas in GMAW, is preferred for its excellent arc stability and its suitability for welding a wide variety of materials, including steel, stainless steel, aluminum, and various alloys (Öberg, 2017). On the other hand, although less commonly used, helium is sometimes combined with argon to amplify heat input and increase penetration, particularly when welding thicker materials. Employing inert shielding gases is especially beneficial when working with materials that are susceptible to oxidation. This ensures a stable arc and facilitates the production of high-quality welds with minimal spatter (John, 2016).

The specific choice of shielding gas varies depending on the welding application, material type, and thickness, requiring corresponding adjustments in welding parameters to achieve the best results (Dean, 2023). Argon, as the foremost inert gas, is characterized by its low thermal conductivity and ionization energy, resulting in finger-like penetration profiles. It is commonly used for welding nickel, copper, aluminum, titanium, and magnesium alloyed base materials (Ikegami). The low ionization energy of argon assists in arc starting and increases the rate of molten droplet transfer during the welding process. For stainless steel and aluminum applications, helium is often added to the gas mix. Helium boasts very high thermal conductivity, leading to broader but less deep penetration profiles. Consequently, when utilizing helium, adjustments to arc voltage are necessary to maintain arc stability. Taking into account these detailed considerations when selecting and using inert shielding gases is essential for achieving optimal welding outcomes (Nadzam, 2014).

2.3.2 Reactive Shielding Gases

Shielding gases are essential components in the gas metal arc welding (GMAW) process, as they play a vital role in interacting with the weld pool to produce specific and desirable effects. As highlighted by (John, 2016) and (Kumar. M. K., 2019a), gases such as oxygen, hydrogen, nitrogen, and carbon dioxide have a significant impact on this process. Carbon dioxide, typically considered inert at room temperature, exhibits reactive properties in the presence of arc plasma and the molten weld puddle, making it a crucial element in the GMAW process. When an intense arc plasma is applied, carbon dioxide undergoes a process of molecular breakdown, transforming into free carbon, carbon monoxide, and oxygen. The presence of oxygen, which acts as an oxidizer, leads to a reaction with the molten puddle, resulting in the formation of oxides.

When used in small quantities (ranging from 1-5%) in combination with argon, oxygen plays a crucial role in promoting stable arc formation and achieving a visually appealing weld bead. Deoxidizing agents present in the filler alloys work to counteract the oxidizing impact of oxygen. Silicon and manganese are examples of elements that react with oxygen to produce oxides, thereby mitigating its oxidizing effects. The oxides produced during the welding process have a tendency to float to the surface and create small islands. These islands are particularly prominent when using CO_2 shielding gas as compared to a combination of argon and oxygen. Additionally, the addition of hydrogen in small percentages (1-5%) to argon is specifically utilized for the shielding of stainless steel, nickel, and aluminum alloys during the welding process (Paul., 2022). Its higher thermal conductivity promotes a fluid puddle, improving toe wetting and allowing for faster travel speeds. Each reactive gas serves a specific purpose, influencing the welding process and contributing to the overall quality of the weld.

2.3.3 Binary Shielding Gas Blends

The shielding gases used in gas metal arc welding (GMAW) often consist of various combinations as shown in figure 2.3 and 2.4. These blends typically include mixtures of argon and helium, argon and carbon dioxide, and argon and oxygen. In particular, a blend containing 75% argon and 25% helium is highly beneficial for welding Nickel-based alloys and aluminum. This specific blend is suitable for utilizing both axial spray transfer and pulse spray transfer welding modes, making it versatile and effective for a range of welding applications (Schafranski, 2017). The presence of helium improves the fluidity of the welding puddle and encourages a flatter bead shape (Park, 2019).

In GMAW welding of carbon steel, the argon and carbon dioxide blend are widespread, supporting all four modes of metal transfer. Axial spray transfer can be achieved with carbon dioxide levels of less than 18%, while pulsed spray transfer is supported with up to 18% carbon dioxide. Blends for short-circuiting transfer include 75% argon and 25% CO_2, and 80% argon and 20% CO_2, while blends for axial spray transfer comprise 98% argon and 2% CO_2, 95% argon and 5% CO_2, and others. Blends of argon and oxygen, such as 99% argon and 1% oxygen and 98% argon and 2% oxygen, enable axial spray transfer at lower currents compared to argon and CO_2 blends. These blends result in smaller droplet sizes and a more fluid weld pool, benefiting both stainless steel and carbon steel welding applications (Mukherjee, 2015).

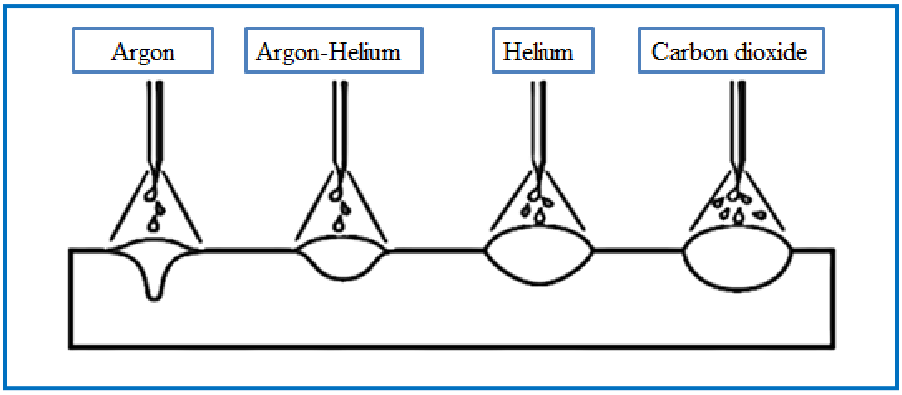


Figure 2.3: Illustration of a shielding gas and metal transfer

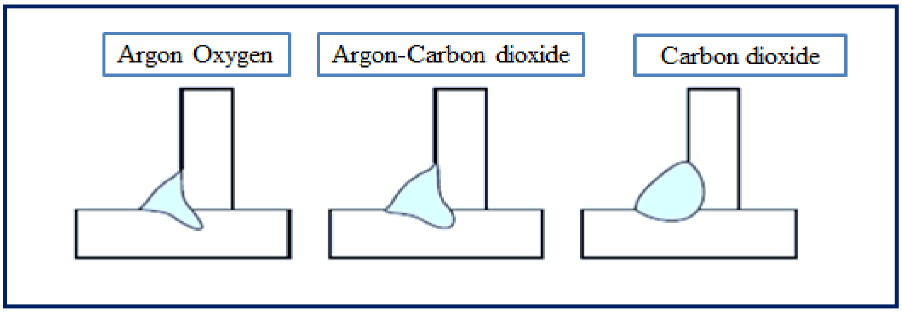


Figure 2.4: Illustration of different shielding gases and penetration

2.3.4 Effect of Shielding Gas Composition

Argon (Ar) is widely favoured in Gas Metal Arc Welding (GMAW) for its inert properties, which contribute to a stable, focused arc. This results in a narrower, more penetrating arc, facilitating deeper weld penetration and a reduced weld pool size. Welds produced with argon-based gases typically exhibit a clean, smooth appearance with minimal spatter, show casing the effectiveness of argon in ensuring high-quality welds. Carbon Dioxide (CO_2) is preferred in Gas Metal Arc Welding (GMAW) for tasks demanding deep penetration due to its characteristics. It generates a wider, more diffuse arc with elevated heat input, resulting in a larger weld pool and enhanced penetration capabilities (John, 2016). However, welds made with CO_2-based gases may display irregular bead appearance and increased spatter when compared to those produced with argon-based gases, reflecting the trade-offs associated with CO_2's higher heat input.

Oxygen (O_2) plays a nuanced role in Gas Metal Arc Welding (GMAW), where minor additions (usually 1-5%) can enhance both arc stability and weld bead appearance. Oxygen-enriched gases contribute to improved weld pool fluidity, facilitating better wetting and the formation of a uniform bead profile. However, caution must be exercised as excessive oxygen levels can lead to oxidation and various welding defects.

Balancing oxygen content is crucial to harness its benefits while mitigating potential risks in GMAW operations. Helium (He) serves as a valuable component in Gas Metal Arc Welding (GMAW), either utilized independently or in conjunction with argon. It enhances arc properties and penetration capabilities by generating a hotter, more concentrated arc with increased energy density. This leads to deeper weld penetration and a narrower, more uniform bead appearance, highlighting helium's role in achieving precise and high-quality welds in GMAW applications (John, 2016).

Gas Metal Arc Welding (GMAW) commonly uses shielding gas combinations, such as argon-CO_2, argon-oxygen, or argon-helium blends, each designed to meet particular application requirements. These mixes are adaptable, enabling the achievement of targeted penetration depths, arc qualities, and bead appearances. The right combination must be chosen based on factors such as base metal type, welding position, joint design, and productivity requirements. Since the composition of the shielding gas has a substantial impact on GMAW results, such as welding productivity, quality, and performance, welders must carefully weigh the trade-offs associated with various compositions in order to achieve the desired weld characteristics and satisfy the particular needs of each application.

2.4 Arc Stability and Weldability in GMAW

High-quality welds in Gas Metal Arc Welding heavily rely on maintaining arc stability. Numerous studies have delved into the relationship between arc stability and weld quality in GMAW. In a study conducted by (Moreno., 2020) the impact of welding parameters such as wire feed speed, arc voltage, and contact tip-to-work distance on arc stability and weld quality in GMAW was investigated. The findings indicated that increasing wire feed speed and reducing arc voltage enhanced arc stability, resulting in improved weld quality, including better bead appearance, deeper penetration, and reduced spatter. However, the study had limitations as it focused on a specific range of welding parameters and did not consider the effect of shielding gas composition on arc stability. Additionally, a study examined the relationship between arc stability and metal transfer modes (short-circuiting, globular, and spray) in GMAW. Researchers found that the short-circuiting metal transfer mode exhibited the highest degree of arc instability, while the spray transfer mode consistently displayed the most stable arc characteristics.

The study also explored how welding parameters influenced the transition between different metal transfer modes, but it did not explore the impact of shielding gas composition on arc stability and weld quality. It further highlighted the critical role of the arc type in welding applications, especially when working with thin or heat-sensitive materials. Understanding various types of arcs, such as constant current (CC) and constant voltage (CV) arcs, and their specific properties is essential in advanced welding processes (Dean, 2023). This knowledge enables the implementation of real-time control and prediction mechanisms, which can lead to potential cost savings, reduced production times, and enhanced overall quality of welded products.

In the context of industrial welding systems, a deeper understanding of arc phenomena becomes essential for developing and refining integrated designs (Alfaro., 2021b). This knowledge plays a pivotal role in controlling and modifying welding processes, contributing to the production of higher-quality welds and reliable joints. Arc stability emerges as a common challenge in the welding industry, closely tied to arc length and influencing metal transfer behaviour significantly (Mukherjee, 2015). An even arc helps to transfer metal consistently and reduces splattering (Hermans & Ouden, n.d.).

The connection between voltage and current in a steady arc condition is derived from Ohm's law (Rahmati, 2023). The slope of the curve is further affected by factors like the atmosphere of the arc, arc length, and the types of metals used. The introduction of digital control in power sources has brought about significant progress in arc control, particularly in short and pulsed arc welding.

The faster response time of power source inverters and the incorporation of advanced software enable direct control of the arc, representing a significant development in welding technology (Mohammed, 2019). In Gas Metal Arc Welding (GMAW), maintaining arc stability is of utmost importance. This is achieved by ensuring a consistent heat input and minimizing spattering during the welding process. It's crucial to understand the interrelationship between voltage and current in GMAW. Higher voltage settings contribute to a wider and shallower penetration, while increased current results in higher deposition rates and deeper penetration into the base metal. Additionally, GMAW exhibits various droplet transfer modes, each of which is influenced by specific welding parameters. These transfer modes include short-circuiting, globular, spray, and pulsed spray. Each mode has distinct characteristics and is utilized based on the specific requirements of the welding process. (Zhai, 2020).

Short-circuiting transfer is suitable for low current and voltage, minimizing spatter. Globular transfer involves larger droplets and is employed at higher current levels, while spray transfer utilizes fine droplets for increased deposition rates. Pulsed spray transfer combines controlled pulsing with the benefits of spray transfer, offering precision in out-of-position welding. The choice of shielding gas, such as argon or carbon dioxide, influences arc stability and weld bead. Maintaining the correct arc length is vital, preventing issues like spattering or poor penetration. Mastering these arc characteristics in GMAW ensures optimal weld quality and performance across diverse applications, with welding parameters adjusted for factors like material thickness and joint configuration. (Wu., 2019) conducted a study examining how different shielding gas compositions, including pure argon, carbon dioxide, and their combinations, influenced arc stability, weld bead characteristics, and mechanical properties in GMAW. The researchers found that utilizing argon-based shielding gases contributed to a more consistent arc, resulting in enhanced weld quality in terms of bead appearance, penetration, and mechanical properties, when compared to CO_2-based shielding gases. However, the study did not investigate the effects of alternative shielding gas compositions, such as those incorporating oxygen or helium, on arc stability and weld quality.

2.5 Modes of Metal Transfer in GMAW

In GMAW, three primary modes of metal transfer govern the process. Spray transfer is characterized by the controlled ejection of small, fine droplets of molten metal from the electrode in a continuous manner, creating a stable and high-energy arc. Typically employed for thicker materials, this mode requires higher current and voltage settings, yielding a smooth and spatter-free weld, making it well-suited for high-production welding. Short circuit transfer, on the other hand, involves the electrode making intermittent contact with the weld pool, resulting in small amounts of molten metal transferring across the arc during each short circuit. Suitable for welding thin materials and positional welding, it operates at lower current and voltage settings, producing a softer and less penetrating weld, albeit with a potential for increased spatter. Lastly, globular transfer is characterized by larger droplets of molten metal forming at the electrode tip before detaching and falling into the weld pool (Park, 2019). Typically used for welding thicker materials with moderate current and voltage settings, it strikes a balance between the smoothness of spray transfer and the stability of short circuit transfer, generating a weld with controlled spatter levels. The selection of a specific mode is contingent upon factors such as material thickness, welding position, and the desired characteristics of the final weld, with adjustments to welding parameters allowing for precise control over the metal transfer mode (Liu, 2021). The modes of metal transfer is illustrated in figure 2.5.

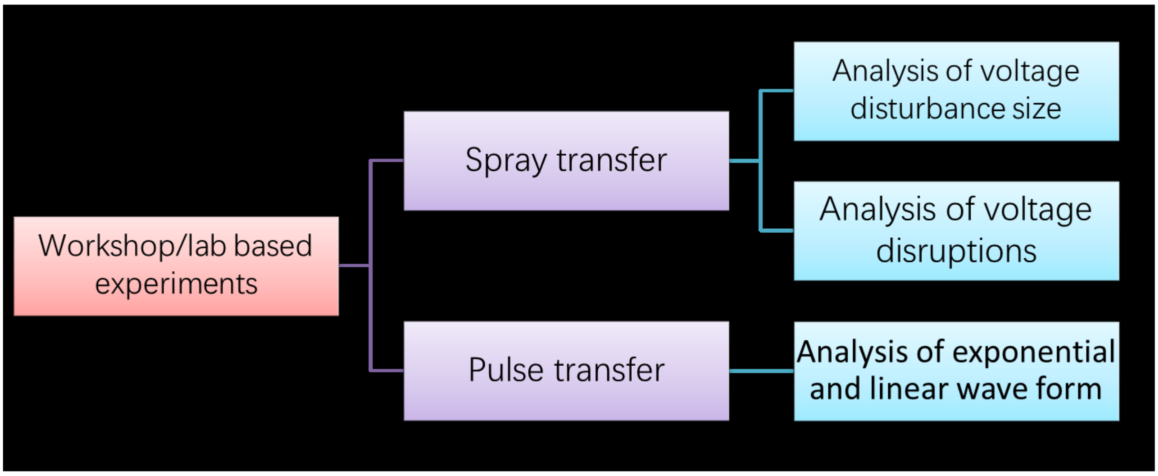


Figure 2.5: Two main modes of metal transfer

2.5.1 Short Circuit Metal Transfer

This metal transfer mode is also known as short-circuiting transfer as illustrated in figure 2.6. It involves the deposition of a continuously fed solid or metal-cored wire electrode during repeated electrical short circuits. Operating as the low heat input mode for Gas Metal Arc Welding (GMAW), its successful execution hinges on factors such as the electrode diameter, shielding gas type, and welding procedure (Wang. J. L., 2020). This mode is optimized for electrodes with diameters ranging from 0.6 to 1.1 mm, utilizing shielding gases of either 100% CO_2 or a mixture of 75-80% argon and 25-20% CO_2. Noteworthy advantages of this mode include its adept handling of poor fit-up, suitability for root pass work on pipe applications, minimal weldment distortion due to low heat input, high electrode efficiency exceeding 93%, and versatility in welding positions (Norrish., 2014).

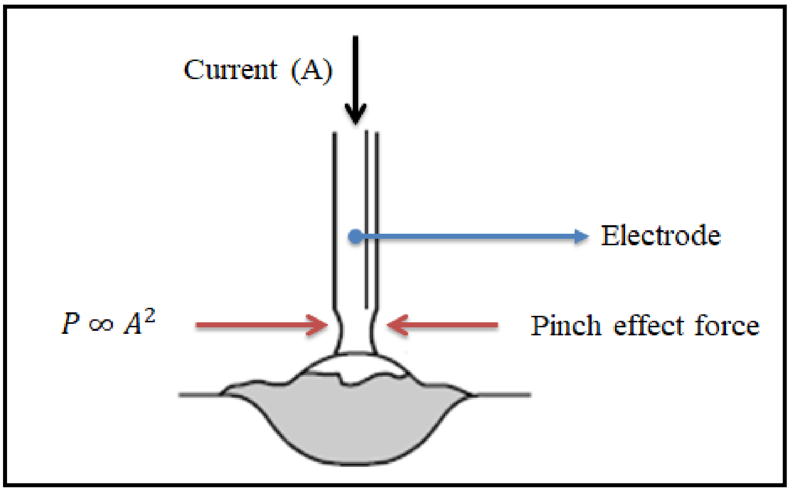


Figure 2.6: Illustration of a Short-Circuit metal transfer mode (Kah., 2014)

However, certain limitations accompany this mode. Incomplete fusion and excessive spatter may occur with poorly controlled welding procedures. To prevent the loss of shielding gas in outdoor welding, welding screens may be necessary (Hermans & Ouden, n.d.). Additionally, the mode is constrained to a specific range of sheet metal thickness and is most applicable to open roots of groove joints in heavier base material sections. Careful consideration of these advantages and limitations is essential for optimal application and control of the short-circuiting transfer mode in GMAW.

2.5.2 Globular Metal Transfer

Globular metal transfer, an older and less frequently employed mode within Gas Metal Arc Welding (GMAW), manifests under conditions of heightened welding current and an extended arc length. As depicted in figure 2.7, the welding wire undergoes melting, forming larger droplets at the electrode tip, surpassing the diameter of the electrode wire. Unlike other transfer modes like spray or short-circuiting, where the welding current propels droplets, globular transfer relies significantly on gravity (Wu., 2019). The larger droplets detach from the wire and descend into the weld pool due to their weight. This transfer is characterized by intermittent short circuits, with the arc undergoing periodic short-circuiting events as molten droplets detach. Occurring at higher welding currents, globular transfer is less suitable for thin materials, and its propensity for larger droplet formation contributes to increased spatter. Cleanup may be more extensive due to the potential for slag inclusion in the resulting weld bead (Kumar., 2019b). Despite its historical usage, modern welding practices often favor more efficient transfer modes, relegating globular transfer to specific applications.

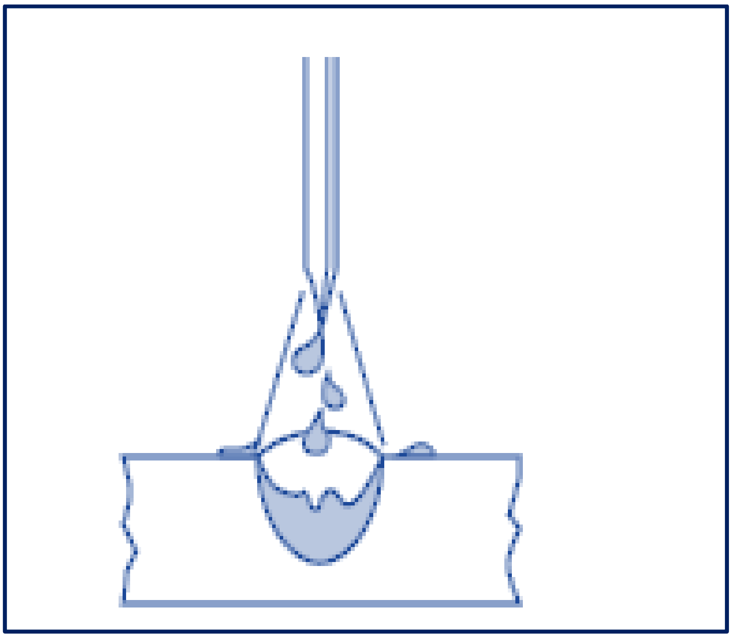


Figure 2.7: Illustration of a globular metal transfer mode. (Eko, 2022)

Advantages of the globular transfer mode include its compatibility with cost-effective CO_2 shielding gas, often used in conjunction with argon-CO_2 blends. Additionally, the mode allows for the use of inexpensive solid or metal-cored electrodes, and the associated welding equipment is relatively affordable (Mohammed, 2019). However, certain limitations accompany this mode. Welded beads in globular transfer tend to exhibit a convex shape with poor wetting at the toes (Zhang, 2017). The presence of high spatter levels results in reduced electrode efficiency, diminished operator appeal, and necessitates costly clean-ups. Despite these limitations, the use of the globular transfer mode remains economically viable, especially in scenarios where cost considerations outweigh aesthetic preferences.

2.5.3 Axial Spray Metal Transfer

The process of axial spray metal transfer is a type of high-energy welding, in which a solid or metal-cored wire electrode is continuously fed and deposited at high energy levels. This leads to the formation of a continuous stream of small molten droplets that are propelled axially across the welding arc. To achieve axial spray transfer, it is necessary to use binary blends that include argon paired with either 1-5% oxygen, or argon combined with CO_2 with CO_2 levels not exceeding 18%. This technique is employed to attain specific welding outcomes and is an important method in welding processes. (Alfaro, 2021a)

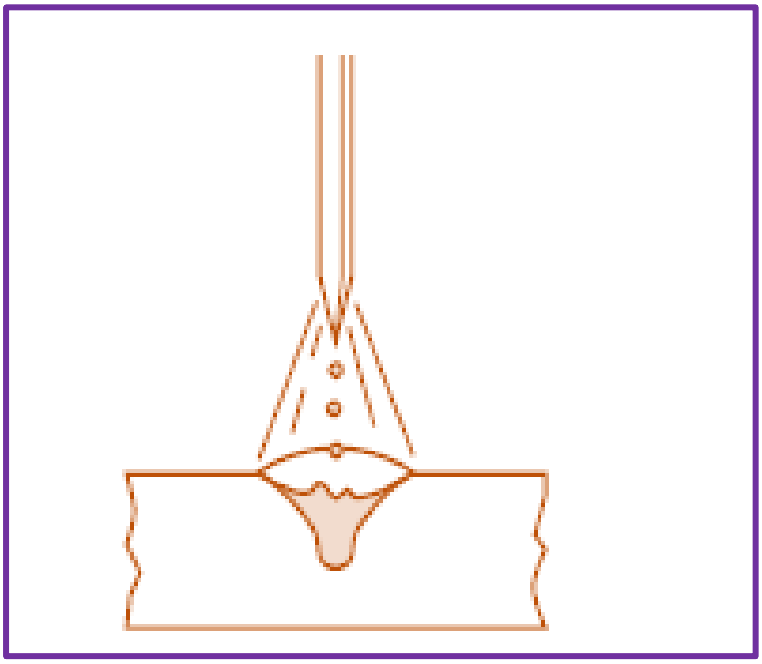


Figure 2.8: Illustration of an axial spray metal transfer mode. (Desineni, 2003)

The axial spray transfer mode as shown in figure 2.8 above is a versatile welding technique that can be used with various alloys, including aluminium, magnesium, carbon steel, stainless steel, nickel alloys, and copper alloys. This mode is particularly beneficial for heavier section thickness materials such as fillets and groove-type weld joints in the case of carbon steel. It offers several advantages, including exceptional electrode efficiency exceeding 98%, excellent weld bead appearance, versatility with a wide range of filler metal types and electrode diameters, higher deposition rates, superior weld fusion, minimal post-weld cleanups, high operator appeal, ease of use, absence of weld spatter, and compatibility with semi-automatic, robotic, and hard automation processes (Wu., 2019). However, when using the axial spray mode of metal transfer, it is important to be aware of the limitations. This mode produces high radiated heat and a bright arc, necessitating additional protection for the welder and bystanders. For outdoor use, windscreens are essential due to axial spray transfer, and there is also a higher generation of welding fumes. Additionally, this mode is restricted to flat and horizontal welding positions, and the shielding gas used comes at a higher cost than 100% CO_2. It is crucial to thoroughly consider these advantages and limitations for optimal application and safety when utilizing the axial spray mode of metal transfer (Torres, 2014a), (Ikram, 2016).

2.5.4 Pulsed Spray Metal Transfer

The advanced form of axial spray transfer, known as pulsed metal transfer, presents a unique method by modulating the welding current between high peak and low background levels (Jia, 2019). During the high-energy peak, metal transfer occurs in the form of a single molten droplet, which helps alleviate issues such as controlling weld spatter and eliminating incomplete fusion defects that are commonly encountered in globular and short-circuiting transfers (Ikram, 2016). Pulsed metal transfer is adaptable to electrode diameters ranging from 0.8-1.5mm for solid wire electrodes and 1.1-2.0mm for metal-cored electrodes, providing versatility across a wide range of metal types. Additionally, the mode makes use of argon-based shielding gas selections, including a maximum of 18% CO_2 for carbon steels. (Mitchell., 2021)

The pulsed metal transfer process offers a wide range of advantages. Not only does it produce weld beads with excellent appearance, but it also has a high level of appeal for operators. This process provides engineered solutions for controlling the generation of weld fumes, thereby creating a safer work environment. Furthermore, it offers increased resistance to lack of fusion defects when compared to other metal transfer modes in GMAW. One of the key benefits of pulsed metal transfer is the minimal or complete absence of spatter during welding, which contributes to a cleaner and more efficient welding process. Additionally, it results in low heat-induced distortion, allowing for greater precision and accuracy in the welding process. This method also enables welding in various positions, enhancing its versatility. Moreover, pulsed metal transfer leads to low hydrogen deposit, reduced arc blow tendency, and it excels in handling poor fit-ups. (Alfaro., 2021b)

The process is highly cost-effective, boasting a high electrode efficiency of approximately 98%. Its suitability for robotic and hard automation applications makes it a valuable choice for various industrial settings. Lastly, pulsed metal transfer enables welders to achieve arc travel speeds greater than 1.2 meters per minute, further enhancing productivity and efficiency in welding operations (Zhang, 2017). However, certain limitations exist, including higher costs for blends of argon-based shielding gas compared to CO_2, increased welding complexity, the need for windscreens when welding outdoors, additional safety measures for welders and bystanders due to higher arc energy, and the overall higher expense of equipment supporting this process compared to traditional systems. (Dean, 2023) Despite these limitations, the numerous advantages make pulsed metal transfer a viable and efficient option for specific welding applications.

2.6 Factors affecting Metal Transfer Modes

In GMAW, several modes of metal transfer exist each with distinct characteristics and operational variables that influence their performance. These modes include globular transfer, repelled globular transfer, projected spray transfer, streaming transfer, and rotating transfer. Each mode exhibits unique attributes such as arc stability, weld pool penetration, spatter production, porosity occurrence, and the degree of gas entrapment (Alfaro, 2021a). The choice of metal transfer mode depends on various operational variables like welding current, electrode extension, electrode diameter, and polarity (Paul., 2022). It's important to note that the use of carbon dioxide gas shielding results in a different metal transfer mode when compared to argon shielding.

Understanding the complex process of metal transfer in Gas Metal Arc Welding (GMAW) involves considering a multitude of intricate factors that collectively influence this phenomenon. Theoretical models, such as the static force balance theory and the pinch instability theory, have been developed to explain metal transfer dynamics. Despite these efforts, the intricate nature of metal transfer in GMAW remains a challenge to fully capture. A wide range of operational variable influences the mode of metal transfer in GMAW. These include welding current, shielding gas composition (e.g., argon, carbon dioxide), electrode extension, ambient pressure, electrode coatings, wire characteristics, process stability, polarity, and the welding material (Alfaro., 2021b). Of these variables, welding current stands out as a crucial factor that welders often manipulate in order to achieve the desired metal transfer mode.

The globular transfer mode is frequently observed at low welding currents during the welding process, while the spray transfer mode is evident at higher welding currents. As the welding current decreases within the lower range for spray transfer mode, there is a transition from projected transfer, where the droplet diameter is approximately equal to the electrode diameter, to streaming transfer, and ultimately to rotational transfer as the welding current increases. It is important to note that rotational transfer sets a practical upper limit on the current, as further increases lead to unstable metal transfer. (Torres., 2014b) This sequence of metal transfer modes is observed specifically when welding steel with an argon-rich shielding gas composition (Ghazvinloo., 2021). However, when using different materials or other shielding gases, not all metal transfer modes may be observed. For instance, when carbon dioxide, helium, or nitrogen is employed as a shielding gas, the repelled globular transfer mode is typically observed. This understanding of the interplay between operational variables provides welders with valuable insights into optimizing the metal transfer mode for different welding scenarios (Jr, 2008).

2.7 GMAW Welding Parameters

The GMAW process involves the control of multiple input parameters to ensure successful welding (Wordofa, 2023). These parameters include the welding current, flow rate of the shielding gas, orientation of the electrode, distance between the welding gun nozzle and the workpiece, welding voltage, welding speed, and the diameter of the welding wire, among others. Each of these parameters plays a crucial role in determining the quality of the welding bead and the mechanical properties of the welded joint. Current is responsible of melting the wire and the base plate (Venkadeshwaran, 2015). In GMAW, current is anonymous to travel speed. Hence the wire that comes out has to be melted and deposited to the base metal in relation to travel speed. The knob current controls the wire motor speed of the system. The guideline to calculate the current is the thickness to be welded or the welding area thickness of the work. The thumb rule for current calculation is 40 amps for 1mm welding area thickness. Example, for 2mm thickness the current is 80 amps. Voltage is the pressure or force to drive current. Voltage is realized by using an empirical formula from current that is calculated. Voltage is calculated for different shielding gases. When carbon dioxide is used as shielding gas, the formula is $V=14 + 0.05I$, for argon or argon carbon dioxide mixture $V= 12 +0.05I$ (Tukahirwa, 2023).

Stickout is defined as the length of the wire protruding outside from the contact tip. The operating voltage is the outcome of set voltage and stickout. When stickout increases, the operating voltage decreases for the set voltage and vice versa. Stickout is maintained by the welder to get the desired result in welding. The normal stickout range varies from 10 to 15mm. however large stickout range that is more than 15mm can be used by bringing corresponding change in gas flow rate if needed. Gas flow rate defines the amount of shielding gas flowing through the nozzle to provide effective shielding for the weld metal from atmospheric contamination (Wordofa, 2023). The flow rate is set on the flow meter which is seated on the regulator. The regulator regulates the pressure of the gas from the cylinder to operating pressure. This pressure is further controlled by flow meter to provide desired flow rate. The normal flow rate for the stickout of 15 is around 12 to 15 liters per minute when operating in a closed shade. Wind speed of 4miles per hour is sufficient to wash away the shielding envelope provided by the shielding gas. Exposure of weld metal to atmosphere leads to porosity which leads to weld failure (Marônek, 2023). Travel speed is defined as speed at which welding progresses. The travel speed depends totally on welder's hand movement which depends on metal deposition (Chen, 2020). In GMAW, travel speed is influenced by technique, current, voltage and stickout. Current density is defined as current per unit area. Current density determines the melting rate of the wire, the penetration depth of the weld metal into the base metal as shown in figure 2.9 below.

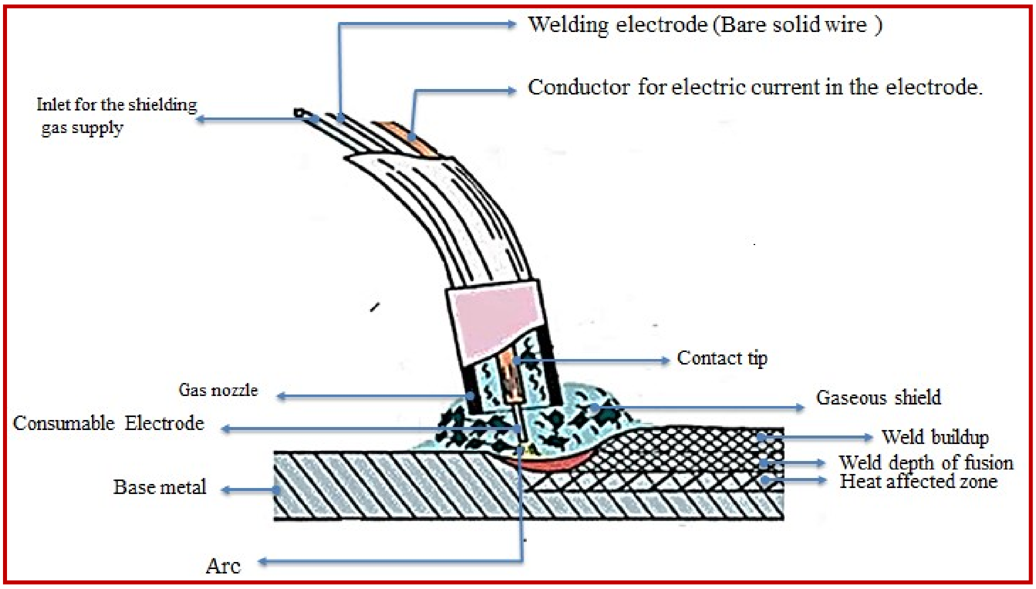


Figure 2. 9: Illustration of a gas metal arc welding process. (Mallick, 2021)

2.8 Methods used to Monitor Welding Process Stability

Monitoring the stability of the welding process is critical for ensuring the quality and consistency of welds (Torres., 2014b). Various methods are employed for this purpose. Voltage and current levels are regularly measured to maintain stability, while arc length control is implemented to monitor and adjust the distance between the electrode and the work piece, ensuring a steady welding arc. Weld pool characteristics are observed to verify stability, and travel speed is controlled to maintain a consistent weld (Wang. J. L., 2020). Temperature monitoring of the work piece and the surrounding environment helps keep conditions within specified ranges. Wire feed rate and gas flow rate are regulated to ensure proper feeding of the welding wire and adequate shielding gas coverage. Real-time data logging and analysis, along with feedback systems, provide comprehensive insights into the welding parameters, allowing for timely adjustments to uphold stability. Additionally, methods such as non-destructive testing, radiographic inspection, and destructive testing can be employed to assess the quality and integrity of the welds produced during the monitored welding process.

There are various techniques for assessing the stability of the welding process, most of which involve analyzing signals obtained from a monitoring system. This system works by continuously measuring different physical quantities, with welding current intensity and voltage playing crucial roles. Stability of the welding process is determined through the analysis of signals, which encompass factors such as noise emission, arc light, acoustic emission from the material, and events within the welding arc captured by high-speed camera recordings. Essentially, the monitoring system serves as a crucial tool by continuously measuring and assessing these key parameters, allowing for prompt adjustments to maintain the stability of the welding process and ensure the production of high-quality welds.

Ensuring the stability of the Gas Metal Arc Welding (GMAW) process involves a multifaceted approach employing various monitoring methods. Visual inspection remains foundational, allowing welders and inspectors to assess weld appearance and detect irregularities. Welding parameters including voltage, current, and travel speed are continuously monitored to detect deviations that may signal potential issues and adjustments can be made in real-time. Arc monitoring systems analyse arc characteristics for stability and irregularities (Alfaro., 2021b). Infrared thermography evaluates temperature distribution while acoustic emission sensors detect sound waves both providing insights into welding conditions. Weld pool monitoring assesses pool characteristics and advanced computerized systems offer real-time feedback and automation. Non-destructive testing methods, such as ultrasonic testing and X-ray inspection are employed post-welding to identify defects. Collectively, these methods ensure a comprehensive approach to monitoring and maintaining the stability of the GMAW process ultimately contributing to the production of consistent and high-quality welds. Regular training is essential to empower personnel in effectively utilizing these monitoring techniques.

2.8.1 Acoustic Emission Technique

Enhancing the monitoring of acoustic emission signals generated by processes aims for a more precise correspondence to the phenomenon under study albeit at the cost of increased complexity (Mitchell, 2021). To comprehensively evaluate the behaviour of the GMAW process, especially with varying modes of metal transfer, statistical characterization of the acoustic emissions it produces is essential. Understanding how the acoustic emission signal responds to changes in process variables becomes paramount for analyzing stability or functionality (Luo, 2017).

The unique aspect of the acoustic emission technique among non-destructive tests (NDTs) is its passive nature and it can identify defects or their development only during the execution of the process or testing (Sakari, 2019). The popularity of acoustic emissions has grown facilitated by advances in microelectronics and computer-based analysis techniques over the past two decades. The technique's acceptance is also attributed to its successful application in studying various phenomena. When the arc is uniform and its power remains constant, minimal or no sound is generated. Changes in energy supplied to the arc result in variations in heat, light, and sound production (Mitchell., 2021). The fluctuations in arc sound are attributed to changes in geometry and voltage as the energy supply undergoes alterations as explained in figure 2.10 below.

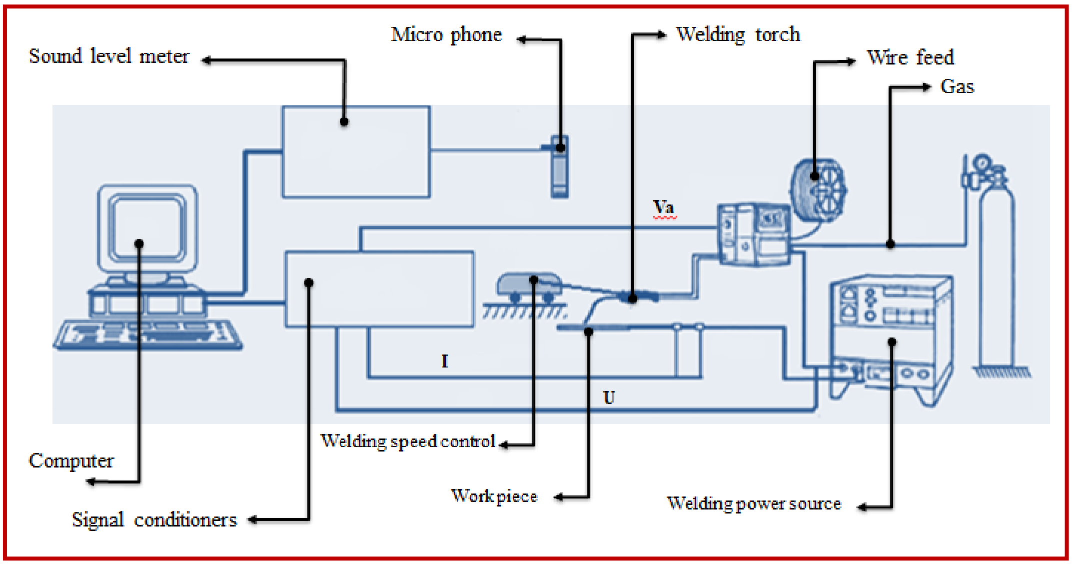


Figure 2.10: Illustration of the setup of acoustic emission process. (Wang, 2020)

The welding system comprises several key components such as a standard power supply or welding machine the ISKRA E-450, is employed to provide consistent welding current and voltage. A welding trolley ensures uniform torch movement controlling welding speed for a consistent bead on the workpiece. To measure welding current accurately, a shunt resistor is utilized offering low-resistance precision. Sound during the welding process is captured by a half-inch Bruel & Kjear type 4134 condenser microphone. The computer analyzes sound signals generated by the arc assessing arc stability. Utilizing an ER70S-6, 1.2 diameter consumable electrodes the system fuses the workpiece. Shielding gas specifically 75% Argon/25% CO_2 prevents exposure of the molten weld pool to atmospheric elements. Finally, a measuring amplifier filters enhance and amplifies the arc-generated sound for comprehensive analysis (Addamani, 2021).

2.8.2 Arc Voltage and Current

The assessment of welding arc stability is reliant on analyzing the fluctuations in arc voltage and current throughout the welding process, as highlighted by research (Zhang, 2017). Arc voltage is gauged by connecting a voltage-measuring instrument between the grounding wire and the welding torch cable. To enhance accuracy, these connections are ideally positioned in close proximity to the welding arc to minimize disturbances. Concurrently, the measurement of current involves connecting a current-measuring instrument within the circuit strategically positioned near the welding arc (Zhou, 2019). Given the rapid and dynamic nature of changes in arc voltage and current, manual recording becomes impractical. Therefore, the utilization of recording instruments becomes imperative for precision. An illustrative experiment was conducted that employed a combination of a shunt, low-pass filters, analogue-to-digital and digital-to-analogue (A/D–D/A) converters, along with a personal computer as integral components of the measuring instruments in a fully automated setup. While these components may pose challenges due to limited local availability and expensive international shipment, it is noteworthy that a semi-automated experiment can be facilitated using locally accessible alternatives. This adaptability underscores the feasibility of employing locally sourced components without compromising the essence of the experiment making it more accessible and cost-effective (Kumar., 2018).

2.8.3 Visual Inspection

Visual inspection is a fundamental aspect of weld quality assessment, adhering to the ISO 17637:2003 standard procedure (Wang., 2020). This method involves scrutinizing welds for various discontinuities and defects including but not limited to overlap, surface cracking, undercut, undersized welds, surface porosity, underfill, incomplete root penetration, excessive root penetration, burn-through, excessive reinforcement, slag inclusion, and spatters. Employing a range of specialized tools enhances the accuracy of visual inspection. the Palmgren weld gauge checks butt weld reinforcements, the high-low gauge measures internal misalignment and crown height of butt welds, the Cambridge gauge assesses weld reinforcement height, depth of undercut, misalignment, and angle of penetration and the digital Vanier caliper precisely measures bed width, material thickness, root gap, root face and distance covered. Additional aids such as magnifying glasses and loupes enhance visual capabilities for scrutinizing small details while tools like the steel rule and taper gauge contribute to measuring weld lengths, determining travel speed, and assessing gaps and groove dimensions, respectively. This comprehensive approach ensures a thorough visual inspection process contributing to the overall quality control of welding operations (Cook, 1995).

In summary, the literature review emphasizes the key factors influencing welding process stability, including welding speed, electrode characteristics, and shielding gases. The methods section outlines the experimental setup, including the welding machine, trolley, and chosen consumable electrode. It also discusses the use of various shielding gases and monitoring instruments for real-time measurement of arc voltage and current. The recording, analysis, and interpretation of the experimental data are described, with an emphasis on statistical methods and the consideration of assumed constant variables.

2.9 Welding Procedure Specification

The Welding Procedure Specification (WPS) plays a pivotal role in ensuring the reliability and quality of welds during Gas Metal Arc Welding (GMAW). It delineates specific parameters and guidelines imperative for the welding process (Rudi, 2022). Key components of the WPS that influence arc stability and weldability include welding parameters, shielding gas composition, preheat and interpass temperature control, joint preparation and fit-up, welding sequence and technique, and inspection and quality control measures. In terms of welding parameters, the WPS defines optimal ranges for variables like wire feed speed, arc voltage, and contact tip-to-work distance. These parameters directly impact arc stability, thus influencing weld quality. Additionally, the WPS stipulates the required shielding gas composition. The selection of appropriate gases, such as argon-based mixtures, contributes to maintaining a stable arc and enhancing weld characteristics (Rudi, 2022).

2.9.1 Description of Welding Procedure Specification

The WPS provides guidelines for controlling preheat and interpass temperatures. Effective control is crucial, especially for materials susceptible to cracking. Joint preparation and fit-up specifications outlined in the WPS are also critical. Proper preparation and fit-up ensure consistent arc stability and overall weldability. Moreover, the welding sequence and technique are detailed in the WPS, encompassing factors like the order of welding passes and the preferred welding method. These elements significantly impact arc stability and weld quality. Finally, inspection and quality control requirements are integral aspects of the WPS, ensuring welds meet specified standards and any issues related to arc stability and weldability are identified and addressed. Adhering to the WPS is essential for maintaining consistent arc stability and achieving high-quality welds in GMAW. Continuous refinement of the WPS based on research findings and practical experience can further optimize the GMAW process and enhance its overall performance (Rachmat, 2022).

2.9.2 Purpose of Welding Procedure Specification

In essence, the WPS is indispensable for maintaining arc stability, weld quality and efficiency in GMAW, making it integral to successful implementation of this welding technique. The Welding Procedure Specification (WPS) offers numerous advantages in Gas Metal Arc Welding (GMAW), namely:

(i) ***Uniform weld quality***: The WPS provides standardized welding parameters and guidelines, ensuring consistent and high-quality welds.

(ii) ***Stable arc***: By specifying optimal welding parameters like wire feed speed and arc voltage, the WPS helps maintain a stable arc, critical for consistent weld quality.

(iii) ***Increased productivity***: Optimization of welding parameters reduces trial-and-error adjustments, enhancing productivity by streamlining the welding process.

(iv) ***Defect reduction***: The WPS identifies and addresses potential issues, minimizing weld defects such as porosity or lack of fusion.

(v) ***Compliance***: Adherence to industry standards and regulations is ensured through the WPS, vital for applications in critical sectors.

(vi) ***Knowledge transfer***: Documented reference in the WPS facilitates knowledge transfer within an organization, aiding training and process changes.

(vii) ***Cost Efficiency***: Reduced defects and improved efficiency lead to significant cost savings in material, labor, and rework.

(viii) ***Traceability***: The WPS provides a structured framework for documenting the welding process, ensuring traceability and quality assurance.

CHAPTER THREE: METHODOLOGY

The stability of the arc in a GMAW process was examined in this research, specifically focusing on two different transfer modes: the spray and pulse transfer modes. This section describes the techniques used to analyze the behavior of arc stability in the short circuit GMAW process.

3.1 Research design

The research was undertaken as an experimental study in which a combination of qualitative and quantitative methods was employed for a comprehensive analysis of the arc stability in the GMAW welding process. The welding setup and experimental procedures are designed to investigate welding process arc stability. Three key parameters were considered current (measured in Amperes, A), voltage (measured in Volts, V), and welding speed (measured in centimeters per minute, cm/min).

3.2 Description of the Experiment

The aim of the experimental study was to establish the arc dynamic characteristics in Gas Metal Arc Welding (GMAW) and to investigate the influence of arc behavior on weld quality in selected conditions of Gas Metal Arc Welding (GMAW). The effects of welding parameters on arc stability in Gas Metal Arc Welding (GMAW) of mild steel were determined and the optimal conditions for arc stability in GMAW of mild steel were established. This section presents the descriptions of materials and material preparation, equipment, experimental set-up, experimental design, and experimental test procedure.

3.2.1 Materials Used and Material Preparation

The workpiece was mild steel plate of specification given in Table 3.1 was used for the experiment because it is renowned for its excellent weldability; the workpiece material provided a well-balanced combination of toughness, strength and ductility boasting of high mechanical properties. The workpieces (test pieces) were prepared to the required dimensions of 200mm x 50mm by 5 mm. Joint and workpiece preparations adhered to the standards outlined in ISO 9692 for joint preparation. The wire electrode employed was ER 70S-6, with a diameter of 1.2 mm

Table 3.1: Properties of materials

Chemical Elements	Unit	Value
Iron (Fe)	%	98.81
Carbon (C)	%	0.14-0.20
Manganese (Mn)	%	0.6-0.9
Phosphorus (P)	%	≤0.04
Sulfur (S)	%	≤0.05
Mechanical Properties	Unit	Value
Tensile Strength (Ultimate)	Mpa	440
Tensile Strength (Yield)	Mpa	370
Percentage Elongation	%	15
Hardness Rockwell B	HB	71

3.2.2 Description of Equipment Used

The welding process was made easier using the ESAB Aristo 500ix welding power source, which was equipped with a strong feed unit and U82 control. The features of the equipment can be found in Tables 3.2 and 3.3. The Aristo 500ix is a versatile three-phase DC power supply that can operate in both Constant Voltage (CV) and Constant Current (CC) modes, making it suitable for a wide range of industrial applications. This durable and portable heavy-duty pulse power source is specifically designed for industrial use, with a robust mechanical design that ensures reliability and durability. When used with the Robust Feed U6, it becomes the ideal choice for pulse applications. The advanced pulse functionality includes up to 250 pre-programmed synergic lines, effectively minimizing heat input and spatter, making it a practical and efficient solution for industrial welding and fabrication needs. Furthermore, its IP23 rating allowed for usage in both indoor and outdoor environments.

A standard power supply or welding machine was employed to ensure consistent delivery of welding current and voltage. A welding trolley was used to achieve a uniform welding speed, while a carefully selected consumable electrode with specific melting properties was chosen for proper fusion. Some of the experiments were conducted at a lab in China utilizing equipment a welding robot, a high-speed video camera for recording weld metal droplet detachment during the welding process and a high-power laser was used to enhance image quality. Monitoring instruments such as voltmeters and digital ammeters were utilized for real-time measurement of arc voltage and current.

Table 3.2: Features of the Welding Power Source

Equipment Features and Capabilities	
Weight	58,5 kg
Efficiency at max current	88%
Open circuit voltage	58 V
Dimensions L × W × H	712×325×470mm
Power factor at max current	0.91
Enclosure class	IP23
Operating temperature	– 20 to + 40 °C
Insulation class	H
Application class	S
Certification Mark (Standards)	CE

Table 3.3: Technical Specifications of Voltage Supply

Technical Specification	Value
The main supply voltage specifications	40 VAC
The cooling power	1 kW
Dimensions L × W × H	680 × 330 × 230 mm
Coolant volume	4,5 l
Max pressure	4.6 bar
Max flow	1,8 l/min
Weight	15 kg

3.2.3 Experimental Set-Up

The experiment set-up shown in the Figure 3.1 was used in the welding experiments for investigation of arc behavior in two different protective gases under selected parameters. The arc voltage and current values were captured from Ammeter (A) and the Voltmeter (A) respectively.

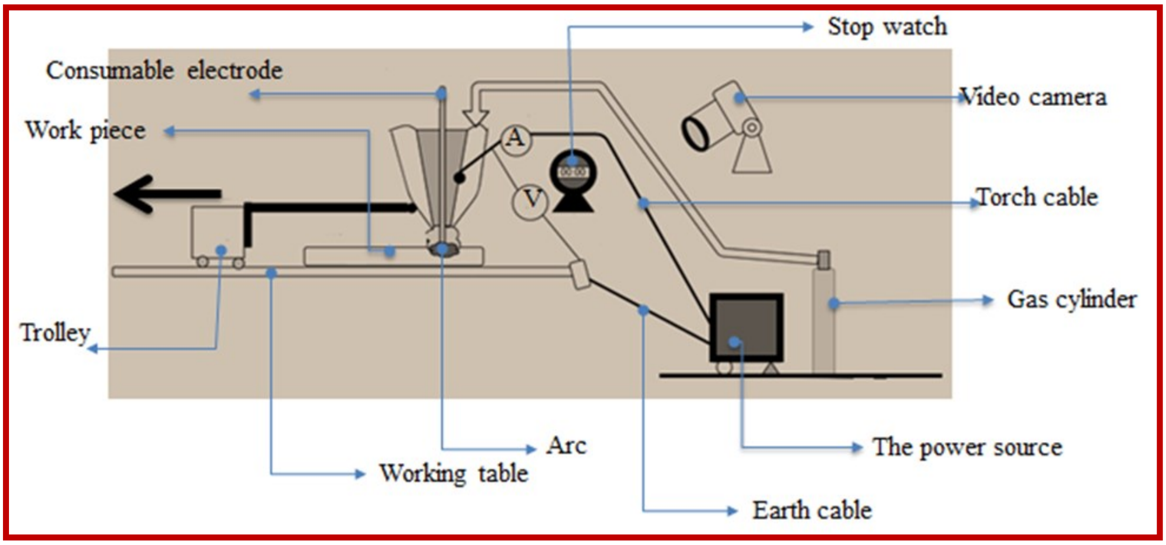


Figure 3.1:Layout of the welding experimental set-up (Alfaro, 2021a).

3.2.4 Experimental Design

The experiments were designed to evaluate the impact of various welding parameters, such as voltage, current, and welding speed, on the stability of the Short Circuit Gas Metal Arc Welding (GMAW) process. Specific values for these parameters were carefully chosen to analyze their influence on the welding process stability. The process parameters used in the experiment are detailed in Table 3.4, while the experimental design is presented in Table 3.5. The welding experiments, involving welding bead on plate, were conducted in three phases, with each phase consisting of 9 levels, resulting in a total of 27 welds.

The welding process parameters were systematically verified, including welding current, arc voltage, and arc length, while using four different shielding gas combinations to examine arc stability under specific welding conditions. The experiment encompassed three different current values (100A, 150A, and 200A) to represent varying energy intensities during welding. Similarly, three voltage values (20V, 25V, and 30V) were selected to study the influence of electrical potential on the welding outcome. Additionally, the critical factor of welding speed, which impacts bead formation and overall process stability, was set at 20 cm/min, 40 cm/min, and 60 cm/min. These precise process parameter values constituted a comprehensive matrix of welding variables, allowing for a methodical exploration of their individual and combined effects on the Short Circuit GMAW process.

Table 3.4: Input Process Parameters used in the Welding Experiment

Parameters	Current (A)	Voltage (V)	Welding Speed (cm/min)
Value	100 - 150 - 200	20 - 25 - 30	20 - 40-60

Table 3.5: Experimental Design

Welding Process Parameters	Test Level 1	Test Level 2	Test Level 3
Current measured (A)	100	150	200
Arc Voltage (V)	20	25	30
Welding speed (cm/min)	20	40	60

3.2.5 Experimental Procedure

In this research project, a series of experiments were carried out to explore the process of fusing 5 mm mild steel plates by welding applying short circuit metal transfer, along with different welding parameters. The main aim of the experiment was to analyze the consistency of the welding arc. The input parameters included welding current, arc voltage, and welding speed, while the measured output parameters were the penetration depth into the steel plate, arc voltage and arc current. And other observable indicators such as bead geometry and surface appearance. The research experiment involved the systematic adjustment of welding conditions, with a specific focus on welding current and arc voltage. These parameters were varied while keeping the welding speed constant in order to observe the resulting changes in penetration depth which is one of the indicators of a good quality weld. The objective here was to analyze how alterations in welding current and arc voltage at specific constant welding speeds affected the penetration depth.

A configured high-speed camera and electrical signal acquisition system was used to capture and analyze data. Welding was conducted using the short-circuiting transfer mode at three distinct welding voltages and current values. Simultaneously, analyzed voltage fluctuations and explosion levels using image data. The objective of the test was to reproduce the arc stability characteristics by manipulating voltage and current control to analyze factors pertinent to arc stability and identify those with significant influence. A systematic monitoring of welding parameters, such as arc voltage and current was ensured. A consistent welding speed was maintained and appropriate electrode characteristics and shielding gases were chosen to achieve stable and uniform welds. Pure and blended shielding gases were employed to protect the molten weld pool from atmospheric exposure.

3.2.6 Monitoring of Metal Droplet Transfer

The stability of the GMAW process is greatly influenced by the method of metal transfer and the shape of the weld. Factors such as current, voltage, type of shielding gas, and its composition all play a crucial role in determining how the metal is transferred, which in turn affects consistency, arc length, and the number of molten droplets. To investigate the selected metal transfer methods, videos were recorded using a high-speed camera with laser backlighting. This method involved capturing the moments when droplets detach and the disturbances that occur during the metal transfer.

3.3 Data Analysis

A high-speed monochromatic imaging technique was used to capture the images of the molten droplets during the welding process. The signal acquisition by the camera and signal acquisition system took place after the welding arc generated triggered the synchronization signal. It was observed that the electrical signal collection and camera recording stopped when the arc got extinguished. At this stage the high-speed camera pictures were stored before the next round of the experiment was performed. The data collected encompassed parameters such as arc voltage, current, and specific timings.

The samples obtained from the experiments were taken to the laboratory for comprehensive analysis of the welds in order to ascertain the impact of welding parameters on specific mechanical properties of the weld. This involved conducting mechanical testing, visual inspections, and metallographic examinations of the weld bead and the heat-affected zone. The experimental data was captured and analyzed. In addition, post-welding measurements were derived from the image data.

3.3.1 Visual Examination of Welds

The weld surface was visually inspected to evaluate the impact of arc stability on weld quality and to observe how changes in gas flow rate affect mild steel welds. The influence of the shielding gas on welding results was assessed through visual examination, and the findings were systematically compared to draw conclude arc stability and weld quality. This approach facilitated a comprehensive investigation into the effects of various protective shielding gas combinations on welding results, with a specific focus on understanding the impact of these combinations on mild steel welding under the test conditions. It was observed that arc stability is directly correlated with spatter during welding, with a more stable arc resulting in less spatter from the weld.

3.3.2 Measurement of the Penetration depth

The study carefully measured the penetration depth to analyze how welding current and arc voltage impact the penetration of the mild steel base metal, which was 5 mm thick. This analysis was conducted for different combinations of GMAW process parameters that were investigated. The weld bead geometry schematic is presented in figure 3.2 below.

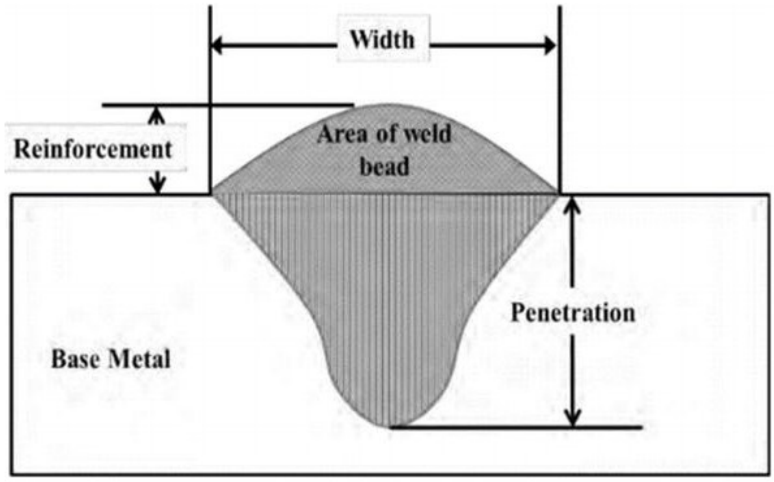


Figure 3.2: schematic illustration of the weld bead geometry (Alfaro., 2021b).

Samples were sectioned from each weld coupon. Cut through the weld section, ground and polished to 2000 grit size. The polished pieces were etched using Nital and the weld zones were revealed. Then the penetration depth was measured using a digital Vanier caliper. Figure 3.3 below illustrates the process of measuring the penetration depth obtained from some of the samples.

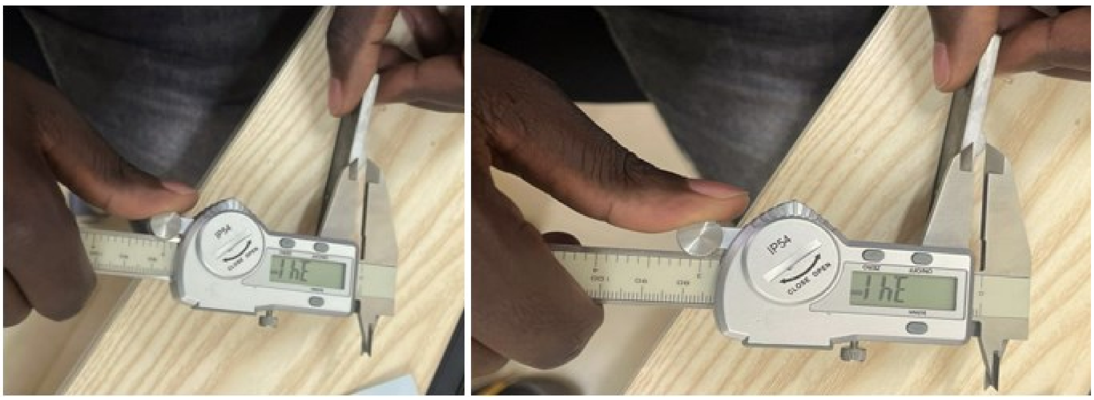


Figure 3.3: Laboratory determination of the weld penetration depth.

3.3.2 Hardness and Tensile Tests

The specimen got from the provided sample was used for the hardness test. The surface was smoothened by grinding and polishing using a rotary polisher and loaded to a Digital Rockwell Hardness Testing machine, model – JMHR-150ZS as shown in the figure 3.4. Six specimens were extracted from the samples and tested on a tensile testing machine model; Denison T42B4, shown in figure 3.5.

Figure 3.4: Rockwell Digital Hardness Testing Machine

Figure 3.5: Tensile Testing machine

3.3.3 Metallographic Examination

The microstructure examination was done at Uganda Industrial Research Institute. Microstructure analysis was done using an Optical metallurgical microscope Model CDM-902C shown in figure 3.6. The surfaces were polished and finished to a grit size of 2000; they were etched with 4% Nital solution. The specimen was then observed in the metallographic microscope and photographs were taken to show the structures and their magnifications. Surface and cross-sectional appearances of weld beads were compared by capturing photos of bead-on-plate welds without cleaning. Cross-section specimens were obtained from 5 mm welded mild steel plates and for microstructure analysis, specimens were cut from butt joints on the 5 mm mild steel plate. The cross-sections of the specimens were ground with various sizes of metallographic abrasive papers, followed by polishing with 3 μm diamond paste on cloth. Subsequently, acid chemical reagent (4% HNO_3 + 96% absolute alcohol) was used for etching. Microstructures were observed using an optical microscope.

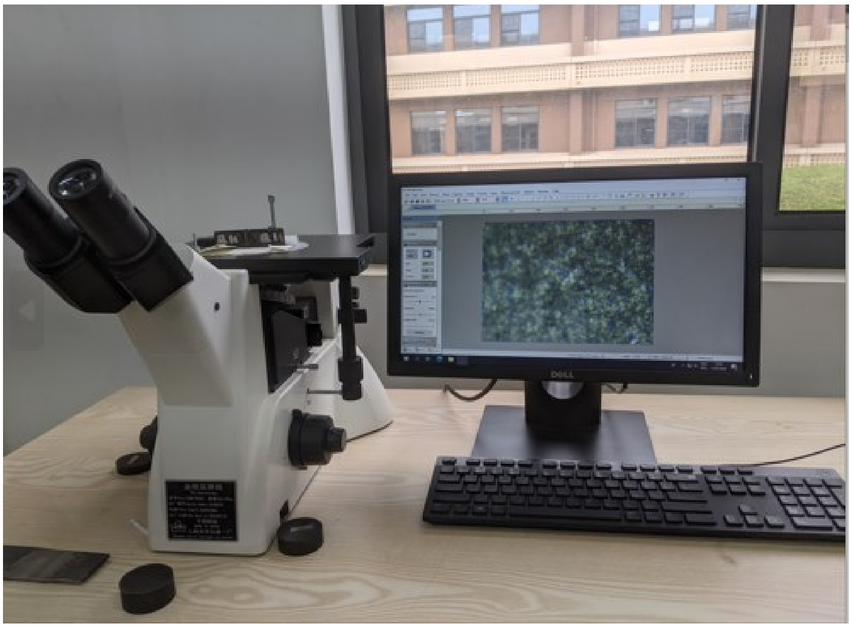


Figure 3.6: Optical metallurgical microscope

3.4 Data Analysis

The quantitative data obtained from hardness, tensile strength and microstructure tests were analyzed descriptive statistics and the effects of various GMAW welding process parameters on penetration depth were presented in line graphs. The observable visual effects of welding parameters on weld quality were presented in pictorial format.

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter discusses the results obtained from welding of mild steel plates using different parameter settings and using two types of shielding gases i.e. 100% Ar and 80% Ar + 20% CO_2; the results of assessment of arc stability in GMAW process and the weld quality aspects are presented and discussed to provide an understanding of the influence of arc stability characteristics in gas metal arc welding on weld quality.

4.1 Effect of Shielding Gas on GMAW Arc Stability

4.1.1 Visual Observation of Welds

During the visual inspection, the welded sample pieces were examined using both pure argon and 80% Ar-20% CO_2 gas mixtures. All six samples passed the visual acceptance criteria and were deemed suitable for further analysis. The assessment of the sample surfaces involved evaluating them for spatters, cracks, bead geometry, porosity, and undercuts based on the ASME standards and acceptance criteria (ASME, 2019). Furthermore, a detailed qualitative comparative analysis of spatter is provided in table 4.1, which offers additional insight for thorough examination. The samples were categorised as described in Table 4.2. Sample were welded in accordance with the specific production parameters and welding conditions outlined in Figure 4.1 and 4.2. Visually, A. ii and B.ii appear with uniform beads with fewer discontinuities visible. B.ii (V: 25, A: 150, speed: 40) set up had the best optimisation. Visually, A. ii and B.ii appear with uniform beads with fewer discontinuities visible. B.ii (V: 25, A: 150, speed: 40) set up had the best optimisation.

Table 4.1: Weld parameters at different parameters and conditions

Sample Identification	Welding Conditions			
	Welding Variables			Shielding Gas Mixture
	Travel Speed (cm/min.)	Voltage (v)	Amperage (A)	
A. i	20	20	100	100% Ar.
A. ii	40	25	150	
A.iii	60	30	200	
B. i	20	20	100	80% Ar. – 20% CO_2 blend
B. ii	40	25	150	
B.iii	60	30	200	

Figure 4.1: Appearance of the bead surface conditions for welded samples A. i; A.ii & A.iii.

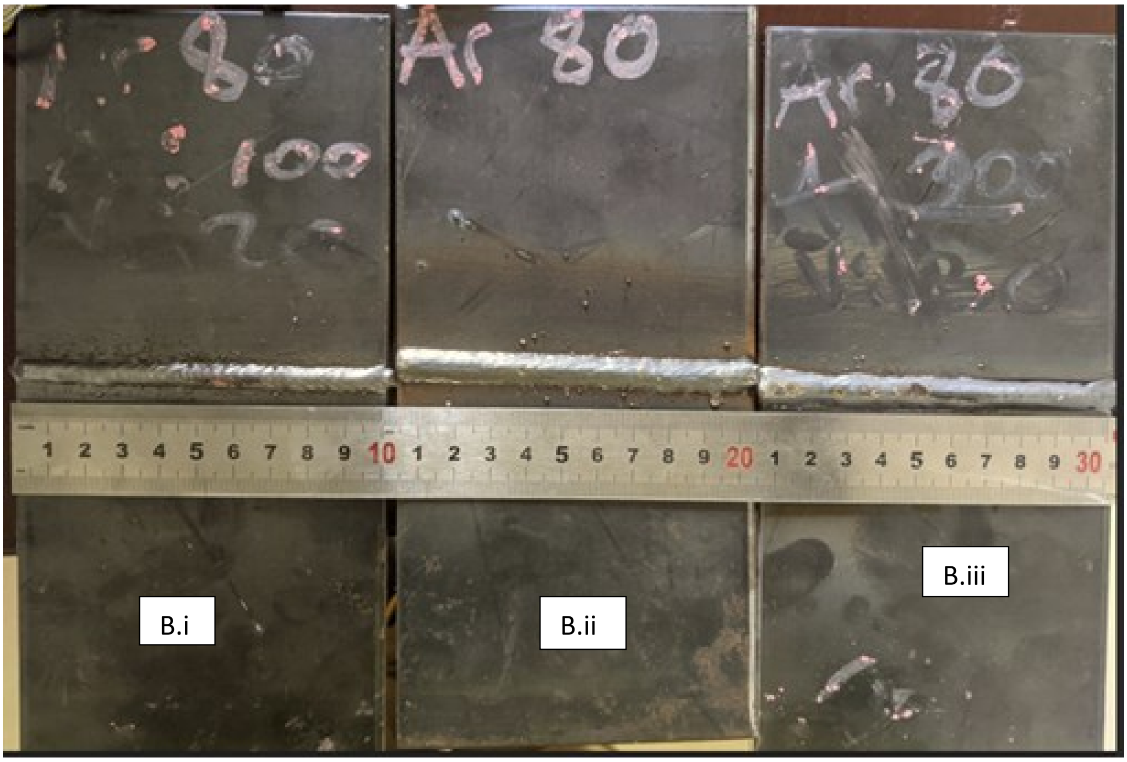


Figure 4.2: Appearance of the bead surface conditions for welded samples B. i; B.ii & B.iii.

Table 4.2: Appearance of the bead surface conditions for welded samples B. i; B.ii & B.iii.

Qualitative Spatter Analysis			
Ar. 100%		**Ar.80%**	
Sample Identification (corresponding parameters)	**Observation**	**Sample**	**Observation**
A.i (V: 20, A:100, speed: 20)	Less spatter within a distance of 30mm to 80 mm.	**B.i** (V: 20, A:100, speed: 20)	No visible spatter within the same distance.
A.ii (V:25, A: 150, speed:40)	Spatter of large sizes between a distance of 140mm to 200mm.	**B.ii** (V:25, A: 150, speed:40)	Spatters of small size within the same distance.
A.iii (V:30, A: 200, speed:60)	Clear surface for a full length of the sample.	**B.iii** (V:30, A: 200, speed:60)	Some spatters within a distance of 210 mm to 270mm.

4.1.2 Assessment of GMAW Arc Stability under Shielding Gas of 100% Argon

The experimental results for GMAW arc stability data for different combinations of set voltages (20V, 25V, & 30V), currents (100A, 150V, 200A) and speeds of (20mm/s, 40mm/s, 60mm/s) under 100% argon gas shielding is given in Table 4.3. The data shows how variations in voltage, current and speed impact on arc stability as evidenced by slight fluctuations in arc voltage and current. It was observed that 100% Argon results in smooth metal transfer with reduced spatter compared to mixtures with CO_2. Arc Voltage remains stable across all settings, with only minor fluctuations at high speeds and high currents; and arc current is also consistent, with 25V and 30V settings providing the most stable behavior. Instability is more noticeable at higher currents (200A) and higher travel speeds (60 cm/min), particularly at lower voltage settings (20V).

In figure 4.3 (a), the arc voltage generally increases with the set voltage, but the behavior varies across different currents and speeds. At higher set-currents, the arc voltage shows greater variations, indicating the potential instability caused by higher currents. In figure 4.3 (b), the arc current tends to fluctuate more at higher set-currents, with differences based on the set voltage and speed. This suggests that controlling the set current is critical for maintaining arc stability, especially at higher currents. For figure 4.3 (c), as the welding speed increases, the arc voltage exhibits variation, particularly at lower voltages. Higher speeds may cause more instability, especially at low set voltages and higher currents. In figure 4.3 (d), the arc current remains relatively stable with speed, but some fluctuations occur at higher speeds and higher set currents.

It was observed that stability is best at moderate voltage (25V) and current (150A) across most travel speeds. Instability (excess spatter and arc fluctuation) increases at high current (200A) and low voltage (20V), especially at slower speeds. At higher voltages (30V), performance remains stable but with higher risks of overheating and spatter at the highest current and speed settings.

Table 4.3: Arc Stability Assessment Results Using 100% Argon Gas

Set Voltage (V)	Set Current (A)	Travel Speed (cm/min)	Arc Voltage (V)	Arc Current (A)	Observations
20V	100	20	20.1	97	Smooth metal transfer-stable arc
	100	40	20.3	100	Minimal spatter-stable arc
	100	60	20.5	99	Scattered molten drops-slight instability at higher speed
	150	20	19.9	147	Slight spatter – stable arc
	150	40	20.1	150	Good bead formation - consistent arc
	150	60	20.3	149	Decreased current – stable arc
	200	20	19.7	195	Minor spattering – arc slightly unstable
	200	40	20.0	198	Smooth transfer – stable arc
	200	60	20.4	197	Minor arc instability – stable arc
25V	100	20	25.0	99	Minimal spatter - stable arc
	100	40	25.2	101	Good transfer - consistent arc
	100	60	25.3	100	Smooth arc behavior – stable rc
	150	20	24.8	148	Slight spatter – stable arc
	150	40	25.1	150	Good bead formation - stable arc
	150	60	25.3	152	
	200	20	24.7	194	Spatter observed - slight instability
	200	40	25.0	198	
	200	60	25.5	200	High speed, minor spatter - stable arc
30V	100	20	29.9	99	Smooth transfer - stable arc
	100	40	30.1	100	Consistent behavior - stable
	100	60	30.4	102	Good transfer - stable arc
	150	20	29.7	147	Minimal spatter - stable
	150	40	30.0	150	
	150	60	30.5	153	Higher spatter -stable
	200	20	29.6	193	Excessive spatter - unstable arc
	200	40	30.1	198	Slight spatter - stable
	200	60	30.6	201	Good transfer - stable at higher speed

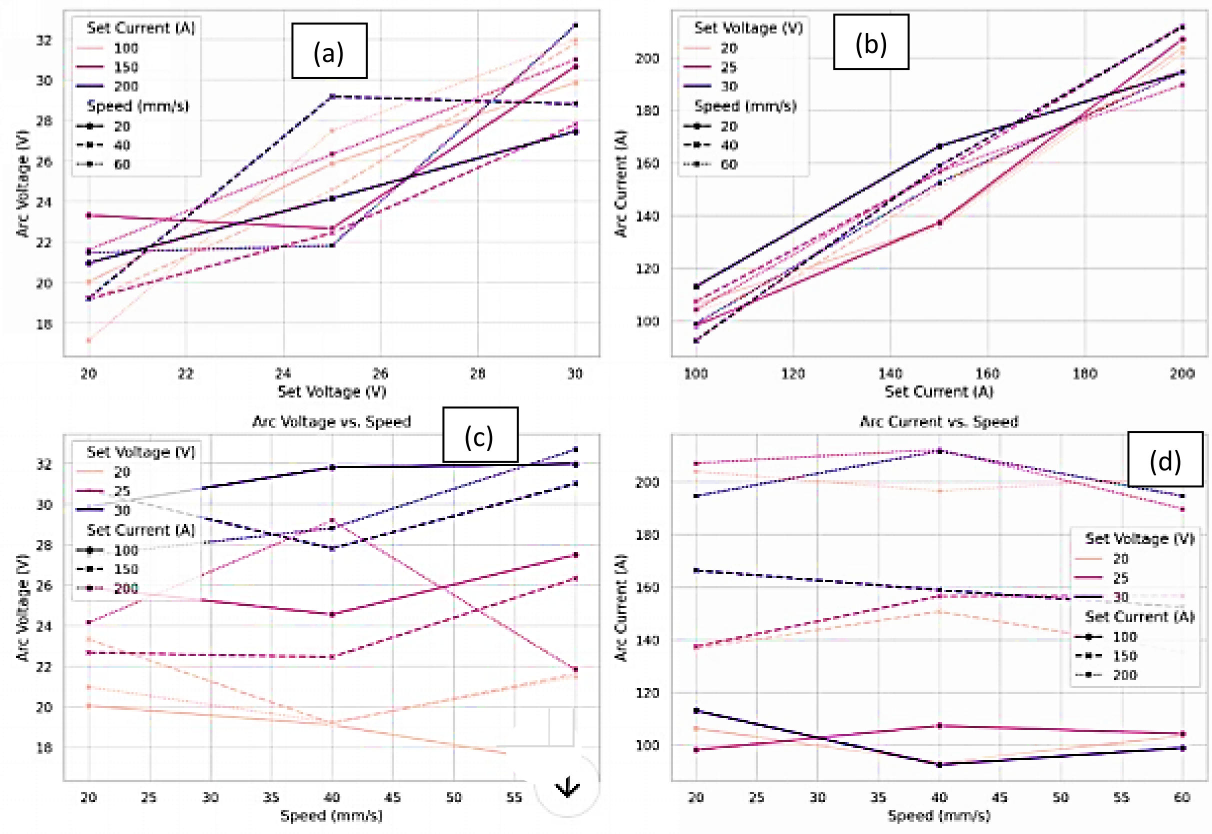


Figure 4.3: Electrical signal analysis under various conditions.

4.1.3 Assessment of GMAW Arc Stability under Shielding Gas of 80% Ar and 20%CO_2

The experimental results for GMAW arc stability data for different combinations of set voltages (20V, 25V, & 30V), currents (100A, 150V, 200A) and speeds of (20mm/s, 40mm/s, 60mm/s) under shielding gas of 80% argon gas and 20% CO_2 gas mixture is given in Table 4.4. In figure 4.4 (a), the arc voltage shows a consistent trend across different current settings. As the travel speed increases, the arc voltage slightly increases for all voltage settings (20V, 25V, 30V). At the 25V, setting generally provides better stability across all currents and travel speeds, indicated by relatively smooth voltage variations. The higher voltage setting (30V) results in a slightly larger variation, particularly at higher speeds and currents, leading to possible instability at extreme settings (200A, 60 cm/min).

In figure 4.4 (b), as the travel speed increases, the arc current generally remains stable but fluctuates slightly depending on the voltage. The 20V setting shows more variation, especially at higher speeds (60 cm/min), leading to a potential decrease in arc stability. At lower travel speeds (20 cm/min), there is more heat input into the material, leading to higher arc currents, especially at higher voltage settings (30V). This increased heat can cause more spatter and arc instability at high currents (200A). At the 25V and 30V settings maintain more stable current levels, particularly at moderate speeds (40 cm/min), which is ideal for consistent bead formation and arc stability. In figure 4.4 (c), the arc voltage increases slightly as the current increases across all voltage settings (20V, 25V, and 30V). At 25V shows the most stable and consistent behavior across the range of currents, maintaining a balanced arc voltage. At 30V tends to have a higher arc voltage overall, with noticeable increases at higher currents, which could lead to more heat and spatter at extreme settings. In figure 4.4 (d), the arc current generally increases with the set current for all voltage settings. At 20V shows more fluctuations, especially at higher currents (200A), suggesting potential instability. At 25V and 30V provide more stable arc currents across different settings, with 25V being the most balanced overall.

Figures 4.5 (a), (b) & (c) illustrate the high-speed camera images, weld sample and the electrical signal wave form respectively for sample A.iii. While, Figures 4.6 (d), (e) & (f) illustrate the high-speed camera images, weld sample and the electrical signal wave form respectively for sample B.iii. Arc observatory results obtained are much related to the work done by (Paul., 2022) and (Xi'an Fan., 2021)

Table 4.4: Arc Stability Assessment Results 80% Arc and 20% CO2 gas mixture

Set Voltage (V)	Set Current (A)	Travel Speed (cm/min)	Arc Voltage (V)	Arc Current (A)	Observations
20V	100	20	19.8	95	Slight spatter - stable arc
	100	40	20.0	100	Minimal spatter - stable arc
	100	60	20.2	98	Higher speed, smooth - stable
	150	20	19.5	145	Increased heat - slight instability
	150	40	20.0	150	Good bead formation - stable
	150	60	20.3	148	Speed affects stability
	200	20	19.3	190	Excessive spatter - unstable arc
	200	40	20.1	198	Minor spatter - stable,
	200	60	20.5	200	good metal transfer Stable,
25V	100	20	24.8	98	Smooth metal transfer - stable arc
	100	40	25.0	100	Consistent metal transfer, stable
	100	60	25.2	101	Stable at higher speed
	150	20	24.6	148	Stable, slight spatter
	150	40	25.0	150	Balanced arc stability
	150	60	25.4	152	Increased spattering - decreased stability at higher speed
	200	20	24.5	192	Increased spatter - unstable
	200	40	25.2	198	Good bead penetration - stable arc
	200	60	25.5	201	
30V	100	20	29.7	97	Stable arc, minimal spatter
	100	40	30.0	100	Smooth transfer, high speed – stable arc
	100	60	30.2	102	Consistent transfer - stable
	150	20	29.5	148	Slight spatter - stable
	150	40	30.0	150	Uniform deposition – stable arc
	150	60	30.5	154	
	200	20	29.3	190	Excessive spatter - unstable
	200	40	30.1	198	Increased spattering – unstable
	200	60	30.6	202	

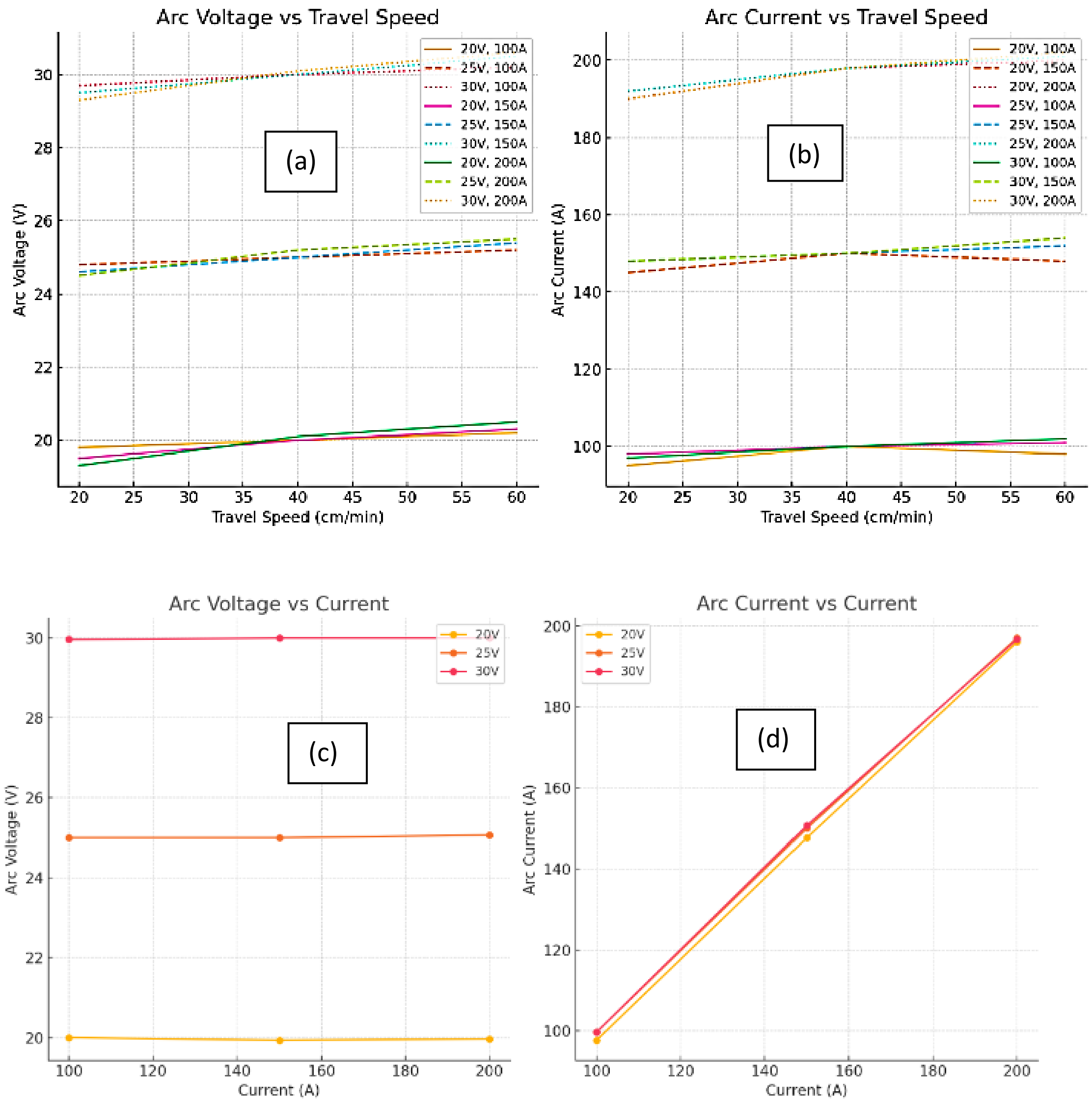


Figure 4.4: Electrical signal analysis under various conditions.:

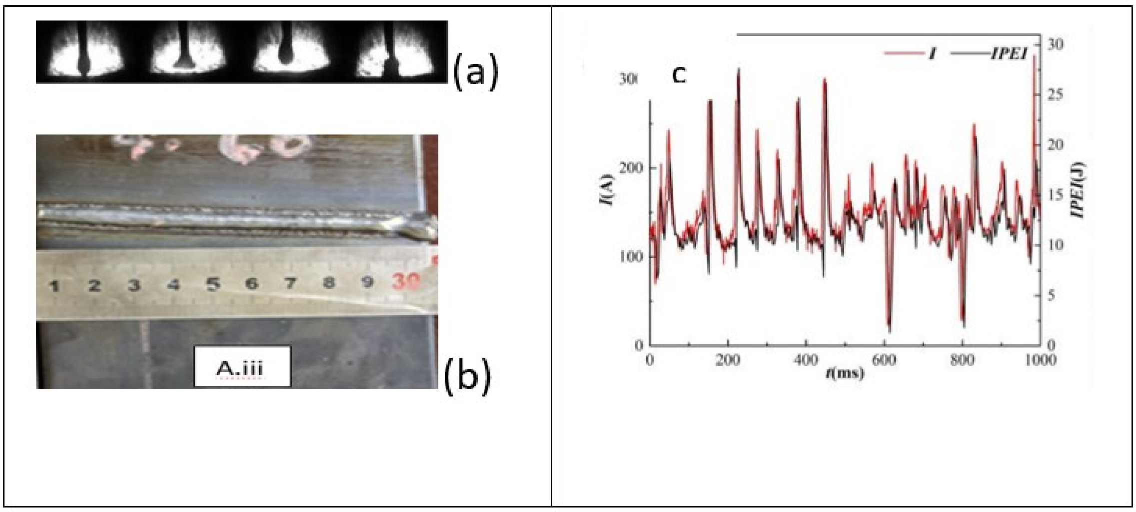


Figure 4.5: Image processing for sample A.iii using a high-speed camera

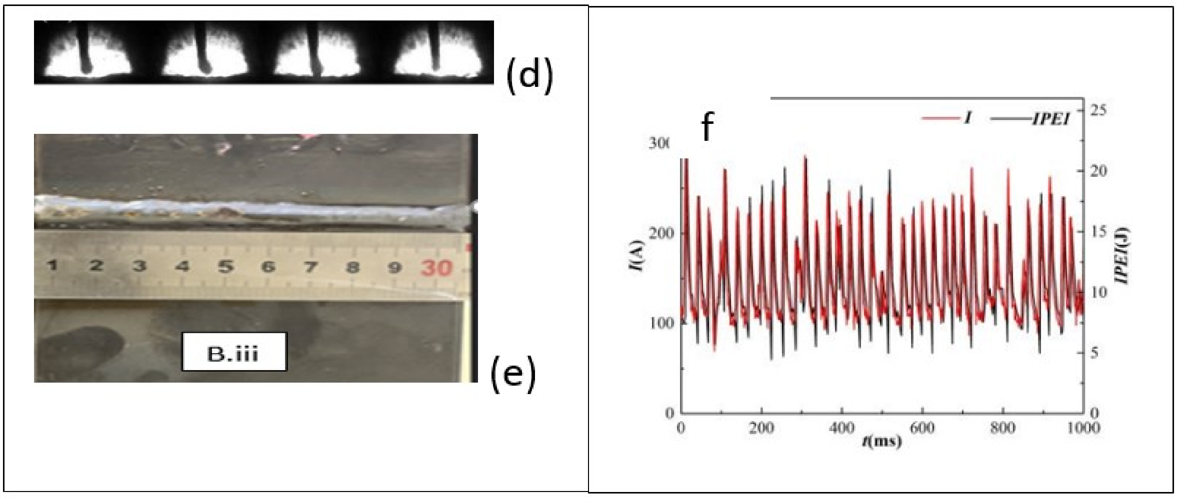


Figure 4.6: Image processing for sample B.iii using a high-speed camera.

4.2 Effect of Welding Current on Weld Penetration

Using the gas blend of Ar. 80% & CO_2 20%, an acceptable weld bead with a better penetration depth was achieved as indicated in the Figures 4.7 and 4.8. The investigation studied the effect of welding current on the depth of weld penetration in a 5mm thick mild steel plate. The experiment comprised a range of welding current levels from 100A to 200A, arc voltage levels from 20V to 30V, and welding speeds set at 20 cm/min, 40 cm/min, and 60 cm/min. The impact of welding current on weld penetration at different welding speeds and arc voltage levels is depicted in Figures 4.9 and 4.10. The welding current levels tested were 100A, 150A, and 200A, arc voltage levels were 20V, 25V, and 30V, and welding speed levels were 20 cm/min, 40 cm/min, and 60 cm/min. The results demonstrated that an increase in welding current led to a greater penetration depth.

Comparing the two shielding conditions, the Ar 80% & CO_2 20% blend had the most optimal penetration depth with the most acceptable welds produced. This was achieved under B.ii (V: 25, A: 150, speed: 40) test condition; with 2.0 mm as the most optimal recorded penetration depth. Figures 26.4 (a, b & c) illustrate that an increase in welding current and arc voltage results in greater penetration depth. Generally, raising the welding current from 100A to 200A and arc voltage from 20V to 30V led to an increase in penetration depth. Operating at a welding speed of 20 cm/min, the maximum penetration depth of 1.74 mm was achieved using 200A and 30V, while the minimum penetration depth of 1.05 mm was observed with 100A and 20V. The trend of penetration depth with welding current at a 40 cm/min welding speed was similar to that observed at 20 cm/min, with increased welding current resulting in greater penetration depth. At a welding speed of 40 cm/min, it was found that the maximum penetration depth of 2.0 mm was achieved when using a welding current of 200A and an arc voltage of 30V. Conversely, the minimum penetration depth of 1.05 mm was observed with a welding current of 100A and an arc voltage of 20V. This trend was consistent at welding speeds of both 20 cm/min and 40 cm/min, indicating that the effect of welding current on penetration depth remained constant across these different speeds. Further experimentation at a welding speed of 60 cm/min reinforced this observation, with the highest penetration depth of 2.44 mm occurring when using a welding current of 200A and an arc voltage of 30V.

It was noted that when different welding speeds were tested, there was a clear correlation between the welding current and penetration depth. Specifically, as the welding current increased, the penetration depth also increased. However, it was observed that the penetration depths tended to be generally lower compared to the thickness of the welded mild steel plate. Additionally, it was found that the use of 80% Ar + 20% CO_2 shielding gas had a modifying effect on the relationship between welding parameters and penetration depth, ultimately resulting in lower penetration depths. Figure 4.9 (graphs a, b & c) illustrates the values of penetration depth at varying amperage at given speeds.

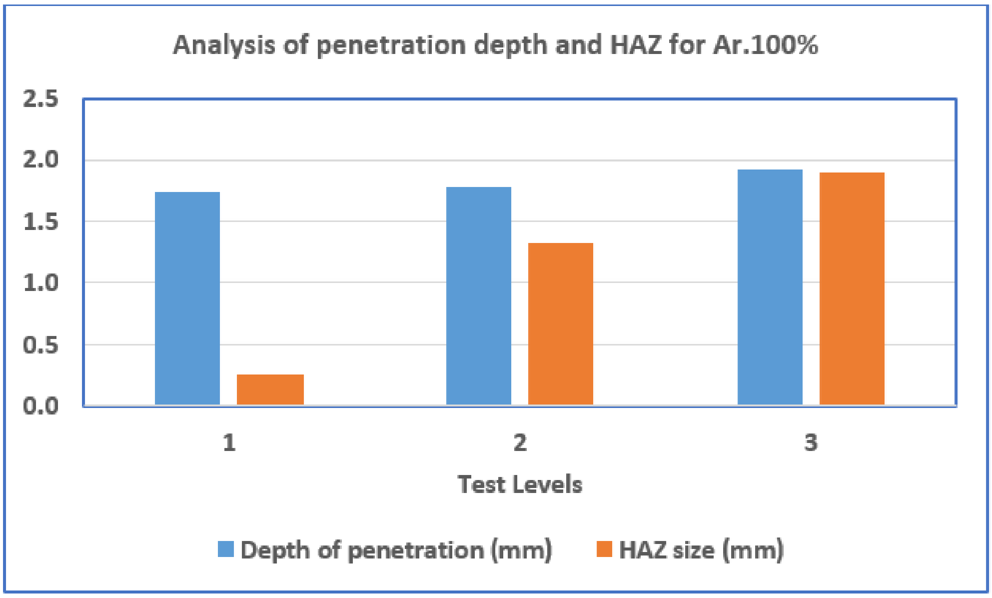


Figure 4.7: Welding performance at Ar. 100%

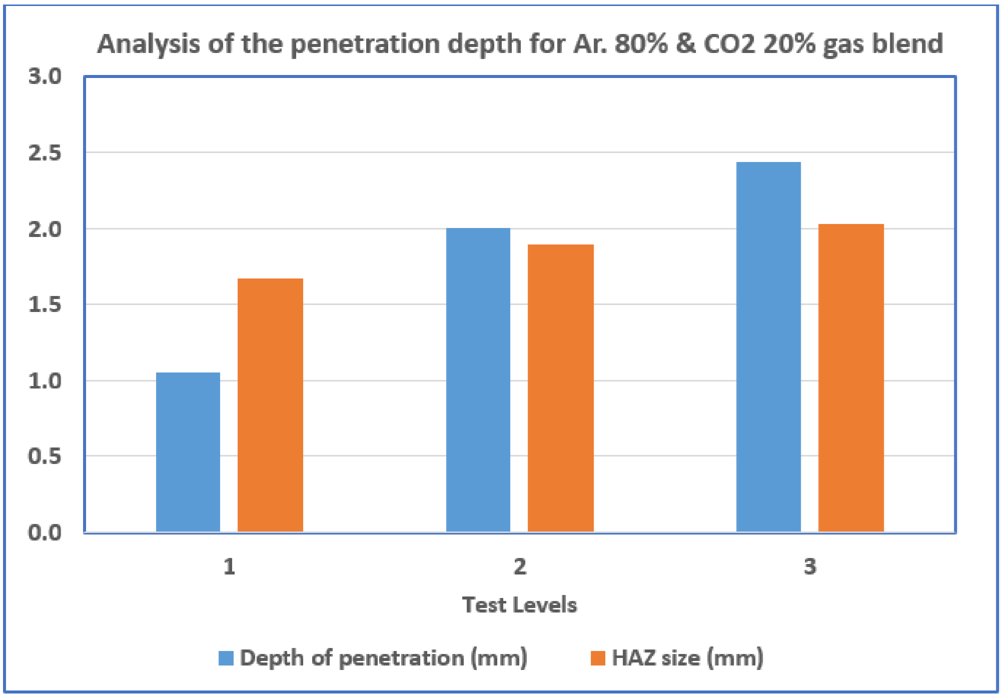
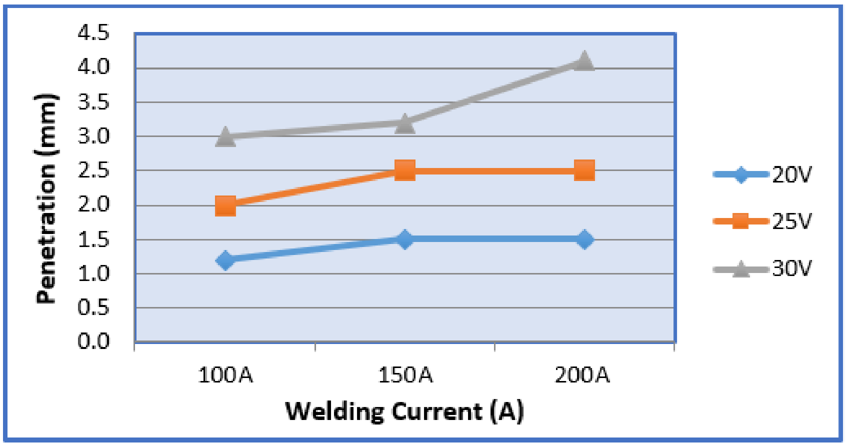
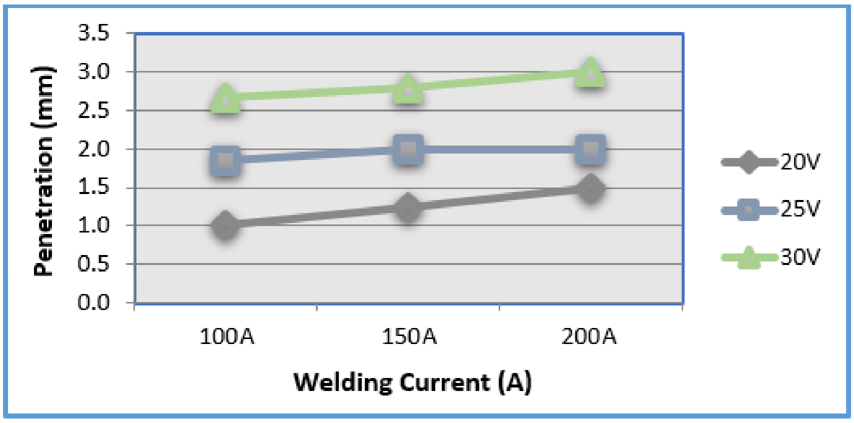


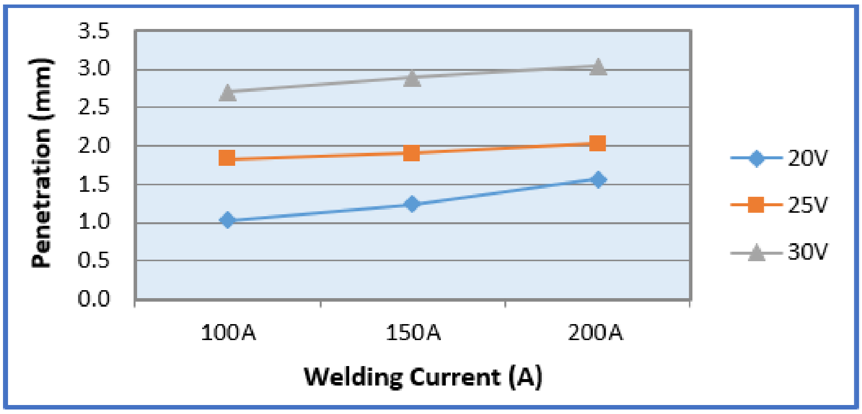
Figure 4.8: Welding performance at Ar. 80% & CO_2 20% gas blend



(a) Penetration versus welding current at 20cm/min welding speed



(b) Penetration versus welding current at 40cm/min welding speed



(c) Penetration versus welding current at 60cm/min welding speed

Figure 4.9: Effect of Welding Current on Penetration Depth at Different Welding Speed.

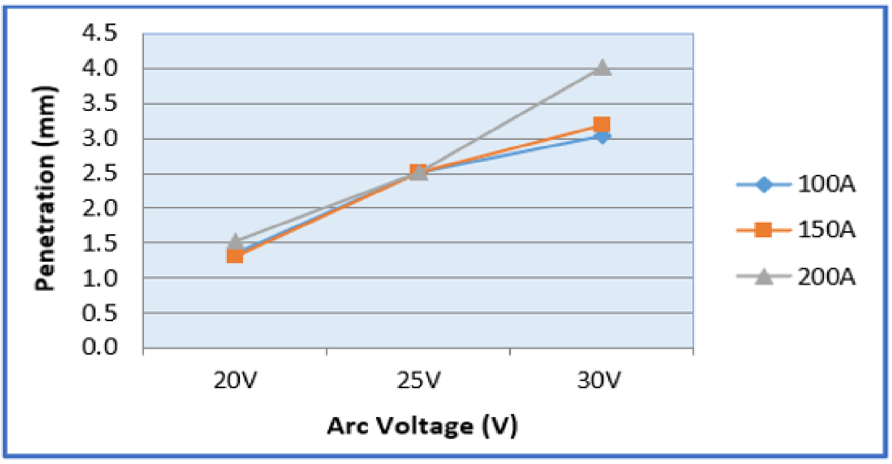
4.3 Effect of the Arc Voltage on Weld Penetration

The research project delved into the effects of arc voltage on the depth of weld bead penetration in a 5 mm thick mild steel plate. The investigation involved a comprehensive range of welding parameters, with welding currents spanning 100A to 200A, arc voltages ranging from 20V to 30V, and welding speeds set at 20 cm/min, 40 cm/min, and 60 cm/min. The findings, illustrated in Figure 4.10, display the influence of varied arc voltage on weld penetration across different welding speeds and currents. The experiment included testing arc voltage levels of 20V, 25V, and 30V, coupled with welding currents of 100A, 150A, and 200A, and welding speeds of 20 cm/min, 40 cm/min, and 60 cm/min. As observed, an increase in arc voltage correlated with greater penetration depth. However, the penetration values at the specified welding current and arc voltage levels were lower in comparison to the 5 mm workpiece thickness.

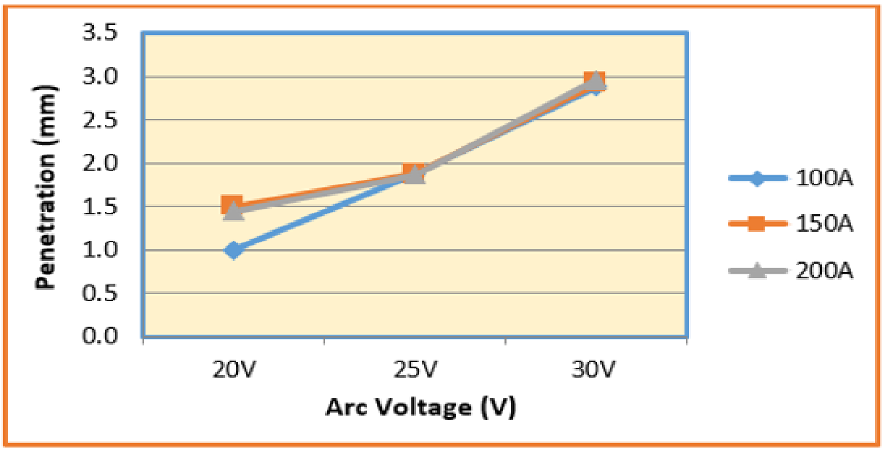
The results presented in Figures 4.10 (a, b & c) shows that an increase in arc voltage results in a deeper penetration. The study's findings demonstrated that the maximum penetration depth was measured at an arc voltage of 30V, while the minimum depth was observed at 20V. Notably, maintaining a welding speed of 20 cm/min and an arc voltage of 30V, the penetration depths for welding currents of 100A, 150A, and 200A were found to be 1.03 mm, 2.0 mm, and 2.44 mm, correspondingly. These results underline the substantial impact of welding current on penetration depth, particularly when the arc voltage is held constant. Moreover, it was discovered that at arc voltages of 25V and 30V, enhanced penetration depths were attained with a welding speed of 20 mm/min and a welding current of 200A. This outcome was attributed to the increased heat input resulting from these specific combinations of parameters. The relationship between penetration depth and arc voltage at welding speeds of 40 cm/min and 60 cm/min mirrored the pattern observed at 20 cm/min. However, the highest penetration depth was observed at the lower welding speed of 20 cm/min, while the lowest was noticed at the highest welding speed of 60 cm/min for a given arc voltage, as depicted in Figures 4.10 (b) and (c).

The correlation between arc voltage and penetration depth was determined to be linear across the different welding speeds that were examined. As arc voltage increased, so did the penetration depth. However, the penetration depth values were comparatively modest in relation to the thickness of the welded workpiece. When Ar+20% CO2 shielding gas was utilized, the impact of arc voltage on penetration depth mirrored that of using inert shielding gas (Argon). Nevertheless, penetration depth was reduced when employing the Ar+20% CO2 shielding gas.

(a) Penetration Vs voltage at 20 cm/min welding speed



(b) Penetration Vs voltage at 40 cm/min welding speed



(c) Penetration Vs voltage at 60 cm/min welding speed

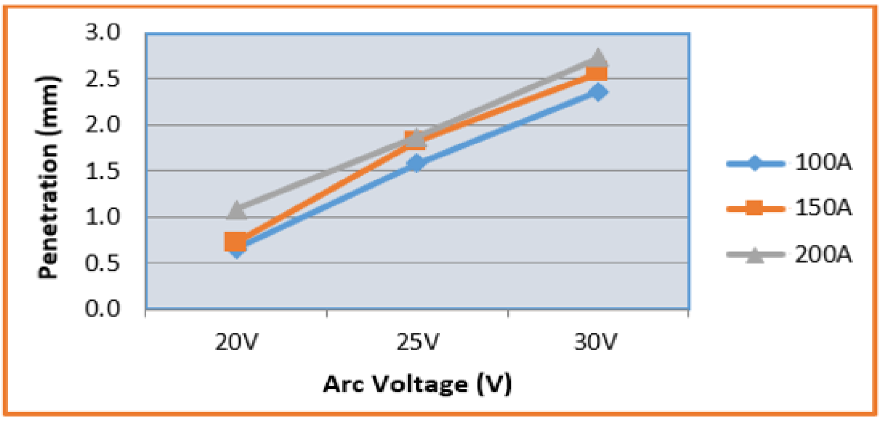
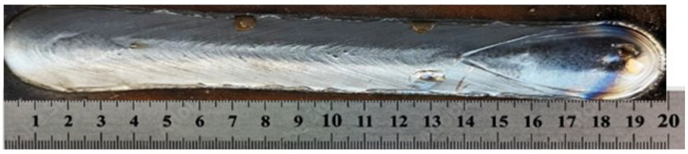
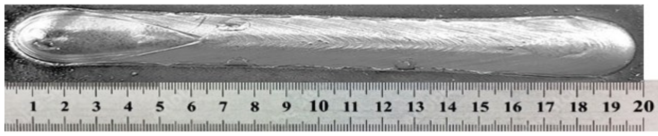


Figure 4.10: Effect of Arc Voltage on Penetration Depth at Different Welding Speeds

4.4 Effects of Gas Combinations on Weld Quality

The ideal physical attributes of a high-quality Gas Metal Arc Welding (GMAW) weld involve a seamless and gracefully curved weld bead, minimal spattering, and the absence of slag. Additionally, specific dimensions such as penetration depth, bead width, and bead height are crucial for achieving the desired weld quality. A detailed visual representation of the weld under varying experimental conditions can be located in Table 4.5. When performing GMAW using an inert shielding gas with a purity of 99.95% Argon at a flow rate of 15 cubic feet per minute (cfm) and employing a 1.2 mm wire electrode (ER 70S-6), optimal weld quality is achieved by using a welding current of 150A, arc voltage of 30V, and a welding speed of 60 cm/min. When conducting GMAW with a metal active gas (MAG) produced by combining 20% CO_2 with Argon at a flow rate of 15 cfm, it is recommended to use a 1.2 mm diameter wire electrode (ER70S-6). Improved results are obtained with a welding current of 200A, arc voltage of 30V, and a welding speed of 40 cm/min. The appearance of the MAG weld is characterized by a rough surface on the weld bead, smooth reinforcement at the edges, convexity at the center, increased spattering, and slight slag formation at the edges of the weld bead, as shown in Table 4.5.

Table 4.5: Effects of variations in current, voltage and speed on weld quality

SN	Welding Parameters	Appearance of the bead
1	Current of 200 A Voltage at 30 V Welding Speed 20 cm/min. Shielding gas Ar+20%CO_2	
2	Current 150 A Voltage 30 V Welding speed 40 cm/min Shielding gas Ar 100%	
3	Current 200A Voltage 30V Welding Speed 60cm/min Shielding gas Ar 100%	

4.5 Influence of Weld Transfer Modes

Figure 4.11 presents the weld bead cross-section (bead width and height) and penetration depth for different metal droplet transfer modes of Multiple Drops Per Pulse (MDPP), One Drop Per Pulse (ODPP) and One Drop Multiple Pulses (ODMP).

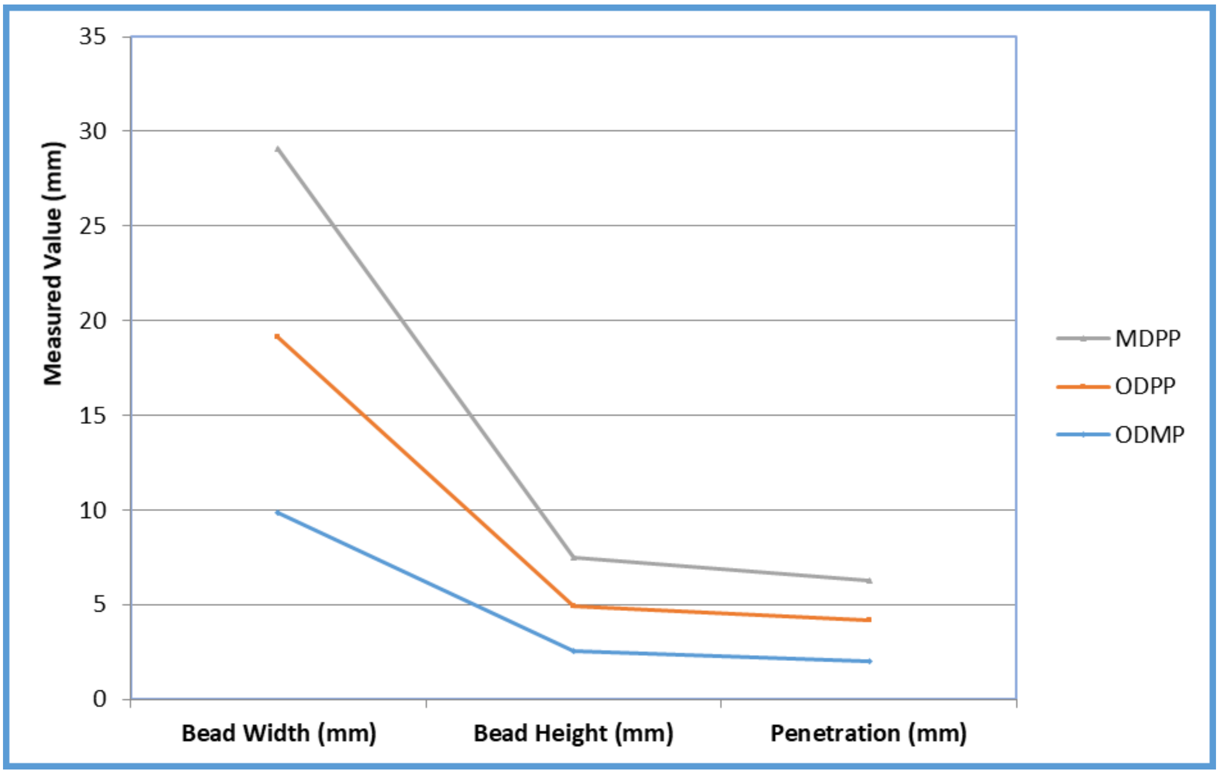


Figure 4.11: Weld Bead Cross-Section and Penetration for Different Droplet Transfer Modes

4.6 Effect of Welding Parameters on Weld Quality

Welding discontinuities have the potential to affect the quality of welds, and their acceptability is determined by specific criteria established in welding standards such as ISO 9606, ASME, D1.1, etc. The presence of discontinuities in welded joints can lead to a decreased lifespan of structures, which is undesirable. In fusion welding processes like MIG/MAG, the quality of the weld is influenced by the heat input, which is reliant on factors such as travel speed, welding amperage, and voltage. Excessive heat input has the potential to compromise the structural integrity of welded joints, particularly at a microstructure level, due to increased carbide precipitation, grain segregation, and variations in phases. The welded samples were subjected to tensile, hardness, and microstructural tests to evaluate the impacts of the chosen conditions on the material.

4.6.1 Effect of Welding Parameters on Mechanical Properties

The samples that were welded underwent testing under tensile loading conditions, and the results have been documented in tables 4.6, 4.7, 4.8, 4.9, 4.10, and 4.11, as well as in figures 4.12, 4.13, 4.14, 4.15, 4.16, and 4.17. Summary of the tensile test results can be found in Table 4.12. Figures 4.12, 4.13 and 4.14 depict the behavior of samples A.i, A.ii, and A.iii under tensile loading, indicating ductile characteristics typical of medium carbon steel. Notably, it was observed that using pure argon as a shielding gas does not significantly compromise the material's ductility, even in the absence of post-weld heat treatment. On the other hand, figures 4.15, 4.16, and 4.17 illustrate the behavior of samples B.i, B.ii, and B.iii under tensile loading, showing curves indicative of brittle materials, similar to those of high carbon steels. This brittleness is notably exacerbated by blending pure argon with carbon dioxide, attributed to the reactivity of carbon dioxide, which contributes more carbon atoms in solid solution and increases the heat input. Post-weld heat treatment for recrystallization and to eliminate residual heat stresses can rectify this issue. The acceptance criteria for mechanical tests were as given in ASME section ix (ASME, 2019).

Table 4.6: Analysis of sample A.i under stress loading

	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	elongation
	0.0	20.0	42.0	5.0	100	0	0	0	
	40.0	19.6	43.4	4.7	92.12	434.2	0.033	0.0014	
	43.0	18.7	445.6	4.4	82.28	522.6	9.610	0.4036	
	31.0	18.0	47.7	4.2	75.6	410.1	0.136	0.0057	
Necking	45.0	16.0	53.4	3.8	60.8	740.1	0.271	0.0114	
Failure	26.5	13.3	54.0	2.6	34.58	766.3	0.286	0.012	0.029

It was noted that A.i experienced necking at 740.1 MN/m2 and failure at 766.3 MN/m2. The above analysis was anlysed graphically to located the yield points and the shape of the cure. The curves were compared with standard to make more so of them. Table 4.6 above illustrates the results obtained when sample A.i was subjected to tensile loading conditions.

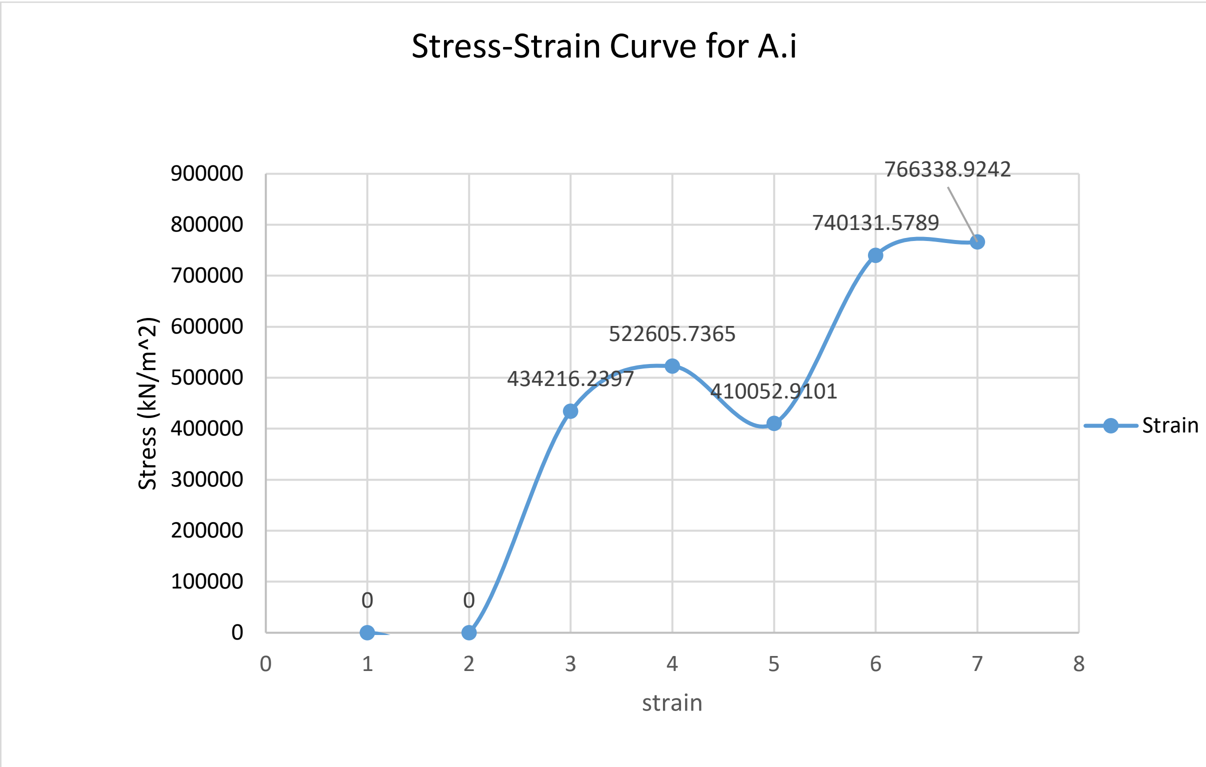


Figure 4.12: Stress-strain graph for Ai

Table 4.7: Sample group A.ii tensile test results

A.ii									
Original	width (mm): 21 -gauge length (mm): 41								
	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	elongation
	0.0	20.0	42.0	5.0	100	0	0	0	
Necking	30.5	20.2	49.4	4.6	92.9	328.2	0.176	0.0074	
Failure	31.5	19.9	51.5	4.6	91.5	344.1	0.226	0.0095	
	25.3	18.0	54.0	3.6	64.8	390.4	0.286	0.012	0.029

Table 4.7 above illustrates the results obtained when sample A.ii was subjected to tensile loading conditions.

It was observed that A.ii experienced necking at 344.1 MN/m^2 and failure at 390.4 MN/m^2. The above analysis was further analysed graphically was shown in figure 4.14.

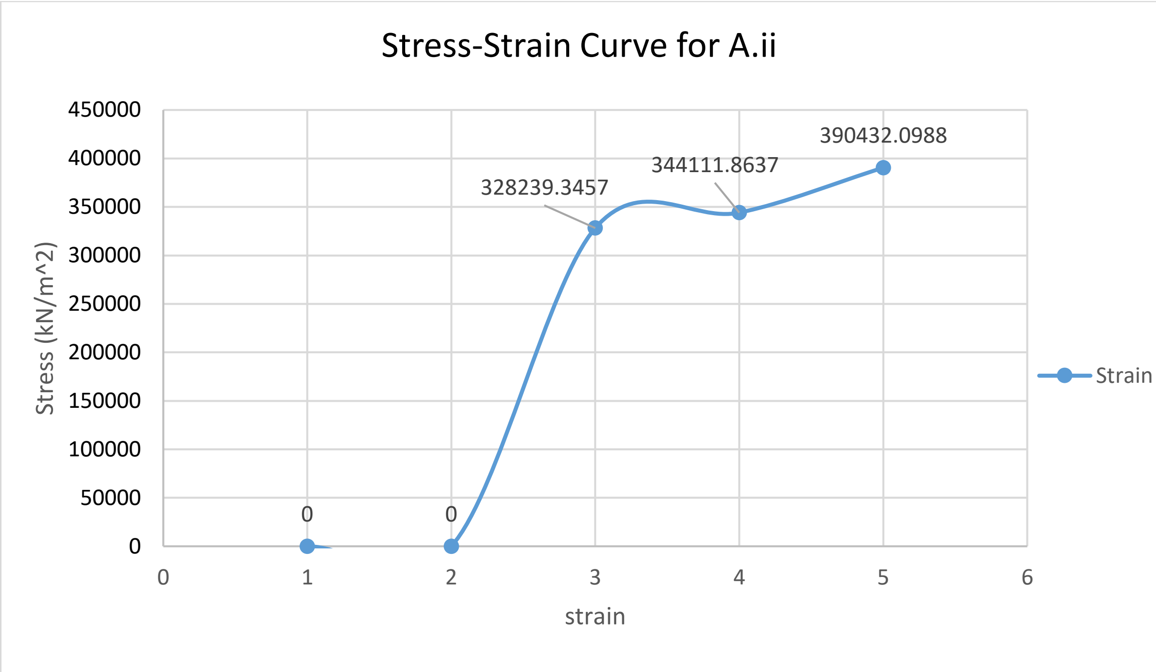


Figure 4.13: Analysis of sample A.ii under stress loading

Table 4.8: Sample group A.iii tensile test results

Original									
	width (mm): 20-gauge length (mm): 42								
	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	%age elongation
	0.0	20.0	42.0	5.0	100	0	0	0	
	40.0	19.6	43.4	4.7	92.12	434.2	0.033	0.0014	
	43.0	18.7	445.6	4.4	82.28	522.6	9.610	0.4036	
	31.0	18.0	47.7	4.2	75.6	410.1	0.136	0.0057	
Necking	45.0	16.0	53.4	3.8	60.8	740.1	0.271	0.0114	
Failure	26.0	13.3	54.0	2.6	34.58	751.9	0.286	0.012	0.029

Table 4.8 above illustrates the results obtained when sample A.iii was subjected to tensile loading conditions.

It was noted that A.iii experienced necking at 740.1 MN/m^2 and failure at 751.9 MN/m^2. A graphical analysis from the above data was captured in figure 4.14.

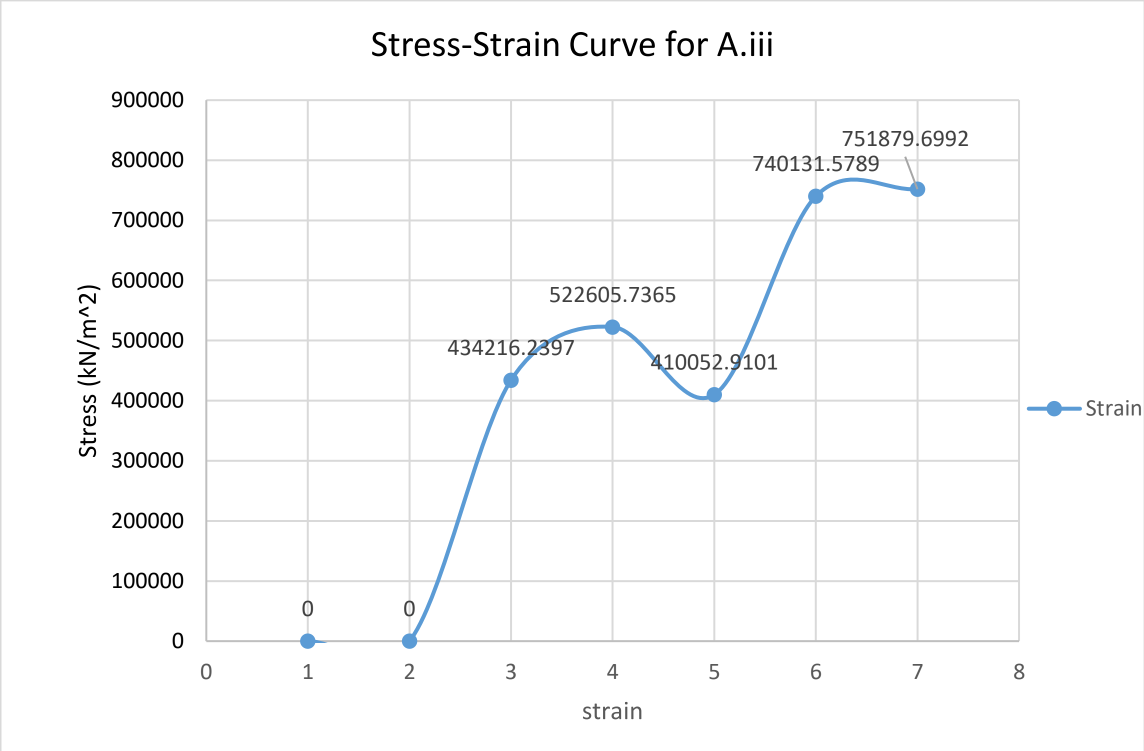


Figure 4.14: Analysis of sample A.iii under stress loading.

Table 4.9: Sample group Bi tensile test results

B.i									
Original	width (mm): 20-gauge length (mm): 42								
	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	%age elongation
	0.0	20.0	42.0	5	100	0	0	0	
	26.0	16.4	48.0	4.0	65.6	396.3	0.143	0.006	
Necking	27.0	14.0	50.0	3.4	47.6	567.2	0.190	0.008	
Failure	22.0	13.0	50.6	2.6	33.8	650.9	0.205	0.0086	0.020

Table 4.9 above illustrates the results obtained when sample B.i was subjected to tensile loading conditions.

It was noted that B.i experienced necking at 567.2 MN/m^2 and failure at 650.9 MN/m^2.

The experimental data above was analysed graphically as shown below in figure 4.15.

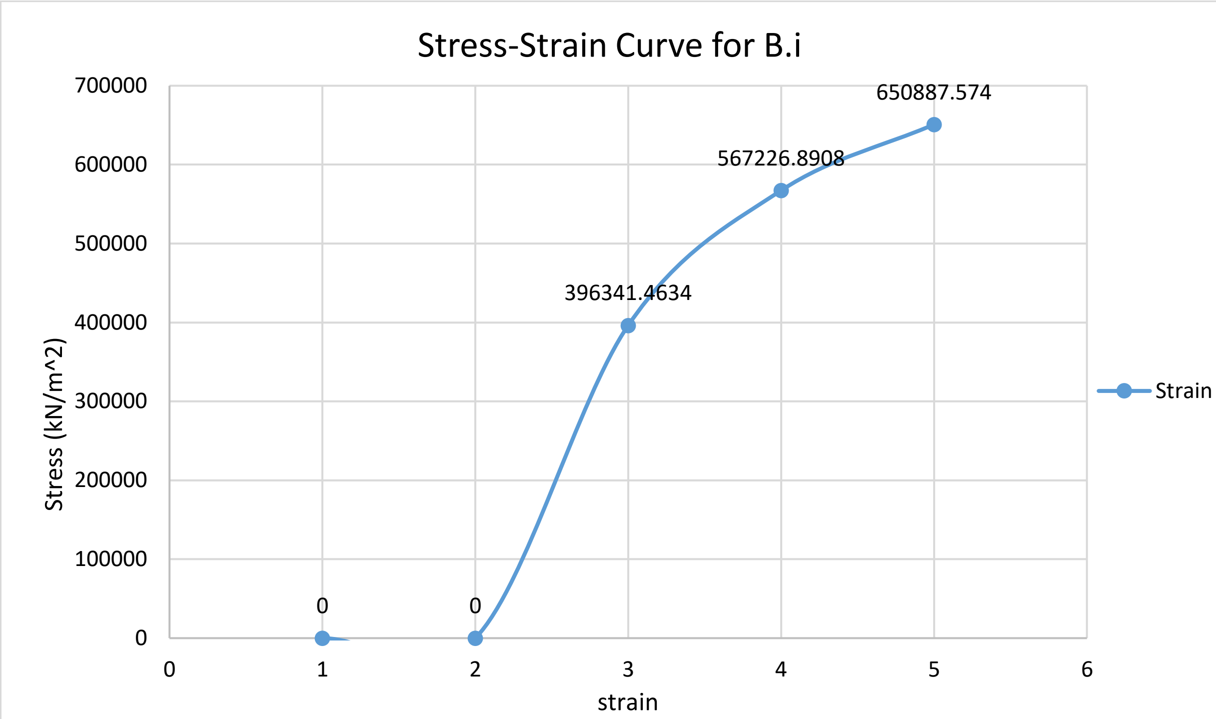


Figure 4.15: Analysis of sample B.i under stress loading

Table 4.10: Sample group Bii tensile test results

B.ii									
Original	width (mm): 21-gauge length (mm): 41								
	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	%age elongation
	0.0	20.0	41.0	5	100	0	0	0	
	26.5	17.7	42.7	4.6	81.42	325.5	0.017	0.0007	
	28.5	16.3	55.6	3.8	61.94	460.1	0.324	0.0136	
Necking	26.5	14.6	56.8	3.4	49.64	533.8	0.352	0.0148	
Failure	22.0	13.5	58.4	2.4	32.4	679.0	0.390	0.0164	0.04

Table 4.10 above illustrates the results obtained when sample B.ii was subjected to tensile loading conditions.

It was noted that B.ii experienced necking at 533.8 MN/m^2 and failure at 679.0 MN/m^2. A graphical analysis was made to depict the behaviour of the material under load as illustrated in figure 4.16 below.

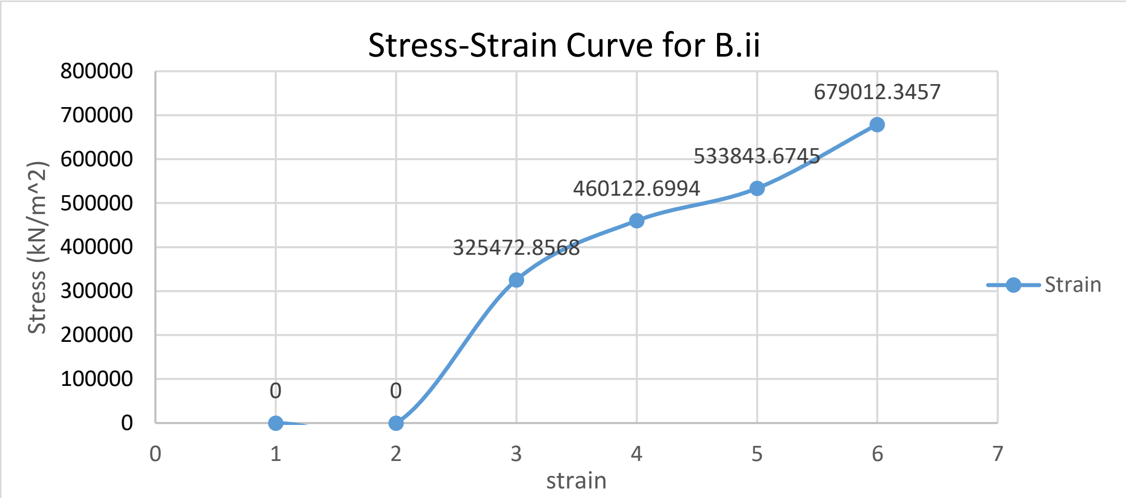


Figure 4.16: Analysis of sample B.ii under stress loading.

Table 4.11: Sample group Bii tensile test results

B.iii									
Original	width (mm): 20-gauge length (mm): 42								
	Load (kN)	Width (mm)	Gauge Length (mm)	Thickness (mm)	Area (mm^2)	Stress (MN/m^2)	Strain	Δl (m)	%age elongation
	0.0	20.0	42.0	5	100	0	0	0	
	25.0	17.0	44.4	4.6	78.2	319.7	0.057	0.0024	
Necking	25.6	13.4	47.0	3.0	40.2	636.8	0.119	0.005	
Failure	9.0	12.8	48.8	2.8	35.84	251.1	0.162	0.0068	0.016

Table 4.11 above illustrates the results obtained when sample B.iii was subjected to tensile loading conditions.

It was noted that B.iii experienced necking at 636.8 MN/m^2 and failure at 251.1 MN/m^2. The data above was graphically illustrated, as shown below to analyse the shape and locations of yield points.

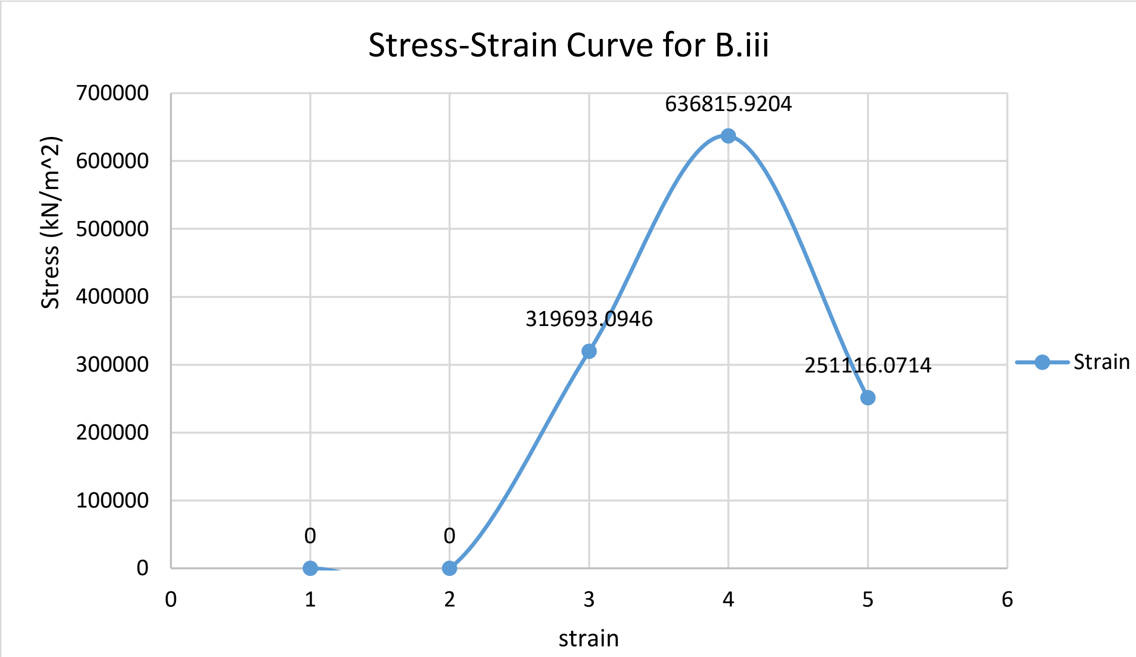


Figure 4.17: Analysis of sample B.iii under stress loading

4.6.2 Summary of tensile tests

The Tensile test results show that; highest strength was observed from the material welded using a mixed gas of 80% Argon and 20% CO_2. The percentage elongation of 4.0 is the best with the same gas combination. Figures 4.18 & 4.19 provides comparative results for the performance of the weld samples under tensile loading.

Figure 4.18 below gives comparative analysis of samples in category A under tensile loading. It was observed that the curves depicted the shape of the curves of low carbon steel, which is typical of mild steel. The curves clearly illustrate the upper yield, lower yield and ultimate yield points. Samples A.i & A.ii showed same upper yield and lower yield of 522.6MN/m^2 and 410.1MN/m^2 respectively. However, their ultimate yield points varied by 4.46MN/m^2.

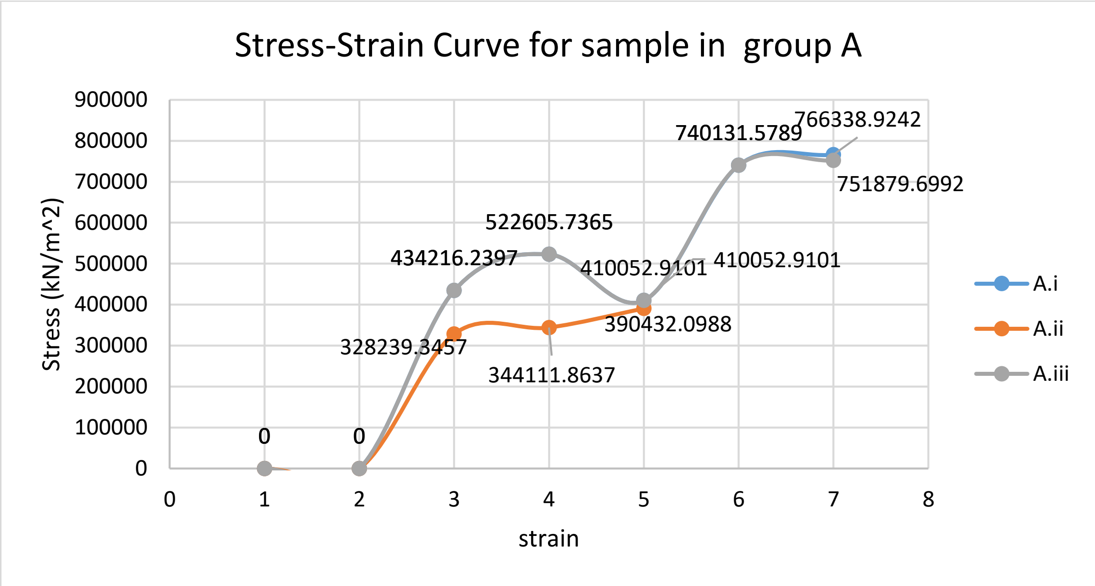


Figure 4.18: Comparative Analysis of samples in group A samples under stress loading

Figure 4.19 below gives comparative analysis of samples in category B under tensile loading. It was observed that the curves depicted the shape of the curves of medium carbon steel. Sample B.ii showed the highest ultimate yield point of 6679 MN/m^2.

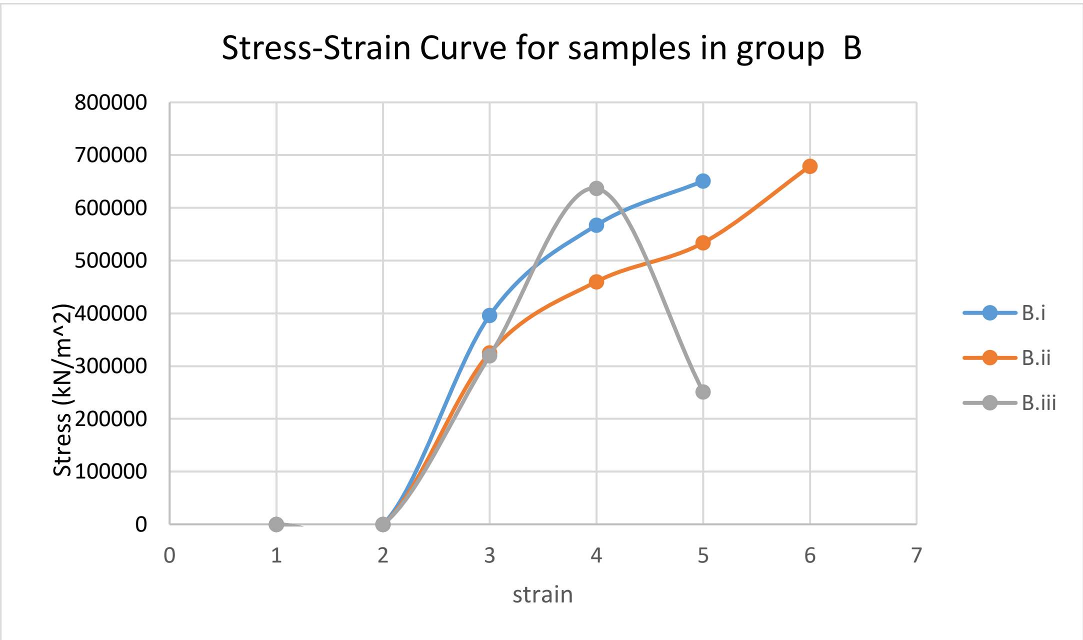


Figure 4.19: Comparative Analysis of sample in-group B under stress loading

Table 4.12: A summary of the behavior of the samples under tensile loading

	Yield strength (MPa)	**Ultimate Tensile strength (MPa)**	**Elongation (%)**	**Shielding gas Mixture**
Base material (control sample)	370.0	440.0	15.0	
Sample Categorization				
A.i	434.2	522.6	2.66	100%Ar.
A.ii	328.2	344.1	2.86	
A.iii	434.2	522.6	2.86	
B.i	369.3	567.2	2.05	80%Ar.- $20\%CO_2$ blend
B. ii	325.5	460.1	4.0	
B.iii	319.7	636.8	1.61	

The above gives a summary comparison between the two categories of the samples and shielding conditions. Sample B.ii was recorded to have the largest percentage elongation of 4.0. This means using 80% Ar. & 20% CO_2 does not compromise with the matrerials performance under tensile conditions.

4.6.3 Effects of Welding Parameters on Microstructure of HAZ and Fusion Zone

The microstructure examination included analysis of the weld-zone, heat-affected zone, fusion line, and areas near the HAZ samples. Figures 4.20, 4.21 & 4.22 depict the grain appearance for samples A.i, A.ii & A.iii, which were welded using pure argon as a shielding gas. It was observed that the microstructure in the welded zone resembled that of high carbon steel. In this sample category, the HAZ exhibited large grain structures with noticeable grain segregations in the fusion zones.

Figures 4.23, 4.24 & 4.25 depict the grain appearance of samples (B.i, B.ii & B.iii) welded using pure argon as a shielding gas. The microstructure in the welded zone resembles that of high medium steel, consisting of pearlitic and ferritic phases. This appearance is attributed to the addition of carbon dioxide gas in argon, which makes it more reactive with an increase in heat input. The microstructure is consistent with that of the base metal. Sample B.ii exhibited superior grain sorting with a uniformly structured microstructure in all zones.

The weld metal sample in figure 4.26 welded using a mixture of 80% Argon and 20% CO_2 displayed larger grains compared to the sample welded with 100% Argon, which had finer grains. This difference is visible in figures Ai, A.ii, A.iii and Bi, Bii, and Biii, respectively. The finer grains in figures Ai, A.ii, and A.iii are a result of the lower heat input facilitated by pure Argon during the welding process. It is clear that the addition of 20% CO_2 increased the heat input, leading to greater melting and subsequent growth in the grain size of the weld metal in figures Bi, Bii, and Biii.

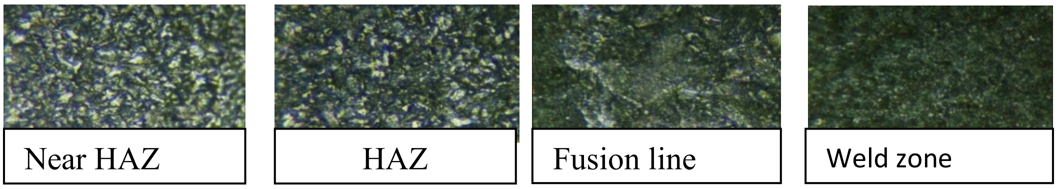


Figure 4.20: Microstructure of Sample A.i (magnification X200)

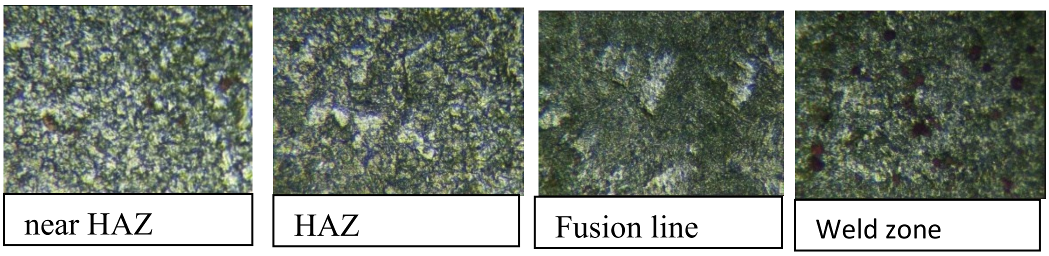


Figure 4.21: Microstructure of sample A.ii (magnification X200)

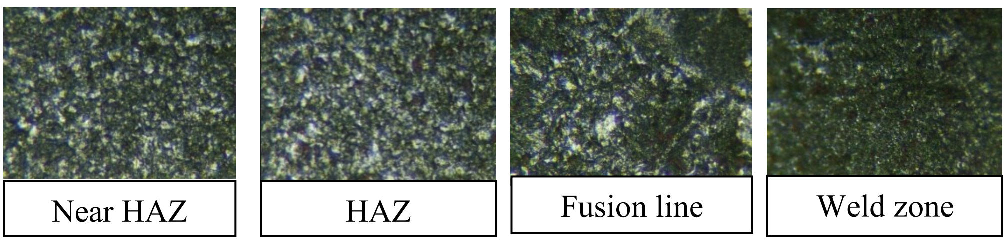


Figure 4.22: Microstructure of sample A.iii (magnification X200)

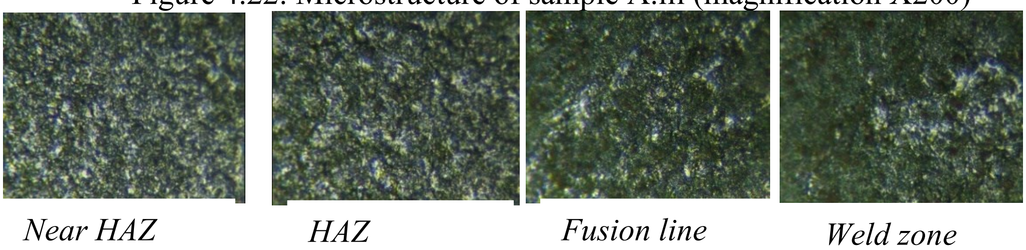
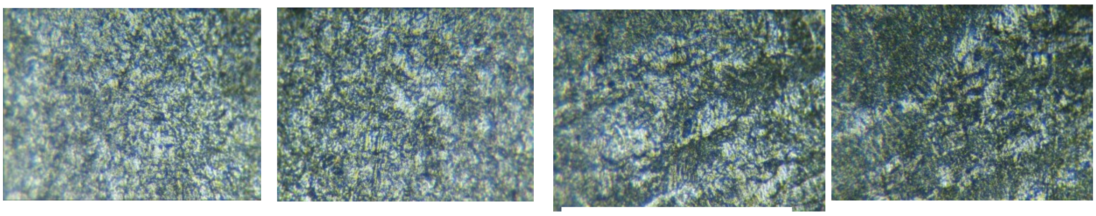
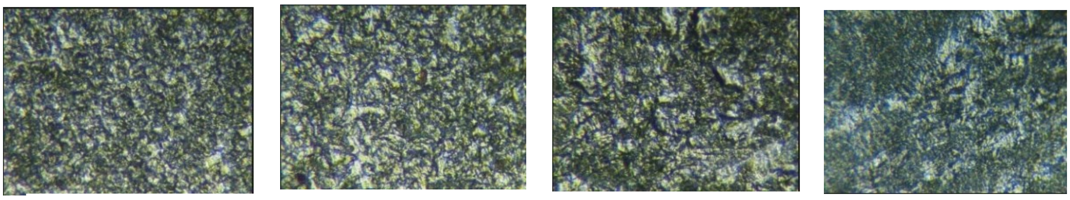


Figure 4.23: Microstructure of sample B.i (magnification X200)



near HAZ HAZ Fusion line Weld zone

Figure 4.24: Microstructure of sample B.ii (Magnification X200)



near HAZ HAZ Fusion line Weld zone

Figure 4.25: Microstructure of sample B.iii (magnification X200)

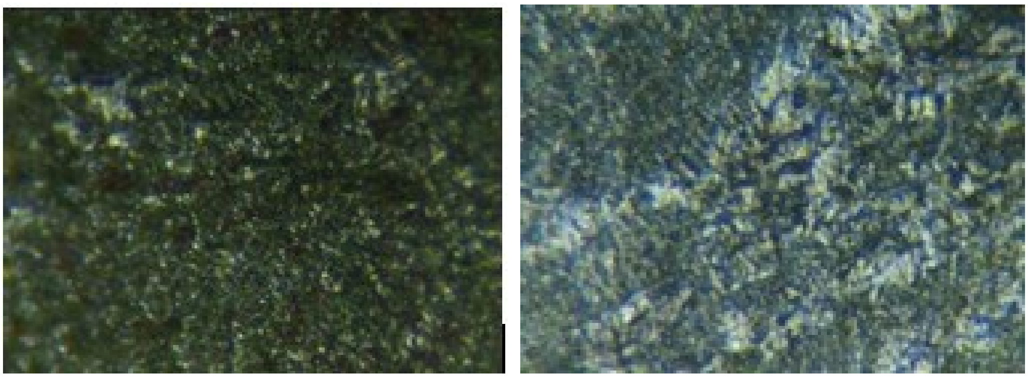


Figure 4.26: Comparative analysis of the microstructures of A.iii -100% Ar and B.ii i- 80% Ar

4.6.4 Effects of Welding Parameters on Hardness of HAZ and Fusion Zone

The hardness test results for samples welded with 100% Argon are detailed in table 4.13 below. The average HRC values are slightly elevated in the weld metal, which can be attributed to the hardening of the microstructure due to the heating and subsequent cooling processes. In addition, A.ii exhibited a weld metal that was softer than the base metal, potentially influenced by the formation of precipitates or a combination of travel speed and amperage resulting in lower heat input. The hardness test results for the samples welded with 80% Argon and 20% CO_2 have been meticulously documented in table 4.14. Upon thorough examination, it has been consistently noted that the weld metal exhibits a lower hardness in comparison to the base metal. This intriguing finding could potentially be attributed to the elevated presence of the ferritic phase as opposed to the pearlitic phases in the weld metal.

Table 4.13: hardness test analysis for test samples shielded with Ar. 100%

Sample	Average HRC Values	
	Base metal	Weld metal
A. i	51.35	53.5
A. ii	52.4	51.3
A.iii	52.925	53.4

Table 4.14: hardness test analysis for test samples shielded with Ar.80%-CO2 20% blend

Sample	Average HRC	
	Base metal	Weld metal
B. i	54.075	52.2
B. ii	52.225	50.4
B.iii	53.55	45.25

In experiments where the welding atmosphere consisted of 100% Argon, there was an increase in hardness observed. However, when the samples were welded using an 80% Argon and 20% CO_2 gas mixture, a decrease in hardness was noted. This outcome further supports our earlier finding that the incorporation of 20% CO_2 resulted in higher heat input, leading to increased melting and subsequent enlargement of grain size in the weld metal in Bi, Bii, and Biii.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

This study investigated the arc stability under various conditions of the gas metal arc welding (GMAW) process of a mild steelwork piece, focusing on the influence of welding parameters.

5.1 Conclusion

The research provided valuable insights into the impact of various welding parameters on the quality of GMAW for mild steel. Specifically, the study analyzed the effects of welding current, arc voltage, shielding gas, and metal transfer modes on the welding process. The findings indicated as follows:

(i) Stability is best at moderate voltage (25V) and current (150A) across most travel speeds but instability is more noticeable at higher currents (200A) and higher travel speeds (60 cm/min), particularly at lower voltage settings (20V).

(ii) 100% Argon results in smooth metal transfer with reduced spatter compared to the 80%-20% CO_2 mixture.

(iii) That certain welding parameters, particularly welding current, arc voltage, and welding speed, had a significant impact on the penetration depth during the welding process. It was observed that higher welding current and arc voltage led to increased penetration depth. Notably, the study emphasized that arc voltage emerged as the most influential factor affecting penetration depth in gas metal arc welding.

(iv) That the welding wire feed had a significant impact on the penetration depth during the welding process. Higher speeds led to greater penetration depth. The effect of welding current on penetration was consistent regardless of the welding speed used. Moreover, arc voltage was identified as a crucial factor influencing penetration.

(v) The influence of welding current on penetration depth was more pronounced when the arc voltage was kept constant.

(vi) Visually, A. ii and B.ii appeared with uniform beads and less discontinuities visible. B.ii (V:25, A: 150, speed:40) set up had the best optimization. Therefore, the 80% Argon + 20% CO_2 gas mixture is recommended for welding low-carbon steel materials as opposed to pure Argon.

(vii) That the material samples welded using 80% Argon and 20% CO_2 had a better ultimate strength and percentage elongation. Having observed, larger grains in the samples welded using the 80% Argon + 20% Co_2 gas mixture, it can be concluded that this gas blend produces a tougher weld joint compared to 100% Argon gas weld.

(viii) The addition of 20% CO_2 to 80% Argon gas formed a gas mixture that was not only beneficial in improving penetration but also reducing the heat affected zone on the parent metal as seen in the prepared cross-sections of the welded samples.

(ix) The study concluded that the best shielding gas option for welding low carbon steel is the 80%Ar + 20%CO_2 gas blend.

Therefore, the findings of this study have implications for welding practitioners in industry who are seeking to enhance weld quality and tailor GMAW welding process parameters to achieve desired welding outcomes. This study offers valuable contribution to future studies that are focusing on optimization of welding processes for improved welding process efficiency and weld quality.

5.2 Recommendations

The study's findings suggest several recommendations for future research in the field of gas metal arc welding (GMAW):

(i) Future studies should focus on refining the GMAW process parameters - including current, voltage, and speed - to achieve specific penetration depths tailored to different applications.

(ii) There is a need to investigate the influence of various shielding gas compositions on penetration and weld quality.

(iii) It is recommended to develop process optimization strategies informed by the study's insights, which may include defining guidelines for GMAW process parameter and gas composition selection, as well as implementing in-process monitoring for consistent weld quality.

(iv) Further research should explore the effects of weld joint design and post-weld treatments on arc stability within the GMAW welding process.

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APPENDICES

Appendix A: Introductory Letters

Appendix B: Plagiarism Test