

**ANALYSIS OF THE EFFECTS OF DIFFERENT TYPES OF WELDING
ELECTRODES ON THE INTEGRITY OF SMAW-WELDED RECYCLED
STEEL IN UGANDA**

BY

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DECLARATION

I, Banura Pascal, declare that this dissertation titled "Analysis of the effects of different types of welding electrodes on the integrity of SMAW-welded recycled steel in Uganda" represents my original work and intellectual contribution. I affirm that all ideas, methodologies, and findings presented herein are my own, unless otherwise cited. I have adhered to principles of academic integrity and ethical conduct throughout the preparation of this report, acknowledging any sources of information used. This report has not been submitted elsewhere for any academic or professional purpose. I accept full responsibility for the accuracy and validity of the content presented and grant permission for its evaluation by relevant academic authorities.

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APPROVAL

This dissertation, entitled “Analysis of the effects of different types of welding electrodes on the integrity of SMAW-welded recycled steel in Uganda”, prepared and submitted by Banura Pascal in partial fulfilment of the requirements for the Master of Science in Advanced Manufacturing Systems Engineering of Kyambogo University. It has been under our supervision and is ready for submission for an academic award.

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DEDICATION

I dedicate this dissertation to my beloved wife, Joy- your name embodies the joy you bring to each moment. Through every challenge, your quiet strength and unwavering faith have been my compass and my calm.

To my precious children – Adrian, Jovan, Ameria, Joan, and Felix – your boundless wonder and bright spirits continually remind me why the pursuit of knowledge matters. You are my greatest teachers and my deepest inspiration.

This work is my humble offering – not merely an academic achievement, but a testament to: The love that sustains us through absence, the sacrifices that build tomorrow's promise, and the invisible threads that weave together what we learn in books with how we live our lives.

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LIST OF ACRONYMS

AC	Alternating Current
AISI	American Iron and Steel Institute
ANOVA	Analysis of Variance
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
AWS	American Welding Society
BHN	Brinell hardness number
BM	Base Metal
BS	British Standard
CO ₂	Carbon Dioxide
Cr	Chromium
DC	Direct Current
DCEN	Direct Current Electrode Negative
DCEP	Direct Current Electrode Positive
FAT	Factory Acceptance Testing
FZ	Fusion Zone
GMA	Gas Metal Arc
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc welding
HAZ	Heat Affected Zone
HIC	Hydrogen Induced Cracking
IIW	International Institute of Welding
ISO	International Standards Organization
LOP	Lack of Penetration
MIG	Metal Inert Gas

MMA	Manual Metal Arc
Ni	Nickel
NPA	National Planning Authority
OES	Optical Emission Spectroscopy
PWHT	Post Weld Heat Treatment
SAW	Submerged Arc Welding
SMAW	Shielded Metal Arc Welding
TBW	Temper Bead Welding
TIG	Tungsten Inert Gas
UTM	Universal Testing Machine
UTS	Ultimate Tensile Strength
WPS	Welding Procedure Specification

ABSTRACT

The mechanical performance of welded joints in Shielded Metal Arc Welding (SMAW) of recycled steel are significantly influenced by the type of electrode used. Different welding electrodes produce varying mechanical and microstructural properties in the weld because each electrode introduces distinct thermal and metallurgical conditions during welding. This study examined the effects of different welding electrodes (E6013, E7018, and E7024) on the hardness, tensile strength (breaking load), and microstructural characteristics of SMAW-welded recycled steel with the aim of determining the optimal electrode for achieving a balance between strength, hardness, and ductility. Rockwell hardness tests, tensile strength tests, and microstructural examinations were performed on welds made on steel samples obtained from three steel manufacturers in Uganda. The findings revealed that the E6013 electrode produced welds that exhibited moderate hardness across all steel manufacturers while E7018 electrodes produced the highest breaking load (78.4kN) indicating superior tensile strength and ductility; whereas E7024 electrodes produced welds that exhibited the highest hardness value of 63.9 HRB but with lower breaking load (28.2kN) suggesting a more brittle nature. Furthermore, microstructural analysis confirmed that E7018 welds had fine-grained acicular ferrite and bainite which enhanced toughness while E7024 welds displayed coarse martensitic structures which increased hardness but reduced ductility. The results suggest that E7018 electrodes are ideal for load-bearing structural applications whereas E7024 electrodes are better suited for applications where hardness is prioritized over toughness. Although this study provides valuable insights into electrode selection, further study is needed to explore the effects of welding parameters, long-term durability, and alternative welding techniques to enhance the performance of SMAW-welded recycled steel.

Keywords: SMAW, Welding Electrodes, Hardness, Tensile Strength, Microstructure, Recycled Steel.

CHAPTER ONE: INTRODUCTION

1.1 Background

The construction industry is booming worldwide, leading to an ever-increasing demand for steel (Ary et al., 2023). Primary steel production is energy demanding which makes it expensive and produces substantial greenhouse gas emissions (Werner et al., 2023). Therefore, recycling of steel has become a prominent practice in Uganda's steel manufacturing industries producing construction steel that contributes to sustainability goals in infrastructure development, and resource conservation prioritized in Uganda's National Development Plan III (NPA, 2020). Steel is the most extensively used building material in the global construction industry. It has substantial advantages in terms of strength and rigidity, making it ideal for long spans or high ceilings (Alam et al., 2023). The use of recycled steel in fabrication and construction is gaining popularity. Reusing structural steel elements can significantly reduce carbon emissions from steel production and construction processes (Kanyilmaz et al., 2023). In fact, recycling steel is cheaper than mining primary ore to manufacture new steel (Sarkar, 2015). The benefits of recycling steel include minimizing steel waste, cost-effective use of steel, and sustainable use of metals (Diener & Tillman, 2015; Sahoo et al., 2019). However, there are still some challenges to overcome, such as inadequate material availability, insufficient design norms and standards, high initial costs, and the necessity to engage and coordinate the entire construction ecosystem (Kanyilmaz et al., 2023).

Welding is a crucial process in metal fabrication, especially in developing countries like Uganda where recycled steel is widely used due to its affordability and environmental benefits.

The utilization of recycled steel in construction and manufacturing necessitates reliable joining techniques, with shielded metal arc welding (SMAW) standing out due to its accessibility and adaptability (Kumar et al., 2020). Previous studies, including (Musa et al., 2023), established that the choice of welding electrodes significantly affects the quality of SMAW welds on

unrecycled steel. However, the impact of welding electrode selection on the structural integrity of welds made on recycled steel remains unaddressed and is a critical area requiring in-depth investigation. The variability in composition and impurities of recycled steel, coupled with the choice of welding electrodes, introduces a complicated interaction that directly influences the mechanical properties and long-term stability of welded joints. Numerous investigations have shown that welding electrode composition influences the mechanical characteristics and microstructure of SMAW-welded joints. For example, (Arifin, 2020) demonstrated that using specific low-carbon welding electrodes improved the tensile strength and ductility of dissimilar welds between high-strength low-alloy steel and mild steel. Similarly, (Yousaf & Marwat, 2021a) found that optimizing welding electrode alloying elements like chromium and molybdenum enhanced the hot cracking resistance of SMAW-welded stainless steel. These findings suggest that tailoring welding electrode properties to the specific characteristics of the base material can significantly improve weld quality.

The investigation of (Senfuka & Kirabira, 2012; Perera & Guluwita, 2018) on 10mm square recycled steel bars using the E6013 electrode, 198A, and 100V; reported that the steel exhibited acceptable strength, ductility, resilience, and some metallurgical properties despite a relatively high and irregular carbon content. Other limitations identified included reduced weldability, an uneven distribution of microscopic elements, and variations in mechanical properties along the length of the bars. Overall, the research suggested that while recycled steel in Uganda demonstrates some positive qualities, there are inconsistencies and limitations that must be addressed to warrant consistent quality and performance. (Senfuka & Kirabira, 2012; Perera & Guluwita, 2018) findings highlight the variability in the quality of recycled steel, which include impurities and altered chemical compositions compared to virgin steel. These variations can significantly impact the welding process (Senfuka & Kirabira, 2015), affecting the choice of welding electrodes, welding parameters, and ultimately, the mechanical properties of the welded joints. The effects of welding electrodes in SMAW welding of recycled steel thus

becomes a critical area of study, aiming to identify materials and techniques that can overcome the inherent challenges posed by recycled steel's variability.

The use of recycled steel in fabrication and construction is a promising approach to reducing carbon emissions (Irfanul & Siddiqui, 2023), but the microstructure alterations and the mechanical properties of welded joints need to be better understood to ensure the safety and reliability of structures (Helan Sar et al., 2020). The choice of welding electrode can significantly affect the mechanical properties of SMAW-welded recycled steel joints, but there is a lack of consensus on the optimal welding electrode for this application (Jha & Jha, 2014a). While studies have investigated the influence of welding electrodes on SMAW-welded joints (Azwinur et al., 2022; Pagare et al., 2020a), existing research primarily focuses on primary steel with limited knowledge specific to recycled steel applications (Gao et al., 2023; Gorgolewski, 2006). Furthermore, a lack of standardized procedures and regulations for welding recycled steel in Uganda adds to the complexity of ensuring joint integrity.

This study aims to offer useful insights into optimizing the selection of welding electrodes for SMAW-welding of recycled steel by investigating the effect of different types of welding electrodes on the integrity of SMAW-recycled steel welds. The results of this study are helpful in identifying the optimal welding electrodes for SMAW welding of recycled steel in Uganda and contribute to the development of sustainable construction and fabrication materials.

1.2 Problem Statement

Uganda's infrastructure development heavily depends on recycled steel for fabrication and construction (Senfuka & Kirabira, 2015). The unique characteristics of Ugandan recycled steel, arising from diverse sources and varying processing conditions, introduce distinct challenges such as significant variations in alloy composition and the presence of potential contaminants, which affect the weld quality (Saini & Singh, 2022). While recycling of steel is a standard universal practice and welding is a common industrial process globally, there are specific issues

related to welding of recycled steel. Despite the reliance on Shielded Metal Arc Welding (SMAW) for welding recycled steel in Uganda, there is limited understanding of how different welding electrodes affect the integrity of the welded joints. According to research, the optimal use of welding electrodes for recycled steel applications is not well understood. Furthermore, the absence of standardized procedures and regulations for welding recycled steel in Uganda worsens the problem, making it difficult to ensure the integrity of welded joints. Identifying the best combination of welding electrodes and welding settings is critical for enhancing the structural performance and reliability of SMAW-welded recycled steel joints. It is important to analyze the effects of different types of welding electrodes on the integrity of SMAW-welded recycled steel in Uganda in order to improve the quality and safety of welded structures.

1.3 Research Objectives

1.3.1 Main Objective

The main objective of this study is to analyze the effects of different welding electrodes on the integrity of SMAW-welded recycled steel joints in Uganda.

1.3.2 Specific Objectives

The specific objectives of the study are:

- (i) To examine the mechanical properties of SMAW-welded recycled steel made with different welding electrodes.
- (ii) To investigate the microstructural characteristics of the weld metal in SMAW-welded recycled steel made with different welding electrodes.
- (iii) To determine optimal welding parameter combinations for SMAW welding of recycled steel.

1.4 Research Questions

The research questions guiding this study are:

- (1) How does the microstructure of the weld metal in SMAW-welded recycled steel vary with different welding electrodes?
- (2) How do varying SMAW welding parameters (e.g., current, voltage) affect the mechanical properties (e.g., tensile strength, impact toughness) of the welded recycled steel made with different welding electrodes?
- (3) Which SMAW parameter combinations offers the best balance of properties for welding Ugandan recycled steel?

1.5 Significance of the Study

In the context of Uganda's expanding construction landscape, where the utilization of recycled steel is increasingly prevalent, understanding the detailed relationship between welding electrodes and the integrity of SMAW-welded joints is essential. The consequences of this study have the potential to transform local construction practices by providing tailored insights into the optimal selection of welding electrodes for recycled steel welding, thereby enhancing structural reliability and longevity. Moreover, the study contributes to the broader global discourse on sustainable construction methodologies. By aligning with environmental sustainability goals, the research can guide the industry towards more eco-friendly practices, reducing the ecological impact of construction activities. The economic implications are noteworthy as well, as the study may pave the way for cost-effective welding solutions, influencing both local construction practices and contributing to the global pool of knowledge on sustainable infrastructure development. Ultimately, this research provides valuable insights for welders, engineers, and policymakers in Uganda, aiding in the selection of appropriate electrodes for welding Ugandan recycled steel. The findings will help improve the quality and durability of welded structures, contributing to safer and more sustainable construction practices.

1.6 Justification of the Study

As Uganda increasingly embraces recycled steel in construction, the specific influence of welding electrodes on the structural integrity of SMAW-welded joints remains poorly understood. This study is essential to filling this gap by providing a systematic analysis that can inform welders, engineers, and policymakers on the optimal selection of welding electrodes for recycled steel welding. The outcomes have direct implications for enhancing the resilience and durability of constructed infrastructure, aligning with global sustainability goals of Industry, Innovation and Infrastructure; Sustainable Cities and Communities; Responsible Consumption and Production; and Climate Action, by promoting the efficient use of recycled materials. Furthermore, the economic implications of potentially identifying cost-effective welding solutions underscore the study's significance, as it stands to positively impact construction practices not only in Uganda but also beyond, contributing valuable insights to the broader field of sustainable infrastructure development worldwide.

1.7 Scope of the Study

The study involved welding experiments, standardized mechanical testing, and microstructural analysis, followed by data analysis, interpretation, and dissemination of actionable findings. The mechanical properties and overall structural integrity of SMAW-welded recycled steel joints made using different welding electrodes were analyzed to ascertain the influence of the different welding electrodes on the weld quality. The three most commonly used welding electrodes, which are E6013, E7018, and E7024, were tested on representative recycled steel samples sourced from three steel manufacturers in Uganda: Steel and Tube Industries Ltd., Tembo Steels (U) Ltd., and Pramukh Steel Ltd.

1.8 Conceptual Framework

Figure 1.1 depicts the conceptual framework for investigating the effectiveness of welding electrodes on the integrity of SMAW welded recycled steel in Uganda. It is based on

understanding how different welding electrodes, current, voltage, and welding speed and chemical composition of recycled steel (independent variables) influence the mechanical properties and microstructural characteristics (dependent variables) of welded joints. This study looks at welding joint design, arc length, and pre-heat and post-heat weld heat treatment as intervening variables that could modify the relationship between welding electrodes and weld integrity. The research outputs are expected to include an assessment of the weld tensile strength, hardness, and microstructural features, providing insights into the optimal welding electrode type for recycled steel welding applications in the context of Uganda’s construction sector.

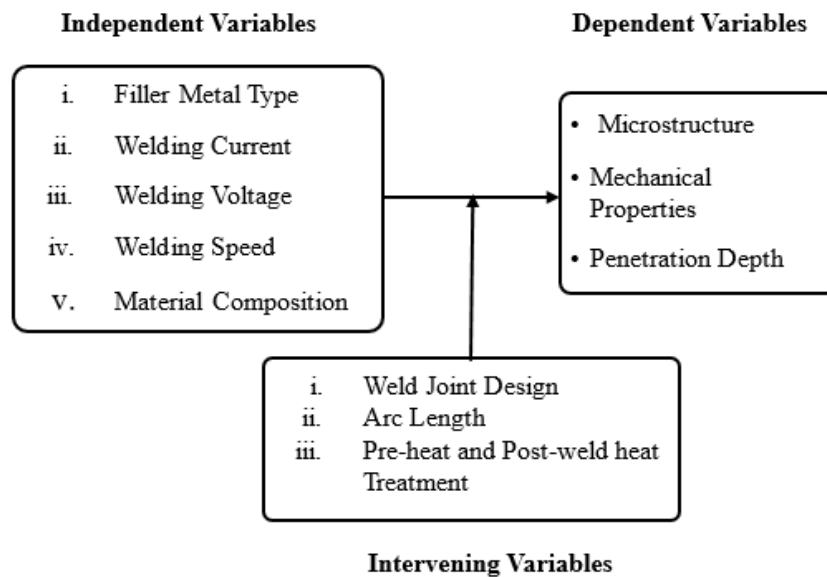


Figure 1.1: Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 The Shielded Metal Arc Welding (SMAW)

Among various welding methods used in mild steel welding, Shielded Metal Arc Welding (SMAW) is a manual arc welding technique that is widely preferred due to its simplicity, portability, and suitability for a variety of welding environments (Afriansyah & Arifin, 2020). SMAW employs consumable welding electrodes coated with flux to form the weld. During the welding process, the flux coating decomposes, generating shielding gas and slag that safeguards the weld pool from atmospheric gases and other contaminants. SMAW is the most versatile method for combining ferrous and nonferrous metals (Karunaratne & Pathirana, 2019); it is commonly utilized in the construction, fabrication, pipeline, and maintenance industries (Yousaf & Marwat, 2021b). SMAW relies on electrical power circuit to cause the intense heat required for melting metals. The power source may be either AC or DC, with DC offering better arc stability and penetration. In SMAW, the consumable electrode, a flux-coated long metal rod, and the direction of the welding process are pivotal to the process as presented in Figure 2.1. The flux coating plays a multi-functional role as it decomposes upon heating, producing a shielding gas that protects the weld pool from atmospheric contamination by gases such as oxygen and nitrogen.

Additionally, the flux forms a protective slag layer atop the molten metal, safeguarding it from oxidation during cooling and solidification, while also refining the weld. Some fluxes are infused with alloying elements, which, when transferred to the weld pool, tailor its properties to suit specific application needs (Haider et al., 2019a). During SMAW welding, the welder strikes an arc with an electrode tip and withdraws it, thereby causing the tip of the electrode and a portion of the base metal to melt, leading to the creation of a weld pool, with the molten metal from the electrode core depositing in the pool. As the weld progresses, the flux melts, establishing a layer of slag on top of the weld pool (Pratiwi & Wibowo, 2019a).

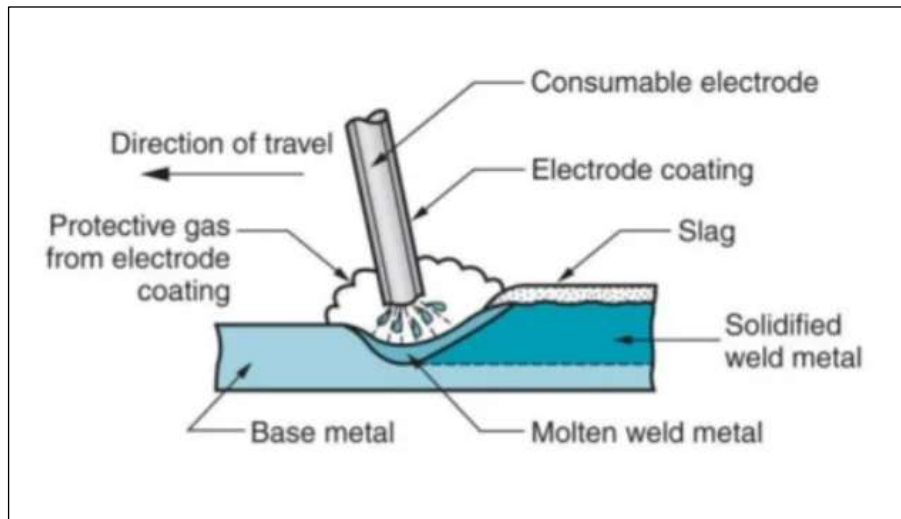


Figure 2.1: Schematic SMAW Process (Pagare et al., 2020a)

2.2 Classification of Welding Electrodes Used in SMAW

Welding electrodes in shielded metal arc welding (SMAW) serve as both filler material and a source of shielding components during the welding process. The electrodes used in SMAW are generally classified by the American Welding Society (AWS) based on core material and flux coating, which affects arc stability, deposition rate, slag formation, and chemical shielding.

2.2.1 Rutile-Coated Electrodes (E6013)

Rutile electrodes are characterized by a high titanium dioxide (TiO_2) content in the flux, which facilitates smooth arc initiation and aesthetic weld beads. These electrodes are widely used in general fabrication due to their easy workability in all positions and low cost (Adeyemi, et al., 2020). However, the high oxygen potential of rutile coatings often results in oxidized weld metals, increasing the risk of inclusions and reduced ductility. While rutile electrodes may offer ease of use and lower costs, they are less suitable for applications demanding high structural integrity.

2.2.2 Basic or Low-Hydrogen Electrodes (E7018)

The low hydrogen electrodes contain calcium carbonate and fluoride-based fluxes, designed to minimize hydrogen pickup in the weld pool. These types of electrodes are well known for their superior mechanical properties, low porosity, and enhanced toughness, they are especially

suitable for welding high-strength and recycled steels, which may contain residual impurities (Olakanmi, et al., 2019). Low-hydrogen electrodes, though more expensive and requiring better storage conditions, provide superior weld quality, especially when used in conjunction with appropriate thermal treatments.

2.2.3 Cellulosic Electrodes (E6010)

Cellulosic electrodes use organic compounds for fluxing, promoting deep penetration and high arc force. Although effective in fieldwork and pipe welding, their high hydrogen content makes them less ideal for recycled steel applications, where susceptibility to hydrogen-induced cracking is elevated (Cetinarslan, et al., 2018).

2.2.4 Flux-Cored Electrodes

The flux-cored electrodes consist of a metal sheath filled with fluxing compounds and alloying elements. While they offer high deposition rates and productivity, their performance in recycled steel applications depends on process parameters and steel composition (Gungor & Gulenc, 2018).

2.3 Types of Weld Joint Geometries

A weld joint is the point or edge where two or more pieces of metal are joined together according to a particular geometry (Srivastava et al., 2016). Weld joints are categorized as butt, lap, edge, tee, and corner joints based on the shape and thickness of the weld component, and the direction of the applied force. Each joint's geometry contributes to the overall strength and quality of the resultant weld (Srivastava et al., 2016). Joint shape geometry significantly influences the microstructure, fracture toughness, and corrosion behaviour in steel welding (Sabzi et al., 2019). Consequently, proper selection of joint geometry ensures optimal penetration, reduced defects, and improved durability, especially when working with recycled steel, which may have inconsistent properties; and proper joint preparation and configuration are crucial for achieving optimal weld strength and minimizing defects.

2.3.1 Butt Joint Welding

Butt welds are formed when two metal parts lying in the same plane are joined along their edges as illustrated in Figure 2.2. These welds require minimal joint preparations and are used for welding thin sheet metals that require single pass, more efficiently with automated welding machines. However, butt joint welds can be weakened by entrapment of slag, excessive porosity, or cracking. Butt-welded joints also have broad uses in industry and offshore construction. Butt welds tend to be areas of vulnerability in a structure due to stress concentration effects, as stresses associated with welds are unpredictable due to the inherent existence of flaws, and also because it is hard to anticipate their material properties, hence being essential linkages in a fabricated structure. Most fatigue failures that arise in butt-welded joints include fatigue cracking due to numerous imperfections that are actually inherent parts of the joint. One such imperfection is a lack of penetration (LOP), which is considered a crack from a fracture mechanics perspective. LOP occurs as a gap remains between two joined plates of butt-welded joints due to inadequate depth of fusion of the weld metal, i.e, the weld metal fails to reach the root of the joint, which is unavoidable due to edge preparation and machining time costs. LOP cracks may initiate once the joint is exposed to loading (Dakkili et al., 2019). The joint design (groove angles) of butt welds using aluminum alloy 5052, GMAW, and consumable wires ER5356 significantly impacts the joint's fracture toughness. The butt welds made with groove angles 60° obtained higher fracture toughness than a butt weld made with groove angles 30° and 90° . A wider groove angle can accommodate a greater amount of deposited filler metal; however, it requires lower fracture toughness. And most of the weld metal of butt welds exhibits ductile fracture, while the Heat Affected Zone (HAZ) exhibits mixed mode fracture (Andud et al., 2018).

Butt-welded joints, while commonly used due to minimal preparation and efficiency, pose structural vulnerabilities-particularly in recycled steel due to inherent imperfections like lack of penetration and unpredictable stress behavior. These issues are compounded by the variable

quality of recycled materials, making joint integrity and fracture resistance critical areas for further study and optimization.

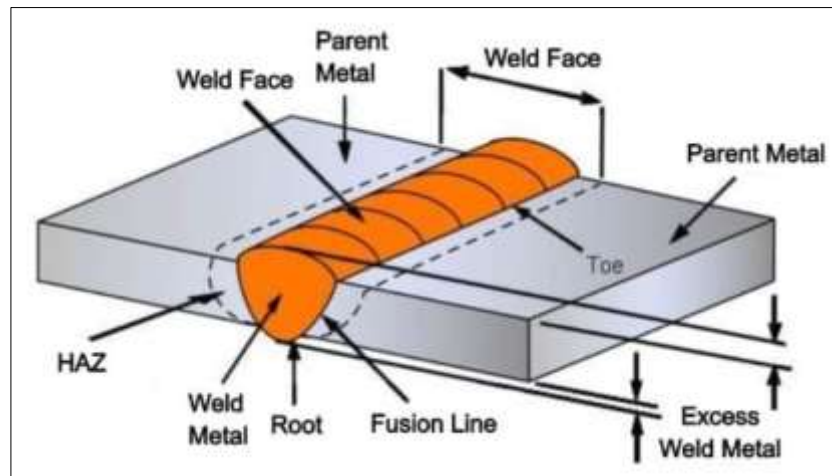


Figure 2.2: Butt Joint (Groover, 2010)

2.3.2 Lap Joint Welding

A lap joint is an improved butt joint, and it is better aligned for materials of varied thickness. It is formed by overlapping the metals, thus establishing an angle of $0-5^\circ$ as shown in Figure 2.3. Moreover, lap joints are prevalent in the repair and sheet metal industries; particularly when thin metals are utilized. In addition, welding joints with this method add greater support to the weld, provided that it is done correctly with no gap between the overlying metals. Nevertheless, corrosion and lamellar tearing are the major reasons of failure for lap joints. Furthermore, the study of the consequences of welding parameters on the weld formation, microstructure, and mechanical properties of a 304L austenitic stainless-steel lap joint while employing pulsed gas tungsten arc welding techniques indicated that the structure of a welded joint varies depending on the amount of heat input, and that the micro hardness of the HAZ is smaller than the FZ and BM. Consequently, as the welding heat input rises, the average hardness of the welded joint declines. However, the tensile strength at first rises and then declines as the heat input increases (Jiang et al., 2024).

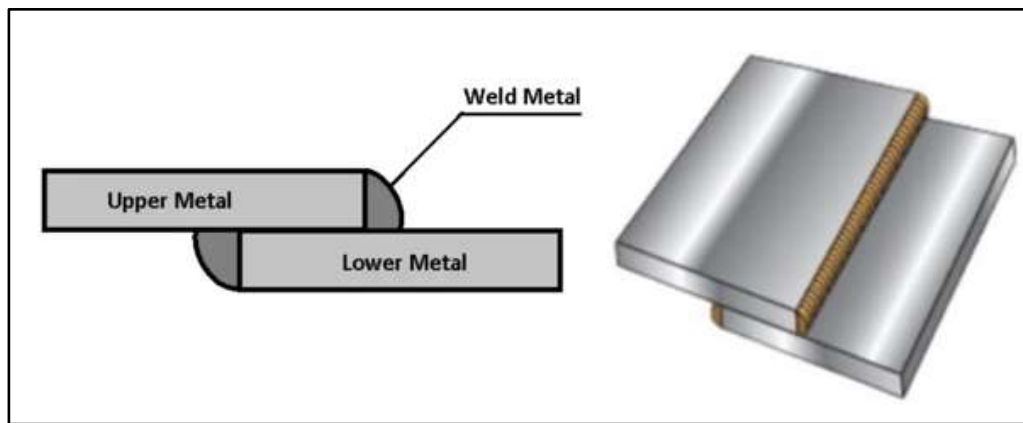


Figure 2. 3: Lap Joint (Yousef, 2023)

Shielded Metal Arc Welding (SMAW) was conducted on A36 low-carbon steel using both butt and lap joint configurations for comparison, and the welding process caused microstructural alterations, leading to minor differences in the mechanical properties. The grain sizes in the A36 low-carbon steel changed progressively with increasing distance from the fusion zone to the base material, demonstrating a recognizable pattern, for the differences in grain sizes between zones were determined by the process temperature and cooling rate. The fusion zones of the welded joints were harder than the heat-affected zones, which in turn were harder than the parent material, and this was due to the microstructure and the statistically significant changes in grain sizes. Specifically, the lap joint weldment exhibited the highest retained average shear strain and hardness at both the heat-affected and the fusion zones.

In contrast, the butt joint weldment demonstrated the greatest ultimate tensile strength, though with lower toughness, making it more suitable for structural applications requiring high strength and hardness, as this was accredited to the grain refinement as a function of the structural integrity of the butt weld joint configuration (Addai et al., 2024). However, when tensile testing was carried out on 4 sets of lap and butt joints of aluminum alloy using the friction stir spot welding technique; all the specimens exhibited lower yield and tensile strength values than the base plate, and the extension ratio and plasticity were correspondingly lower than base plate, so forming capability of welded specimen decreased. Nevertheless, the lap

weld had higher yield and tensile strength values than the butt weld. In addition, tensile strength and yield strength at 1340 rpm were higher than at 870 rpm in both the lap and butt weld (Murari Pandey et al., 2013).

Therefore, much as lap joints offer improved reinforcement and hardness in certain zones, they are prone to corrosion and lamellar tearing. However, in recycled steel applications, their performance depends heavily on heat input and joint configuration, and while lap joints generally show higher shear strain and hardness, butt joints may offer superior tensile strength, underscoring the need to balance joint type with mechanical performance requirements.

2.3.3 Tee-Joint Welding

Tee joints are achieved by welding two perpendicular pieces of metal, forming a T-shape intersecting at approximately 90° as illustrated in Figure 2.4. It is commonly utilized in structural steel, equipment manufacture, and tubing as it entails minimal to no preparation while providing maximum mechanical strength. Tee joints are welded on one side where the load is applied or on both ends to attain maximum strength, but the tee joint design is prone to lamellar tearing due to the restriction between the two workpieces. The outcome of deposited metal composition on the mechanical properties of single-pass fillet welds in T-joints made of high-strength alloyed steel as well as the resistance of these joints to delayed fracture, was investigated in relation to hydrogen concentration, welding heat input, and shielding atmosphere composition. It was reported that the resistance of tee joints on high-strength steel is impacted by the composition of the deposited metal, the concentration of diffusible hydrogen, and the preheating temperature (Poznyakov & Paton, 2008). The influence of residual stresses on fatigue behavior of welded T-joints was analyzed using finite element methods and a combined stress-energy criterion requiring two key material properties: the fatigue threshold value and fatigue limit. The study found that residual stresses significantly affected fatigue strength when the stress ratio $R < 0.5$, but had minimal impact for $R \geq 0.5$. The

residual stresses changed the crack deflection direction, resulting in a loss in ductility, and the anticipated fatigue strength coincided with the International Institute of Welding's factory acceptance testing (FAT) value (Wang et al., 2016).

In recycled steel, Tee joints can as well deliver robust mechanical strength with minimal preparation; however, due to the variability inherent in recycled materials, strict control over welding parameters - such as deposited metal composition, hydrogen content, preheating, and residual stresses - is essential to mitigate risks like lamellar tearing and fatigue degradation. This underscores the need for rigorous process control and post-weld inspections when applying tee joint welding techniques to recycled steel, ensuring consistent and reliable joint performance even in challenging material conditions.

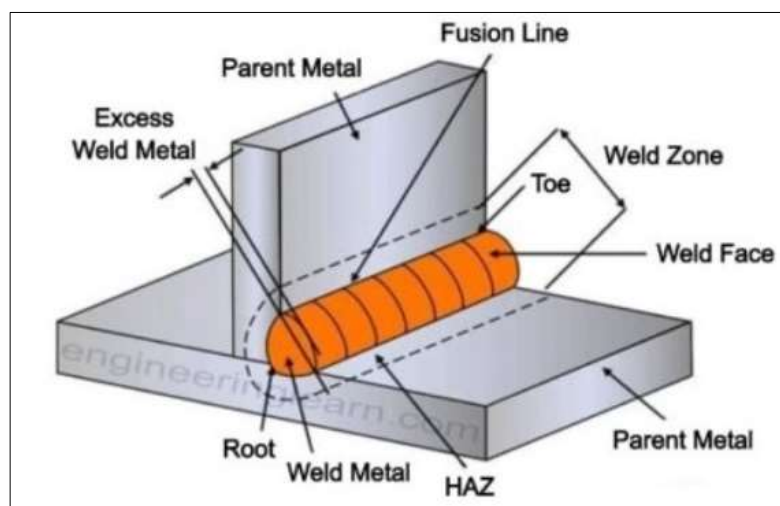


Figure 2.4: Tee-Joint (Groover, 2010)

2.3.4 Corner Joint Welding

Corner joints in Figure 2.5 are comparable to Tee joints in that two metal bars make a 90° fit with each other at the corner, forming an L-shape. It is popular for sheet metal welding and in the construction of frames and tables. Corner joints welding has two approaches; either open or closed corner. In an open corner joint, the two metal pieces form a V-shape where their edges meet at a point. In contrast, a closed corner joint is created when the edge of one metal piece

contacts the flat surface (face) of the other. Much as a closed corner joint is more difficult than an open corner joint, it often delivers greater overall mechanical strength. When fatigue assessments of corner welded joints in low cycle fatigue zones were executed using the effective notch strain technique, it was discovered that in all specimens, low cycle fatigue cracks originated at the weld root tip. These cracks appeared in early cycles, and their propagation accounted for the majority of the specimen's overall fatigue life. The low cycle fatigue strength of corner welded joints is highly influenced by the magnitude of the weld root face (Hanji et al., 2014).

The experimental study on how weld joint configuration affects stressed components, residual stresses and mechanical properties revealed that using corner welded joints in components subjected to tensile loading significantly reduces the joint's shear strength and yield capacity (Çevik et al., 2014). To enhance weld microstructure, a zipper-shaped joint design was introduced to reduce the cooling rate during welding. Finite element simulations comparing traditional straight-line and zipper-shaped joints in TiAl alloy showed that the zipper-shaped configuration significantly lowers the cooling rate, provides preheating and post-heating effects, and extends the high-temperature dwelling time (above 750°C) which facilitates the $\alpha \rightarrow \gamma$ phase transformation. Although this design introduces stress concentration at the corners, it notably reduces the occurrence of welding cracks. Tensile tests further demonstrated that the zipper-shaped joint achieved a strength of 417MPa-40.4% higher than the 297MPa strength of the straight-line joint (Zhang et al., 2022).

While effective as L-shaped connections, corner joints in recycled steel are prone to fatigue cracking, largely due to inconsistent material properties and sensitive welding processes. Mitigating these issues requires meticulous weld root design, controlled cooling, and novel geometries like zipper-shaped joints to boost strength and minimize residual stresses, thereby improving overall performance and reliability.

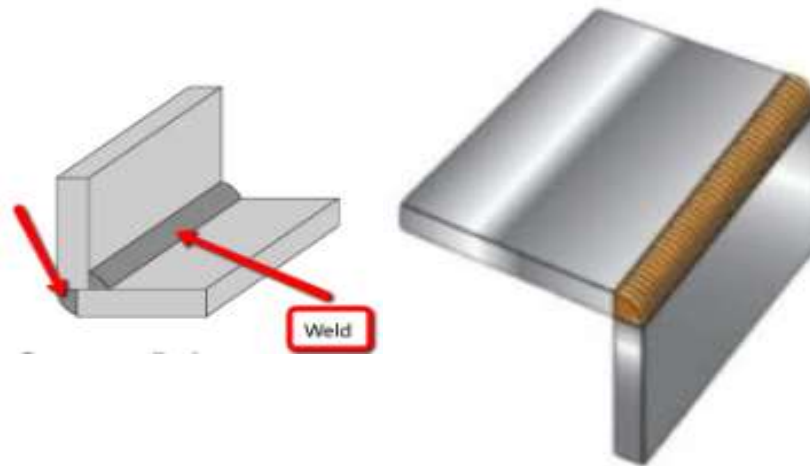


Figure 2. 5: Corner Joint (Groover, 2010)

2.3.5 Edge Joint Welding

Edge joints are comparable to corner joints, in that two metals intersect at a shared mating edge with both metal pieces placed adjacent to one another. The type of edge joint depends on the preparation of the metal edges by cutting, grinding, or machining into numerous groove types that lead to different amounts of penetration, and subject to the project prerequisites, edge joints can be welded solely along their edges or entirely around the joint. Figure 2.6 illustrates the edge type of welded joints. In recycled steel, where material inconsistencies may affect weldability, precise groove design and edge conditioning are essential to ensure joint integrity and performance.

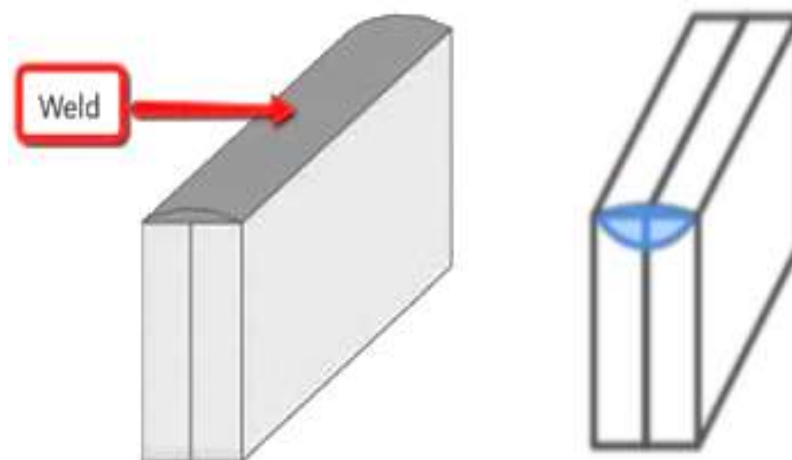


Figure 2. 6: Edge Joint (Groover, 2010)

2.4 Welding Positions

Welding position is the specific posture or arrangement of a welder and the workpiece being welded throughout the welding process. It determines how the weld joint is approached and can impact the ease, quality, and strength of the weld (Cheng et al., 2021). It also ensures that the weld penetrates the joint adequately and that the weld metal is evenly dispersed. Common welding positions include flat, horizontal, vertical, and overhead, each requiring different techniques and control based on gravity, access, and joint configuration (Cheng et al., 2021). Incorrect welding position can result in weak, incomplete, or irregular welds, compromising the strength and durability of the finished product (Cheng et al., 2021).

2.4.1 Flat Welding Position

Figure 2.7 depicts the flat position, also known as the “down hand” position, in which the metals to be joined are set flat and the welder passes the electric arc across them, moving along the workpiece in a horizontal direction. The top side of the joint is welded together, enabling the molten material to flow downward into its edges or groove; gravity helps to hold the weld pool in place, making it easier to regulate the weld - an advantage particularly beneficial when working with recycled steel (Chen et al., 2013; Cheng et al., 2021). When combined with suitable SMAW electrodes like E6013 or E7018, this setup promotes strong, consistent joints, reinforcing the viability of recycled steel in structural and fabrication applications. It is broadly applied in fillet welds and lap joint configurations (Chen et al., 2013; Cheng et al., 2021).

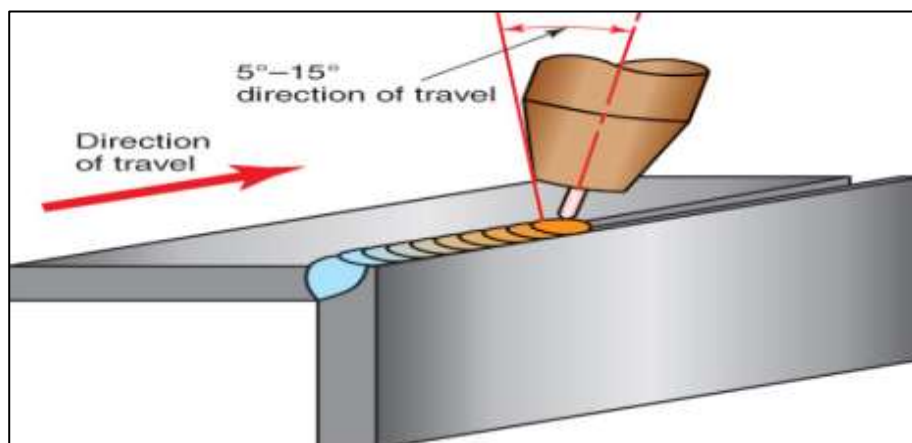


Figure 2.7: Flat Welding Position (Chen et al., 2013)

2.4.2 Horizontal Welding Position

The horizontal welding position Figure 2.8, is a welding orientation in which the weld axis is positioned in horizontal plane, while the weld face remains at an angle. In this position, gravity affects the molten weld metal, prompting it to settle to the lower side of the weld. There are two main types of horizontal welding, namely fillet weld in horizontal position (2F) and groove weld in horizontal position (2G).

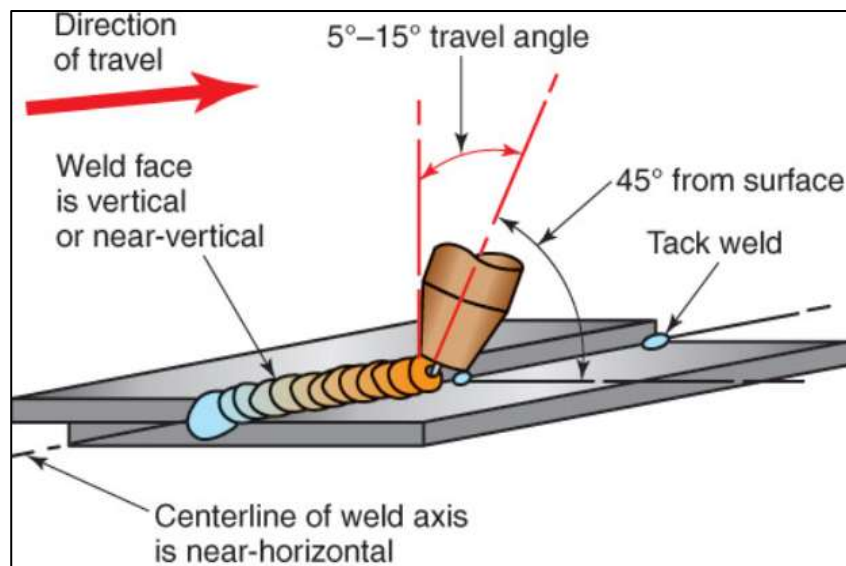


Figure 2. 8: Horizontal Welding Position (Chen et al., 2013)

2.4.3 Fillet Weld in Horizontal Position (2F)

The joint is placed on a horizontal plane, but the weld face is angled upward, typically in a T-joint or lap joint configuration as illustrated in Figure 2.9. Although fillet weld is the most prevalent weld type utilized in the fabrication of structural elements in industries, these bonds habitually suffer from numerous welding distortion trends, such as longitudinal shrinkage, transverse shrinkage, angular distortion, and longitudinal bending, which negatively affect fabrication precision, outward appearance, and different strength characteristics of the welded assemblies. Welding deformation in fillet-welded joints is influenced by flange thickness, while temperature gradient across thickness is a major element that greatly influences the formation of angular distortion (Ding et al., 2024).

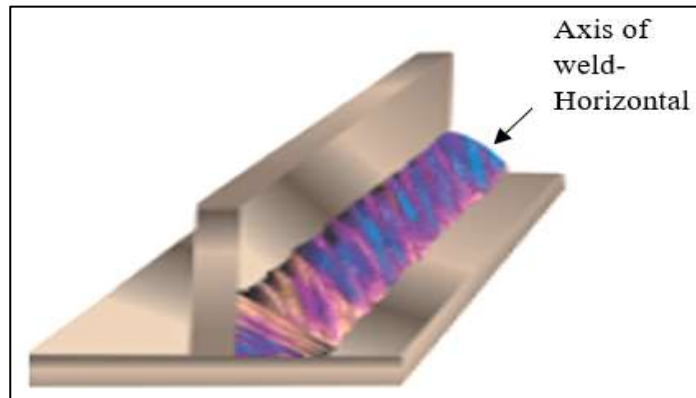


Figure 2. 9: Horizontal Position-2F (Chaitanya, 2024)

2.4.4 Groove Weld in Horizontal Position (2G)

The axis of the weld joint is horizontal as shown in Figure 2.10, often in butt joints, requiring the welder to control the flow of molten metal to prevent sagging or undercut. Horizontal welding is slightly more challenging than flat welding as it requires careful control to prevent the weld puddle from sagging. Research on groove welding in horizontal position (2G) using SMAW and laser welding techniques reveals several key findings. Horizontal welding generally offers a wider processing window and better defect control compared to flat (1G) position welding (Shen et al., 2016); (Shen et al., 2021). In SMAW, horizontal (2G) welding of S45C and SKD11 steels resulted in lower hardness values (29 HRC) compared to vertical (3G) and downhand (1G) positions (Ramadhan et al., 2023). For laser welding of thick ultra-high strength steels, 2G position welding demonstrated improved weld appearance, reduced defects, and more uniform residual stress distribution compared to 1G position (Shen et al., 2021). However, in SMAW of AWS E7018 electrodes, horizontal welding showed lower yield strength (22.98kgf/mm²) compared to vertical (24.30kgf/mm²) and overhead (24.14kgf/mm²) positions, but higher ultimate strength (27.93kgf/mm²) than vertical (26.06kgf/mm²) and overhead (22.24kgf/mm²) positions (Safriwardy, 2019).

Horizontal welding poses challenges due to weld pool sag and welding distortions, but its controlled execution can improve defect management - a critical advantage when working with recycled steel. For SMAW applications, optimizing electrode selection (favouring low-

hydrogen, high-deposition electrodes such as AWS E7018 variants) becomes vital to counteract recycled steel's variability and ensure strong, uniform weld quality.

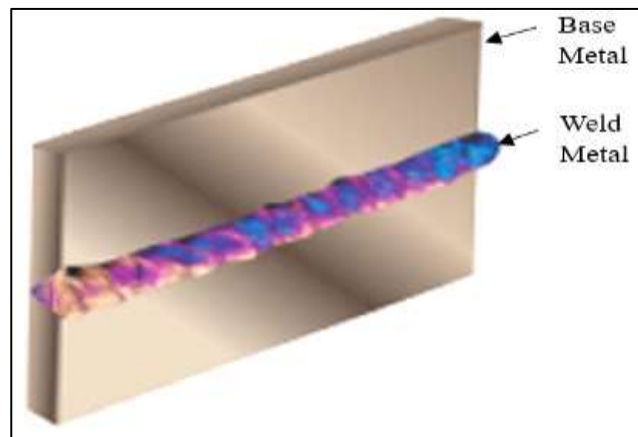


Figure 2. 10: Horizontal Position-2G (Chaitanya, 2024)

2.4.5 Vertical Welding Position

Vertical welding refers to welding where the joint axis is oriented vertically, typically at an angle between 45° to 90° relative to the ground, as illustrated in Figure 2.11. In this position, a fillet weld on a tee or lap joint is classified as a 3F position, while a groove weld on a butt joint is referred to as a 3G position. The vertical position can either be weld up or down, and in either case, it poses a challenge as gravity draws the molten metal off the puddle before it coagulates in the joint. As a result, without precise settings and puddle control, you may experience flaws like spatter, porosity, undercut, and lack of fusion. To achieve satisfactory vertical welds, creating a smaller puddle by using a thinner electrode, lower amperage, and shorter arc length and maintaining consistency from beginning to end is critical. Smaller molten pools are more manageable and coagulate at a faster rate. Research on vertical position SMAW welding has shown varied effects on weld quality. While some studies found no significant impact of welding position on tensile strength (Ahmadi et al., 2023); (Masoumi & Shahriari, 2010), others reported higher tensile strength in vertical positions compared to horizontal and overhead positions (Safriwardy, 2019). However, vertical welding may result in lower toughness compared to flat position welding (Masoumi & Shahriari, 2010). Microstructural

analysis revealed dominant acicular ferrite formation in vertical welds (Ahmadi et al., 2023). Welding current variations in vertical SMAW affect hardness, with higher currents producing harder welds (Muhammadiyah et al., 2021). Bending tests showed that vertical welding positions exhibited intermediate strength compared to horizontal and overhead positions (Safriwardy, 2019). Overall, while vertical SMAW welding can produce satisfactory results, its effectiveness may depend on specific application requirements and welding parameters.

Vertical welding, while inherently challenging due to gravity-driven weld pool instability and potential toughness issues, can yield reliable joints in recycled steel when precise SMAW parameters are met. Employing low-hydrogen, thin electrodes - such as appropriately formulated E7018 variants - ensures manageable puddle size, optimal fusion, and dependable mechanical properties despite the variability of recycled material.

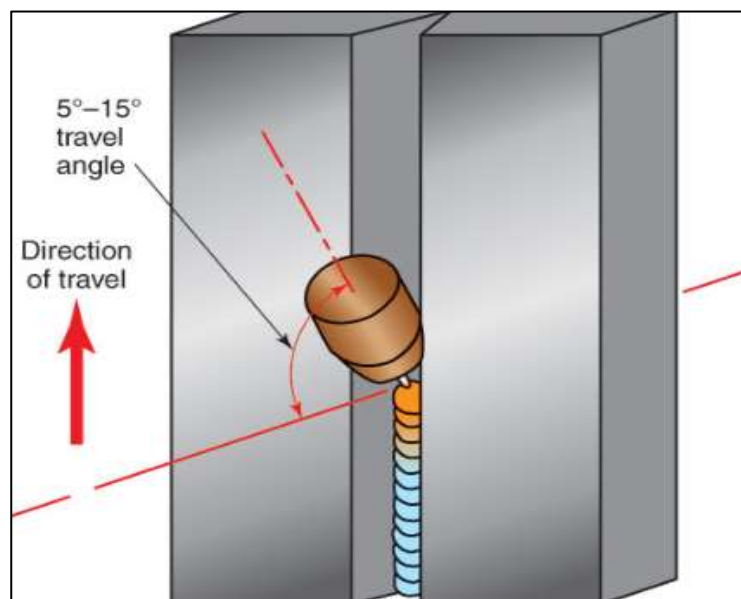


Figure 2.11: Vertical Welding Position (Chen et al., 2013)

2.4.6 Overhead Welding Position

Overhead welding illustrated in Figure 2.12 is carried out from beneath the joint, where gravity causes the molten metal to sag or drop, often resulting in a weld bead with a high crown. To address this challenge, it is important to maintain a small weld puddle and add sufficient filler metal to ensure proper fusion and slight reinforcement of the bead. Research on overhead

position SMAW welding has shown that welding position significantly affects weld quality and mechanical properties. Vertical welding generally produces higher tensile strength compared to overhead welding (Ahmadi et al., 2023); (Safriwardy, 2019); (Pribadi & Gunawan, 2021). Overhead welding poses challenges due to gravity, often resulting in irregular weld beads and defects like undercuts (Shoichi et al., 2012). However, innovative techniques such as electromagnetic controlled molten pool welding can improve overhead welding outcomes by using upward electromagnetic forces to control molten metal flow (Shoichi et al., 2012). Microstructural analysis reveals that vertical welding produces a more uniform and tightly packed acicular ferrite structure compared to other positions (Ahmadi et al., 2023). While overhead welding generally yields lower tensile and bending strengths compared to vertical and horizontal positions, it remains a viable option depending on field conditions and welder requirements (Safriwardy, 2019).

Despite the inherent challenges of overhead welding - particularly with molten metal control and potential bead irregularities – utilising SMAW with low-hydrogen electrodes like E7018 – designed for finer puddle control, can still yield functional joints on recycled steel regardless of the material’s variability

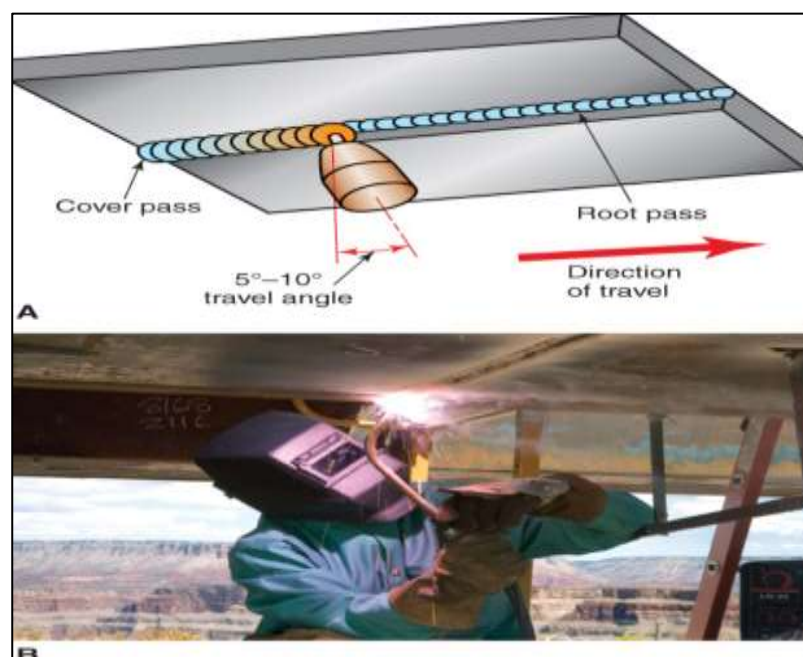


Figure 2.12: Overhead Welding Position (Bale, 2022; Rohit Chitnis, 2023)

2.5 Welding Passes and Weld Pass Sequence

The weld pass detail section of a Welding Procedure Specification (WPS) offers information regarding the way in which multiple layers of weld metal (passes) should be applied to achieve the final weld. In most cases, the weld metal is deposited in multiple layers, especially for thicker materials, to ensure proper fusion, minimize defects, and control heat input.

The number of weld passes relates to the quantity of welding passes necessary to complete the joint. For example, in a single-pass weld, only one pass is applied, while in multi-pass welds, several layers of weld metal are deposited. Multi-pass welding is common for thicker joints, while thin materials may require just a single pass. Multiple studies found out that increasing the number of passes affects the microstructure, with grain growth and wider heat-affected zones observed (Ambade et al., 2021; Sar et al., 2021). The hardness of the welded area generally increases with more passes, particularly in the heat-affected zone (Pratiwi & Wibowo, 2019b; Sar et al., 2021). However, tensile strength and ductility tend to decrease with additional passes (Ambade et al., 2021). The choice of electrode also influences weld properties, with E7016 showing higher hardness and tensile strength compared to E6013 (Abdullah et al., 2019). Corrosion resistance may be compromised with increased passes due to chromium carbide precipitation at grain boundaries (Ambade et al., 2021). These observations stress the significance of carefully considering the number of passes and electrode type in SMAW to attain the targeted mechanical and microstructural characteristics of welded joints.

The weld pass sequence describes the sequence in which the weld passes are applied. This may include the root pass, which is the first weld pass that fuses the base metals together, fill passes that build up the weld to the desired size, and the cap pass, which is the last layer that gives the weld its finished contour and look. Other key elements of weld pass detail include; weld layer thickness, bead shape, direction of welding, heat input control, and inter-pass temperature.

2.6 Weld Quality Characteristics

The primary characteristics that determine the quality of a weld include; penetration depth, heat affected zone, weld zone inclusions, microstructural changes, and weld strength. Optimization of welding parameters to achieve desired weld quality can be accomplished using statistical and numerical approaches, including design of experiments, evolutionary algorithms, and computational networks (Aiyemo et al., 2025). These methods help establish relationships between input parameters and output variables, enabling the prediction and control of weld quality characteristics.

2.6.1 Penetration Depth

Penetration depth, as illustrated in Figure 2.13 depicts the distance from the plate surface to the bottom of the weld pool, a significant metric for weld joint quality and is vital for evaluating weld metal strength. Proper penetration guarantees that the weld is robust and the base metals are completely fused. Inadequate penetration can result in weak joints, whereas excessive penetration might lead to burn-through or excess reinforcing. Research on penetration depth in SMAW welding consistently shows that polarity and electrode angle significantly affect penetration. Studies comparing DCEP (or DCRP) and DCEN (or DCSP) polarities found that DCEP/DCRP consistently produces deeper penetration across various currents when using E6013 and E7018 electrodes on ASTM A36 low carbon steel (Hidayat et al., 2021; Ramdani et al., 2023). Additionally, electrode angle influences penetration depth and weld width. A study comparing 70° and 85° electrode angles in reverse welding technique found that a 70° angle resulted in 1.14% greater penetration than an 85° angle (Hafni & Rifqi, 2022). These verdicts highlight the significance of choosing the right polarity and electrode angle to realize anticipated penetration depths in SMAW welding processes with recycled steel to ensure structural integrity and durability.

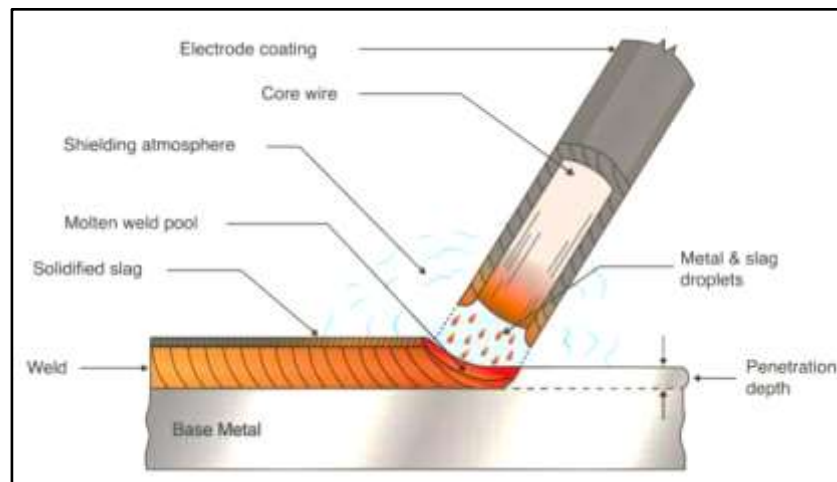


Figure 2.13: Illustration of penetration depth (Al-Sabur, 2017)

2.6.2 Heat Affected Zone

Heat affected zone shown in Figure 2.14 is the area of the base metal adjacent to the weld, which is affected by the heat of welding but does not melt. In recycled steel welding, especially with SMAW, HAZ alterations can reduce material strength and toughness, making its control vital for maintaining weld quality. HAZ softening can affect bead geometry, penetration depth, and microstructure (Anshul Yadav et al., 2018). Controlling parameters such as welding current, arc voltage, and welding speed can help improve metallurgical properties in the HAZ (Anil Parmar & Aakash Dubey, 2017), whereas, low heat input has been found to increase microhardness in the weld metal and HAZ (Purushottam & Sarathe, 2016). Understanding and controlling the HAZ is crucial for reducing the probability of fatigue failures resulting from thermal cycles in the weld zone (Anshul Yadav et al., 2018; A. Ghosh et al., 2011).

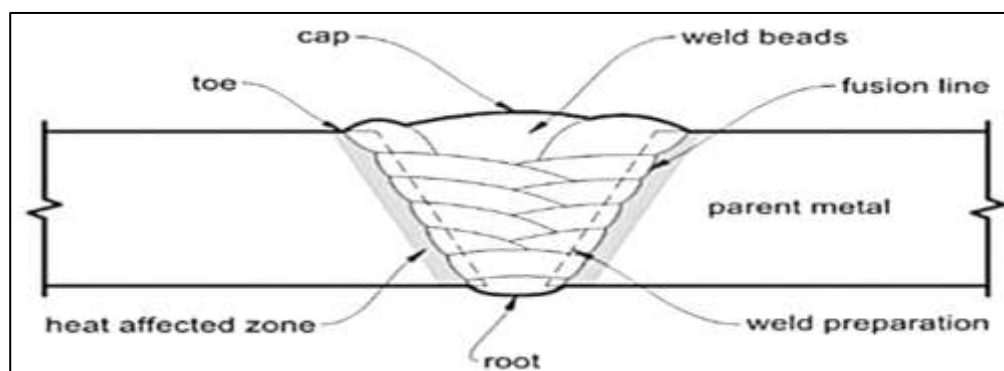


Figure 2. 14: Illustration of heat affected zone (Shane, 2024)

SMAW welding creates three main zones in the recycled steel metal as in Figure 2.15: the weld metal zone, the heat-affected zone (HAZ), and the unaffected base metal. The weld metal, formed from melted base and filler materials, shows the highest hardness due to elements like manganese. The HAZ, the most critical zone, undergoes structural changes from rapid heating and cooling, affecting mechanical properties. The base metal retains its original characteristics but has the lowest hardness. Variations in grain size and defects like slag inclusions, porosity, and overlap across these zones can impact overall weld quality.

Regarding toughness, the weld metal zone also boasts the highest value at 251 joules/mm², demonstrating superior resistance to crack propagation compared to other areas. This is followed by the base metal, with a toughness of 133 joules/mm². The HAZ, however, presents the lowest toughness at 119 joules/mm², highlighting the significant effect of welding on the mechanical properties of materials across these zones. This distribution of mechanical properties underscores the complexity of welding metallurgy and the substantial effect of recycled steel material composition and thermal cycles on the resulting welded structure (Husaini et al., 2019).

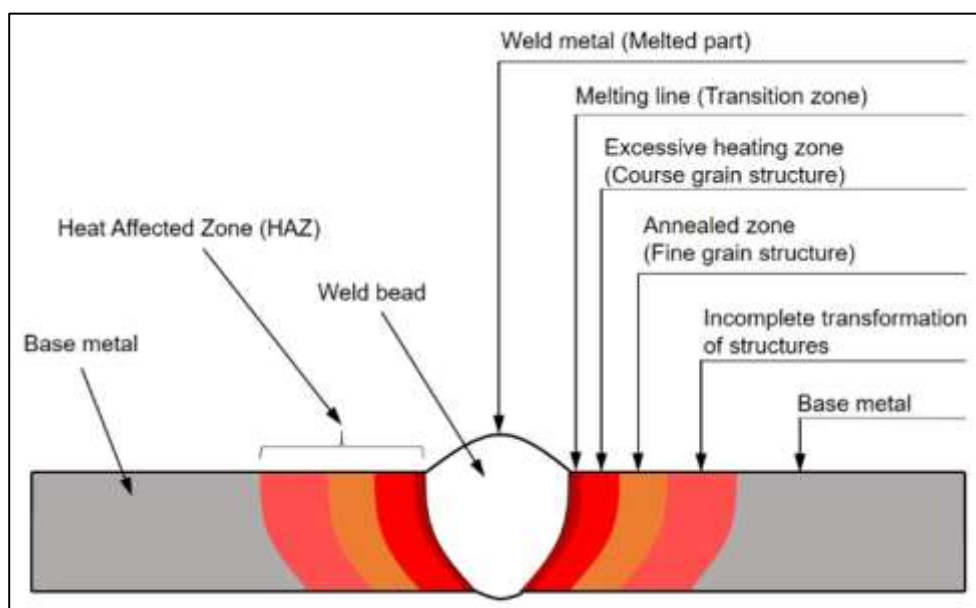


Figure 2.15: Schematic diagram of the welding zone (Husaini et al., 2019).

2.6.3 Weld Zone Inclusions

In SMAW welding of recycled steel, weld zone inclusions such as slag, gas porosity, tungsten inclusions, iron oxide, dirt, sand, or foreign materials form when oxidation-deoxidation patterns freeze in the weld pool, influenced mainly by electromagnetically induced motion (Milner, 2013). These inclusions are critical as they can disrupt the microstructure and degrade mechanical properties. Recycled steel impurities coupled with differing filler compositions and coating characteristics further encourage inclusion formation. For example, electrodes with higher manganese content (e.g., E7018) may form complex inclusions that can both promote acicular ferrite for toughness and, in excess, contribute to cracking or pitting. But also, in low carbon low alloy steel weld metal, multi-phase inclusions consisting of MnS, MnAl₂O₄, and amorphous phases, enclosed by Ti-concentrated areas, contribute to acicular ferrite formation (Takada et al., 2015). Therefore, process control and electrode selection are essential for maintaining weld integrity, minimizing defects, and ensuring improved mechanical and corrosion properties of welded materials.

2.6.4 Weld Strength

Weld strength refers to the ability of a welded joint to withstand various forms of mechanical stresses, such as tensile, compressive, shear, torsional, and bending forces, without failure. It is a critical property that determines whether the welded structure can carry its intended loads safely and efficiently over time. The shielded metal arc welding (SMAW) process is influenced by several factors that affect weld strength. Welding current, electrode diameter, and welding speed are key parameters (Mohd-Lair et al., 2021a; Pagare et al., 2020b; Pathak et al., 2019; Ranjan, 2014). Increasing current generally improves tensile strength, but excessive current can decrease it (Mohd-Lair et al., 2021a). Current was found to significantly influence tensile strength, with an optimal current of 120A identified for mild steel (Jha & Jha, 2014b). However, another study reported the highest tensile strength at 150A for AISI 1050 steel (Mauliza & Usman, 2022). Smaller electrode diameters tend to produce higher tensile strength, while larger

diameters increase deposition rate and heat-affected zone, potentially reducing weld strength (Mohd-Lair et al., 2021a; Pagare et al., 2020b).

Welding speed has an inverse relationship with weld deposit area (Baghel, P.K., 2022). The choice of filler material also impacts weld strength, with E7016 producing higher tensile strength compared to E6013 (Pagare et al., 2020b). Additionally, electrode angle affects tensile strength (Pathak et al., 2019). The interaction between current and rod diameter is significant in affecting ultimate tensile strength, with rod diameter being more influential than current (Mohd-Lair et al., 2021a). The Arc gap was also investigated as a factor influencing weld strength (Nayak & Nagendra, 2018). These studies highlight the importance of optimizing SMAW parameters such as current, electrode size and type given the variable quality of recycled steel, in order to enhance weld strength in SMAW processes.

2.6.5 Microstructural Characteristics of the Weld Metal

Microstructural evolution during welding significantly affects the mechanical properties and service performance of a welded joint. These characteristics are dictated by the electrode's chemical composition, heat input, and cooling rates (Rozmus-Górnikowska et al., 2014; Xavier et al., 2015). (Patel & Dey, 2022) provided detailed insights into phase transformations (formation of ferrite, pearlite, and bainite) based on electrode type and thermal cycling. Their findings showed that SMAW welds using low-carbon steel exhibit variable microstructures across the weld zone and heat-affected zone (HAZ), directly influenced by cooling rates and electrode coatings. (Alipooramirabadi et al., 2017) also investigated residual stresses and microstructure changes in HSLA steel welds using various welding techniques. They found that the welding process and filler metal composition control the distribution of heat and chemical elements, which in turn determine grain size and phase composition. While their study focused on MSAW and FCAW processes, the principle extends to SMAW, where the choice of electrode influences the cooling rate and resultant microstructure. Moreover, the

electrode flux composition affects solidification behavior, influencing whether the weld metal solidifies into ferrite, bainite, or martensite. These transformations are critical for recycled steel, which may contain varying alloying elements, making the control of microstructure even more vital.

Studies on different steel types also show that welding parameters like heat input, current, and electrode choice strongly affect microstructure of steel welds and joint strength, which is especially important for recycled steel with its variable composition. For instance, in duplex stainless steels, increased heat input leads to ferritic grain growth and a decrease in austenite in the high temperature heat affected region (Xavier et al., 2015). Similar transformations are found in Ti containing twinning induced plasticity steels as well as in high performance steels like S960 MC and XAR 400, where welding produces dendritic structures, equiaxed grain growth, and a mix of martensite, bainite, and acicular ferrite (Hernández-Belmontes et al., 2020; Medvecká et al., 2022; Bramowicz et al., 2016). These changes directly impact hardness, tensile strength, and overall joint performance, making the careful selection of welding conditions and SMAW electrodes essential to achieve strong and reliable welds in recycled steel.

According to (Mudiantoro et al., 2019), the microstructure generated during the welding process is associated with the thermal cycle and the base material's alloying element composition. (Pratiwi & Wibowo, 2019a) investigated the consequence of electrode and number of passes on the hardness and microstructure of shielded metal arc welding while using low-carbon steel, followed by a welding procedure based on differences in electrode selection and pass count. It was observed that the electrode types and the number of passes had a significant impact on the hardness and microstructure of the weld. The hardness test findings showed that utilizing the E6013 electrode resulted in a greater hardness rating than using the E7016 electrode. The microstructure test outcomes unveiled that the HAZ region for electrodes

E6013 and E7016 included both ferrite and perlite. However, the E6013 specimens welded with 3 passes and 6-pass layers exhibited the highest pearlite content, indicating greater hardness due to increased carbon presence. These results may be applied to recycled steel, where careful electrode and pass selection is necessary due to compositional changes. As with regulated low-carbon steels, recycled steel is susceptible to heat cycles due to its uneven carbon and alloy concentration, which impacts its microstructure and hardness.

2.7 Effect of Welding Parameters on Weld Quality Attributes

In automated SMAW, welding parameters such as speed, angle, and electrode diameter were optimized using the Taguchi method to evaluate bead width and penetration (Tayier et al., 2021). Increasing welding speed decreased bead width and penetration, while increasing welding angle had the opposite effect which highlights the importance of welding parameter optimization in enhancing the integrity of welded joints in SMAW. During the SMAW process, base metals undergo deformation due to high heat, which can impact joint strength, integrity, and overall weld quality. Factors such as heat input, electrode selection, and welding parameters influence the deformation and performance of SMAW joints (P. Vara Lakshmi et al., 2023). Finite element analysis can be used to estimate joint strength and residual stress formation in welded structures (Rajshekhar et al., 2022).

2.7.1 Effect of Filler Metal Type

The performance and durability of welded structures are heavily influenced by the type of welding consumables used, particularly the filler materials and the welding technique adopted. Key parameters such as filler material chemistry, deposition characteristics, joint geometry, and heat input play significant roles in governing microstructural evolution during welding, which in turn affects mechanical performance (Buchely et al., 2015). (Mukherjee & Pal, 2012) examined the impact of using dissimilar filler wires (ER308L and ER316L) at varying heat inputs (0.4, 0.5, and 0.6 kJ/mm) in gas metal arc welding (GMAW) of SS409M steel. Their

study found that the resulting differences in martensite formation and impact strength were directly tied to the filler wire selection and heat input.

In the context of shielded metal arc welding (SMAW), electrode type significantly influences the tensile properties of welded low-carbon steel (Pagare et al., 2020a). (Janasekaran Shamiand Tayier, 2021) observed that the use of E6013 and E7018 electrodes (both 3.25 mm diameter) yielded notable differences in tensile strength, yield strength, and elongation. Specifically, the E6013 electrode resulted in higher fracture toughness and ultimate tensile strength compared to the E7018 electrode. However, (Mattoo, 2015) reported that tensile strength peaked with the use of the E7018 electrode, while maximum hardness was attained using a ferritic stainless steel 430 electrode. Microstructural examination revealed the presence of ferrite and pearlite in dendritic form within the heat-affected zone (HAZ), and grain coarsening was evident through the merging of finer grains into larger ones. The influence of welding parameters such as current and electrode diameter has also been extensively studied. (Jha & Jha, 2014c), along with (Ogbunnaoffor C. K. et al., 2016), emphasized that while both parameters affect tensile strength in SMAW, electrode diameter had a more pronounced impact. These findings underscore the necessity of choosing an appropriate rod diameter to achieve desirable weld strength, rather than relying solely on current adjustments.

Further research has explored the relevance of these welding considerations in the context of recycled steel. According to (Senfuka & Kirabira, 2012), recycled steel in Uganda often presents challenges such as inconsistent mechanical properties and reduced weldability due to its heterogeneous composition. Nonetheless, filler material selection remains a key strategy for overcoming these limitations. (Aghayar et al., 2021) demonstrated that different types of filler materials significantly affect the mechanical properties of arc-welded joints. Similarly, (Kandavel et al., 2021) found that nickel-coated filler materials contributed to improved microstructural characteristics and enhanced mechanical performance in welded steel joints.

These collective findings highlight that, for recycled steel, often characterized by variable composition and unpredictable behavior, careful selection of filler materials and optimization of welding parameters are essential. Doing so can mitigate defects, enhance mechanical integrity, and promote consistent weld quality in SMAW applications.

2.7.2 Effect of Welding Current

Research indicates that welding current significantly influences mechanical properties and microstructure of welded joints. Variations in current affect bead geometry, including reinforcement height, penetration depth, and heat-affected zone width (J. Singh & Singh, 2022). In addition, welding current, along with voltage and speed, impacts the heat input rate, which in turn influences material structure and properties (Prakash et al., 2021b). For instance, higher currents (70A) have been shown to improve impact and hardness properties in low carbon steels (Fitri et al., 2021), while studies on C1035 medium carbon steel weldments using the SMAW technique demonstrate that increases in current can lead to decreases in UTS, yield strength, and ductility, possibly due to the formation of martensite.

Furthermore, welding current plays a crucial role in determining weld hardness in mild and low carbon steels, with hardness rising up to 115A and 116A, respectively, due to grain size distortion and the development of martensite or bainite during heating; however, hardness diminishes with further current increase. The ultimate tensile strength shows a decline with increased current, though it may rise again at 200A for mild steel and 115A for low carbon steel, while both yield strength and impact strength tend to decrease (Oluwasegun et al., 2016). Figure 2.16 depicts the effect of welding currents on heat produced during sheet metal welding, indicating that the presence of filler material produces higher heat. This observation underscores that welding current is the most important variable in determining the melting rate of the electrode, the fusion depth, the weld pool shape and velocity, and ultimately, the weld quality (Sabeeh, 2019). These findings are particularly critical for recycled steel, which

inherently exhibits variable composition and properties, necessitating careful optimization of welding current when using SMAW electrodes to achieve consistent mechanical performance and reliable weld quality.

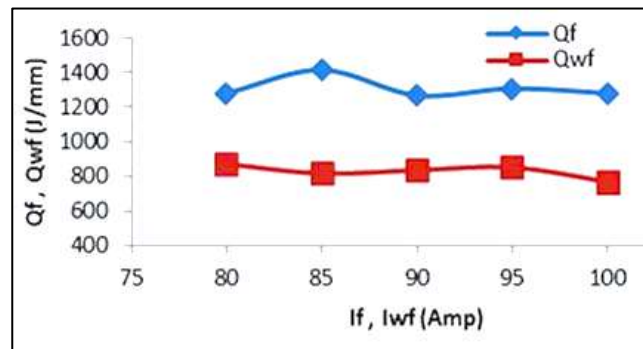


Figure 2.16: Effect of current with and without the electrode on the heat generated (Sabeeh, 2019)

2.7.3 Effect of Welding Voltage

Welding voltage significantly influences weld quality in various welding processes. In shielded metal arc welding (SMAW), voltage, along with current and speed, affects the heat input rate, which impacts the material's mechanical and microstructural properties (Prakash et al., 2021c). For aluminum-stainless steel dissimilar welding using metal inert gas (MIG) welding, higher voltages led to poorer weld joint appearance and defects like porosity and incomplete fusion (Jawad et al., 2024). In gas metal arc welding (GMAW) of steel, arc voltage is one of the key parameters affecting weld quality characteristics, including penetration, bead geometry, and heat-affected zone (Wordofa & Ramulu, 2023).

Similarly, in submerged arc welding (SAW), voltage is a crucial input parameter influencing weld bead geometry and mechanical properties (Patel et al., 2021). The influence of different welding parameters on the performance of welded low-carbon steel was investigated. Findings revealed that higher arc voltage and welding current led to increased hardness but reduced yield strength, tensile strength, and impact toughness. This was attributed to the elevated heat input, which promotes defect formation and compromises mechanical properties. Increased hardness

could possibly be linked to the alloy additions from the electrode's coating during welding (Talabi et al., 2014).

Across various welding processes, welding voltage has a significant influence on weld quality, and this is especially important when working with recycled steel. Because recycled materials can have different compositions and possible impurities, managing the voltage helps avoid common problems like porosity, weak fusion, and degradation of mechanical properties that are more noticeable in recycled steel.

2.7.4 Effect of Welding Speed

Welding speed is a critical parameter in precision applications, influencing penetration depth, weld bead width, and the mechanical performance of welded joints. Studies indicate that increasing welding speed generally enhances penetration but narrows the bead width (L. Singh et al., 2013). Additionally, welding speed, along with current and voltage, significantly affects heat input, which in turn alters the microstructure and mechanical properties of welded materials (Haider et al., 2019b; Singh et al., 2021) While faster welding speeds are often recommended to mitigate solidification cracking, their effectiveness is variable due to complex interactions with stress cells, grain structure, and mushy zone extent (Coniglio & Cross, 2020). The optimization of welding speed is especially relevant in working with recycled steel, where variations in material properties necessitate careful parameter adjustments.

When applied to recycled steel, the control of welding speed becomes even more important due to the variability in composition and mechanical consistency of the base material. A study conducted by (Burkul, 2016) investigated welding speeds of 0.3 cm/sec, 0.6 cm/sec, and 0.9 cm/sec for V-groove butt weld joints with a 60° included angle. Results showed that higher welding speeds improved impact strength, reaching a maximum at 0.9 cm/sec. However, the trade-off included increased residual stresses and distortion with larger groove angles, which also affected weld economy due to greater filler material usage.

Figures 2.17 and 2.18 illustrate the impact of welding speed on tensile and yield strengths. A study by (Kumar Yadav et al., 2020) found that increasing welding speed initially led to reductions in both tensile and yield strengths for single V-groove welds, up to a threshold of 117 mm/min. Beyond this point, both properties began to increase. Furthermore, the relationship between welding speed and impact strength varied by joint type. Impact strength increased with welding speed for single bevel and V-groove joints, while it decreased linearly for straight-edge welds. Hardness values showed a linear decrease with increasing speed in V-groove welds, whereas no consistent trend was found in other joint types, indicating potential defects in those welds. Additionally, increasing welding speed consistently reduced penetration depth across all joint types.

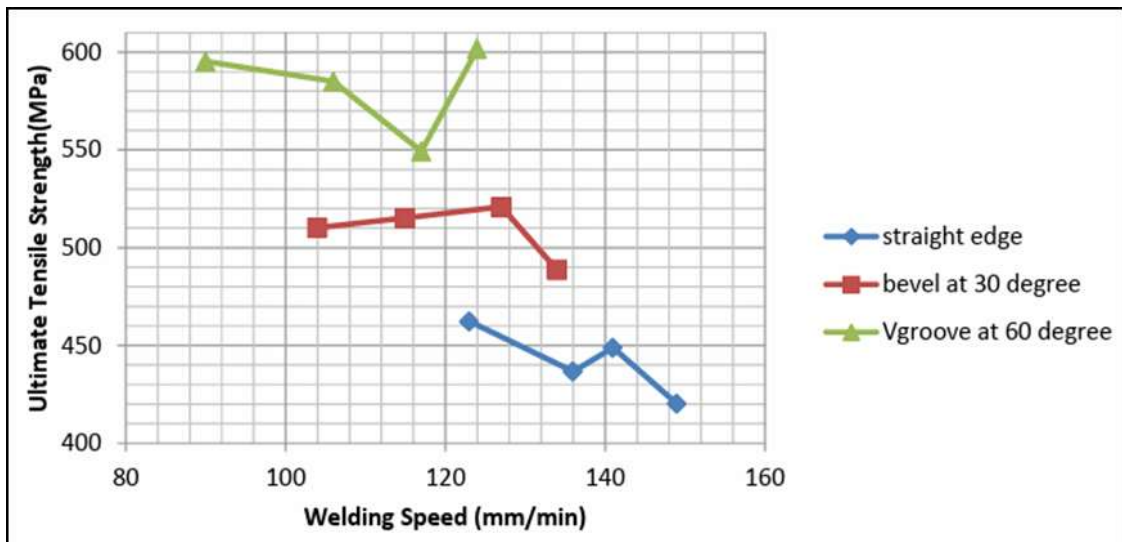


Figure 2.17: Effect of welding speed on tensile strength (Kumar Yadav et al., 2020)

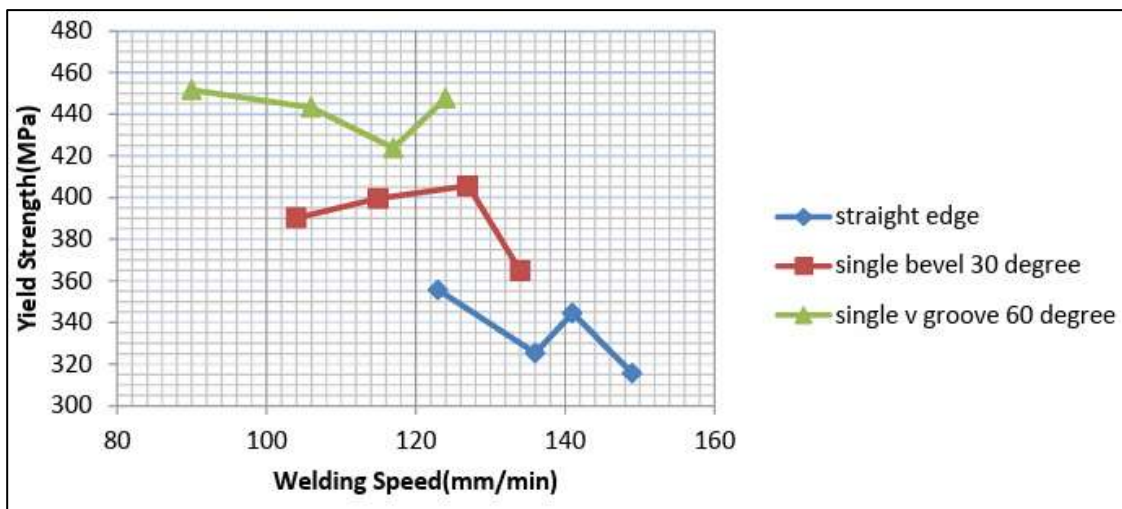


Figure 2. 17: Effect of welding speed on yield strength (Kumar Yadav et al., 2020)

Although one experiment used keyhole tungsten inert gas (K-TIG) welding rather than SMAW, it still supports the broader understanding of how welding speed influences weld microstructure. (Cui et al., 2021) found that higher welding speeds in duplex stainless steel welding reduced austenite content and increased ferrite fraction, while improving microhardness and tensile strength. These findings, while specific to TIG welding, underline the general principle that faster welding speeds can enhance certain mechanical properties even as they modify microstructure.

Selecting appropriate welding parameters, including speed, is essential for achieving high-quality welds with the desired strength and hardness (Haider et al., 2019b). The interaction between welding speed and SMAW electrodes affects heat input, solidification patterns, and grain structure, making it a critical factor in maintaining consistency and reliability in recycled materials. Careful control of these variables enhances weld integrity, reduces defects, and improves the overall sustainability of welded recycled materials.

2.7.5 Effect of Material Composition

The material composition of electrodes significantly affects the quality attributes of welds produced on recycled steel. In shielded metal arc welding (SMAW), electrodes are categorized based on their coating and core materials, which influence arc behavior, slag formation, and mechanical properties. Common electrode types include cellulosic (E6010), rutile (E6013), basic low-hydrogen (E7018), and iron powder-based (E7024). Cellulosic electrodes like E6010 are widely used in structural and pipeline welding due to their deep penetration and fast-freezing slag. These electrodes directly affect the chemical composition and microstructure of the fusion zone, often producing acicular ferrite and contributing to variations in manganese content and non-metallic inclusion formation, all of which influence mechanical performance (Khamouli et al., 2016; Zidani et al., 2019). Rutile-coated E6013 electrodes, though easier to use, show mechanical properties that can vary depending on the manufacturer, with an inverse

relationship often observed between impact strength and surface hardness (Basori & Susetyo, 2019). Among the E70-- series, E7018 low-hydrogen electrodes are preferred for applications requiring superior mechanical properties, such as construction and piping. They provide higher tensile and yield strengths compared to E6013 (Alhassan, 2021; Syukran et al., 2022), and demonstrate higher hardness values at various current levels, particularly peaking at 130A and 80A for certain weld conditions (Jasman et al., 2018; Syukran et al., 2022).

However, drawbacks such as difficult slag removal and rapid flux degradation at high amperage can hinder performance; challenges that may be mitigated by modifying the electrode coating, for instance with zirconium silicate additives (AbdElkarim et al., 2020). Additionally, the inclusion of iron powder in E7024 electrodes enhances deposition rates and welding efficiency, making them suitable for high-productivity settings (Izotova, 2019). Overall, the chemical composition and additives in welding electrodes greatly influence the microstructure, hardness, toughness, and productivity of welds, especially when working with recycled steel. Electrode selection and modification play a key role in overcoming the variability and potential weaknesses inherent in recycled materials.

Recycled steel is increasingly used in construction due to its economic and environmental benefits, yet its variable composition and potential impurities pose challenges for welding applications. Recent research on recycled steel composition in relation to SMAW has explored various aspects of weld metal chemistry and properties. (Saini & Singh, 2023) investigated the use of recycled steel slag in submerged arc welding, finding that welding parameters significantly influence element transfer and weld metal composition. (Sampath, 2021, 2024) analyzed a large SMAW database, emphasizing the importance of controlling carbon content, carbon equivalent number, and phase transformation temperatures to develop high-performance electrodes for high-strength steels. Their findings suggest that deliberate adjustment of alloying elements such as titanium, boron, aluminium, Oxygen, and Nitrogen in

controlled amounts can improve weld metal strength and toughness. These studies collectively underscore the importance of material composition in optimizing SMAW welding for recycled steel, ensuring improved structural integrity and performance in various applications.

Furthermore, the effect of material composition on recycled steel weld quality is closely linked to the interaction between base metal characteristics and welding parameters, particularly in SMAW. Researchers have explored how variations in alloy elements, flux composition, and shielding gas influence mechanical properties such as hardness, tensile strength, and microstructure (Haider et al., 2019c). The microstructure of SMAW welds often differs from the parent metal due to changes in grain size and chemical composition, which directly affect performance and durability (İrsel et al., 2022). Additionally, welding flux composition in processes like Submerged Arc Welding (SAW) significantly influences metallurgical properties, impacting strength and toughness (Manish Kumar & Krishna, 2020). Studies on Metal Active Gas (MAG) welding reveal that shielding gas composition determine cooling rates whereby elevated carbon dioxide levels extend cooling times and decrease weld metal hardness (Çelik & Akkuş, 2024; Şimşek & Akkuş, 2022). Proper control of welding parameters and material composition contributes to defect-free, high-performance welds, ensuring recycled steel meets the demands of modern structural applications.

2.8 Pre-Heat and Post-Weld Heat Treatment

Pre-heating and post-weld heat treatment (PWHT) significantly influence the mechanical properties of welded joints in various steels. For SMAW welding of Amutit K-460 steel, PWHT at 650°C resulted in the highest tensile strength and hardness values (Hestiawan & Surono, 2014). In P-91 alloy steel, increasing PWHT duration improved impact toughness (Pal Singh et al., 2013). For enhanced 9Cr-1Mo (V-Nb) steel pipes, a high preheating temperature of 573K proved advantageous, while PWHT was essential to minimize the risk of cold cracking. PWHT at 1123K enhanced ductility but decreased tensile strength, causing fracture near the HAZ.

Shielded metal arc (SMA) welds showed superior tensile properties compared to tungsten inert gas (TIG) welds, specifically for PWHT as high as 1023K (Ghosh & Singh, 2004). These studies demonstrate that appropriate pre-heating and PWHT can enhance mechanical properties and reduce welding-related issues in various steel types.

The Temper Bead Welding (TBW) method has been explored as a substitute for Post Weld Heat Treatment (PWHT) to lessen residual stresses and enhance the mechanical properties of welded joints. TBW involves strategic placement of weld beads to modify the microstructure and mechanical properties of the material (Aloraier et al., 2021). Studies have shown that TBW can effectively decrease the scope of the Heat Affected Zone (HAZ) and improve microstructure and hardness compared to conventional welding (Aloraier et al., 2010). In terms of hydrogen-induced cracking (HIC) susceptibility, TBW at specific temperatures (700°C, 725°C, and 735°C) has demonstrated high resistance, comparable to or better than PWHT (Mohammadi et al., 2023). However, welding parameters such as current and post-weld heat treatment temperatures significantly influence the mechanical properties of welds. Increasing welding current tends to enhance hardness and resistance to tension but decrease impact strength, while post-weld normalizing generally reverses these trends (Olawale et al., 2012). For recycled steel welded with SMAW electrodes, pre-heating, PWHT, and TBW are key to improving mechanical properties and minimizing defects linked to variable base material quality, especially when using electrodes like E7018, which benefits more from heat control due to its low-hydrogen characteristics.

2.9 Characteristics of Welding of Recycled Steel

Recycled steel is a sustainable alternative to virgin steel, particularly in the context of circular economy goals and resource conservation. However, maintaining the mechanical and structural integrity of recycled steel during welding remains a critical challenge. The choice of welding

electrode plays a pivotal part in defining the final properties of the weld joint, including tensile strength, toughness, hardness, and microstructural stability.

2.9.1 Impact of Electrode Material Properties on Recycled Steel Welding

Several studies have examined how various electrode types influence the performance of recycled steel during welding, and their findings provide crucial insights. According to (Adeyemi et al., 2020), different electrodes contribute significantly to variations in the microstructure and mechanical properties of welded recycled steel. A comparison of mild steel electrodes (E6013) with low-hydrogen electrodes (E7018), observed that E7018 electrodes, which have lower hydrogen content, tend to produce welds with superior toughness and reduced porosity. This is particularly important since recycled steel often contains residual impurities that can react with hydrogen to create cracks or reduce ductility.

Furthermore, (Olakanmi et al., 2019) investigated the weldability of recycled steel obtained from scrap automobile components and noted that basic-coated electrodes like E7018 produced cleaner welds with fewer inclusions compared to rutile-coated electrodes. The basic electrodes enhanced the diffusion of hydrogen and minimized entrapment, which is vital in maintaining the fatigue resistance of steel. Additionally, the microhardness profiles showed that basic-coated electrodes maintained a more consistent hardness across the heat-affected zone (HAZ), which correlates with improved integrity under cyclic loads. In contrast, (Chukwueke et al., 2021) highlighted that rutile electrodes (E6013), while easier to handle and suitable for general-purpose welding, often result in increased spatter and larger grain growth in the HAZ. This grain coarsening can negatively affect the tensile strength and make the weld area more susceptible to brittle fracture, especially under dynamic loading conditions. Moreover, rutile electrodes typically introduce higher levels of oxygen and other inclusions into the weld metal, which might degrade the overall soundness of the joint.

It is also important to study the role of post-weld heat treatment (PWHT) in conjunction with electrode selection. (Ibrahim & Adebayo, 2022) demonstrated that combining proper PWHT with the use of low-hydrogen electrodes significantly improved the ductility and tensile strength of recycled steel weldments; this suggests that the choice of electrode not only affects the quality of the weld but also determines how well the material can be enhanced through subsequent thermal treatments. Additionally, (Gungor & Gulenc, 2018) explored the fatigue behavior of recycled steel welds using different electrodes and found that welds produced with low-hydrogen electrodes had significantly longer fatigue lives, especially when welded under controlled environmental conditions. This aligns with broader industry practices that recommend low-hydrogen electrodes for structural applications involving recycled or high-strength steels thus indicating the importance of electrode selection in welding recycled steel materials.

The chemical composition of welding electrodes influences arc stability, slag formation, and the chemical behavior of the weld pool. In recycled steels, which typically contain tramp elements such as sulfur, phosphorus and copper, the electrode must compensate for these impurities to prevent the development of flaws like porosity, hot cracking, or segregation. Studies by (Chukwueke, et al., 2021) showed that rutile-coated electrodes tend to introduce more oxygen into the weld, resulting in inclusions and rough bead appearance. In contrast, low-hydrogen electrodes produced cleaner welds with fewer discontinuities, thus improving overall structural integrity. (Olanmi et al., 2019) further emphasized that basic-coated electrodes not only reduced surface and sub-surface defects but also improved the fusion zone's homogeneity, particularly in recycled steel sourced from automobile scrap.

2.9.2 Influence of Electrodes on Mechanical and Microstructural Properties

Electrode type has a direct effect on mechanical properties, such as tensile strength, hardness, impact toughness, and fatigue resistance. According to (Adeyemi et al., 2020), E7018

electrodes resulted in weld joints with higher tensile strength and lower hardness gradients across the weld metal and heat-affected zone (HAZ), indicating superior stress distribution. On a microstructural level, basic-coated electrodes were found to generate fine-grained ferrite-pearlite structures, resulting in improved ductility and toughness. In contrast, rutile electrodes often caused grain coarsening in the HAZ, which is associated with brittle fracture and low fatigue life (Gungor & Gulenc, 2018). This grain coarsening is particularly detrimental in recycled steels, where initial heterogeneity already exists. (Ibrahim & Adebayo, 2022) noted that the combination of low-hydrogen electrodes with post-weld heat treatment (PWHT) further optimized the mechanical performance by homogenizing the microstructure and relieving residual stresses.

2.9.3 Influence of Electrode Type on Corrosion Resistance and Weld Durability

The corrosion behavior of welds in recycled steel is strongly influenced by weld metal chemistry, porosity, surface finish, and residual stress. In this context, the choice of electrode becomes critical. Basic electrodes help reduce the risk of corrosion by limiting inclusions and hydrogen entrapment, while also producing a smoother surface and dense microstructure (Ibrahim & Adebayo, 2022). (Chukwueke et al., 2021) reported that welds made using rutile electrodes were more prone to pitting and crevice corrosion, particularly when exposed to moisture-rich or saline environments. These outcomes are linked to the increased oxide content and porous weld structure induced by TiO₂-rich flux coatings. In durability studies, (Gungor & Gulenc, 2018) found that joints made with E7018 electrodes outperformed E6013 welds in cyclic loading tests and salt spray exposure, indicating better fatigue life and corrosion resistance, respectively. Table 2.1; presents the electrodes performance.

Table 2.1: Electrode Performance

Electrode Type	Advantages	Limitations	Suitability for Recycled Steel
E6013 (Rutile)	Easy to use, low spatter	High oxygen content, porosity risk	Moderate (general fabrication)
E7018 (Low-Hydrogen)	High strength, low hydrogen, good toughness	Requires dry storage and handling	High (critical applications)
E6010 (Cellulosic)	Deep penetration, fast freeze	High hydrogen content, poor finish	Low (risk of hydrogen induced cracking in recycled steel)
Flux-Cored	High productivity	Sensitive to parameter variation	Variable (process-controlled environments)

2.9.4 Mechanical Properties of SMAW-Welded Recycled Steel

The mechanical performance of a welded joint, particularly when using recycled steel, depends heavily on the electrode type and associated welding parameters. These properties include tensile strength, hardness, ductility, and impact resistance, which are critical indicators of weld integrity. Ensuring high weld quality is essential in maintaining safety, performance, and compliance with industry standards (Azida et al., 2009; Zhou et al., 2003). (Benyounis & Olabi, 2007) emphasized that welding input parameters such as current, arc voltage, and travel speed significantly affect weld quality. They noted that these factors interact with electrode composition to influence bead geometry, distortion, and mechanical strength. (Haider et al., 2019) elaborated that increasing the welding current tends to increase hardness while reducing tensile strength, whereas increasing the welding speed improves both properties. Additionally, (Dele, 2020) investigated SMAW welds on low-carbon steel and concluded that electrode variation plays a crucial role in the strength of the weldment. His findings highlight the need for careful selection of electrodes to ensure mechanical reliability, particularly when using variable-quality recycled steel. (Ali et al., 2023) compared the mechanical performance of rutile and basic-coated electrodes and found that basic electrodes (E7018) produced welds with

higher tensile strength and better ductility. Similarly, (Khan & Qureshi, 2022) analyzed SMAW welds on low-grade recycled steel and concluded that E7018 electrodes provided more consistent strength than E6013, especially under variable base metal conditions typical of recycled materials.

2.9.5 Optimal Welding Parameters for SMAW-Welded Recycled Steel

Determining the optimal welding parameters for SMAW requires balancing variables such as current, voltage, arc length, and electrode angle. These factors must be tailored to the type of electrode and the quality of recycled steel being used. (Zhang & Liu, 2023) used Taguchi and Grey Relational Analysis methods to optimize welding parameters, showing that even minor adjustments in current and voltage could lead to significant improvements in tensile strength and weld bead formation. Their study demonstrates that multi-objective optimization can yield welds with superior integrity and minimal defects. Meanwhile, (Benyounis & Olabi, 2007) proposed broader statistical approaches for optimization, whereas (Haider et al., 2019) showed how parameter variation directly affects mechanical performance. For Uganda's context, where technical infrastructure may be limited, simplified but effective optimization methods like these could be invaluable.

2.10 Environmental Relevance of Welding Recycled Steel

The steel industry is both a major polluter and a key contributor to sustainable solutions through the recycling of scrap steel. According to *Environment: Science and Policy for Sustainable Development* (1973), the recyclable nature of steel can address environmental challenges such as pollution, resource depletion, and energy consumption. (Rodriguez & Kim, 2024) discussed how welding is a critical challenge when using recycled steel, particularly in construction. They emphasized that quality assurance in welding is necessary to unlock the full potential of recycled steel in sustainable development. In Uganda, where the use of recycled materials is growing due to economic and environmental considerations, reliable welding practices are

essential for sustainable infrastructure growth. Integrating recycled steel into mainstream manufacturing, especially with reliable welding techniques like SMAW, can significantly reduce the environmental footprint of Uganda's construction and metal fabrication sectors. The integrity of such welded joints, however, must be assured through appropriate electrode selection and parameter control.

2.11 Summary of Literature and Research Gaps

Electrode type, in combination with welding parameters, profoundly affects the mechanical and microstructural characteristics of SMAW welds, particularly in recycled steel. Recent studies (2022–2024) confirm the importance of optimizing these variables to achieve welds with high strength, durability, and environmental relevance. Optimal welding practices not only improve joint strength but also promote environmental sustainability. Consequently, this review supports the study's focus on evaluating the performance of different electrodes to establish practical and high-integrity welding techniques for recycled steel in Uganda. Despite the growing interest in sustainable manufacturing practices, particularly in the recycling and reuse of steel, there is a noticeable gap in the research concerning the use of different welding electrodes in the shielded metal arc welding (SMAW) process, especially in the context of recycled steel in Uganda. Most studies have focused on fresh or virgin materials and their welding characteristics, leaving a significant knowledge gap regarding how recycled steel, which may have varying compositions and impurities, reacts to different welding electrodes. This gap is critical for Uganda's developing economy, where recycling steel could offer a cost-effective and environmentally friendly alternative to importing new materials. Understanding the effects of various welding electrodes on the structural integrity and performance of SMAW-welded recycled steel is essential for optimizing manufacturing processes, ensuring product safety, and promoting sustainability within the local industry. Without substantial literature on this topic, efforts to enhance the efficiency and reliability of welded recycled steel structures in Uganda remain speculative, underscoring the urgent need for targeted research in this area.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This chapter describes the approach adopted in executing the research on the effects of different welding electrodes on the structural integrity of SMAW-welded recycled steel. The methodology includes a detailed explanation of the research design, materials and equipment used, specimen preparation, welding procedures, and quality assessment techniques.

3.2 Research Design

The experimental research design presented in Table 3.1 was used to systematically examine the mechanical and microstructural properties of SMAW welds produced using three different electrode types (E6013, E7018, and E7024 electrodes) on recycled steel from three distinct sources. The variables investigated included the welding electrode type, recycled steel materials, and welding parameters, with the mechanical properties (tensile strength and hardness) and microstructural characteristics serving as the dependent variables. The experimental design aimed to isolate the effects of electrode composition while controlling confounding factors such as base metal composition, welding current, and arc length. All experiments were conducted in a controlled laboratory environment to ensure consistency and accuracy.

3.3 Materials

3.3.1 Base Metal

The base material consisted of low-carbon recycled steel flat bars procured from three reputable steel recycling companies in Uganda:

- (i) Tembo Steels Uganda Ltd. (Sample T)
- (ii) Steel and Tube Industries Ltd. (Sample ST)
- (iii) Pramukh Steel Ltd (Sample PS)

The three recycled steel manufacturing companies were selected based on their annual production capacities: Steel and Tube Industries Ltd (130,000 MT/year), Pramukh Steel Ltd (80,000 MT/year), and Tembo Steels Uganda Ltd (72,000 MT/year). These companies are among the leading steel manufacturers in Uganda, each representing a significant share of the recycled steel market. Sampling materials from these sources ensures that the study reflects products commonly used in local fabrication and manufacturing, thereby increasing the industrial relevance and applicability of the findings.

Moreover, all three companies operate under certification by the Uganda National Bureau of Standards (UNBS) and are subject to regulatory oversight, which helps ensure that their materials meet the required minimum mechanical and chemical property standards. Their respective UNBS permit numbers are as follows: Tembo Steels Uganda Ltd, 00347-0950-0006; Pramukh Steel Ltd, 00394-0951-0005; and Steel and Tube Industries Ltd, 00648-0162-0010. This compliance enhances the reliability and comparability of the results obtained from different samples. Each flat bar specimen was 100mm × 40mm × 6mm in dimension. These materials were selected to reflect the variability in recycled steel used in industrial applications and to ensure the relevance of the study's findings.

Table 3.1: L27 Array of Design of Experiment

Run	Welding electrode Types (G10)	Electrode Ø	Welding Current (A)	Welding Voltage (V)	Material's Company		
					Tembo Steel (T)	Steel & Tube (ST)	Pramukh Steel Ltd (PS)
1	E ₁ (E6013)	3.2mm	130	27	2T	2ST	2PS
	E ₂ (E7018)	3.2mm	130	27	2T	2ST	2PS
	E ₃ (E7024)	4mm	130	27	2T	2ST	2PS
2	E ₁ (E6013)	3.2mm	145	32	2T	2ST	2PS
	E ₂ (E7018)	3.2mm	145	32	2T	2ST	2PS
	E ₃ (E7024)	4mm	145	32	2T	2ST	2PS
3	E ₁ (E6013)	3.2mm	200	36	2T	2ST	2PS
	E ₂ (E7018)	3.2mm	200	36	2T	2ST	2PS
	E ₃ (E7024)	4mm	200	36	2T	2ST	2PS

3.3.2 Welding Electrodes

The distinct chemical compositions and flux coatings of the electrodes provided a basis for analyzing their effects on weld quality. Three types of commercially available SMAW electrodes were used in the experiments:

- (i) **Rutile Electrodes (E6013):** Known for their general-purpose usability and smooth arc characteristics.
- (ii) **Basic Electrodes (E7018):** Selected for their excellent mechanical properties and minimal defect generation.
- (iii) **Iron Powder Electrodes (E7024):** Chosen for their efficiency and high deposition rates.

3.4 Equipment

3.4.1 Welding Equipment

The equipment used included the following:

- (i) **SMAW Welding Machine:** Capable of delivering precise arc conditions and adjustable current and voltage settings for consistency across specimens. Figure 3.1 shows an Inverter Five function welding machine HYWEL-350A that was used to join the experimental specimens.
- (ii) **Welding Torch and Earthing Wire:** Ensured safe and effective welding operations.
- (iii) **PPE:** Helmets, gloves, aprons, and other safety gear were used to protect welders throughout the experiments.

The base metals were analyzed using a spark emission spectrometer model MAXx LMM05 to determine their elemental composition as illustrated in Figure 3.2 and Tables 3.2, 3.3, 3.4. This information was utilized in appraising the influence of base metal chemistry on weld quality.



Figure 3.2: Spectro max used to determine the chemical composition of the welds

Table 3.2: Chemical Composition for Welded Tembo Steels Recycled Steel

Material; Tembo								
	C	Si	Mn	P	S	Cr	Mo	Ni
	%	%	%	%	%	%	%	%
1	0.444	0.724	2.16	0.0025	0.0996	0.370	0.0102	0.0434
2	0.330	0.701	2.09	0.00073	-0.100	0.368	0.0095	0.0431
3	0.265	0.515	1.56	<0.00050	0.0703	0.305	0.0077	0.0406
	Al	Co	Cu	Nb	Ti	V	W	Pb
	%	%	%	%	%	%	%	%
1	0.0074	0.0338	0.0949	0.0033	0.0021	0.0151	0.224	>0.00300
2	0.0073	0.0334	0.101	0.0038	0.0018	0.0146	0.209	-0.0282
3	0.0037	0.0252	0.103	0.0015	0.00092	0.0111	0.175	0.0282
	Sn	As	Zr	Bi	Ca	Ce	Sb	Se
	%	%	%	%	%	%	%	%
1	0.0264	0.0291	0.0093	0.0019	0.0101	0.0246	0.0083	0.0042
2	0.0241	0.0314	0.0084	<0.0010	0.0015	0.0321	0.0102	<0.0020
3	0.0211	0.0145	0.0068	<0.0010	0.00012	0.0256	<0.0010	<0.0020
	Ta	B	Zn	La	N	Te	Fe	
	%	%	%	%	%	%	%	
1	>0.252	0.0112	>0.0324	0.0443	>0.0360	-0.0340	95.20	
2	>0.252	0.0105	>0.0324	0.0405	>0.0360	-0.0340	95.45	
3	>0.252	0.0048	>0.0324	0.0355	>0.0360	0.0306	96.44	

Table 3.3: Chemical Composition for Welded Steel and Tube Recycled Steel

Material; Steel and Tube								
	C	Si	Mn	P	S	Cr	Mo	Ni
	%	%	%	%	%	%	%	%
1	0.0021	0.264	0.796	<0.0050	0.0154	0.0657	0.0030	0.0270
2	0.0567	0.223	0.629	<0.0050	0.0137	0.0484	0.0024	0.0282
3	0.102	0.284	0.866	<0.0050	0.0276	0.0676	0.0037	0.0235
	Al	Co	Cu	Nb	Ti	V	W	Pb
	%	%	%	%	%	%	%	%
1	0.00082	0.0227	0.0728	<0.0010	0.00037	0.0069	0.125	0.0140
2	0.00054	0.0204	0.0821	<0.0010	<0.00020	0.0057	0.111	0.0118
3	0.0013	0.0240	0.0677	<0.0010	0.00063	0.0079	0.133	0.157
	Sn	As	Zr	Bi	Ca	Ce	Sb	Se
	%	%	%	%	%	%	%	%
1	0.0202	0.0042	0.0044	<0.0010	0.00056	0.0183	<0.0010	<0.0020
2	0.0182	0.0052	0.0046	<0.0010	0.00016	0.0143	<0.0010	<0.0020
3	0.0160	0.0025	0.0053	<0.0010	0.00069	0.0181	<0.0010	<0.0020
	Ta	B	Zn	La	N	Te	Fe	
	%	%	%	%	%	%	%	
1	-0.211	0.00035	>0.0324	0.0242	>0.0360	<0.0010	98.14	
2	0.131	<0.00020	>0.0324	0.0233	>0.0360	<0.0010	98.50	
3	-0.223	0.00051	>0.0324	0.0250	>0.0360	<0.0010	98.01	

Table 3.4: Chemical Composition for Welded Pramukh Steels Ltd Recycled Steel

Material; Pramukh Steels								
	C	Si	Mn	P	S	Cr	Mo	Ni
	%	%	%	%	%	%	%	%
1	0.196	0.378	1.19	<0.00050	0.0430	0.203	0.0048	0.0385
2	0.206	0.316	1.03	<0.00050	0.0359	0.191	0.0039	0.0407
3	0.244	0.465	1.48	0.0017	0.0576	0.235	0.0051	0.0357
	Al	Co	Cu	Nb	Ti	V	W	Pb
	%	%	%	%	%	%	%	%
1	0.0055	0.0241	0.113	<0.0010	0.0017	0.0073	0.153	0.0197
2	0.0030	0.0222	0.117	<0.0010	0.0010	0.0064	0.140	0.0180
3	0.0044	0.0257	0.108	0.0011	0.0018	0.0087	0.166	0.0226
	Sn	As	Zr	Bi	Ca	Ce	Sb	Se
	%	%	%	%	%	%	%	%
1	0.0232	0.0078	0.0058	<0.0010	<0.00010	0.0211	<0.0010	<0.0020
2	0.0213	0.0064	0.0054	<0.0010	0.00019	0.0199	<0.0010	<0.0020
3	0.0221	0.0074	0.0066	<0.0010	0.0010	0.0239	<0.0010	<0.0020
	Ta	B	Zn	La	N	Te	Fe	
	%	%	%	%	%	%	%	
1	>0.252	0.0020	>0.0324	0.0293	>0.0360	<0.0010	97.20	
2	-0.239	0.0012	>0.0324	0.0269	>0.0360	<0.0010	97.47	
3	>0.252	0.0036	>0.0324	0.0317	>0.0360	0.0011	96.71	

3.5 Workpiece Preparation and Labelling

3.5.1 Specimen Preparation

The flat steel bars were sectioned into smaller specimens with dimensions of 100mm × 40mm × 6mm using a metal cutting saw. Each specimen was cleaned thoroughly using acetone and sandpaper to remove rust, grease, and other contaminants that could interfere with the welding process.

3.5.2 Workpiece Labeling System

A systematic labeling system in table 3.5 was implemented to ensure traceability. For example, specimens labeled R₁E₁T, R₁E₁ST and R₁E₁PS denoted a rutile electrode (E₁), steel from Tembo Steels Uganda Ltd (T), Pramukh Steel Ltd (PS), Steel and Tube Industries Ltd. (ST) and the Experiment run (R).

Table 3. 5: A systematic labeling of specimen and Welding electrodes

Welding Run Number (Experiment Run)	Electrodes		Recycled Steel Specimens from Three Manufacturers		
	Type	Code	Steel & Tube (ST)	Pramukh Steel Ltd (PS)	Tembo Steel (T)
Run One (R ₁) 130A/27V	E6013	E ₁	R ₁ E ₁ ST	R ₁ E ₁ PS	R ₁ E ₁ T
	E7018	E ₂	R ₁ E ₂ ST	R ₁ E ₂ PS	R ₁ E ₂ T
	E7024	E ₃	R ₁ E ₃ ST	R ₁ E ₃ PS	R ₁ E ₃ T
Run Two (R ₂) 145A/32V	E6013	E ₁	R ₂ E ₁ ST	R ₂ E ₁ PS	R ₂ E ₁ T
	E7018	E ₂	R ₂ E ₂ ST	R ₂ E ₂ PS	R ₂ E ₂ T
	E7024	E ₃	R ₂ E ₃ ST	R ₂ E ₃ PS	R ₂ E ₃ T
Run Three (R ₃) 200A/36V	E6013	E ₁	R ₃ E ₁ ST	R ₃ E ₁ PS	R ₃ E ₁ T
	E7018	E ₂	R ₃ E ₂ ST	R ₃ E ₂ PS	R ₃ E ₂ T
	E7024	E ₃	R ₃ E ₃ ST	R ₃ E ₃ PS	R ₃ E ₃ T

3.6 Experimental Procedure

Welding experiments were performed under controlled conditions using the following parameters:

- (i) **Current Setting:** Maintained at 130 -200A and depending on the electrode type, penetration depth and material thickness.

- (ii) **Voltage Settings:** Maintained at 27-36V and depended on type of electrodes, arc stability, transfer mode (SMAW).
- (iii) **Arc Length:** Consistently kept at approximately 3mm.
- (iv) **Welding Speed:** Controlled manually to ensure uniform weld bead formation.

The specimens were welded in a flat position with a single pass, and a minimum of three specimens were prepared for each combination of electrode type and steel source as demonstrated in Figure 3.3.



Figure 3.3: Specimens welded in a flat position with a single pass

3.7 Examination of Mechanical Properties of SMAW Welds

The mechanical properties of the SMAW welds on recycled steel were determined through the hardness and tensile testing.

3.7.1 Hardness Testing

Hardness measurements were conducted using a Super Rockwell–Duplex-713-SR hardness tester. Indentations were made on the weld metal to evaluate the distribution of hardness. Figure 3.4 illustrates the specimen under evaluation for hardness test; the hardness of the tested specimens was measured using the Rockwell hardness test on the B scale (with an indenter of 1/16” and a load of 100kg).



Figure 3. 4: Specimen under evaluation for hardness

3.7.2 Tensile Testing

The tensile strength of each welded specimen was tested using Denison model T42-B4 tensile testing machine, in accordance with ASTM E8/E8M standards. Welded specimens were mounted on the machine as showed in Figure 3.5.



Figure 3.5: Specimens mounted on Denison tensile testing machine

3.8 Examination of Microstructural Characteristics of SMAW Welds

Optical microscopy facilitated the evaluation of the weld metal and heat-affected zone. Samples were polished, etched with Nital solution, and analyzed to observe grain structure and defects such as porosity or inclusions as shown in Figure 3.6.



Figure 3.6: Optical Microscope used to analyze the grain structure of the welds

3.9 Determination of Optimal Welding Parameter Combinations in SMAW

The collected data was subjected to statistical analysis using both descriptive and inferential methods. For each welding parameter, mean values and standard deviations were calculated to summarize the central tendency and variability across all experimental replicates, providing a foundational understanding of data distribution and consistency. To evaluate the statistical significance of differences between electrode types and steel sources, an Analysis of Variance (ANOVA) was executed, a procedure which involved partitioning the total observed variance in the data into components attributable to the different factors (electrode type, steel source) and random error, allowing for a test of the null hypothesis that the means of the groups defined by these factors were equal. The outcomes were systematically presented through tables, graphs, and micrographs, enabling clear visualization and comparative evaluation of the results.

These visual and tabular representations played a critical role in identifying the optimal combination of welding parameters. Tables provided a concise summary of numerical data for easy reference and comparison across variables, including the calculated means, standard deviations, and the F-statistics and p-values derived from the ANOVA. Graphs visually highlighted the trends, patterns, and outliers in the data, which facilitated quick assessment of parameter interactions and performance of the outcomes, with main effects plots illustrating the influence of individual parameters and interaction plots revealing whether the effect of one parameter depended on the level of another. Micrographs offered a microscopic view of weld quality, such as grain structure and defect presence, allowing a direct correlation between the process parameters and metallurgical properties. Together, these tools supported informed decision- linking statistical outcomes to practical, observable effects in the welds.

3.10 Ethical Considerations

The study adhered to ethical standards, including ensuring safety during welding operations and proper disposal of waste materials. The recycled steel samples were sourced legally, and all laboratory procedures complied with institutional and environmental regulations. Therefore, the methodology employed in this study was designed to comprehensively evaluate the effects of different welding electrodes on SMAW-welded recycled steel. By incorporating rigorous experimental protocols, advanced testing methods, and statistical analysis, the study aimed to generate a reliable analysis of the performance of SMAW-welded recycled steel.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents a detailed analysis of the results and discussion of the research findings, focusing on the impact of different welding electrodes on the mechanical properties of Shielded Metal Arc Welded (SMAW) recycled steel joints. The results of the Rockwell hardness test, tensile test (breaking load), and microstructural analysis are examined in relation to the welding electrode type. The discussion highlights key trends, compares different electrode performances, and identifies gaps that require further investigation.

4.2 Results

The hardness test, tensile test and microstructural examination were used to analyze the effect of electrode type on the weld quality in recycled steel welding.

4.2.1 Hardness of SMAW-Welded Recycled Steel

The Rockwell hardness test results are presented in Figure 4.1; the hardness values of the welded joints on the tested specimens were observed to vary based on the electrode type and the recycled steel materials from different steel manufacturing companies as shown in Figure 4.1. Tembo specimens demonstrated a wide range of hardness values, with R₃E₂T recording the lowest (35.8) and R₂E₂T showing the highest (63.4); and Steel & Tube samples followed a similar trend where R₃E₂ST had the lowest hardness (30.8), while R₃E₃ST exhibited the highest (63.3). Pramukh Steel Ltd specimens displayed a relatively high and consistent hardness range, with R₃E₂PS registering the lowest (39.0) and R₂E₃PS the highest (63.9).

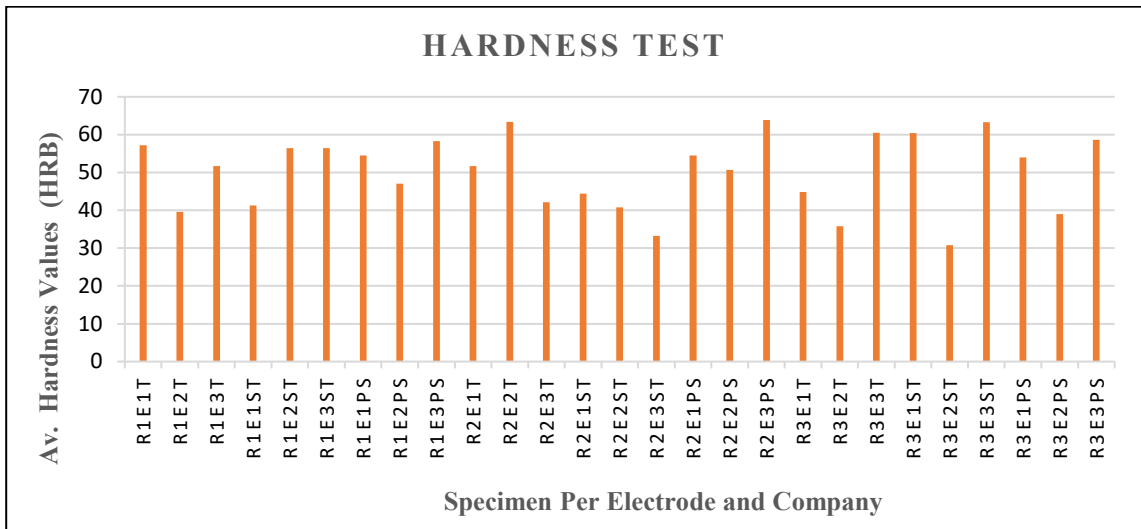


Figure 4.1: Hardness values for different welding electrodes and steel sample sources

Figure 4.2 presents the average hardness values (in HRB) for SMAW-welded recycled steel using different electrode types across three companies: Tembo, Steel & Tube, and Pramukh Steel Ltd. The results indicate significant variations in hardness depending on both the welding electrode type and the company. For Tembo, the hardness value starts at approximately 52 HRB for E6013, then decreases sharply to around 40 HRB when E7018 is used. However, with E7024, there is a substantial increase in hardness, reaching approximately 51 HRB. This suggests that E7018 produces the least hardness for Tembo-welded steel, while E6013 and E7024 result in relatively higher hardness values. In contrast, Steel & Tube exhibits a more stable trend, with hardness values remaining nearly constant for E7018 and E7024 at around 56 HRB. However, the use of E6013 results in a slight reduction in hardness to approximately 42 HRB. This indicates that, for Steel & Tube, E6013 may slightly compromise hardness compared to the other two electrodes.

For Pramukh Steel, the hardness follows a different trend, starting at around 55 HRB with E6013, decreasing to nearly 52 HRB for E7018, and then rising to the highest value of approximately 58 HRB when E7024 is used. This trend suggests that E7024 contributes to the highest hardness levels for Pramukh Steel, making it the most effective electrode in enhancing hardness. Comparing all three companies, it is evident that Pramukh Steel produces the hardest

welded steel, particularly when using E7024, while Tembo's E7018-welded steel exhibits the lowest hardness as shown in Figure 4.2. The variations across the companies may be attributed to differences in material properties, welding procedures, or quality of the recycled steel used.

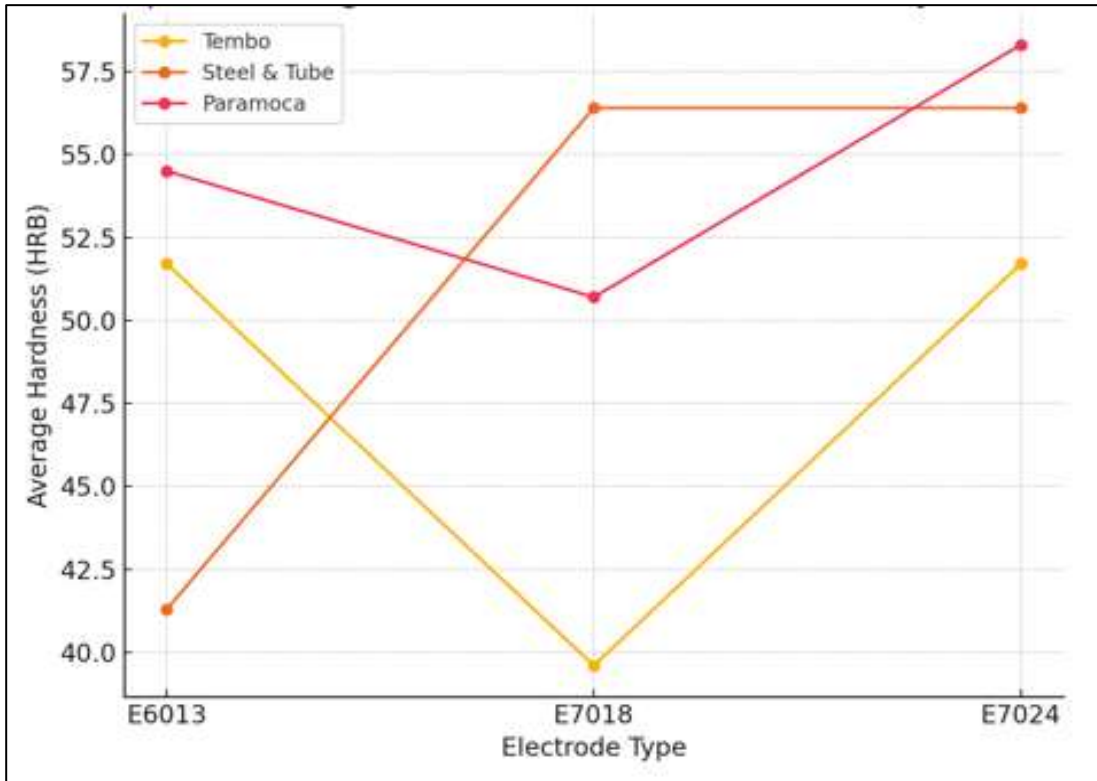


Figure 4.2: Average hardness values for SMAW-welded recycled steel using different electrodes across various companies.

4.2.1.1 Metallurgical Basis for Hardness Variation

The comparatively lower hardness associated with the E7018 electrode can be attributed to its low-hydrogen and iron-powder coating composition, which facilitates a slower cooling rate and promotes the development of a refined ferrite–pearlite microstructure within the weld metal. This microstructural refinement, combined with reduced diffusible hydrogen and residual stress levels, results in a tougher but softer weld deposit, characterized by improved ductility and lower hardness values (Falodun, et al., 2025). Conversely, the higher hardness values observed with E7024 are primarily due to its rutile–iron powder flux composition and higher deposition efficiency, which generate increased heat input and faster solidification rates.

These conditions promote the formation of harder transformation products, such as bainite or martensite, especially in steels containing elevated carbon or alloying elements (Takayama, et al., 2018). Furthermore, the enhanced oxygen and silicon content introduced from the E7024 coating contributes to oxide dispersion strengthening and solid-solution hardening, thereby elevating the overall hardness of the welded joint (Li, 2023). Thus, the observed hardness variation between E7018 and E7024 is primarily governed by differences in electrode chemistry, heat input, and the resultant microstructural transformations within the weld and heat-affected zones.

4.2.2 Tensile Strength of SMAW-Welded Recycled Steel

The tensile strength values also exhibit variations, influenced by the choice of electrode and welding parameters as observed in Figure 4.3. The tensile test results reveal a significant variation in breaking load across different welding electrode and steel sample sources (Baciu, et al., 2020). Tembo specimens exhibited breaking loads ranging from 28.2kN (R₂E₃T) to 57.8kN (R₁E₂T), indicating that electrode type significantly impacts tensile strength. Similarly, Steel & Tube samples showed diverse breaking loads, with R₃E₂ST registering the lowest value (29.2kN) and R₂E₂ST achieving the highest (67.8kN). Pramukh Steel specimens displayed the highest breaking load variation, where R₃E₃PS recorded the lowest (36.0kN) while R₂E₂PS exhibited the highest (78.4kN). The observed variations in breaking load suggest that electrode E7018 enhance the tensile strength of recycled steel, while others lead to weaker joints Liu, et al., (2018). Higher breaking load values indicate better weld quality, whereas lower values suggest weaker bonding and structural integrity Liu, et al., (2018). The tensile strength results presented in Figure 4.3 highlight the impact of different electrodes on the breaking load of SMAW-welded recycled steel. E7018 generally demonstrates the highest tensile strength, particularly in Pramukh Steel Ltd samples, while E6013 and E7024 show relatively lower tensile performance. These findings indicate that E7018 provides better fusion and load-bearing capacity.

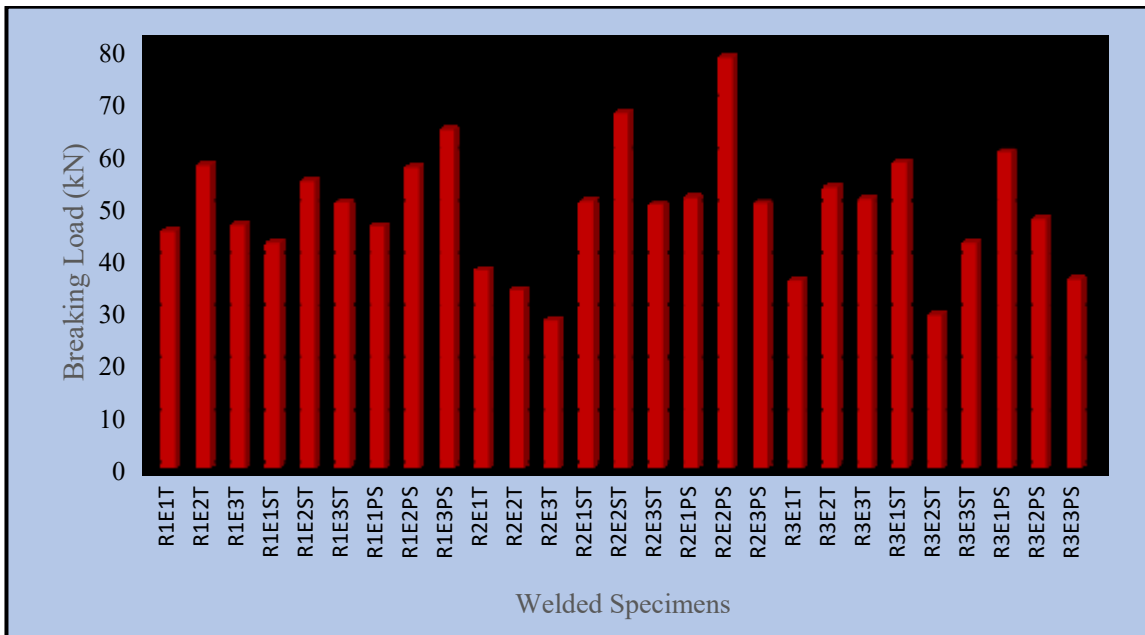


Figure 4.3: Tensile Strength shows significant variation in breaking load across different welding electrodes and steel sample sources

Figure 4.4 illustrates the tensile strength (in kN) of SMAW-welded recycled steel for different welding electrodes across the three companies. The trends observed in tensile strength vary from those seen in hardness, highlighting the distinct influence of electrode selection on mechanical properties (Baciu, et al., 2020; Liu, et al., 2018). For Tembo, the tensile strength starts at around 40kN with E6013, increases to approximately 47kN with E7018, and then drops back to around 42kN with E7024. This indicates that E7018 provides the highest tensile strength among the three electrodes for Tembo-welded steel, while E6013 and E7024 result in similar but slightly lower values. Steel & Tube follows a different trend, where tensile strength starts at approximately 45kN with E6013, peaks at 55kN when using E7018, and then declines to about 50kN with E7024. This pattern suggests that E7018 is the most effective electrode for maximizing tensile strength, while E7024 causes a slight reduction in strength. In the case of Pramukh Steel Ltd, tensile strength consistently increases across all three electrode types. It starts at 50kN with E6013, rises to 60kN with E7018, and reaches the highest value of approximately 65kN with E7024. This indicates that, unlike the other two companies, Pramukh

Steel experiences continuous improvement in tensile strength with each successive electrode type, making E7024 the most effective electrode for enhancing strength in their welded steel.

When comparing the three companies, it is clear that Pramukh Steel Ltd achieves the highest tensile strength overall, particularly when using E7024, while Tembo records the lowest values as shown in Figure 4.4. The difference in tensile strength trends among the companies may be attributed to variations in welding techniques, electrode efficiency, and the quality of the recycled steel used. Figure 4.5 indicate that a higher hardness value does not always correspond to higher breaking load. For example, Tembo (E7018-R₂E₂T) had the highest hardness (63.4 HRB) but a relatively low breaking load of 34.0kN, suggesting that excessive hardness may lead to brittle failure. In contrast, Pramukh Steel Ltd (E7018-R₂E₂PS) achieved a balance between hardness (50.7 HRB) and tensile strength (78.4kN), indicating a well-optimized weld microstructure.

4.2.2.1 Tensile Variation in Relation to Chemical and Microstructural Characteristics

The variations in tensile strength observed among the welded samples can be directly correlated with the chemical composition and resulting microstructural features of the weld metal and heat-affected zone (HAZ). Electrodes such as E7018, which contain iron powder and low hydrogen content, promote refined grain structures and uniform ferrite-pearlite distributions, thereby enhancing tensile properties. In contrast, electrodes like E6013 and E7024, which have relatively higher hydrogen and silica content, tend to produce coarser grains and occasionally promote the formation of brittle phases such as martensite or carbide networks at the weld interface, leading to reduced ductility and strength.

Furthermore, the recycled steel sources contribute to these variations due to differences in base metal chemistry-particularly in carbon, manganese, and residual element content. Higher carbon or impurity levels can lead to increased hardness and brittleness, which compromise

tensile performance. Conversely, steels with balanced alloying elements and fewer inclusions tend to produce more homogeneous welds with superior mechanical integrity.

Microstructural examination supports these findings: samples with higher tensile strength typically exhibit fine-grained ferrite-pearlite matrices with minimal porosity and slag inclusions, while those with lower breaking loads show coarser grains, microcracks, and inclusions along the fusion line. Therefore, the tensile variation among electrodes and steel types reflects the combined influence of weld metal chemistry, electrode coating composition, and thermal cycling during SMAW. The superior performance of E7018 can thus be attributed to its ability to promote cleaner weld pools, better deoxidation, and a refined microstructure that enhances load-bearing capacity and structural cohesion.

The observed variations in tensile strength across the three companies can be closely related to the interplay between electrode composition, base metal chemistry, and microstructural evolution during the welding process. The superior tensile strength achieved using the E7018 electrode in most cases reflects its low-hydrogen and iron-powder coating, which facilitates deeper penetration, improved fusion, and refined weld microstructures. Its ability to minimize hydrogen-induced cracking and produce a denser, more uniform ferrite-pearlite structure contributes to enhanced load-bearing capacity. Conversely, E6013 and E7024 electrodes, which contain higher levels of rutile and silicate fluxes, may promote slower cooling and coarser grains in the weld metal, thereby reducing tensile strength in some samples despite good surface finish and bead appearance.

The divergence in performance among the three steel sources also highlights the role of base metal chemistry in influencing weld quality. Recycled steels often contain varying amounts of carbon, manganese, silicon, and trace impurities such as sulfur and phosphorus. Higher carbon or impurity levels can increase weld hardness but simultaneously reduce ductility, leading to premature fracture under tensile loading, as observed in Tembo samples. In contrast, the

recycled steel used by Pramukh Steel Ltd likely has more balanced alloying constituents, which, combined with optimized welding parameters, resulted in improved weld homogeneity and tensile behavior.

Microstructural evidence supports these mechanical trends: samples with higher tensile strength generally display a fine-grained ferrite-pearlite or bainitic matrix with minimal porosity and inclusion content, while weaker samples often exhibit coarse grains, partial fusion defects, and the presence of brittle martensitic regions. The case of Tembo (E7018-R₂E₂T), where high hardness did not correspond to high tensile strength, demonstrates how excessive hardening-often caused by rapid cooling or higher carbon content-can create brittle microstructures prone to cracking. On the other hand, Pramukh Steel's E7018-R₂E₂PS sample shows a desirable balance between hardness and ductility, resulting from controlled heat input and improved metallurgical bonding across the fusion boundary.

Overall, the tensile variations reflected in Figure 4.3 can be attributed to the combined effects of electrode type, chemical composition of both base and filler materials, and the resultant microstructure. A well-selected electrode such as E7018, when paired with properly refined recycled steel and optimal welding parameters, fosters a microstructure that balances strength and ductility-key for producing structurally sound and reliable weld joints

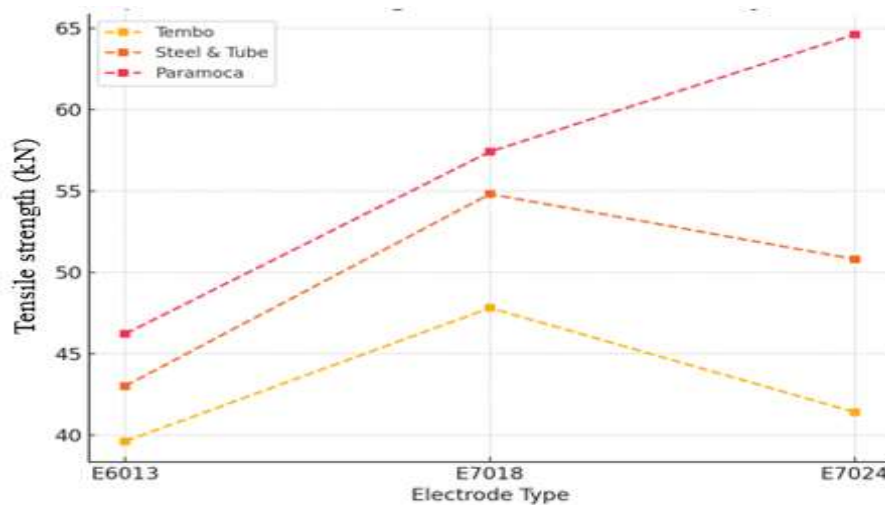


Figure 4. 4: Tensile strength of SMAW-welded recycled steel made with different electrodes, categorized by company

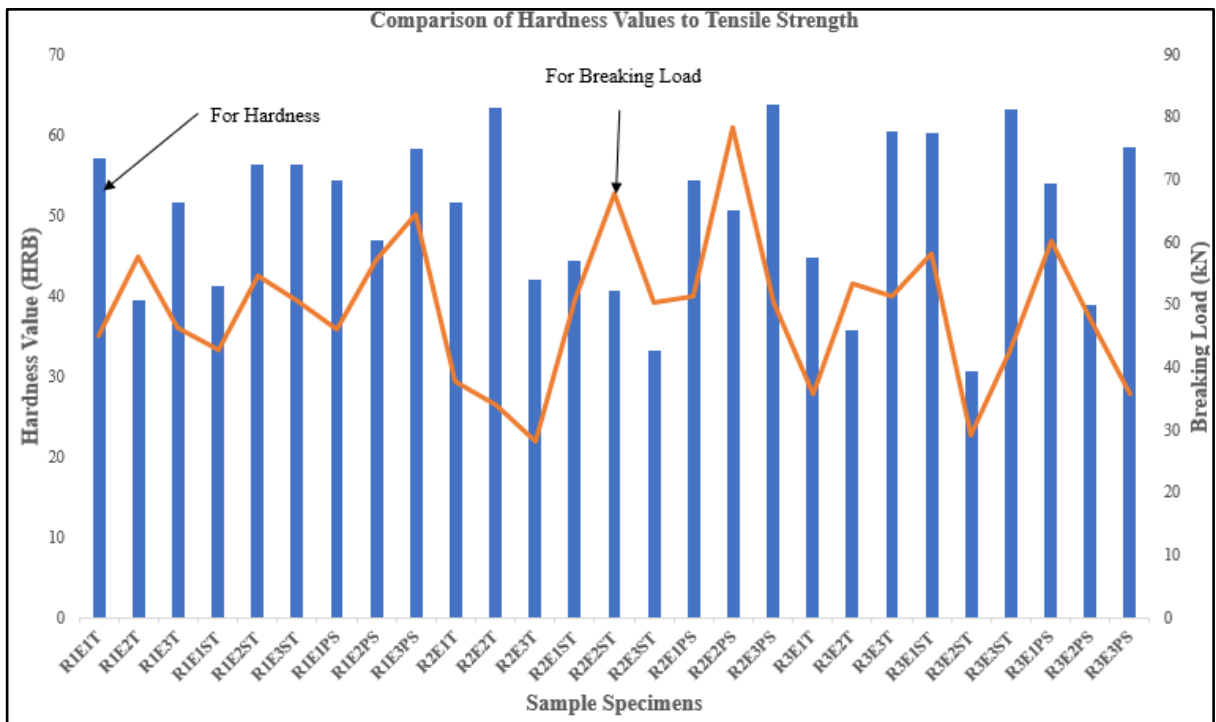


Figure 4. 5: Comparison of hardness and tensile strength of the welded samples using different electrodes

4.2.3 Microstructural Characteristics of SMAW-Welded Recycled Steel

The microstructures of the weld metal from the different electrodes exhibited significant variations in grain structure and phase distribution as presented in Figure 4.6. The microstructural observations are categorized based on the three electrode types. The microstructure of the tested specimens provides insight into the mechanical properties observed in the hardness and tensile tests. Microstructural examination reveals variations in grain size, phase distribution, and potential defects introduced during welding.











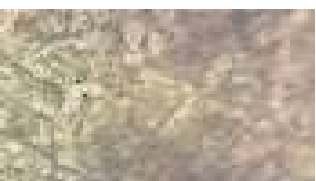





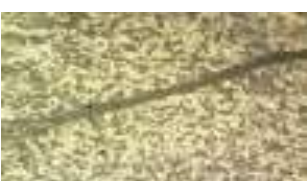

		
E6013 Tembo R ₁ E ₁ T	E7018 Tembo R ₁ E ₂ T	E7024 Tembo R ₁ E ₃ T
		
E7018 Steel & Tube R ₁ E ₂ ST	E7024 Steel & Tube R ₁ E ₃ ST	E7024 Pramukh R ₁ E ₃ PS
		
E6013 Tembo R ₂ E ₁ T	E7018 Tembo R ₂ E ₂ T	E7018 Tembo R ₂ E ₃ T
		
E6013 Steel & Tube R ₂ E ₁ ST	E7018 Steel & Tube R ₂ E ₂ ST	E7018 Steel & Tube R ₃ E ₂ ST
		
E6013 Pramukh R ₂ E ₁ PS	E7024 Pramukh R ₂ E ₃ PS	E7018 Pramukh Steel R ₃ E ₂ PS
		
E6013 Tembo R ₃ E ₁ T	E7018 Tembo R ₃ E ₂ T	E7024 Tembo R ₃ E ₃ T

Figure 4. 6: Micrographs of SMAW welded recycled steel at X500

(i) Tembo Specimens

The microstructure of Tembo samples showed significant differences in grain size, depending on the electrode used. Samples with higher hardness, such as R₂E₂T (63.4HRB), displayed coarser grains, contributing to increased hardness but lower ductility, as reflected in the relatively low breaking load (34.0kN). Conversely, R₁E₂T, which had the lowest hardness (39.6HRB), exhibited a finer grain structure, contributing to a higher breaking load (57.8kN).

(ii) Steel & Tube Specimens

The Steel & Tube samples revealed similar trends. R₃E₃ST, with a high hardness value (63.3HRB), exhibited a refined grain structure with average crystal size, which generally correlates with improved strength. However, samples such as R₃E₂ST, which had a low hardness (30.8HRB) and breaking load (29.2kN), showed evidence of larger grain size, leading to reduced mechanical performance.

(iii) Pramukh Steel Specimens

The Pramukh Steel specimens demonstrated a more uniform microstructure, with specimen R₂E₂PS resulting in the highest breaking load (78.4kN) and a relatively high toughness (50.7HRB). The fine-grained microstructure of these samples suggests that the electrode composition played a crucial role in improving both hardness and tensile strength. Therefore, from Table 4.1, the E6013 electrode exhibited fine and uniform grain structures but showed signs of porosity in some specimens, likely due to increased oxygen pickup (Liu, et al., 2023). The E7018 electrode produced refined grain structures with minimal porosity, contributing to higher tensile strength. The E7024 electrode displayed mixed grain structures with occasional coarse regions, potentially affecting ductility and performance under load. The microstructural observations confirm the mechanical test findings, showing that E7018 provides a balanced structure with minimal defects, whereas E7024 enhances hardness but can introduce coarser grains.

Table 4.1: Microstructural observations for different electrode types

Electrode Type	Grain Structure	Defects Observed
E6013	Fine and Uniform	Porosity in some specimens
E7018	Refined, Minimal Porosity	Minimal defects
E7024	Mixed, Some Coarse Regions	Occasional coarse grains

The microstructural observations align with the hardness and tensile test results, confirming that grain structure and phase composition directly impact mechanical properties as presented in Table 4.2 and Figure 4.7.

- (i) Fine-grained structures (as observed in E7018 welds) contributed to higher breaking loads, confirming that smaller grains improve tensile strength and ductility.
- (ii) Coarse-grained structures (as observed in E7024 welds) resulted in higher hardness but lower breaking loads, highlighting the trade-off between hardness and toughness.
- (iii) The occurrence of acicular ferrite and bainite in E7018 welds enhanced impact resistance, while martensite-rich structures in E7024 welds increased hardness but led to brittleness.

These findings suggest that electrode selection should be based on the required balance between hardness and strength. Environments that call for high tensile strength (like fabricated structures) should prioritize E7018 electrodes, while applications demanding wear resistance should use E7024 electrodes with controlled heat input to prevent excessive brittleness.

Table 4. 2: Mechanical Properties and Electrode Details of Microstructure Samples

Run	Electrode Type	Company	Specimen ID	Microstructure Observed	Average Hardness (HRB)	Breaking Load (kN)	Key Observations
R ₁	E6013	Tembo	R ₁ E ₁ T	Fine-grained ferrite and pearlite	57.2	45.2	Moderate strength, good ductility, minor slag inclusions
R ₁	E7018	Tembo	R ₁ E ₂ T	Acicular ferrite and bainite	39.6	57.8	Higher strength, good toughness, minimal defects
R ₁	E7024	Tembo	R ₁ E ₃ T	Coarse ferrite and pearlite with slag inclusions	51.7	46.4	Moderate hardness, porosity, and slag inclusions affecting strength

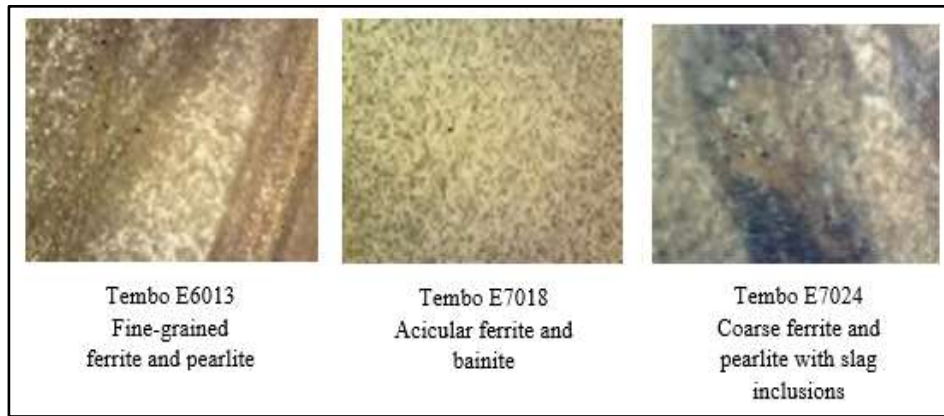


Figure 4.7: Analyzed Microstructural Images for Welded Tembo Steel Specimens

During microstructural examination, some defects were observed in certain weld specimens, which could affect mechanical performance. The most common defects included:

- (i) **Porosity:** Small gas pockets were observed in some E6013 and E7024 welds, likely caused by moisture in the electrode coating or improper shielding gas coverage.
- (ii) **Weld Inclusions:** Some E7024 welds showed slag inclusions, which can act as stress concentration points and lead to crack initiation under loading conditions.
- (iii) **Grain Boundary Segregation:** Observed in some coarse-grained structures, particularly in high-hardness E7024 welds, making them prone to brittle fracture.

These defects highlight the importance of proper welding procedures, including preheating, correct electrode handling, and post-weld heat treatment, to minimize defects and enhance weld integrity. The post-weld thermal dissipation rate significantly influences grain formation and phase distribution in the weld metal. Faster thermal dissipation rates tend to:

- (i) Refine grain structures, leading to improved toughness (as seen in E7018 welds).
- (ii) Promote martensitic formation, increasing hardness but reducing ductility (as seen in E7024 welds).
- (iii) Cause residual stresses, which can lead to cracking or warping of the weld metal.

On the other hand, slower cooling rates allow carbon diffusion, which results in softer, more ductile microstructures. Understanding this relationship is critical in controlling weld quality and optimizing electrode performance. As a consequence, the results indicate that E7018 electrodes provide the best mix of strength and ductility, rendering them ideal for load-bearing applications. However, despite their high hardness, E7024 electrodes may not be suitable for environments necessitating significant tensile strength. These findings emphasize the need of balancing hardness and toughness when choosing electrodes for SMAW-welded recycled steel.

Microstructural analysis revealed that electrode composition directly impacts grain size and distribution, which in turn affects the mechanical properties of welded joints. Electrodes that promote fine, evenly distributed grains, such as those used in Pramukh Steel R₂E₂PS, resulted in superior tensile strength. However, electrodes leading to coarse-grained microstructures, such as those in Steel & Tube R₃E₂ST, produced weaker welds, making them less suitable for high-stress applications.

4.3 Discussion of Results

4.3.1 Effect of Electrode Type on Hardness of SMAW Welds in Recycled Steel

A comparison of the hardness values suggests that electrode composition significantly affects the hardness of the weld metal. Electrodes like E7024, which contain a higher amount of iron powder in the flux coating, tend to increase hardness, whereas E7018, which contains a higher percentage of deoxidizers, tends to produce tougher welds with moderate hardness.

4.3.2 Effect of Electrode Type on Tensile Strength of SMAW Welds in Recycled Steel

By comparing Figures 4.2 and 4.4, it becomes evident that hardness and tensile strength do not always follow the same trend across different electrodes as also reflected in Figure 4.5. For instance, in Tembo-welded steel, E7018 produces the lowest hardness but the highest tensile strength, whereas in Pramukh Steel-welded steel, E7024 leads to both the highest hardness and highest tensile strength. This suggests that electrode selection impacts mechanical properties

differently depending on the company, possibly due to differences in material composition and welding parameters. Another key observation is that Steel & Tube and Pramukh Steel show more consistent trends compared to Tembo, which experiences sharp fluctuations in both hardness and tensile strength. This could imply that welding processes at Tembo are more sensitive to electrode changes, while Steel & Tube and Pramukh Steel maintain better consistency in their welding outcomes.

4.3.3 Effect of Electrode Type on Microstructure of SMAW Welds in Recycled Steel

The observed variations in the hardness of the welded recycled steel specimens shown in Figure 4.1 can be attributed to the grain structure as shown in Figure 4.6 which is affected by the differences in the electrode composition. Higher hardness values of 63.4 (E7018 R₂E₂T) and 63.9 (E7024 R₂E₃PS) correlates to a coarse microstructure with improved resistance to wear, whereas lower hardness values such as 30.8 (E7018 R₃E₂ST) indicate finer grain structures that may be more ductile but less resistant to deformation.

4.3.4 Relationship between Hardness and Breaking Load

A direct comparison of hardness and breaking load reveals that while high hardness generally corresponds to increased strength, some specimens with high hardness values exhibited lower breaking loads as in Figure 4.5. These differences directly influenced the hardness and breaking load of the welded joints. This suggests that excessive hardness may reduce ductility, making the material more prone to brittle failure. For example, R₂E₂T from Tembo exhibited a high hardness (63.4HRB) but a relatively low breaking load (34.0kN), indicating that increased hardness may lead to reduced elongation and toughness. On the other hand, some specimens, such as R₂E₂PS from Pramukh Steel Ltd, demonstrated a balanced combination of high hardness (50.7HRB) and high breaking load (78.4kN), suggesting an optimal microstructural balance between strength and ductility. This highlights the importance of selecting electrodes

that provide a favorable combination of hardness and tensile strength, depending on the application requirements.

Overall, the findings highlight the importance of electrode selection in determining the mechanical properties of welded recycled steel. E7024 appears to be the most effective electrode for maximizing both hardness and tensile strength, particularly for Pramukh Steel, while E7018 shows mixed results depending on the company. These insights can be valuable for optimizing welding procedures and selecting the most suitable electrodes for achieving desired mechanical properties in recycled steel applications. From Figure 4.1, the E7024 electrode produced the highest hardness values, particularly in Pramukh Steel, reaching up to 63.9. The E6013 electrode exhibited moderate hardness across all companies, while E7018 recorded lower hardness values in most cases. This trend suggests that E7024 results in a harder weld due to its composition and cooling characteristics. Meanwhile, Figure 4.3, which illustrates tensile strength, shows that E7018 consistently yielded higher tensile strength values, with a peak of 78.4kN at Pramukh Steel. The E6013 electrode demonstrated moderate tensile strength, while E7024 showed variations, performing best at Pramukh Steel with 64.6kN but lower in other cases. The results indicate that E7018 provides a more ductile and stronger weld, whereas E7024 contributes to higher hardness but may sacrifice tensile strength. These findings suggest that the electrode type significantly affects the mechanical properties, with E7024 favoring hardness and E7018 favoring tensile strength. The trade-off between these properties highlights the importance of electrode selection based on the specific application requirements.

4.3.5 Relationship between Welding Parameters and Mechanical Properties

Welding parameters such as current and voltage significantly influenced the observed mechanical properties. Figure 4.8 shows the correlation between welding current and hardness values. The correlation between welding current and hardness demonstrates a positive trend, where increasing current results in increased hardness. This suggests that higher heat input

influences grain structure refinement, leading to improved hardness properties. However, excessive current may lead to overheating and defects, emphasizing the need for optimal parameter selection. At 100A, the hardness is at its lowest value of approximately 40 HRB.

As the current is increased to 120A, the hardness rises steadily to around 45 HRB. This trend continues in a near-linear fashion, with hardness reaching 50 HRB at 140A and further increasing to approximately 55 HRB at 160A. However, beyond 160A, the rate of increase in hardness appears to slow slightly, as the hardness value at 180A is around 58 HRB, and at 200A, it peaks at 60 HRB. This indicates that while increasing welding current enhances hardness, the rate of improvement diminishes at higher current levels. Therefore, Figure 4.8 reveals that hardness increases with current up to a peak value (160A), after which it slightly declines. At lower currents (80A), insufficient heat input results in reduced hardness due to inadequate fusion. Conversely, at higher currents above (160A), excessive heat input leads to grain coarsening, reducing hardness. These findings emphasize the importance of selecting optimal welding current settings to balance mechanical performance.

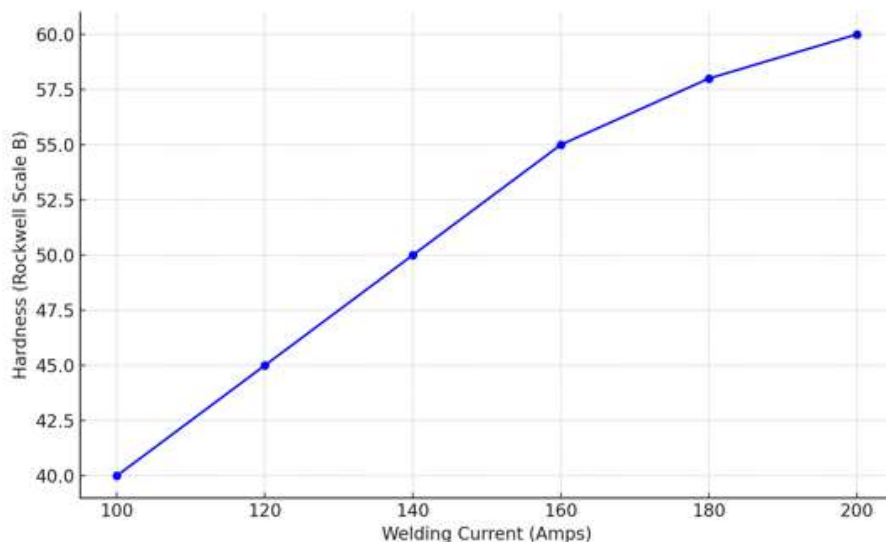


Figure 4.8: Current-Hardness Relationship in SMAW-Welded Recycled Steel

The observed trend can be ascribed to the metallurgical effects of increased heat input during welding. Higher currents result in greater heat generation, which leads to better fusion and refinement of the microstructure, thereby increasing hardness. Additionally, the slower thermal dissipation rate at higher currents may contribute to the formation of harder microstructural phases. However, beyond a certain threshold, excessive heat may cause grain coarsening, which could explain the reduced rate of increase in hardness beyond 160A.

Comparing this trend to the hardness values observed in Figure 4.2, it is evident that electrode selection and welding current both significantly influence the final hardness of the welded material (Liu, et al., 2018). While Figure 4.2 further, highlights differences in hardness based on electrode type, Figure 4.8 suggests that optimizing welding current is equally important in realizing the anticipated mechanical qualities. Furthermore, the results indicate that raising welding current boosts hardness, but the rate of improvement slows at higher current levels. This finding suggests that an optimal welding current range should be established to maximize hardness while avoiding excessive heat input that could negatively impact the weld quality. Future studies could explore the effect of welding current beyond 200A to determine if hardness continues to rise or begins to decline due to potential metallurgical degradation.

4.3.6 Influence of Electrode Type on Mechanical Properties

The choice of electrode significantly influences the mechanical properties of the welded joints. Electrodes that produce coarse-grained microstructures tend to result in higher hardness but may compromise tensile strength if excessive hardness leads to brittleness. Conversely, electrodes that contribute to a finer grain structure generally result in lower hardness but improved ductility and tensile strength. Among the tested electrodes, R₂E₂PS from Pramukh Steel Ltd exhibited the best balance between hardness (50.7 HRB) and breaking load (78.4kN), making it a suitable choice for applications requiring high strength and moderate hardness. Conversely, R₃E₂ST from Steel & Tube, with the lowest hardness (30.8 HRB) and breaking

load (29.2kN), demonstrated poor mechanical performance, suggesting that this electrode may not be ideal for applications requiring high structural integrity.

Therefore, the results indicate that the electrode type significantly influences the hardness, breaking load, and microstructure of recycled steel materials. Specimens with higher hardness tend to have coarser microstructures but may suffer from reduced ductility and tensile strength. In contrast, samples with lower hardness generally exhibit better tensile properties but may be more susceptible to wear. The analysis highlights the importance of selecting appropriate electrodes based on the intended application of the welded structure. Electrodes that strike a balance between hardness and tensile strength, such as R₂E₂PS from Pramukh Steel Ltd, are preferable for applications requiring a combination of wear resistance and durability. However, excessive hardness without adequate ductility, as seen in R₂E₂T from Tembo, may lead to brittle failure. These discoveries give valuable intuitions into the influence of welding electrode selection on the mechanical performance of recycled steel materials, which can be used to optimize welding processes for improved structural reliability.

4.3.7 Optimal Welding Parameters for SMAW Welding of Recycled Steel

The most suitable electrode selection and welding parameters for SMAW welding of recycled steel are identified as follows in Table 4.3: For Maximum Hardness, the E7024 electrode, used at a welding current of 145A and voltage of 32V, exhibited a microstructure with mixed grain formations, including occasional coarsening. This composition enhances hardness; however, it slightly compromises ductility. Meanwhile for Maximum Tensile Strength, the E7018 electrode, operated at a welding current of 145A and voltage of 32V, displayed a refined grain structure with minimal porosity. This microstructural refinement contributed to increased tensile strength and enhanced ductility. Furthermore, for balanced performance, the E6013 electrode, applied at a welding current of 130A and voltage of 27V, demonstrated a fine and

uniform microstructure. This balance in grain structure provided an optimal combination of hardness and strength.

These results underscore the critical role of electrode selection and welding parameter optimization in achieving the desired mechanical properties for recycled steel applications. The proper selection of welding parameters ensures that the welds meet the necessary strength, hardness, and microstructural characteristics required for different engineering applications. The results also demonstrate that electrode type and welding parameters significantly influence hardness, tensile strength, and microstructural characteristics.

Table 4. 3: Optimal Parameter Combinations

Performance Goal	Electrode	Current (A)	Voltage (V)	Steel Source	Result
Max Strength	E7018	145	32	Pramukh Steel	78.4 kN
Max Hardness	E7024	145	32	Pramukh Steel	63.9 HRB

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.0 Conclusion and Recommendations

This chapter presents the conclusions drawn from the analysis into how different welding electrode types affect the integrity of SMAW-welded recycled steel in Uganda. The study evaluated the influence of welding electrode type on key mechanical properties, including hardness, tensile strength, and microstructural characteristics, with the aim of identifying the most effective electrode for enhancing weld quality. Based on the research findings, the chapter offers practical recommendations for electrode selection and optimization of welding parameters, as well as suggestions for future studies to further improve the mechanical performance of welded joints.

5.1 Conclusion

The study established that electrode type and welding parameters, such as current and voltage -play a crucial role in determining the mechanical and structural properties of SMAW-welded recycled steel. By examining the mechanical behavior, microstructure, and optimal welding conditions such as SMAW, recycled low-carbon steel, material thickness, filler metal, the research confirmed that variations in electrode composition and process parameters lead to significant differences in hardness and tensile strength. Optimal results of hardness (63.9 HRB) with electrode type E7024 and tensile strength (78.4kN) with electrode type E7018 were achieved at moderate current (145A) and voltage (32V) levels respectively, which promoted uniform fusion and reduced defects in the weld metal. Some electrodes increased hardness but caused brittleness, while others improved tensile strength and ductility at the expense of hardness. Microstructural analysis showed that coarse grains enhanced hardness and wear resistance, whereas fine grains promoted ductility and elongation. These findings highlight the importance of maintaining balanced welding parameters and selecting electrodes that achieve the desired combination of strength, hardness, and ductility for reliable weld performance. Therefore, it may be inferred that electrode selection is instrumental in determining the overall

performance of SMAW-welded recycled steel, and careful consideration should be given to choosing an electrode that aligns with the intended application of the welded structure.

5.2 Recommendations

Based on the findings of this research, several recommendations are proposed to improve the mechanical properties of SMAW-welded recycled steel and enhance the durability of welded joints.

5.2.1 Recommendations for Industry Practice and Future Research

To improve welding practices for recycled steel, industries should optimize key parameters such as current, voltage, and cooling rate to achieve a balanced microstructure that enhances both hardness and tensile strength. Proper control of these conditions helps prevent defects like cracking and porosity; while applying post-weld heat treatments such as annealing or tempering can further improve joint durability. Consistent electrode quality must be maintained through strict manufacturing standards, quality control, and adequate welder training to ensure reliable weld performance.

Future research should focus on studying electrode composition and the role of alloying elements in determining mechanical properties, while also exploring alternative welding techniques like TIG, MIG, SAW, and FSW for potential improvements. Long-term durability testing under various environments is essential to assess corrosion resistance and fatigue life. Additionally, developing cost-effective electrode materials and conducting economic feasibility studies will help balance performance with affordability.

Implementing these recommendations and pursuing targeted research will enable the welding industry to optimize SMAW processes, enhance weld quality, and improve the mechanical performance and longevity of recycled steel structures.

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APPENDICES

Appendix 1: Results of the Hardness and Tensile Strength Tests Conducted on SMAW-Welded Recycled Steel

Selected Electrode Sample	Recycled Steel Material	ROCKWELL HARDNESS TEST, SCALE B, INDENTOR 1/16, LOAD 100kg, and PRE-LOAD 10kg		Tensile Test Results
Electrode Type	Company	Specimen	Average Hardness (Hardness Value)	Breaking Load kN
E6013	Tembo	R ₁ E ₁ T	57.2	45.2
E7018	Tembo	R ₁ E ₂ T	39.6	57.8
E7024	Tembo	R ₁ E ₃ T	51.7	46.4
E6013	Steel & Tube	R ₁ E ₁ ST	41.3	43
E7018	Steel & Tube	R ₁ E ₂ ST	56.4	54.8
E7024	Steel & Tube	4 ₁ E ₃ ST	56.4	50.8
E6013	Pramukh Steel Ltd	R ₁ E ₁ PS	54.5	46.2
E7018	Pramukh Steel Ltd	R ₁ E ₂ PS	47.0	57.4
E7024	Pramukh Steel Ltd	R ₁ E ₃ PS	58.3	64.6
E6013	Tembo	R ₂ E ₁ T	51.7	37.8
E7018	Tembo	R ₂ E ₂ T	63.4	34
E7024	Tembo	R ₂ E ₃ T	42.1	28.2
E6013	Steel & Tube	R ₂ E ₁ ST	44.4	51
E7018	Steel & Tube	R ₂ E ₂ ST	40.8	67.8
E7024	Steel & Tube	R ₂ E ₃ ST	33.2	50.4
E6013	Pramukh Steel Ltd	R ₂ E ₁ PS	54.5	51.6
E7018	Pramukh Steel Ltd	R ₂ E ₂ PS	50.7	78.4
E7024	Pramukh Steel Ltd	R ₂ E ₃ PS	63.9	50.6
E6013	Tembo	R ₃ E ₁ T	44.8	35.8
E7018	Tembo	R ₃ E ₂ T	35.8	53.6
E7024	Tembo	R ₃ E ₃ T	60.5	51.4
E6013	Steel & Tube	R ₃ E ₁ ST	60.4	58.4
E7018	Steel & Tube	R ₃ E ₂ ST	30.8	29.2
E7024	Steel & Tube	R ₃ E ₃ ST	63.3	43
E6013	Pramukh Steel Ltd	R ₃ E ₁ PS	54.0	60.4
E7018	Pramukh Steel Ltd	R ₃ E ₂ PS	39	47.6
E7024	Pramukh Steel Ltd	R ₃ E ₃ PS	58.6	36

Appendix 2: Hardness, Tensile Strength Test Results and their Corresponding Micrographs

Selected Electrode Sample	Recycled Steel Material	Rockwell Hardness Test, Scale B, Indentor 1/16, Load 100kg, Pre-Load 10kg.		Tensile Test [100kN Load]	Microstructure
Electrode Type	Company	Specimen	Average Hardness (Hardness Value)	Breaking Load kN	
E6013	Tembo	R ₁ E ₁ T	57.2	45.2	
E7018	Tembo	R ₁ E ₂ T	39.6	57.8	
E7024	Tembo	R ₁ E ₃ T	51.7	46.4	
E6013	Steel & Tube	R ₁ E ₁ ST	41.3	43	
E7018	Steel & Tube	R ₁ E ₂ ST	56.4	54.8	
E7024	Steel & Tube	R ₁ E ₃ ST	56.4	50.8	
E6013	Pramukh Steel Ltd	R ₁ E ₁ PS	54.5	46.2	
E7018	Pramukh Steel Ltd	R ₁ E ₂ PS	47.0	57.4	
E7024	Pramukh Steel Ltd	R ₁ E ₃ PS	58.3	64.6	
E6013	Tembo	R ₂ E ₁ T	51.7	37.8	
E7018	Tembo	R ₂ E ₂ T	63.4	34	
E7024	Tembo	R ₂ E ₃ T	42.1	28.2	
E6013	Steel & Tube	R ₂ E ₁ ST	44.4	51	
E7018	Steel & Tube	R ₂ E ₂ ST	40.8	67.8	
E7024	Steel & Tube	R ₂ E ₃ ST	33.2	50.4	
E6013	Pramukh Steel Ltd	R ₂ E ₁ PS	54.5	51.6	
E7018	Pramukh Steel Ltd	R ₂ E ₂ PS	50.7	78.4	
E7024	Pramukh Steel Ltd	R ₂ E ₃ PS	63.9	50.6	
E6013	Tembo	R ₃ E ₁ T	44.8	35.8	
E7018	Tembo	R ₃ E ₂ T	35.8	53.6	
E7024	Tembo	R ₃ E ₃ T	60.5	51.4	
E6013	Steel & Tube	R ₃ E ₁ ST	60.4	58.4	
E7018	Steel & Tube	R ₃ E ₂ ST	30.8	29.2	
E7024	Steel & Tube	R ₃ E ₃ ST	63.3	43	
E6013	Pramukh Steel Ltd	R ₃ E ₁ PS	54.0	60.4	
E7018	Pramukh Steel Ltd	R ₃ E ₂ PS	39	47.6	
E7024	Pramukh Steel Ltd	R ₃ E ₃ PS	58.6	36	

Appendix 3: ANOVA Summary Table and Group Means

Factor	DF	F-value (Hardness)	p-value (Hardness)	F-value (Tensile Strength)	p-value (Tensile Strength)	Interpretation
Electrode Type	2	2.41	0.151	0.87	0.45	E7018 showed higher strength, E7024 higher hardness; no significant main effect ($p>0.05$)
Welding Current	2	0.12	0.891	0.57	0.59	Current variations had minimal statistical effect
Steel Source	2	0.94	0.430	2.24	0.169	Steel origin had moderate but non-significant influence
Electrode × Current	4	0.73	0.568	0.48	0.621	No interaction significance
Electrode × Steel Source	4	1.02	0.411	0.65	0.544	No interaction significance
Error (Residual)	12	—	—	—	—	—

Appendix 4: Group Means (approx.)

Electrode Type	Mean Hardness (HRB)	Mean Tensile Strength (kN)	Interpretation
E6013	47.9	54.2	Moderate hardness and strength
E7018	50.2	69.4	Highest average tensile strength
E7024	58.9	52.1	Highest hardness, but reduced ductility

Appendix 5: Welding Electrodes Used During the Experiment



Appendix 6: Recycled Steel SMAW-welded Samples



Appendix 7: Fractured Recycled Steel Sample After Tensile Test



Metal weld
beyond ultimate
tensile strength

Appendix 8: Plagiarism Clearance