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M.Sc. in Mechanical Engineering

TAMER UÇAR

REPUBLIC OF TÜRKİYE
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

THE EFFECT OF ARC STUD WELDING PARAMETERS ON MECHANICAL PROPERTIES OF DOCOL 1500M STEEL WELDING JOINTS

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submitted by **Tamer UÇAR** in partial fulfillment of the requirements for the degree of Master of Science in **Mechanical Engineering, Gaziantep University** is approved by,

Prof. Dr. Çiğdem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences ………….............

Prof. Dr. Ahmet ERKLİĞ
Head of the Department of Mechanical Engineering ………….............

Prof. Dr. Ömer EYERCİOĞLU
Supervisor, Mechanical Engineering
Gaziantep University ………….............

Exam Date: 02 September 2024

Examining Committee Members:

Prof. Dr. Metin KÖK
Kahramanmaraş Sütçü İmam University ………….............

Prof. Dr. Ömer EYERCİOĞLU
Gaziantep University ………….............

Prof. Dr. Necip Fazıl YILMAZ
Gaziantep University ………….............

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Tamer UÇAR

ABSTRACT

THE EFFECT OF ARC STUD WELDING PARAMETERS ON MECHANICAL PROPERTIES OF DOCOL 1500M STEEL WELDING JOINTS

UÇAR, Tamer
M.Sc. in Mechanical Engineering
Supervisor: Prof. Dr. Ömer EYERCİOĞLU
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Arc stud welding is a welding method that takes advantage of the arc's ability to melt metals. Stud welding is an easy and fast welding method that is generally applied to surfaces where threading is problematic and welding is difficult. Docol 1500M materials are advanced high-strength steels (AHSS) with high tensile strength up to 1700 MPa and good ductility. These materials provide high efficiency in the automotive industry in terms of both vehicle lightness and advanced crash protection. In this study, the weldability of 20MnB4 quality carbon steel threaded studs on the Docol 1500M plate was investigated using the arc stud welding process. The welding process was carried out using ceramic ferrules in different combination values with electric current values ranging from 300A to 500A and different welding times from 0.125 seconds to 0.300 seconds, and variable welding parameters such as 3mm plunge value and 5.9mm lifting distance. To obtain a quality weld, the most suitable welding parameters and the effects of these parameters on mechanical and microstructural properties were examined experimentally, metallurgical examinations such as visual inspection of welded samples, bending tests, tensile strength, and hardness properties were carried out and an attempt was made to explain them with microstructural evaluation.

Key Words: Arc Stud Welding, Ahss, Docol 1500m, 20mnb4, Joint Strength, Tensile Strength, Fea

ÖZET

ARK SAPLAMA KAYNAK PARAMETRELERİNİN DOCOL 1500M KAYNAK BAĞLANTILARININ MEKANİK ÖZELLİKLERİNE ETKİSİ

UÇAR, Tamer
Yüksek Lisans Tezi, Makine Mühendisliği
Danışman: Prof. Dr. Ömer EYERCİOĞLU
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Ark saplama kaynağı, arkın metalleri eritme özelliğinden yararlanan bir kaynak yöntemidir. Saplama kaynağı genellikle diş çekmenin sorunlu olduğu ve kaynağın zor olduğu yüzeylere uygulanan kolay ve hızlı bir kaynak yöntemidir. Docol 1500M malzemeleri, 1700 MPa'ya kadar yüksek çekme mukavemetine ve iyi sünekliğe sahip gelişmiş yüksek mukavemetli çeliklerdir. Bu malzemeler otomotiv sektöründe hem araç hafifliği hem de gelişmiş çarpışma koruması açısından yüksek verimlilik sağlıyor. Bu çalışmada, 20MnB4 kalite karbon çeliği dişli saplamaların Docol 1500M levha üzerine ark saplama kaynağı işlemi kullanılarak kaynak edilebilirliği araştırılmıştır. Kaynak işlemi, 300A'den 500A'e kadar değişen elektrik akımı değerlerinde ve 0,125 saniyeden 0,300 saniyeye kadar farklı kaynak sürelerinde, 3mm dalma değeri ve 5,9mm kaldırma mesafesi gibi değişken kaynak parametrelerinde, farklı birleşim değerlerinde seramik yüksükler kullanılarak gerçekleştirildi. Kaliteli bir kaynak elde etmek için en uygun kaynak parametreleri ve bu parametrelerin mekanik ve mikro yapısal özelliklere etkileri deneysel olarak incelenmiş, kaynaklı numunelerin görsel muayenesi, eğilme testleri, çekme mukavemeti ve sertlik özellikleri gibi metalürjik incelemeler yapılmış ve mikro yapısal değerlendirme ile açıklanmaya çalışılmıştır.

Anahtar Kelimeler: Ark Saplama Kaynağı, Ahss Docol 1500m, 20mnb4, Bağlantı Mukavementi, Sonlu Eleman Analizi

''Dedicated to my beloved wife Evrim Uçar''

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LIST OF SYMBOLS

Ø	Diameter
l	Length
t	Material Thickness
ά	Bending Angle

LIST OF ABBREVIATIONS

ASW	Arc Stud Welding
SG	Shielding Gas
CF	Ceramic Ferrule
DASW	Drawn Arc Stud Welding
CDSW	Capacitor Discharge Stud Welding
I	Welding Current (ampere)
tw	Welding Time
P	Plunge Distance
L	Lift Distance
AHSS	Advanced High Strength Steel
EDM	Electro Discharge Machine
LPT	Liquid Penetrant Testing
Ar	Argon
CO_2	Carbon Di Oxide
Rpm	Revolutions Per Minute
HNO_3	Nitric Acid
ASW	Arc Stud Welding
TTT	Time-Temperature-Transformation
WM	Weld Metal
HAZ	Heat Affected Zone
BM	Base Metal
DOP	Depth of Penetration
GTAW	Gas Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
HSLA	High Strength Low Alloy
MS	Martensitic Steel
ISO	The International Organization for Standardization

CHAPTER 1
INTRODUCTION

1.1 Introduction

This section briefly describes the history of welding, arc stud welding technology, the place of arc stud welding in metal joining, and the properties of the Docol 1500 Martensite Material. The main purpose and details of this study can also be found in this section.

1.2 State of Arc Stud Welding Process In The Metal Joining

Arc stud welding is used the most manufacturing areas widely and the technology of the process is well-known nowadays. The implementation of the stud welding process is well established in different production areas; steam boiler manufacturing, bridge and other types of construction industries, automotive and appliance industry (Samardžić et al., 2009). The process is also used in the manufacture of engine blocks, the marine industry, the electrical and electronics industry, the aviation industry, and in anchoring systems of permanent equipment embedded in concrete parts of dams.

1.3 Importance of High Strength Steels In The Metal Industry

Advanced High Strength Steels or automotive steels enable lighter but stronger automotive productions by increasing the strength, durability, fatigue resistance, and torsional strength of the automobile while reducing the weight of auto parts. These types of steels are important materials that enable automotive designs that provide lower engine and fuel consumption and less carbon dioxide emissions without compromising safety. In addition to its ability to be shaped and welded, it is one of the main steel materials that enables complex sheet metal manufacturing parts and is especially preferred in the automotive industry.

1.4 The Purpose of This Study

The main purpose of this study is to determine the optimum welding parameters as a result of welding 20MnB4 material and Docol 1500M high-strength sheet material by stud welding method and to determine the effect of arc stud welding process parameters on mechanical and microstructural properties.

1.5 The Main Structure of The Thesis

This thesis consists of 6 chapters, including the introduction, conceptual framework, related studies, method, findings, discussion, and results.

In the introduction, part of Chapter 1, general information about arc stud welding technology, its place in metal joining techniques and its usage areas, and general definition and usage areas of Docol 1500M high-strength steels are given.

Chapter 2 includes a summary of different studies and research on arc stud welding and high-strength steels under the name of literature research.

In Chapter 3, general information about the welding process and high-strength sheets, the definition of the welding process, application principles, welding process types and equipment, types of high-strength steels, and their application areas are explained.

Chapter 4, describes the experimental preparations and setup of the arc stud welding process and arc stud welding parameter selections. In addition, the preparation of weld samples, application of the welding process, tensile strength tests, bending tests, hardness tests, penetration depth measurement, and metallurgical examinations of the samples after the welding process is reported.

Section 5 presents Results and discussions. Determination of optimum welding parameters for a strong and durable welded connection, the effects and changes of welding parameters on tensile and connection strength, analysis of tensile tests, bending tests, and metallurgical investigations are also reported in this section.

The results and future work on welding carbon steel studs onto high-strength steel by arc stud welding method are presented in Chapter 6.

CHAPTER 2
LITERATURE SURVEY

2.1 Introduction

In this section, different previous studies on Arc Stud Welding applications and high-strength steels are summarized. All the literature included here summarizes previously completed and published work on the arc stud welding method and high-strength steels.

2.2 Literature Related With This Work

There are several different processes for joining studs to plates or structurally dissimilar materials in welding applications. When we look at these processes, resistance welding, friction welding, and stud arc welding are the most frequently used applications. Stud arc welding is generally the fastest method and is particularly advantageous in production efficiency and threaded s in multiple weld fabrications. The arc stud welding method was first used after World War I at the New York Naval Shipyard in the United States and was later widely used in the construction of military aircraft carriers and the construction industry (Cary, 2004; Miller Welds, 2016).

N. F. Yilmaz et al., (2014) examined the effects of welding parameters such as current, time, plunge, and lift on microstructural properties using AISI 304 quality base material and the same quality stud material. As a result of experimental studies, it has been observed that as the stud diameter increases, more welding current and welding time are needed, and current, plunge, and lift height are decisive in terms of tensile strength. It was also determined that low current and time factors cause insufficient melting, and high current and time values cause the weld to burn.

They concluded that current and time factors have an impact on the penetration depth. Except this, it was seen that at high currents and times, the hardness, melting, and solidification values in the weld area were higher than the base metal and lower at the weld center line (Yilmaz & Hamza, 2014b).

C. Hsu and J. Mumaw et al., (2011) combined M6 studs made of mild steel on usibor, bare boron, HC500C, and AHSS quality materials with different thicknesses and coatings by arc welding method, observed their weldability and evaluated the results comparatively. The results of the study were interpreted separately for each different experiment. As a result of the studies, it has been determined that the AHSS welded quality and the most effective welding parameters vary depending on the steel type, thickness value, and coating. It has been observed that high and low lift values for mild steel material affect the working tolerance and quality. It has been determined that uncoated boron steel has the best welding quality, and poor welding strength is obtained as a result of increasing the lifting settings. It has been observed that Usibor steel has a weaker connection than uncoated boron steel in terms of weldability, and although the welding process is performed slowly and at low temperatures, boron steel provides a more successful connection in terms of weld strength. It was also determined that due to the relation between weld strength and melt-through hole, HC500C had the worst weldability properties (Hsu & Mumaw, 2011).

O. Eyercioglu et al., (2021) examined the temperature gradient, bending loads, and springback behavior by performing V-bending tests at different temperatures on the 2 mm thick Docol 1500 Marteniste material. As a result of the experimental study, it was concluded that increasing the local heating values reduced the punch loads, no cracks were observed after bending, and increasing the bending temperature reduced the amount of spring back (Eyercioglu et al., 2021).

G. Kucukturk et al., (2022) investigated the effects of heating temperature and bending angle on spring back after bending in the V-bending process of Docol 1400 steel sheets. As a result of the study, the analysis showed that springback decreased linearly in twisting operations performed under high temperatures and that there was a decrease in the mechanical properties of the material in the heated twisting zone between room temperature and 600°C (Küçüktürk et al., 2022).

S. J. M. Algodi et al., (2023) joined AISI 1106 steel stud to AISI 1045 base metal by arc stud welding method using 200A and 400A welding currents and 1-2 seconds welding times and examined the effects of these parameters on microstructure and mechanics. Additionally, during the process, 0.1- 1gr. SIC powder was added to the welding area and a nanocarbon layer was applied. At the end of the study, it was observed that the welding process performed with 400A current and 0.4 seconds welding time had a tensile strength of 583Mpa, and the strength values of SIC powder and nano carbon coated welding areas decreased. In the tensile tests, three different damage conditions were detected; interface fracture between the stud and the base metal, pullout fracture on the base metal, and fracture from the stud shank. It was observed that the microstructure in the weld zone was primarily composed of equiaxed ferrite grains and pearlite containing a small amount of ferrite, while the fusion zone consisted of fine-grained ferrite. In addition, the hardness of the fusion zone was measured as 132V, while the hardness of the stud was measured as 128HV and the base metal was measured as 164HV (Algodi et al., 2023).

M. Yılmaz et al., (2016) determined that welding parameters are important for a quality weld connection and should be adjusted appropriately according to the material dimensions. For this, they developed a mathematical model between appropriate source parameters and input data. They predicted the tensile strength of weld joints with the Adaptive Neural Network Based Fuzzy Inference System (ANFIS) model they developed. Using stud diameter, current, time, lift height, and plunge amount as input data, they prepared test sets and performed 45 different tensile tests. They developed an (ANFIS) model using the experimental results and increased the number of trials using Trimf, Gauss, and Bell function types. They used statistical data metrics such as R2, MAE, and MSE to evaluate the accuracy of the models and found that the learning performance of the types of functions used was high. They determined that the best model among the models was Trimf and that the function number model was shaped as 2-2-3-2-3 and reported the statistical values of the model as R2 = 0,87, MAE = 43,67 ve MSE = 3353,66. The Gbell function model was determined to be an inappropriate function type and the R2 coefficient of determination and its value were found to be below 0.7. At the end of this study, they concluded that the models created with ANFIS can give appropriate welding parameter values according to the stud diameter to obtain a quality weld (Yilmaz et al., 2016).

2.3 Contribution of This Work In The Literature

In this research, the weldability of carbon steel stud on high-strength steel plate by arc stud welding was examined, and the effect of welding parameters on the welding joint was tried to be determined to obtain a quality and durable welded joint. According to the literature, previous studies on arc stud welding methods and high-strength steel (AHSS) sheets have been examined and their summaries are included in our study. With the experimental study, optimum welding parameters were tried to be determined depending on the size and properties of the materials to obtain a quality weld. At the end of the welding process, the effects of arc stud welding parameters such as welding current, welding time, plunge, and lift distance on mechanical and microstructural properties were examined and the results were reported.

CHAPTER 3

ARC STUD WELDING PROCESS TECHNOLOGY

3.1 Introduction

In this section, general theoretical information about welding applications and welding types is given. At the same time, the definition of the Arc stud welding method used in our research, stud welding application types, the machinery, equipment, and accessories of the application are introduced and information about their features is included.

3.2 Evolution of the Welding Processes

Welding art is an ancient craft that combines science and technology with human skill. The development and change process of welding art dates back to 3000 years before Christ, to the Sumerians and Egyptians. While the Sumerians used the brazing method on their swords, the Egyptians accepted that it was an easier method to join the iron by heating and hammering it. Evidence was uncovered that the method known as "pressure (hammering) welding" was used on various metal materials (gold, iron, bronze, copper, etc.) found in tombs and sarcophagi excavations in ancient times. Although basic welding techniques were well-known in the sixteenth century, they were not widespread. In his book "Pyrotechnia", published in Venice in 1540 by the Italian Engineer Vannoccio Biringuccio, he stated that welding "seems to me to be an ingenious thing, not very useful, but still very useful." The welding method, also known as the hammering method, made it possible to produce all kinds of iron goods with the development of blacksmithing in the Middle Ages. However, the discovery and use of today's welding technology were only possible in the 19th century, and several completely new welding principles and methods emerged during this period (Hamza, 2012). At that time, it was possible to store the flame and heat required for welding by safely combining oxygen and acetylene gases, as well as to generate the necessary and sufficient electric current for resistance welding and arc welding.

The intensity of the heat source allowed heat to be generated on the workpiece faster than it was transferred to the surrounding metal. As a result, a molten pool could be developed that could solidify and form a bond between the parts to be welded. The development of other basic types of welding, such as resistance welding, gas welding, and arc welding, also began before World War I (Weman, 2011).

When we look at welding technology chronologically from the date it was first discovered to the present day, the development of welding technology over the years can be summarized as follows.

According to historians, acetylene was discovered by Edmund Davy in England in 1836, in 1800 Sir Humphry Davy used a battery to create an arc between two carbon electrodes, and arc lighting was developed with the invention of the electric generator in the 19th century. In the late 1800s, gas welding, cutting, carbon arc, and metal arc welding were developed.

In 1881, Auguste De Meritens, based at the Cabot Laboratory in France, pioneered the use of arc heat to join lead plates in storage batteries. His student, the Russian Nikolai N. Benardos, also working in the French laboratory, obtained a patent for welding. Together with fellow Russian Stanislaus Olszewski, Benardos secured a British patent in 1885 and an American patent in 1887, which included designs for an early electrode holder. This marked the inception of carbon arc welding. While Benardos focused primarily on carbon arc welding, he could weld both iron and lead. The method gained significant popularity in the late 1890s and early 1900s.

C.L. Coffin of Detroit received the first U.S. patent in 1890 for an arc welding process using a metal electrode, the first application of a filler metal deposited across the arc by the electrode into the joint to create the weld.

The first metal electrode coated with a thin layer of clay or lime was introduced in Great Britain by Strohmenger in the 1900s. Oscar Kjellberg, a Swede, invented a covered or coated electrode between 1907 and 1914 and produced rod electrodes by dipping and coating bare iron wires in thick mixtures of carbonate and silicate. Resistance welding processes such as spot welding, seam welding, projection welding, and flash-end welding were developed during this period. A German named

Goldschmidt also perfected gas welding and cutting during this period, inventing thermite welding, which was used to weld railway rails in 1903.

The production of oxygen gas and the subsequent liquefaction of air contributed to the development of both welding and cutting, with the invention of the blowpipe and torch in 1887. Before this date, hydrogen and coal gas were used along with oxygen, but a torch suitable for use with low-pressure acetylene was developed in the 1900s.

After World War I, 20 members of the Emergency Fleet Company's Wartime Welding Committee, led by Comfort Avery Adams, formed the American Welding Society, a nonprofit organization dedicated to the development of welding technology. Alternating current was discovered by C. J. Holslag in 1919, and thickly coated electrodes became common in the 1930s.

In 1920, P.O. Nobel of General Electric Company invented the automatic welding method. General Electric used the automatic welding method to manufacture worn engine shafts and worn crane wheels, while the automobile industry used this method to manufacture rear axle housings. Langstroth and Wunder of the A. O. Smith Company developed heavily coated electrodes in 1927, followed by the Lincoln Electric Company in 1929, which manufactured and sold extruded electrode rods, and widespread use of coated electrodes began in 1930. The idea of shielding the arc and weld area with gas originated in the 1920s when Alexander and Langmuir invented the atomic hydrogen welding process while working on gas shielding techniques using hydrogen. This process never became widespread, but it was used in specialty welding applications in the 1930s and 1940s and later for welding tool steels. H.M. Hobart and P.K. Devers conducted comparable research, employing argon and helium atmospheres. In their patents filed in 1926, they pioneered the concept of arc welding with gas surrounding the arc, which laid the groundwork for the gas tungsten arc welding process. Additionally, they demonstrated welding techniques using a concentric nozzle with a wire electrode fed through it, setting the stage for the gas metal arc welding process.

In 1930, welders at the New York Navy Yard pioneered stud welding to secure wood decking to metal surfaces. This technique gained traction in the shipbuilding and construction sectors. An automatic welding method that gained popularity during this time was submerged arc welding. Developed by the National Tube Company for a pipe mill in McKeesport, Pennsylvania, this under-powder welding process was specifically designed for creating longitudinal seams in pipes. Robinoff patented the method in 1930 and subsequently sold it to Linde Air Products Company, which rebranded it as Unionmelt welding. During the defense buildup period in 1938, shipyards and ordnance factories extensively utilized submerged arc welding. Known for its efficiency, this process continues to be a leading choice in the industry today.

Gas tungsten arc welding (GTAW) was invented and patented in 1890 by C.L. Coffin from the idea of welding in a non-oxidizing gas atmosphere. In the late 1920s, H.M. Hobart and P.K. Devers developed the process using helium and argon as shielding gases and were very successful in welding stainless and aluminum materials with magnesium. The process was nearly perfected with the development of the water-cooled torch after it was patented by Meredith in 1941, renamed Heliarc welding, and licensed to Linde Air Products. A new era in welding history began in 1948 when Battelle Memorial Institute, under the sponsorship of the Air Reduction Company, successfully developed the gas metal arc welding (GMAW) process. According to this principle patented by H.E. Kennedy, he used a gas-shielded arc similar to the gas tungsten arc to make the process more effective and usable, replaced it with a continuously fed electrode wire using a small diameter tungsten electrode for greater efficiency, and used a constant voltage power supply. Although it was first introduced for nonferrous metals, it was first tested on steel due to its high deposition rate. Since the cost of the inert gas used in the method applications was relatively high, it took time to achieve cost savings.

In 1953, Lyubavskii and Novoshilov discovered the CO_2 welding method, since the equipment used in this method was also used in inert gas metal arc welding, and it spread rapidly and pioneered an economical welding method. Since the arc in CO_2 welding is very hot, high currents were required for large-diameter electrodes, and it gained popularity with the production of small-diameter electrodes and the introduction of power sources. The short-circuit arc type, known as microwire, short arc, and dip transfer welding, was introduced in late 1958 and has become the most common gas metal arc welding method, allowing for versatile welding of thin materials.

In the 1960s, a different type using a small amount of oxygen-containing inert gas, providing a spray-type arc transfer, emerged and became quite popular. Recently, another type of pulsed current has been used. Accordingly, the method is based on the principle that the current changes from a high value to a low value at a rate of one or two times the line frequency. After the discovery of the CO_2 source, a special wire called the inner-outer electrode was developed, this wire was a special electrode wire with a pipe section and flux material inside. This shielding gas technique, called Dualshield, which refers to the use of an external shielding gas for arc protection in addition to the gas produced by the flux in the wire core, was invented by Bernard in 1954 but patented when it was reintroduced to the market by the National Cylinder Gas Company in 1957. In 1959, a new type of electrode known as the inside-outside electrode was developed, eliminating the need for external gas shielding. This lack of a shielding gas made the process attractive for non-critical applications and became known as Innershield®.

The electro slag welding process, used in the Soviet Union since 1951, was introduced at the Brussels World's Fair in Belgium in 1958, the basis of this welding process was work done by .K. Hopkins in the United States in 1940, but the process was never widely used. Hopkins worked with the Welding Research Laboratory in Bratislava, Czechoslovakia, and the Paton Institute Laboratory in Kyiv, Ukraine, to develop the welding process and equipment. The process was first used in the United States at the Electromotive Division of General Motors Corporation in Chicago, where they called it the "electro molding" process and used it to weld diesel engine blocks. In 1961, Arcos Corporation developed another vertical welding process called "electrogas" using the equipment it had developed for Electroslag welding, this process also used a flux-cored electrode wire and an externally supplied gas shield, and since no slag bath was used in the process, it was defined as an open arc process. These methods made it possible to weld thinner materials than the electro-slag process allowed. Invented by Gage in 1957, plasma arc welding uses an arc passing through an orifice that creates a higher temperature arc plasma than a narrowed arc or tungsten arc and is used for welding as well as metal spraying, cutting, and gouging. Electron welding was discovered by J. A. Stohr of the French Atomic Energy Commission on November 23, 1957, using a focused electron beam as a heat source in a vacuum chamber. The welding method became widely used in the automotive and aircraft engine industries, especially in the United States. The friction welding method was first used in the Soviet Union and is based on the principle of obtaining friction heat using rotational speed and superimposed pressure. This method, called inertia welding, was ideal for welding similar parts, as the initial investment cost was relatively high due to equipment and tools. Laser welding is a cutting-edge technique. It was initially developed by the Bell Telephone Laboratories as a communication tool. Its ability to generate a significant amount of energy in a compact area has made it an effective heat source. Lasers are now employed for cutting both metals and nonmetals, with continuous pulse equipment also available. This technology is increasingly being utilized in automotive metalworking processes (Cary, 2004).

3.3 Welding Process

Welding is a fabrication technique that connects materials by inducing coalescence. This process typically involves melting the workpieces and incorporating a filler material to create a molten weld pool, which solidifies to form a robust joint. Sometimes, pressure is applied alongside heat, or independently, to achieve the weld. This differs from soldering and brazing, where a lower-melting-point material is utilized to bond workpieces together without actually melting them. Welding can be performed using a variety of energy sources such as gas flames, electric arcs, lasers, electron beams, friction, and ultrasound. It can take place in numerous settings, including open air, underwater, and even in outer space. Overall, welding is recognized as the most efficient method for joining metals and alloys. Welded products cover applications such as heat exchangers, tanks, pressure vessels, sheet metal components, prefabricated metal structures, and architectural and decorative designs, as well as shipbuilding, aircraft and spacecraft manufacturing, railways, automobiles, trucks, buses, and bridges made of steel (Valiulis, 2014).

3.4 Classification of Welding Processes

The term "joining" typically refers to processes such as welding, brazing, soldering, and adhesive bonding, all of which create a permanent connection between components. Welding is a process that fuses two or more parts at their contact surfaces through the application of heat and / or pressure. Various welding methods may rely solely on heat, while others employ a combination of heat and pressure, and some use pressure alone without any external heat. Additionally, certain welding techniques involve the introduction of a filler material to aid in the fusion process. The assembly of parts connected through welding is referred to as a weldment. While welding is typically associated with metals, it can also be used for plastic materials. This process is primarily performed on components made from the same type of metal, though certain welding techniques can effectively join different metals as well (Groover, 2010).

Welding methods can be classified in various ways. Generally, this classification is based on the type of material being welded, the techniques used in the welding process, and the purpose for which the weld is being made.

Welding processes can be classified under 4 main headings:

1. **According to the material to which welding is applied;** Welding is divided into two types, "Metal Welding" and "Plastic Material Welding", depending on the type of material to which it is applied,
2. **According to the purpose of the welding;** Welding is divided into two types, “Joining Welding” and “Filling Welding”, depending on the purpose of application.

   Joining welding refers to the process of welding two or more components together to form a single, inseparable unit.

   Filling welding involves welding a material in a specific area to address volume deficiencies in a workpiece or to enhance its volume. It also serves to protect against corrosion or wear. Techniques such as coating, armoring, and applying buffer layer fillings are examples of this process.
3. **According to the welding method;** It can be categorized into four types based on the welding methods used: hand welding, semi-mechanized welding, fully mechanized welding, and automatic welding. **Hand welding** is performed using a welding tool that is solely operated by hand, such as a welding torch. **In semi-mechanized welding,** the welding tool is controlled by a partially automated device rather than being operated manually. **In fully mechanized welding,** the welding tool is managed by a completely automated machine, eliminating the need for hand operation. **In automatic welding,** all primary and auxiliary tasks, including welding and work-piece changes, are fully mechanized.

4. **According to the type of welding process;** It is divided into 2 as fusion and pressure welding**. Fusion welding** is the process of melting a material locally (a limited part) under the influence of heat only and joining it with or without the addition of an additional metal. **Pressure welding** involves the joining of materials under pressure through localized heating, typically without the use of any filler metal (Anık & Tülbentçi, 1980).

When welding processes are categorized, a framework similar to the one below becomes evident ;

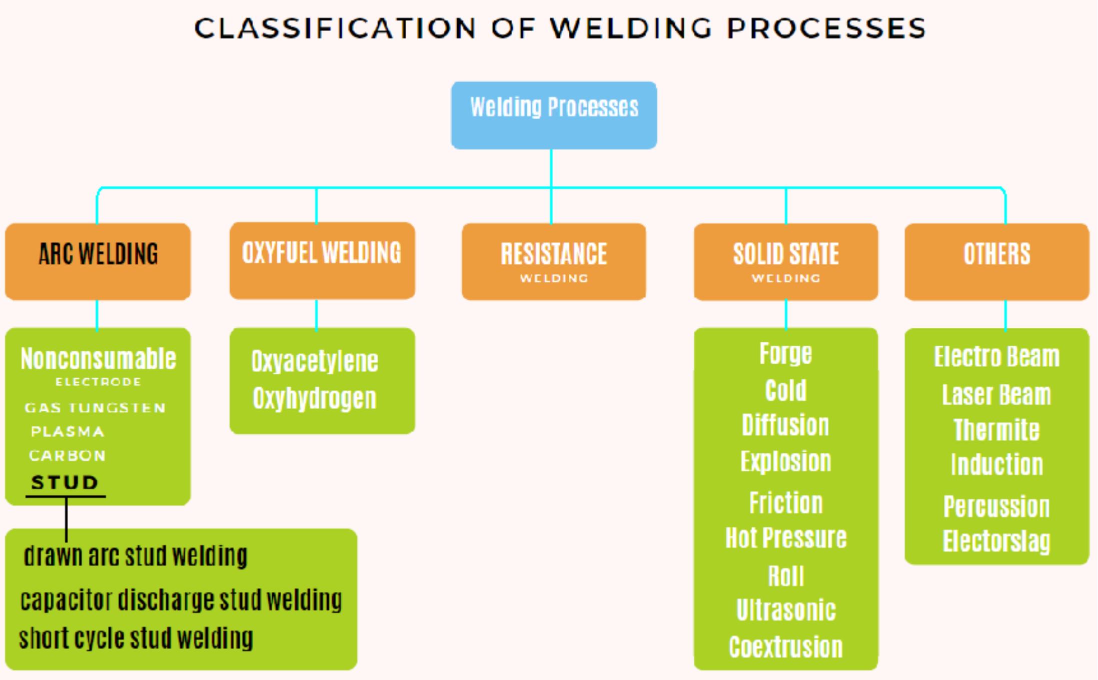


Figure 3.1 General Category of Welding Process Types

3.5 Limitations And Advantages of Welding Processes

Welding has significant technological value because it joins welded components into a single whole by creating a permanent joint. When a filler metal with improved strength and appropriate welding techniques is used, the welded joint can even exceed the strength of the original materials.

Economically, welding is generally the most efficient method of joining components, minimizing material waste and manufacturing costs. In contrast, alternative mechanical assembly methods often involve more complex modifications such as drilling holes and adding fasteners such as rivets or bolts, which often result in a heavier assembly compared to welding. Furthermore, welding is versatile and can be performed in a variety of environments, both indoors and outdoors, provided the necessary conditions are met (Groover, 2010).

Similar to other manufacturing and joining techniques, welding methods possess both advantages and limitations, which are outlined as follows (Aravinda, n.d.);

Advantages ;

1. The procedure is simple and produces an impressive result.
2. When filler material is used, the weld formed is stronger than the original material.
3. Welding can be performed both indoors and outdoors, provided that suitable conditions are met in terms of air, humidity, and wind.
4. It is both efficient and budget-friendly.
5. This technique is utilized across multiple industries, such as automotive, aviation, space industry, construction, shipbuilding and others.
6. It is portable, allowing for easy transport to different sites.
7. It can be applied in hazardous environments.
8. It functions effectively in challenging conditions that may be unsafe.
9. The operation is straightforward and easily applicable.
10. Because of its easy-to-understand principles, even a semi-skilled operator can effectively manage this machine.
11. Welding saves weight and labor,

Limitations;

1. Can be dangerous if occupational health and safety and safety regulations are not followed.
2. Separating bonded materials using welding is a difficult task, requiring cutting and repair procedures.
3. Requires skilled professionals in terms of both electrical power supply and energy.
4. Thin materials can be welded effectively and accurately.
5. Weld metal can flex.
6. Not suitable for continuous operations.

3.6 Arc Stud Welding (ASW) Process

Stud arc welding is a widely recognized welding technique used in various industries, including steam boiler manufacturing, bridge construction, aviation, space industry, shipbuilding, and automobile production. Its application helps lower production costs by leveraging benefits like a short time cycle, and the possibility of automation, among others. As noted in (Ramasamy et al., 2002), quality issues typically linked to drawn-arc welding processes stem from variables specific to stud welding, such as weld current, weld time, arc voltage, and plunge lift, as well as broader manufacturing factors like sheet cleanliness and joint geometry. Factors that can lead to weld stud failures include the use of unsuitable base plate materials or poor plate surface conditions, incorrect welding parameters, faulty or outdated equipment, insufficient training for stud welding operators, and the absence of quality control and inspection protocols (Chambers, 2001).

Arc stud welding can be described as the process of welding studs made from different metals and alloys without the need for extra tools. In this technique, a cylindrical nozzle at the end of the stud is used to generate an arc. There are two fundamental conditions essential for this process; Initially, an arc is used to generate the welding temperature between the components to be joined (the stud and its counterpart). Next, once the melting temperature is achieved, the parts are pressed together with adequate force. To begin with, it is essential to clean the surface thoroughly along with the components to be joined by stud welding. All contaminants and unwanted materials (including foreign substances such as oxides, oils, paint, etc.) that could potentially compromise the weld seam must be removed. In this method, the welding arc is created between the stud and the base metal, the arc stud welding method can generally be performed in the 100 to 1500 millisecond time range on studs with a stud diameter of Ø3mm to Ø25mm, with no filler material is needed, shielding gas or flux can be used, ceramic-ferrule can also be used during welding, ceramic- ferrule is recommended on the stud for diameters over Ø12mm in the arc type welding method.

The arc is started by touching the stud to the surface to be joined and pulling it. When melting occurs along the stud diameter and on the surface to be joined, the surfaces are welded by applying pressure. Studs with a diameter of up to 22 mm can be welded in this method. A current of over 1000 Amperes is needed. In this method, where it is possible to join different materials to each other, the problem arises from different melting points. For example, it may not be possible to weld an aluminum stud to a steel piece. The welding process is very fast, snap to use for the operator, and the damage that the studs give to the outer coating is less than in classical methods (Kahraman & Gülenç, 2016).

Figure 3.2 illustrates the schematic representation of the stages involved in stud arc welding. The process follows these steps (Chambers, 2001)

- **a.** The stud is positioned in the holder, and a ceramic ring is fitted onto its end,
- **b.** The stud is raised slightly to initiate the auxiliary arc, followed by the main arc,
- **c.** During this phase, both the main surface of the stud and the base material start to melt. The stud is then submerged into the molten bath using applied pressure, after which the electric current is halted,
- **d.** Once solidification has occurred, the ceramic ring is detached,

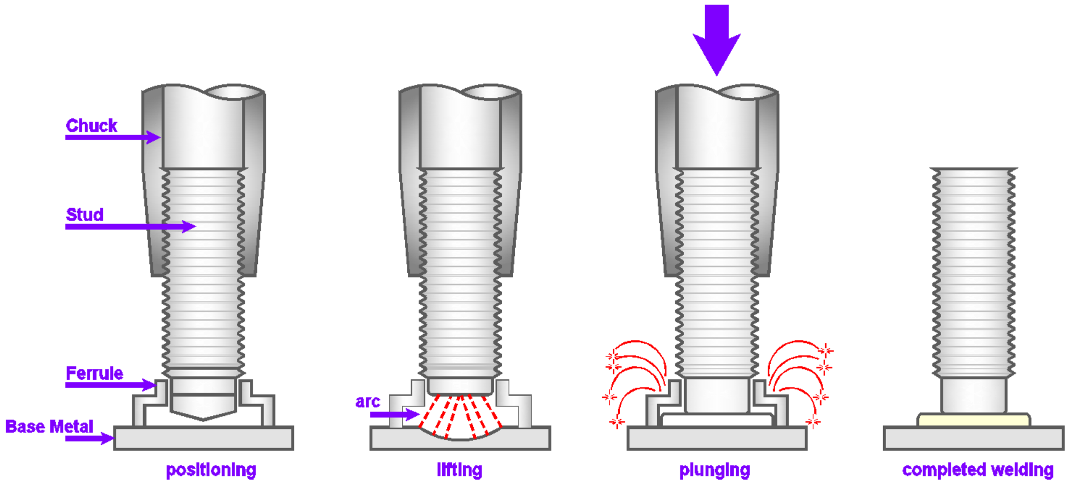


Figure 3.2 Illustration of All Stages of Arc Stud Welding

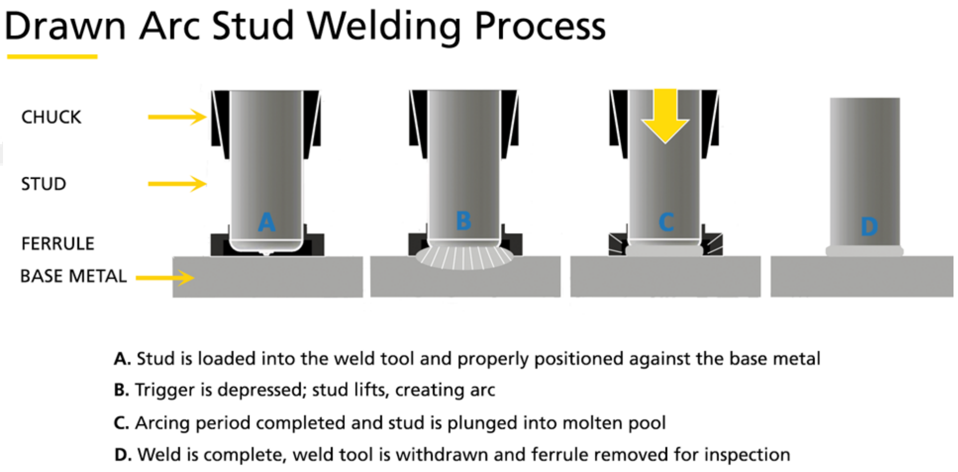
3.7 Types of Arc Stud Welding (ASW) Process

As specified by DIN 1919, stud welding is categorized into two primary types: (1) tip ignition stud arc welding and (2) contact ignition welding. Moreover, each method features distinct applications. In tip-ignition stud arc welding, the ends of the studs must be specially shaped. Additionally, there are three main variants of contact-ignition stud arc welding (Kahraman & Gülenç, 2016).

3.7.1 Arc Stud Welding

Arc stud welding is suitable for diameters between 3 and 25 mm, with welding times spanning from 100 to 1500 ms. Generally, a ceramic ferrule is used, although there are specific cases where shielding gas is utilized or no shielding is applied. This technique encompasses most applications, Contact ignition stud arc welding is primarily divided into three main types: Drawn Arc Stud Welding (DSAW), Capacitor Discharge (CD) Stud Welding, and Short Cycle Stud Welding. (Kahraman & Gülenç, 2016). It is advisable to use ceramic ferrules and aluminum flux when working with large-diameter studs.

Figure 3.3 depicts all the stages involved in this welding process (©2024 Stanley® Engineered Fastening, 2024).

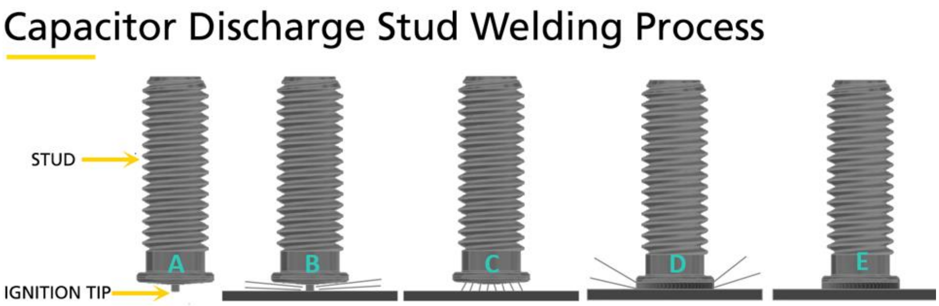


A. Stud is loaded into the weld tool and properly positioned against the base metal
B. Trigger is depressed; stud lifts, creating arc
C. Arcing period completed and stud is plunged into molten pool
D. Weld is complete, weld tool is withdrawn and ferrule removed for inspection

Figure 3.3 Illustration of All Stages of Drawn Arc Stud Welding

3.7.2 Capacitor Discharge Stud Welding (CDSW)

In contact ignition stud welding, achieving weld times of under 10 ms necessitates that the weld current be introduced into the electronic circuit while the plunging motion occurs. This can be accomplished by utilizing energy from a capacitor battery. Typically, bath protection is not needed for these brief weld times. This method is applicable for stud diameters of up to 6 mm (Kahraman & Gülenç, 2016). This method is recommended for non-structural applications with a rapid attachment and an undisturbed backside finish.



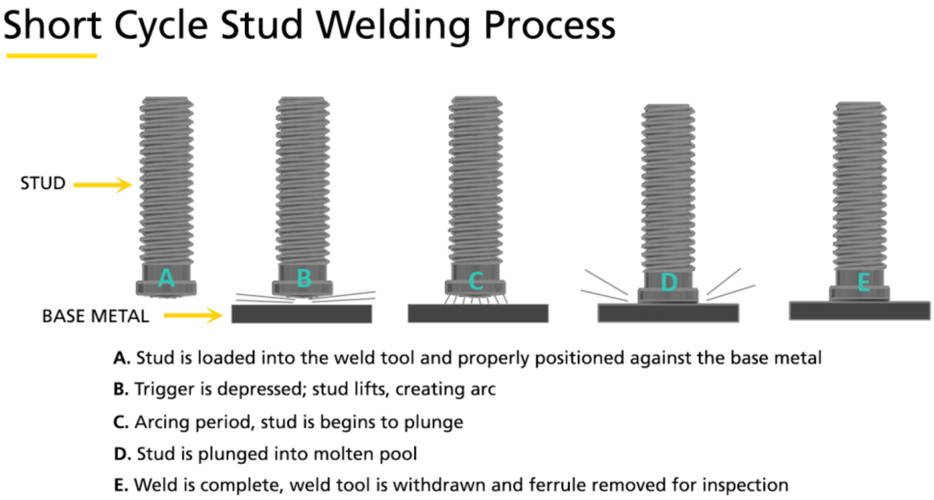
A. Stud is loaded into the weld tool and properly positioned against the base metal
B. Trigger is depressed; tip ignites establishing arc
C. Arcing period, stud begins to plunge
D. Stud is plunged into molten pool
E. Weld is complete, weld tool is withdrawn for inspection

Figure 3.4 Illustration of All Stages of Capacitor Discharge Stud Welding

3.7.3 Short Cycle Welding

Specialized devices can achieve short welding times ranging from 10 to 100 milliseconds. This technique is effective for studs with diameters up to 12 mm, although a protective gas chamber is necessary to prevent the development of strong porosity in studs sized between 8 and 12 mm. The narrow melting zone results in minimal heat input, allowing for the welding of studs up to 12 mm in diameter even on thin materials. For studs measuring between 10 and 12 mm, an additional ceramic ferrule is recommended to ensure an even formation of the weld form seam. Weld protection is generally not required up to 6 mm in diameter. In this case, studs with projecting bloated heads (flanged) are used.

As the weld surface area of these components is larger than that of the stud itself, they can withstand greater tensile forces than the main stud section, despite potential porosity (Kahraman & Gülenç, 2016). This method is recommended for semi-structural applications that provide rapid attachment and an undistributed backing finish.



A. Stud is loaded into the weld tool and properly positioned against the base metal
B. Trigger is depressed; stud lifts, creating arc
C. Arcing period, stud is begins to plunge
D. Stud is plunged into molten pool
E. Weld is complete, weld tool is withdrawn and ferrule removed for inspection

Figure 3.5 Illustration of All Stages of Short Cycle Stud Welding

3.7.4 Using of Ceramic Ferrule (CF) in Arc Stud Welding Processes

When welding, the ceramic ring acts as a combustion chamber surrounding the weld area, shielding the welder from both the arc and spatter. This ring focuses the arc into a defined space, minimizes heat loss, and slows down the cooling process. As the stud is immersed in the weld pool, the molten material that flows outward forms and accumulates around the stud, with its shape by the ceramic ring. This form enables effective welding even in challenging positions. Typically, the ceramic ring is used only once and is expelled after the molten material has solidified (Kahraman & Gülenç, 2016).

3.7.5 Using Shielding Gas in Arc Stud Welding

To reduce pore formation during welding air in the welding area is expelled with the help of a protective gas given from outside; this gas mixture is proportionally 82% Ar + 18% CO_2 for steels. The application of shielding gas during welding influences the arc, the melting processes of both the stud and the material, the stress on the surfaces, and subsequently the shape of the accumulated material and the weld seam. In welding applications, it's advisable to use the horizontal welding position. To achieve improved weld formation and enhance arc concentration in a smaller area, the use of a ceramic ring is recommended (Kahraman & Gülenç, 2016).

3.7.6 Unprotected (without Shielding gas) Arc Stud Welding

The application of stud welding without protection is limited to small diameters (less than 10 mm) and brief weld settings (less than 100 ms). Weld oxidation, severe porosity, and uneven metal build-up are drawbacks. For thin sheet metals and small stud sizes (x <6 mm), short welding (10 ms) yields good results (Kahraman & Gülenç, 2016).

3.7.7 Visual Inspection of Arc Stud Weld

For successful welding outcomes, it's essential to establish an appropriate balance among lift, immersion time, and amperage values. Parameters like length reduction and burn-off degree influence the characteristics of the weld fillet. Visual weld inspection involves analyzing the weld fillet's appearance and can be a highly reliable technique when specific guidelines are adhered to. Figure 3.6 shows visual inspection and technical comments on good, hot, cold and stud hang images taken from samples produced using arc stud welding.

A "normal weld" is defined by the following features: Uniform formation of the flash (fillet), A glossy, bluish tint on the flash surface, A slight flow or curvature of the flash metal into the base material, and Adequate height of the flash, Consistent length after welding, Complete "wetting" meaning the flash surrounds the stud periphery without any undercutting.

A "cold weld" which necessitates additional time, amperage, or both, is characterized by: a low flash (fillet) height, incomplete flash formation, a dull gray appearance on the flash surface, and stringers of flash metal resembling spider legs.

A "hot weld," caused by excessive time, amperage, or both, is characterized by: excessive spatter, a washed-out flash (fillet), undercutting of the stud, and burn-through of the base material.

A "Stud hang-up" can occur due to excessive lift, improper alignment of the stud with the workpiece, and binding during the lift and plunge caused by incorrect centering of the stud in the ceramic ferrule. The characteristics of a stud hang-up include minimal or absent flash (fillet), significant undercutting in the weld, lack of penetration into the base plate, and inadequate stud burn-off (resulting in an excessive after-weld height) (Harry A. Chambers PCI Journal, 2001).

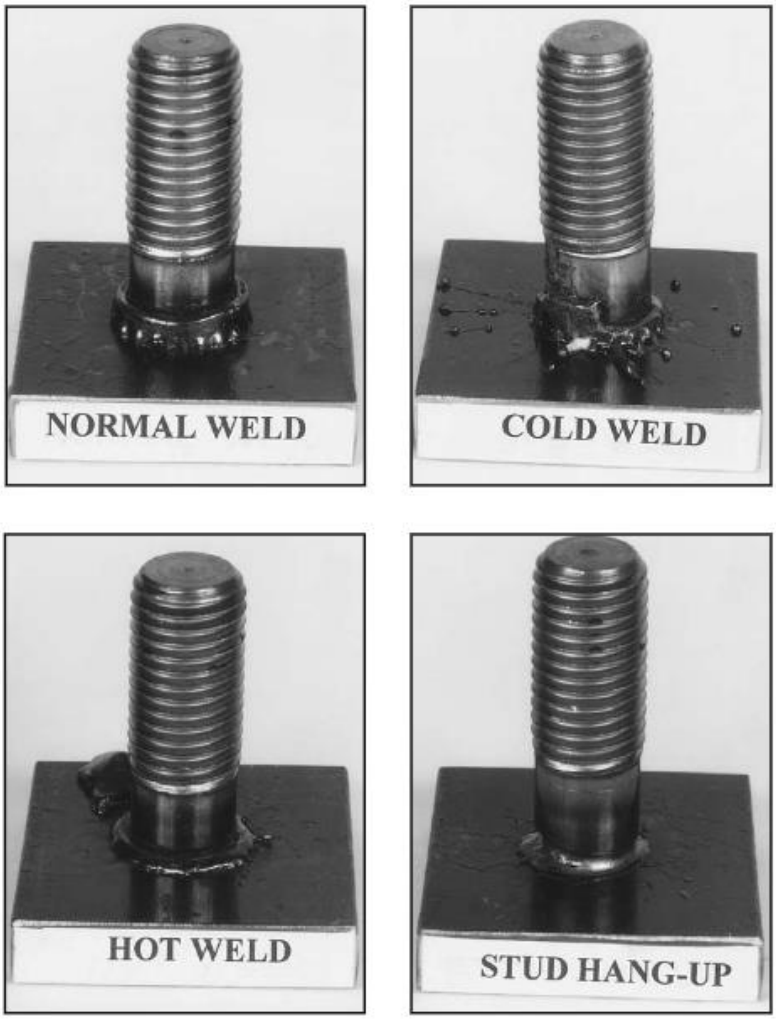


Figure 3.6 Welded Samples for Visual Inspection

3.8 Advantages of Arc Stud Welding (ASW) Process

The speed and efficiency of arc stud welding are its main advantages. This approach is perfect for large projects or when several pieces need to be put together because it can be finished in a fraction of the time it takes for other welding processes. Furthermore, Stud Welding methods take extremely minimal setup time, which facilitates welders starting their job immediately and avoiding lengthy delays. Utilizing Stud Welding has the additional benefit of producing a cleaner weld because of the brief heat application time, which leaves the weld joint region with less distortion or warping. Lastly, since there is no filler material utilized in the process, there is a lower chance of foreign, It does not require extra grinding and is cost-free in terms of labor (Heer Vohera, 2024).

The welding process occurs over a brief duration, typically ranging from approximately 10 milliseconds to 2 seconds, depending on the specific method used. This rapid process results in only a superficial area of the base material melting. Once completed, the joining area remains quite clean, eliminating the need for any additional cleaning. Due to the relatively low heat input in the welding zone, there is minimal to no physical distortion of the materials. Both ferrous and non-ferrous materials, such as aluminum, stainless steel, copper, and zinc can be welded with ease.

Studying welding does not require specialized skills; a basic level of application experience and technical understanding is sufficient. Threaded and threadless studs can be easily welded. The welding process can be executed in a semi-automated, fully automated, or mechanical manner. This method can be effectively applied in horizontal, vertical, and overhead positions without any challenges (Kahraman & Gülenç, 2016).

3.9 Disadvantages of The Arc Stud Welding Process

This method offers numerous benefits when compared to alternative welding techniques; however, it does come with certain drawbacks; Welding high carbon steels using unprotected open arc methods is challenging due to the rapid cooling that occurs, which can lead to the formation of a hard and brittle structure in the joint area. This factor must be carefully considered, as not pre-cleaning surfaces (removing oxide, rust, scale, oil, primer, paint, etc.) can adversely impact the welding process. It is also important to address centering issues during welding.

Typically, studs or similar components should have a circular section in their design. Additionally, when welding certain materials, it is essential to protect the weld pool with a shielding gas. In stud welding, the brief duration of the weld results in high cooling rates, increasing the risk of hardening (Kahraman & Gülenç, 2016).

One notable limitation is the absence of filler material, which can increase the porosity of the weld joint and result in a weaker connection relative to methods like MIG or TIG welding. Arc stud welding depends on electric currents being delivered through a specially designed gun-like apparatus, which poses a risk of electric shock if appropriate safety measures are not observed during operation. Furthermore, this technique is not ideal for large-scale production projects, as the welder needs to physically hold both the stud and the arc gun, making it cumbersome for extensive tasks. Additionally, arc stud welding may not be well-suited for applications requiring a high level of precision, as controlling the weld buildup can be challenging (Heer Vohera, 2024).

3.10 Application of Arc Stud Welding (ASW) Process

While the stud welding method is widely used in different production areas in the industry, from a sectoral perspective; It is used intensively in the production of steam boilers and pressure tanks, bridges, and other construction industries, especially in the automotive, shipbuilding, aviation, space industry, kitchen appliance industry, military applications and power distribution equipment in mobile vehicles and cable connection parts and accessories. Stud arc welding is also used to install insulation on boiler membrane panels and walls in the production of steam boiler components (Samardžić et al., 2008).

The method is an extremely fast and efficient welding process in which a stud is welded to the workpiece based on the heat generated in the short-term electric arc that melts the weld point regionally in the cross-sectional area and the short-term pressure that creates the physical union of the weld piece. Sample images of the applications are also given below ;

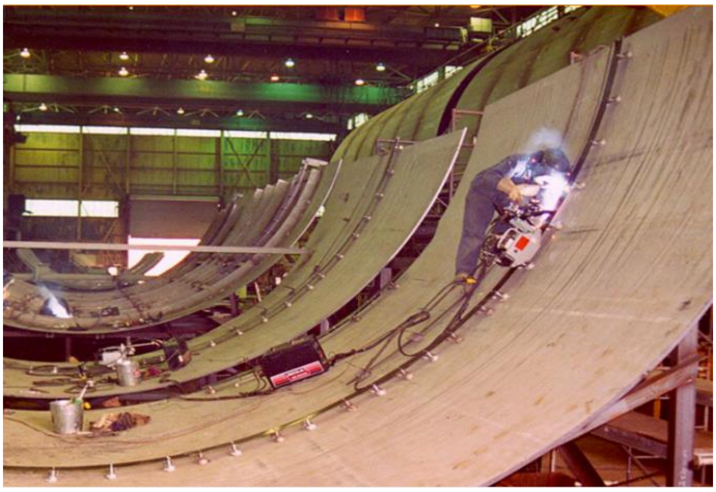


Figure 3.7 Instance of Arc Stud Welding Application in Shipbuilding

Figure 3.8 Instance of Arc Stud Welding Application in Boiler Manufacturing

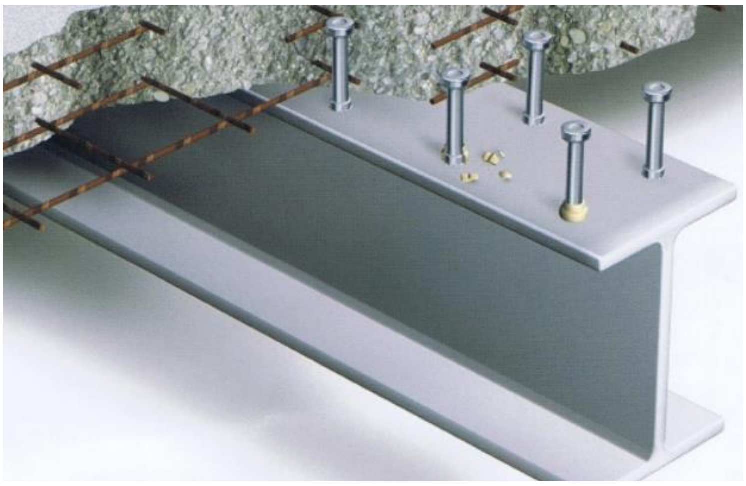


Figure 3.9 Instance of Arc Stud Welding Application in Bridge Building

3.11 Main Equipment of Arc Stud Welding (ASW) Machine

In this section, general information about the features of the welding machine used in the tests performed with arc stud welding and the welding equipment and accessories is given.

3.11.1 Main Properties of BMK 16i Brand Stud Welding Machine

The arc stud welding machine comprises various components, including a stud gun, a control unit, connecting cables, grounding clamps, and an electric power source. The stud gun is linked to the control unit, which in turn is connected to the electric power source. Each component serves a specific purpose. Figure 3.9 illustrates the arc stud welding machine employed in the experiment (Soyer Branch, 2024).

Figure 3.10 The SOYER Arc Stud Welding Machine

This stud welder is a versatile inverter source designed for maximum user convenience, making it perfect for various welding methods, including stud welding, electrode welding, and TIG welding.

3.11.2 Technical Data of The BMK 16i Brand Stud Welding Machine

Welding Range : M3 - M16 RD or 2-13 mm in diameter

Material : Steel, stainless steel, heat-resistant steel (Al and brass depending on respective requirements)

Welding Current : 100 - 1000 A, adjustable and regulated with stud welding, 40-300 A, adjustable with electrode welding, 40-100 A with TIG welding

Welding Time : 3 - 1000 ms with stud welding

Welding Sequence : Ø 6 mm up to 30 studs/min. Ø 13 mm up to 3 studs/min

Mains Supply : 3 x 400 V - 50/60 Hz - 32 AT, other voltage on request

Dimensions : 335 x 440 x 700 mm (w x h x d)

Weight : 36.5 Kg.

3.11.3 Properties of Arc Stud Welding Gun

The PH-3N SRM16 welding gun is the perfect complement to the BMK-16i stud welding inverter. It facilitates the creation of premium welds within a radially symmetrical magnetic field (SRM®). A standout feature is the SRM16 tripod, which supports the welding of studs up to M16 (Soyer Branch, 2024).

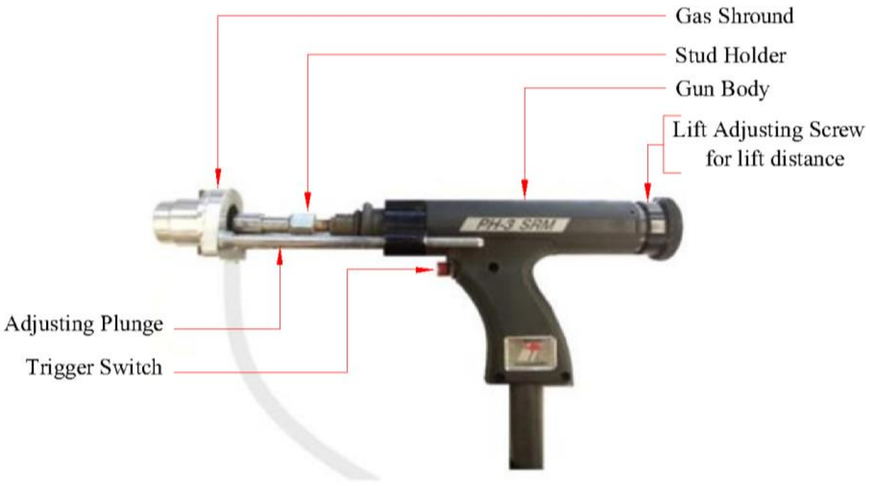


Figure 3.11 The SOYER Arc Stud Welding Machine Gun PH-3 SRM

The welding gun features a trigger-activated circuit that starts the welding process, along with a lifting mechanism designed to lift the stud away from the base material and establish the welding arc. Additionally, the gun is equipped with a stud-holding chuck, two legs, a footpiece, and a ferrule grip to secure the ceramic ferrule (also known as an arc shield), as illustrated in Figure 3.11 (Harry A. Chambers PCI Journal, 2001).

3.11.4 Power Source and Control Unit

Stud welding machines can operate with either AC or DC power supplies, depending on the specific welding application and available facilities. The power source for stud welding typically falls into one of three categories: transformers, generators, or inverters. At its simplest, the equipment includes a stud gun connected to a control unit, which is then linked to a DC power source. While some modern stud welding systems combine the controller and power source into a single unit, it is still possible to pair a controller and gun with an existing DC welding power supply. In Figure 3.12, the essential components of the process are depicted, showing a stud gun, a control unit for weld timing, a DC power source, and an appropriate weld cable (Taylor, 2001).

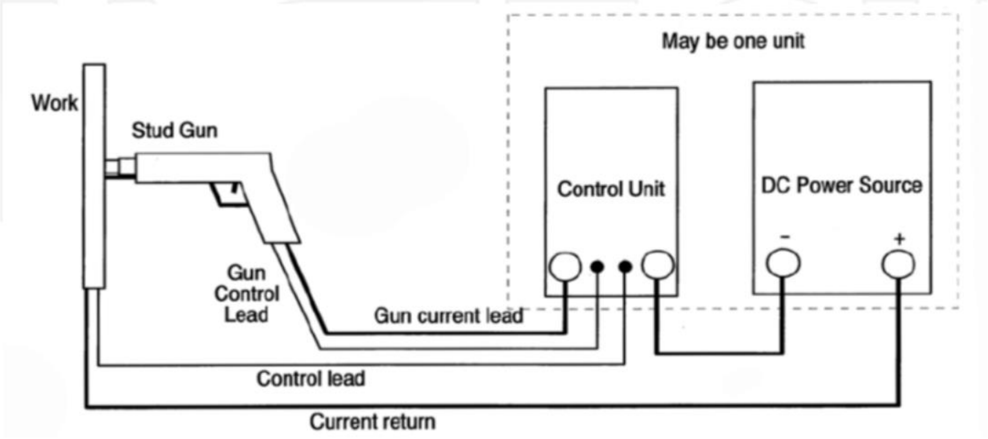


Figure 3.12 Arc Stud Welding Power Source and Equipments (Taylor, 2001)

3.11.5 Stud Types and Ceramic Ferrules (CF)

Studs can come in circular, square, or rectangular forms, and may also feature flange heads, threads, or lack threads altogether. When the base is rectangular, the width should not exceed five times its thickness. The shape must be suitable for gripping in a chuck; otherwise, the design of the stud can be varied. The most prevalent types of studs include screw fasteners and shear studs, although options such as hooks, rings, brackets, and various other configurations are also possible. Studs can be crafted from a wide range of materials. Carbon steel studs typically consist of semi-killed or fully killed carbon steel grades 1010 to 1020, presented in a cold-drawn state (Taylor, 2001).

However, studs made of different materials such as aluminum and copper are also available on the market. Studs come in many different shapes and forms depending on their place of use, their function, and the strength they will be exposed to. Stud types can be seen together as follows in Figure 3.13.

Figure 3.13 Stud Varieties Based on Size and Shape

Ferrules available in the market are typically made from a combination of ball clay and talc, which is an ideal material for resisting heat shock and can endure elevated temperatures without melting or breaking (A.C. Associates, 2024).

The impact of the ceramic ring on the stud can be outlined as follows;

1. Ferrules safeguard the arc by limiting airflow,
2. Focuses the arc's heat on the welding area,
3. Shapes the weld flash,
4. Prevents burning of nearby materials,

and is subsequently fractured and removed once the welding process is finished (Taylor, 2001). Ceramic ferrules (CF) are manufactured in various types, tailored to their application, function, welding method, and welding orientation. The most commonly used ceramic ferrules are shown in Figure 3.14, where the studs are welded.to the workpiece.

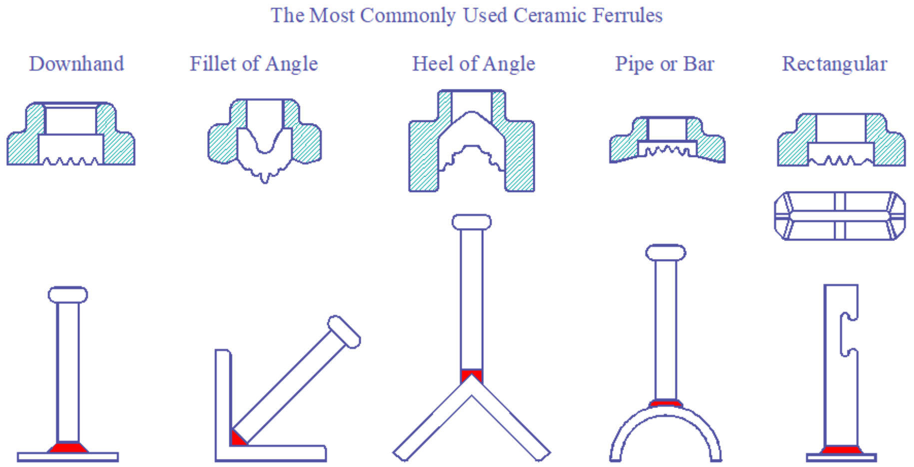


Figure 3.14 Ferrule Varieties Based on Welding Method and Shape (Olson et al., 1993).

3.11.6 Using Shielding Gas (SG) in Arc Stud Welding

The choice of shielding gas affects the arc dynamics, melting behavior, and surface tensions of both the stud and the material, and ultimately the shaping of the weld pile and the seam form (Kahraman & Gülenç, 2016).

Shielding gases play an important role in protecting the molten metal from atmospheric pollutants and increasing the properties of the weld metal (WM) such as strength, corrosion resistance, and toughness by minimizing defects in the weld. Dry atmospheric air contains a variety of gases, including traces of oxygen, nitrogen, and others, each of which affects the weld metal and its solidification properties. Choosing the right shielding gas is vital to achieving quality welding results. A mixture of 82% Ar and 18% CO_2 is recommended for mild steel and stainless steel, while pure Argon or a combination of Argon and Helium is suitable for aluminum. Argon gas is particularly advantageous because it does not adversely affect molten metals during welding, making it ideal for protecting sensitive materials such as aluminum and stainless steel. In our experiments, we chose a mixture of Argon and CO_2 for these beneficial properties (Kou,2003).

CHAPTER 4
EXPERIMENTAL STUDIES

4.1 Introduction

This section provides a detailed explanation of not only the experimental procedures conducted in the laboratory but also the properties of the primary materials used in the experiments, as well as the characteristics of the machines and equipment employed.

4.2 Experimental Prerequisites

In the course of conducting these experiments, several preliminary steps were taken to ensure the achievement of precise and scientifically valid results. These initial preparations include: selecting suitable weldable materials for the stud welding process, providing studs with the correct weldable dimensions, preparing the main material for the experiment by cutting it into the desired shape, and ensuring the availability of stud welding machinery, welding equipment, and shielding gas. For the experiments, the SOYER BMK 16i Stud Welding Machine and the PH 3 SRM welding gun, located in the Mechanical Engineering Materials Laboratory at Gaziantep University, were utilized for the experiment.

4.3 Material Selection

4.3.1 AHSS and Docol 1500 Martensite Plate

AHSS are advanced materials characterized by intricate chemical compositions and multiphase microstructures, developed through meticulously regulated heating and cooling processes. A range of strengthening mechanisms are employed to significantly enhance strength, formability, toughness, and fatigue resistance, ensuring they meet the diverse demands set for automotive body structures (Keeler & Kimchi, 2017). There has been a growing interest in research focused on the development of third-generation AHSS. These steels typically utilize specialized alloying techniques and thermo-mechanical processing to achieve better strength-ductility ratios compared to current first- and second-generation AHSS, while also being more cost-effective. The new generation of AHSS grades incorporates significant alloying and features multiple phases, which lead to enhanced strength and ductility that cannot be achieved with single-phase steels, such as high-strength low-alloy (HSLA) grades (Hance, 2018).

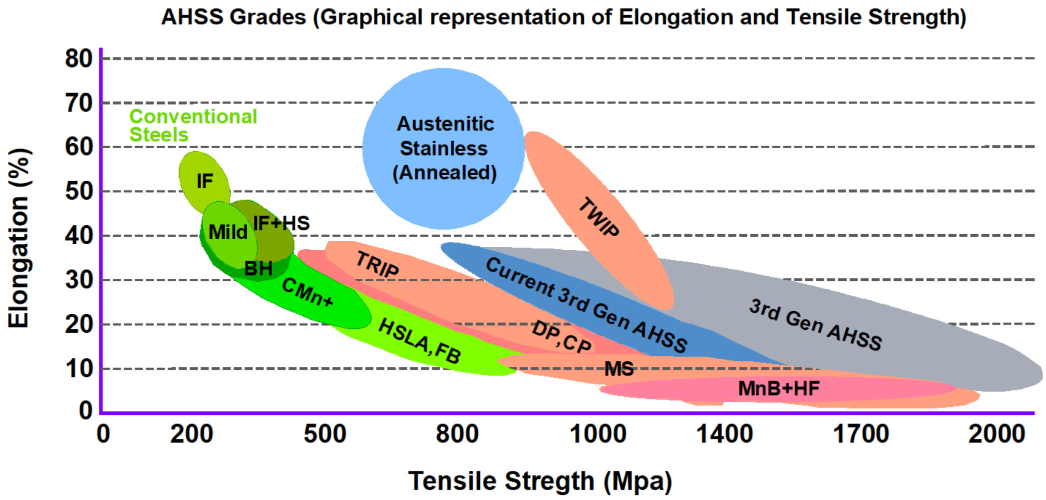


Figure 4.1 Steel Strength Ductility Diagram for Today's AHSS Grades

Technically Advanced High Strength Steel expresses to new technology steel that provides high strength (up to 1700 MPa) and durability without changing formability, which is very important during manufacturing processes. Advanced High-Strength Steels primarily consist of steels characterized by a multiphase microstructure that includes one or more phases beyond ferrite, pearlite, or cementite, such as martensite, bainite, austenite, or retained austenite. The presence of these phases in sufficient quantities imparts distinctive mechanical properties. Some variations of AHSS exhibit enhanced strain hardening capabilities, leading to a superior balance of strength and ductility compared to conventional steels. Others achieve ultra-high yield and tensile strengths, along with a bake hardening response. Besides offering high strength, AHSS also contributes to cost reduction, a critical consideration in engineering. Furthermore, it enhances key aspects of production, including quality, efficiency, emissions, manufacturability, and durability. Thanks to their structural characteristics, AHSS materials excel in meeting these diverse requirements. With their multiphase microstructure, AHSS not only provides impressive ductility and strength but also retains excellent shaping capabilities while delivering the anticipated material performance (World Steel Association AISBL, 2024).

In this study, Docol 1500M sheet metal plate was employed as the primary material. Martensitic steels (MS) primarily consist of a martensitic microstructure, accompanied by minor amounts of ferrite and bainite. They exhibit the highest strength but possess lower formability. Presently, martensitic steels are available with strengths ranging from 900 to 1800 MPa and are utilized for body components where deformation is constrained (Horvath, 2021).

In the production of Martensite steels, almost all of the austenite is transformed into martensite during the quenching process on the run-out table or within the cooling section of the continuous annealing line. These steels are identified by a martensitic matrix that includes minor quantities of ferrite and/or bainite. Among multiphase steels, MS steels exhibit the highest levels of tensile strength. Martensitic steels demonstrate exceptional ultimate strength in final products, reaching up to 1800 MPa or even more (Demeri, 2013). To enhance ductility and ensure suitable formability at very high strength levels, martensite steels are frequently treated with post-quench tempering. The presence of extra carbon in martensitic steels enhances their hardenability and strengthens the martensite structure. Other alloying elements—such as manganese, silicon, chromium, molybdenum, boron, vanadium, and nickel—are utilized in different combinations to further improve hardenability. The microstructure of martensitic steels primarily consists of lath martensite, which forms when austenite transforms during the quenching process following hot rolling or annealing. Due to their high hardness, martensitic steels are challenging to shape; therefore, they are often processed through roll forming or hot stamping techniques. (Sharma et al., 2020).

This martensitic steel is specifically designed for automotive applications, offering enhanced crashworthiness, lightweight construction, and cost-effective production methods within the automotive sector. As one of the strongest advanced high-strength steels available, Docol 1500M has emerged as the preferred choice for various automotive components, including EV battery protection, Sill reinforcements, Door/side intrusion beams, bumpers, and structural parts. (SSAB, 2024).

The usage areas of high-strength steels, especially used in automotive production, in vehicles are shown in Figure 4.2 and Figure 4.3 (Baluch et al., 2014)

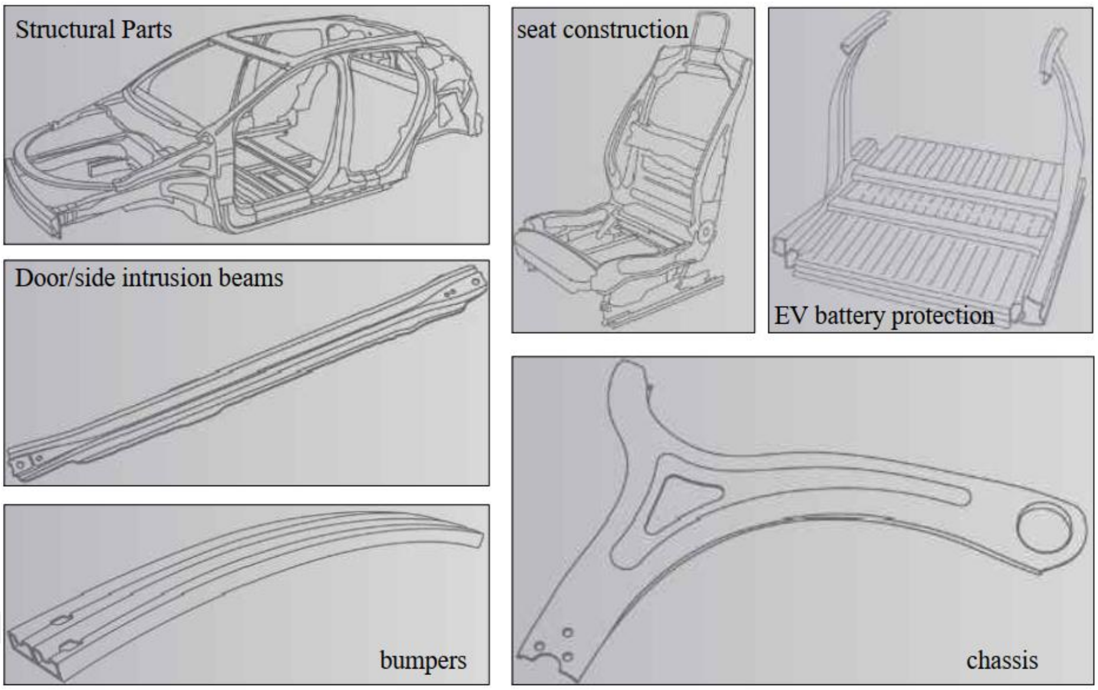


Figure 4.2 Various Applications of Docol 1500MS in Automotive Components

Structural Parts: Components like threshold reinforcements and cross members should provide excellent energy absorption while remaining lightweight. By optimizing their shape, hardness can be preserved. All these qualities can be attained using 1500 martensite steel.

Seat Construction: Car seats offer essential safety support for passengers. Utilizing advanced high-quality steels in the seat frame helps to substantially decrease weight while still adhering to, or surpassing, relevant safety standards.

Door / Side Instruction Beams: The increasing level of strength of AHSS steel enables substantial weight savings when enhancing side impact beams.

Bumpers: AHSS steels offer excellent force absorption for bumper reinforcements and contribute to noteworthy weight reduction.

Chassis: High-strength steels offer the chassis remarkable formability and fatigue resistance characteristics.

EV Battery Protection: Electric car batteries can be costly and pose safety risks if they are harmed during an accident. To mitigate these risks, they need to be shielded from road debris and housed to contain any battery fluids that may leak after a collision. Docol AHSS steels offer an effective solution, delivering robust protection for EV batteries while keeping weight to a minimum (Ssab, 2024).

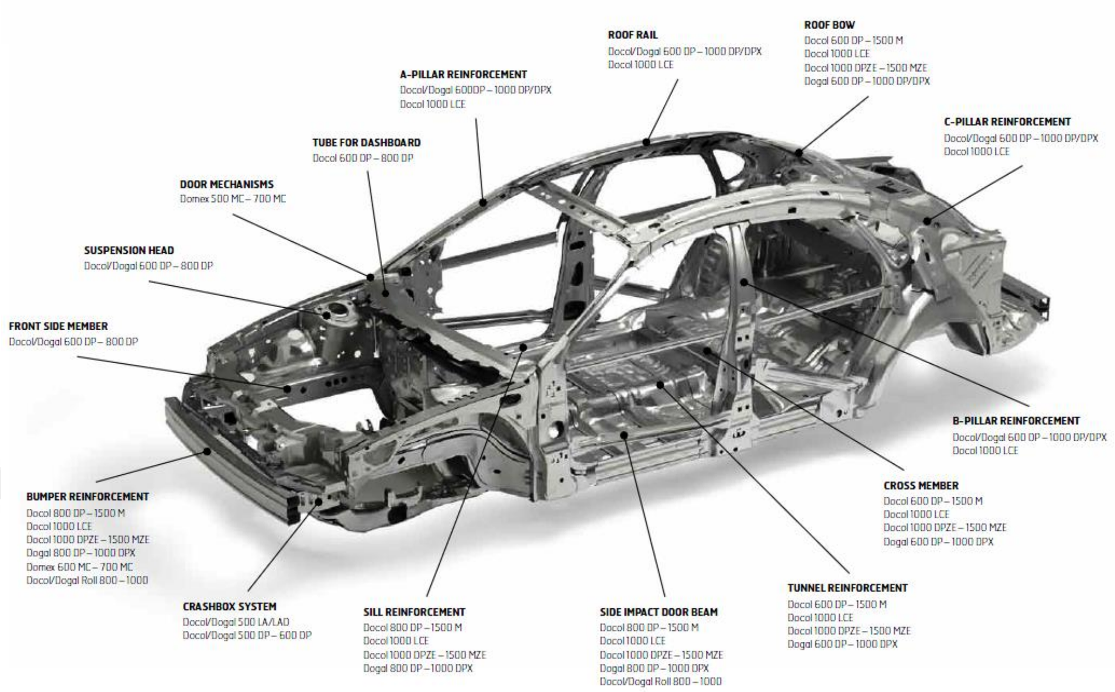


Figure 4.3 Applications of Docol 1500M Steel on Automobiles

Honda was among the pioneers in integrating advanced high-strength steel (Ahss) with strengths of 980 MPa and above into their body structures, as illustrated in Figure 3.17. The 2011 CR-Z features a sleek and aerodynamic body design that prioritizes high safety standards. It incorporates Advanced Compatibility Engineering™ (ACE™), a unique structural framework that improves occupant safety and crash compatibility in frontal impacts. With the use of high-strength steel making up 45 percent of its construction, the CR-Z achieves a remarkable combination of rigidity, reduced weight, and enhanced safety performance. This robust body structure allows for stability as the suspension operates independently, providing a smooth ride and a strong "connected-to-the-road" sensation (American Honda Motor Co., 2010).

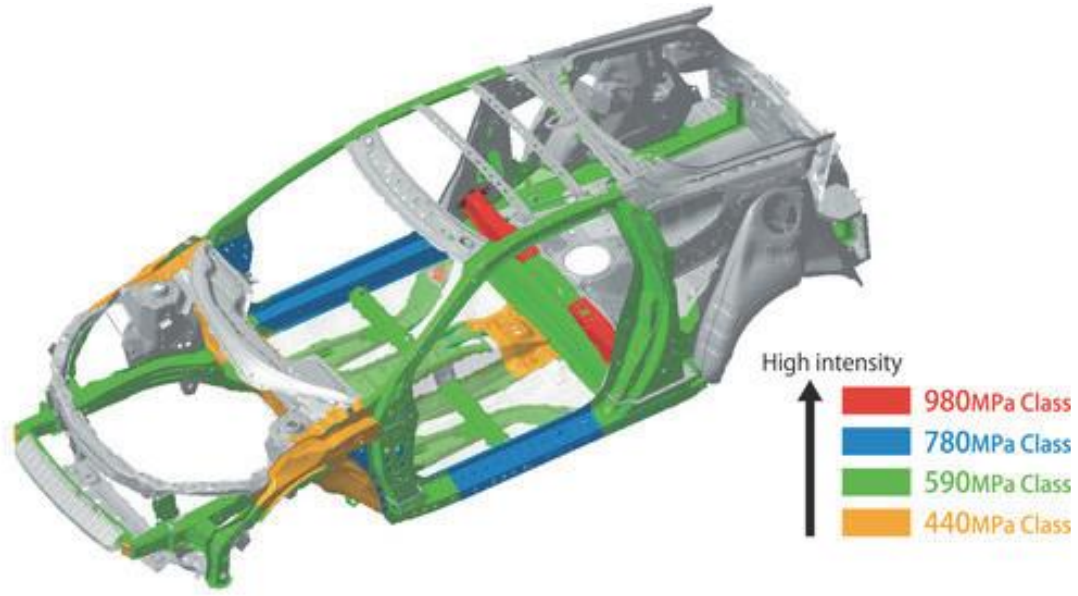


Figure 4.4 Docol 1500M Applications on 2011 Honda CR-Z Car

4.3.2 20MnB4 (Stud Material)

Weld studs are metal components that are either cold-formed or CNC machined, and are designed for attachment to similar metal substrates through stud welding. They offer a quicker installation process compared to traditional fasteners that require drilling, screwing, or tapping. They can be fabricated from materials such as low-carbon steel, stainless steel, aluminum, copper, brass, and even nickel-iron alloys. Their diameters range from approximately 4 mm to 25 mm, and their lengths start from 6 mm and can vary upward (Image Industries Inc., 1993).

In the experimental study, 20MnB4 material was selected as the stud material according to the EN 10263-4 raw material standard, which includes steels that can be shaped plastically, malleable, and heat treated. Figure 4.5 shows the TTT diagram of the standard 20MnB4 material from the literature According to this diagram, Ac3 = 827°C, Ac1 = 719°C. Furthermore, Ms = 385°C and Mf = 225°C. The conversion ranges of the ferrite, perlite, and bainite phases are also indicated (Laber & Koczurkiewicz, 2015).

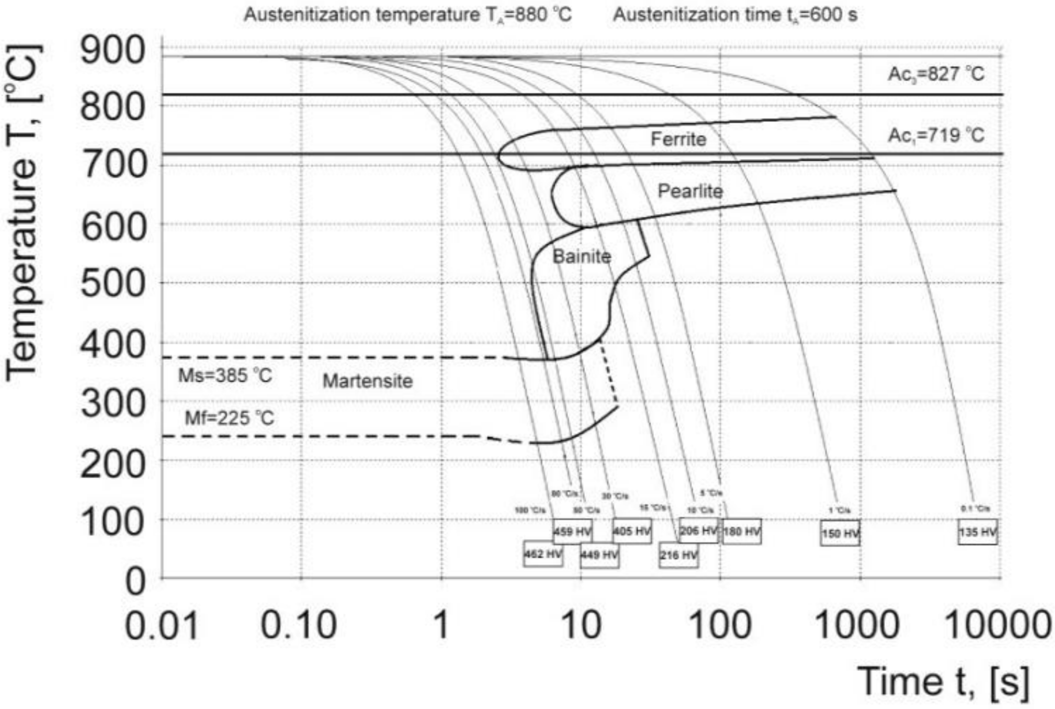


Figure 4.5 Real TTT Diagram for 20MnB4 Steel

The tables below present the chemical and mechanical properties of the 20MnB4 and Docol 1500 M materials utilized in the experiment.

Table 4.1 The Chemical Composition of Stud and Base Plate

Material	C	Si	Mn	P	S	Cr	Cu
20MnB4	0.18-0.23	0.30	0.90-1.20	0.025	0.025	0.30	0.25
Docol 1500M	0.28	0.40	1.30	0.020	0.010	1.00	0.20

Table 4.2 The Mechanical Properties of Stud and Base Plate

Material	Yield $Rp_{0.2}$ MPa	Tensile Rm MPa	Elongation
20MnB4	897 (≥)	659 (≥)	A (%) 31
Docol 1500M	1220-1520	1500-1750	A_{80} (%) 3

4.4 Finite Element Modelling

Finite Element Method (FEM) was utilized to simulate and analyze the joint strength of the stud weld structure. Both 2D and 3D structural analyses were carried out by using DEFORM software. The material properties and boundary conditions were defined by using the commercial finite element code and automatic mesh generated for the models. The solution algorithm of the Newton-Raphson iteration was employed.

4.5 Methodology And Experimental Procedure

The Arc Stud welding process is executed using a welding gun, allowing for application in various directions and shapes based on the welding location. The welding can be performed overhead, downward, vertically, or at an angle. In our work, we have utilized the downward direction for the welding process. The details of the setup in the experiment can be seen in Figure 4.6.

Figure 4.6 Installation View of Experimental Equipment

Choosing the right process parameters and settings to achieve a high-quality welded joint is crucial. The experiments aimed to identify the optimal amperage, welding duration, immersion depth, and lifting height to ensure strong joint integrity. In the experiments, Ø8mm and l=75mm fully threaded studs made of 20MNB4 quality material and Ø45mm diameter and t=2mm Docol 1500 Martensite sheets were used, and all samples were of the same material size and quality. After selecting the primary test materials, it was crucial to assess their weldability. Four different parameters were taken into account during the welding process. The key parameters include ampere, holding time, immersion, and lifting distance. The welding process was performed by varying these parameters to determine the optimum welding parameters for the test materials. An understanding of the settings and adjustments and their relationship to weld quality is required to ensure consistent stud welding results. Amperage and dwell time can be conveniently adjusted digitally on the machine, whereas the plunge distance (P) and lift distance (L) can be modified directly from the welding gun handle. Additionally, the cleanliness of the surfaces to be welded is crucial, as these factors can significantly influence the quality of the weld. The impact of these parameters on the welding process can be summarized as follows:

1. **The welding current**, refers to the flow of electric charge, measured in amperes and indicated by (I). It can be adjusted using the control buttons on the stud welder.
2. **The welding time**, is defined as the time from the moment the arc appears until it disappears. This is measured in seconds and indicated as (tw) in our study, and adjustments are made via a control unit on the stud welder.
3. **The plunge** refers to the length of the stud metal visible at the end of the gas jacket ring. It is measured in millimeters (mm). Its value can be changed using the support foot on the stud gun (Yilmaz & Hamza, 2014c). The plunge value plays a critical role in shaping the quality of the weld fillet. If the plunge height is too high, it can lead to fillets that are incomplete or have an irregular appearance. Conversely, insufficient plunge can also produce incomplete fillets. Additionally, the amount of plunge affects the level of spring pressure used to drive the stud. Excessive plunge can cause the weld to "splatter," while inadequate plunge will result in incomplete fillets (Image Industries Inc., 1993).

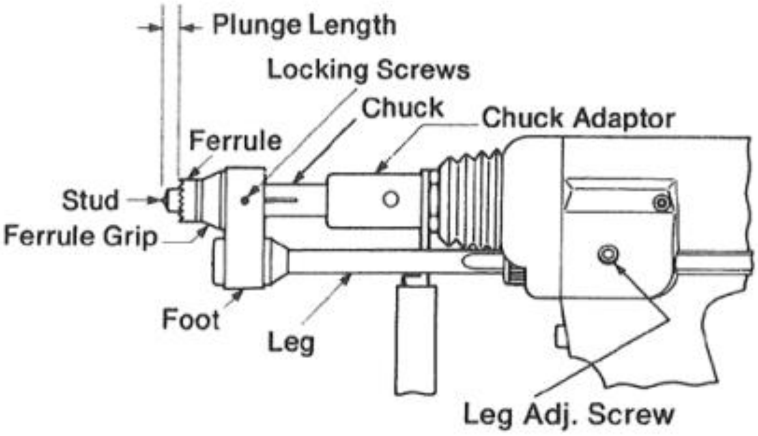


Figure 4.7 Representation of the Plunge Distance in a Stud Welding Gun(Crdcreighton, 2016).

4. **The lift** generates an air gap that the electric current needs to cross. As the current flows through the resistance of this gap, it produces arc heat that melts both the stud and the base material (Harry A. Chambers PCI Journal, 2001). Its value is given in millimeters (mm), and its value can be changed using the adjustment screw on the stud gun. The lifting motion is a crucial part of the stud welding process, as it creates a gap that the electrical current must cross. This air gap raises the resistance in the circuit, producing the heat needed to melt both the stud and the base material for welding. Without this gap, the current would create a direct short to the base material, preventing the development of adequate heat (Image Industries Inc., 1993).

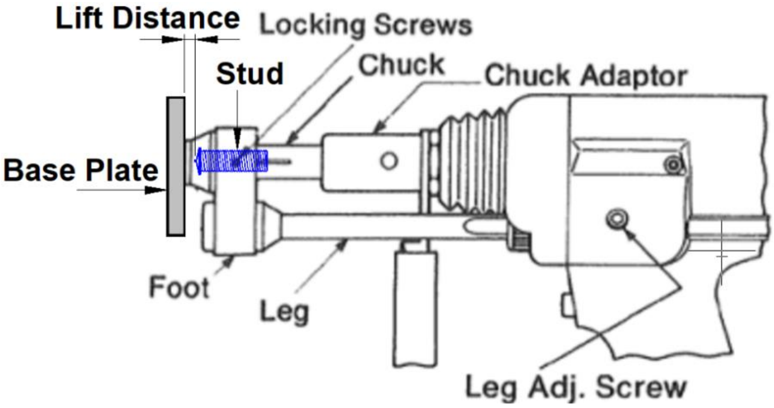


Figure 4.8 Representation of the Lift Distance in a Welding Gun (Crdcreighton, 2016)

The parameters and their respective values utilized in the experiments are displayed in Table 4.3 below ;

Table 4.3 Welding Process Parameters and Corresponding Levels

Sample No	I (Amp)	t (sec)	P (mm)	L (mm)	Welding Conditions
S1	500	0,220	3	5,9	Clean surface Ceramic ferrules were used during the implementation
S2	500	0,250	3	5,9	
S3	350	0,280	3	5,9	
S4	350	0,270	3	5,9	
S5	500	0,200	3	5,9	
S6	500	0,150	3	5,9	
S7	500	0,175	3	5,9	
S8	350	0,275	3	5,9	
S9	500	0,125	3	5,9	
S10	350	0,300	3	5,9	

In this experimental study, the weldability of 20MnB4 carbon steel and Docol 1500 martensite material was investigated using the arc stud welding method. Since there are no tables to determine the optimum welding parameter levels for the high-quality performance of welded joints, the "rule of thumb" method was used for parameter settings. According to the preliminary results of welding trials, the most suitable plunge (3mm) and lift (5.9mm) values were taken constant for Ø8mm stud diameter and t=2mm base metal, the values of welding current and welding time were changed and 10 different samples with the best welded joint results were determined. The effects of arc stud welding parameters such as welding current, welding time, plunge, and lift distance on mechanical and microstructural properties at the end of the welding process were investigated experimentally.

Three groups of test sets, all with identical parameters, were established. Tensile tests were done on the first set, while bending tests were performed on the five samples with the strongest welded joints in the second set. In the third set, penetration depth was assessed, and hardness tests were carried out on the samples exhibiting both the highest and lowest joint strength. Additionally, the micro-hardness structure of the sample with the most robust joint strength was analyzed.

4.6 Arc Stud Welding Operation

To achieve high-quality welding, it is crucial to carefully select the process parameters and levels. As there are no existing parameter tables for the samples used in this experiment, we employed a "rule of thumb" approach to determine the parameters, considering the characteristics, diameters, and material thicknesses of the test materials. Based on the rule of thumb, the following formula can be applied to determine the welding amperage and time, using the stud diameter as a reference(Nelson, 2021).

Rule of thumb for drawn arc process:

1. Weld current I [A] ≈ 80 × Weld Ø [mm]
2. Weld time t [ms] ≈ 40 × Weld Ø [mm]

The parameter settings derived from this formula may lead to some variations and fluctuations in sheet metal thickness and properties. Additionally, factors such as changing working conditions, longer welding cables, or overloaded power networks can cause actual values to deviate slightly from the specified data. This is also true for welding in challenging positions, like vertical welding against a wall or overhead welding. Consequently, it is important to verify the settings with test welds before commencing work (Nelson, 2021).

Another approach is that 100 amps are required for every 1.5875 mm of stud diameter, and 0.1 seconds are required for every 100 amps of current.

After determining the welding amperage and time according to the stud diameter using the rule of thumb approach, we determined ten separate welding parameters derived from the main calculated settings. These parameters were analyzed to determine the optimum welding conditions considering the deviation conditions that may occur during the welding process. First, we produced test weld joints by selecting one of the calculated parameter settings. We also determined the optimum plunge and lift distances and kept these values as constant plunge and lift values throughout the entire experimental set, thus allowing the amperage and welding time to vary.

After the test welds, the main experimental set welds were started, firstly the surface of the base plate was cleaned from dust, foreign materials, and oils, then it was meticulously cleaned and dried using ethyl alcohol. The parameter settings of the SOYER BMK 16i Stud arc stud welding machine were made diameter of 8mm fully threaded stud material and disposable ceramic ferrule was placed in the PH 3 SRM welding gun. As seen in the table above, welding operations were performed at welding parameters between 350 amperes-500 amperes and 0.125 seconds-0.300 seconds, the immersion distance was kept constant at 3 mm, and the lifting heights were kept constant at 5.9 mm. At the end of the welding process, the effects of arc stud welding parameters such as welding current, welding time, plunge, and lifting distance on mechanical and microstructural properties were experimentally investigated.

Figure 4.9 Samples Welded for Tensile and Bending Testing

4.7 Preparation of Test Specimens

In our welded joint experiments, we utilized carbon steel studs with a diameter of Ø8mm, specifically from the 20MnB4 class and categorized as strength class 8.8. Each stud measures 75 mm in length and features a fully threaded design, complete with a firing tip and heat treatment. The primary material used for the base is Docol 1500 Martensite, which was laser cut into 45 mm diameter discs from a 2 mm thick sheet. All studs and the base material share identical dimensions, quality, and material properties.

To ensure optimal welding preparation, the surfaces of the samples were thoroughly cleaned to remove any moisture, dust, oil, rust, paint, or other contaminants. Detailed drawings and sketches of the prepared samples are included below.

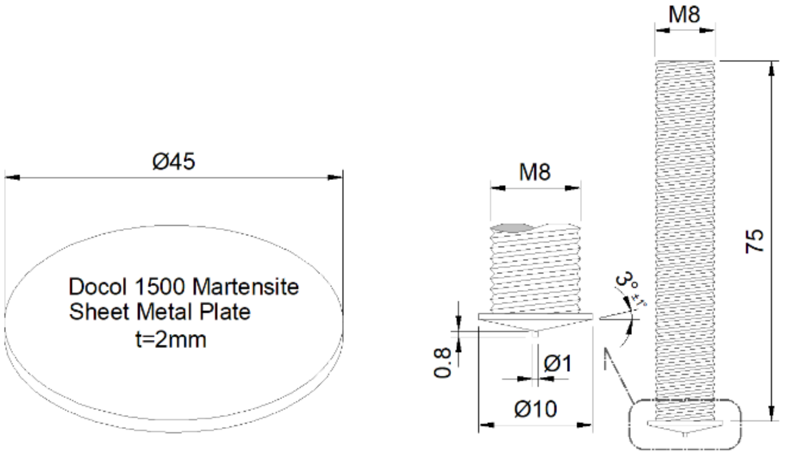


Figure 4.10 Demonstrations of Prepared Test Samples

After the weld samples have been prepared, additional processing steps are needed to enable metallurgical examination and measurements of the samples and to evaluate the weld penetration depth. Initial evaluations were conducted to identify the sample with the highest joint strength, allowing for hardness measurements to be performed. After visual inspection of welds in 3rd groups of samples with the same parameters, tensile tests were applied to samples of group 1. After determining the sample showing the best joint strength based on the analysis of tensile test results, the sample with the same parameters was taken from group 2nd and cut vertically from its exact center using an electrical discharge machining machine (EDM). This cutting method was chosen to obtain the thinnest possible cut line and smoothest surface while minimizing heat input to the sample and avoiding microstructural deformation. First, we cut the long section of the stud using a manual tape cutter. Then, we fixed the sample to the milling machine and ran the milling machine at low speed to avoid overheating while machining half of the surface. Finally, we carefully cleaned the surface of the sample and prepared it for sanding and polishing.

Figure 4.11 View of the Cut Sample

Polishing is a crucial step in the preparation of a specimen for microstructural analysis. The polishing process involves three stages: rough, intermediate, and fine polishing, which are determined by the quality of the ground surfaces. Polishing aims to eliminate scratches from the ground surfaces, resulting in exceptionally smooth and shiny finishes (Vander Voort & Handbook, 2004). Numerous factors influence the quality of the polished surfaces, including the type of cloth used, the abrasives employed, as well as the pressure, speed, and duration of the polishing process (Cunat, 2001).

Mechanical preparation is the most widely used technique for preparing materialographic specimens for microscopic analysis. The required characteristics of the prepared surface depend on the specific type of analysis or examination being conducted. This type of work falls within the domain of metallography, the science dedicated to uncovering and assessing the internal structures of materials. Today, metallography stands as one of the most crucial methods in materials research, serving as an essential resource for both scientists and engineers. Metallography involves examining the physical structure and characteristics of metals, usually through microscopy. The preparation of a metallographic specimen's surface is accomplished through various techniques, including grinding, polishing, and etching. Following this preparation, analysis is often conducted using optical or electron microscopy. The most common preparation technique is mechanical preparation, which employs increasingly finer abrasive particles to remove material from the sample surface until the desired finish is attained. A wide range of machines is available for grinding and polishing, catering to varying requirements for quality, capacity, and reproducibility (Di Gianfrancesco, 2016). The polishing process of Docol 1500 martensite material welded to 20MnB4 grade stud steel is similar to the polishing process of other types of steel. In the sample grinding process, various sandpapers are initially used, especially sandpapers containing abrasive particles of 320, 600, 800, and 1000 grit sizes. This step is performed using a double-disc machine known as the Metkon branded Grinding and Polishing system, where the sandpaper is applied sequentially to the samples. Water is used throughout the process to minimize heat accumulation and to remove metal particles and abrasive residues from the grinding paper. In this study, polishing was performed with a 380 RPM double-disc polishing machine equipped with a silk cloth, medium pressure, and a monocrystalline diamond suspension.

Figure 4.12 Metkon Double Discs Grinding and Polishing Machine

Following the grinding and polishing procedures, the samples were etched to reveal the appearance of both the macrostructure and microstructure of the welded area. The choice of an appropriate etchant is based on the material's chemical composition and the processing conditions.

Three different techniques are employed for etching samples: immersion, swabbing, and electrolytic etching. In this study, the etching process commenced with cleaning the samples to remove oil and polishing residues with acetone, after which the samples were dried (Astm, 1999; Small et al., 2008).

An appropriate etchant for the samples has been chosen based on the AHSS material. A solution was prepared consisting of 4% nitric acid (HNO_3) and 96% ethyl alcohol. The combination of these acids and chemicals results in a solution known as Nital. The samples were swabbed with a cotton pad soaked in the etchant for approximately 5-10 seconds. Following the etching process, the samples were rinsed with water, then with alcohol, and finally dried using hot air.

4.8 Evaluation of Samples

Numerous techniques and assessments exist to assess the performance of welded joints and to explore how welding parameters influence the quality of welded specimens. In this study, each welded specimen underwent tensile tests, bending tests, hardness assessments, penetration depth measurements, and microstructural analyses, and the results are reported.

4.8.1 Tensile Test

Tensile tests are conducted for various purposes. The results from these tests help in selecting suitable materials for engineering applications. Additionally, tensile properties are often assessed during the development of new materials and processes to facilitate comparison among different options. Furthermore, tensile properties are frequently utilized to forecast a material's behavior under various loading conditions beyond simple axial tension (Davis, 2004). Among testing methods, tensile testing is particularly reliable for evaluating the performance of weld metal and weld joints. By applying uniaxial load to the specimen, this method enhances welding procedures and ensures weld quality. Welded joints, a crucial method of joining in engineering, play a vital role in determining their load-bearing capacity and strength, especially when subjected to various loading conditions as dictated by the design. The tensile test fundamentally involves positioning a material sample between two clamps that exert pressure on it. This sample has predetermined dimensions, including length and cross-sectional area. A weight, referred to as load or force, is then applied to one end of the material, while the other end remains fixed. As the load increases, the change in the sample's length is monitored until it ultimately breaks. In the materials laboratory, tensile tests were conducted using a Shimadzu testing machine capable of handling a maximum tensile load of 300 kN. A specialized apparatus was employed to securely hold the welded samples during the testing process. Uniaxial loads were applied to the samples until failure, after which the tensile strength values were recorded electronically. The testing machine and specialized holding apparatus are depicted in Figure 4.13. The holding apparatus was specifically designed based on the dimensions and sizes of the welded connection samples and was fabricated in the workshop of Gaziantep University.

Figure 4.13 Shimadzu Testing Machine and Holding Apparatus

4.8.2 Bending Test

The bend test is a simple qualitative assessment used to assess the ductility and strength of welded specimens when the weld zone is subjected to load. This test serves as a basic method to approximately verify selected weld data. The weld bend test helps to verify that the heat-affected zone and the weld itself have not become brittle during the welding process. During the process, the weld is subjected to an undefined bending action, but if arc flash or other visible defects in the weld zone are suspected, the stud should be bent so that the area to be examined is in the tension zone. Bend tests can be performed on stud weld specimens using three different methods: using a hammer, a metal pipe of appropriate size, or a torque wrench. According to ISO 14555, these tests can be performed by applying a bending moment below the elastic limit of the specimens or by bending the stud axis by at least 30°. For short-cycle drawn arc stud welding, drawn arc stud welding, and spark-tip capacitor discharge welding processes, specimens shall be bent at an angle of at At least 60° from the stud axis. (Iso 14555:2017, 2017).

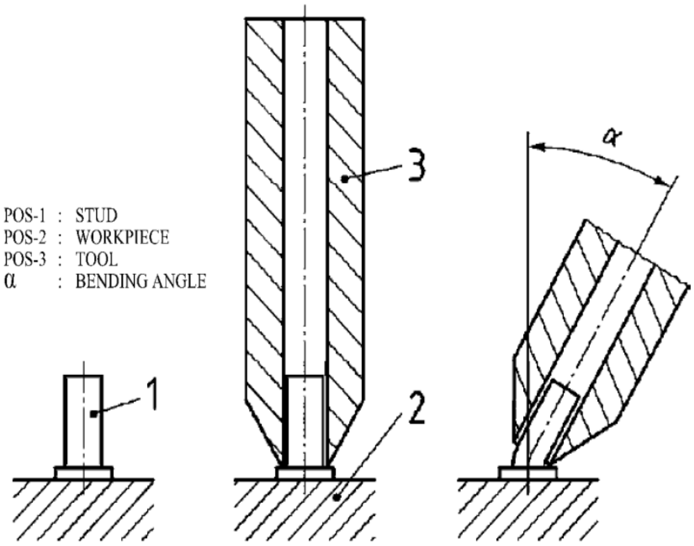


Figure 4.14 Bending Test By Using a Metal Pipe of Suitable Size

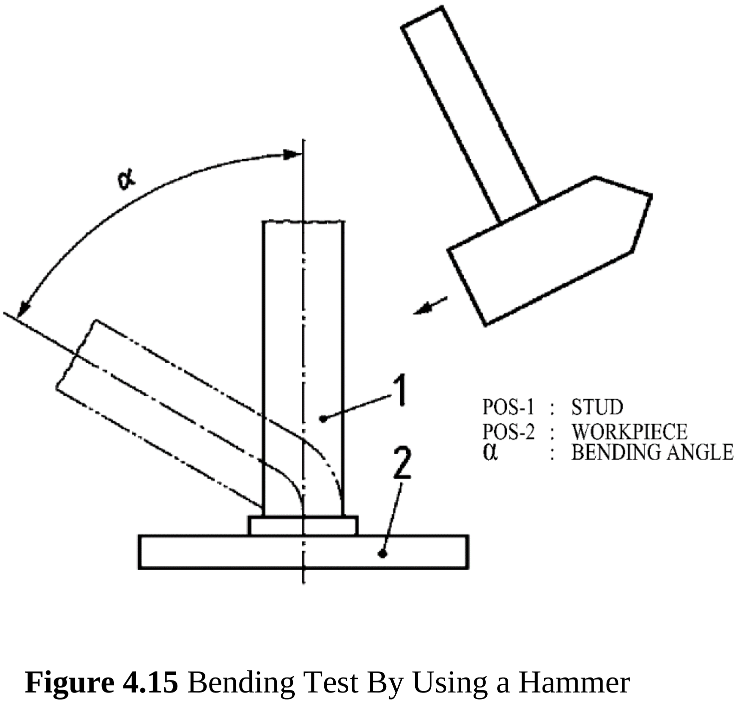


Figure 4.15 Bending Test By Using a Hammer

Figure 4.16 Bending Test By a Torque Wrench

We utilized a metal pipe and adjustable miter to conduct the bending test. The sample was secured in a vise, and we applied force gradually and cautiously using the metal pipe. We maintained control over the bending angle with the adjustable miter, continuing to apply loads until we reached 60 degrees. When the bending angle reached 60 degrees, the applied force was halted, and the bending surface of the sample was examined.

Figure 4.17 Control of Stud Bending Angle with Adjustable Mite

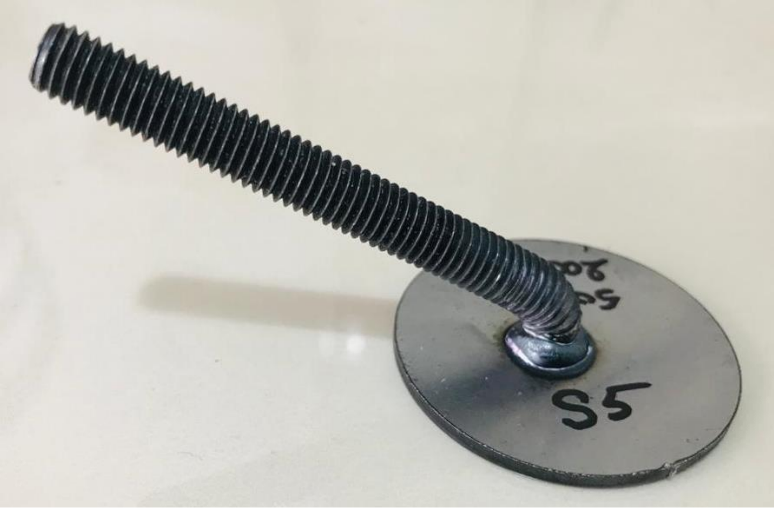


Figure 4.18 View of Bent Form of the Sample

4.8.3 Depth Penetration

The penetration depth in welding refers to the distance from the edge of the base metal to the termination of the fusion line. Once the welding of the samples was finished, a solid piece was obtained by vertically cutting through the center of the sample to analyze the microstructure of the joint with the highest quality weld. An electrical discharge machining (EDM) machine was utilized to avoid any heat-related distortions during the cutting process. Subsequently, the cut sample underwent fine grinding and polishing using a range of sandpapers and silk cloths, progressing from coarse to fine grits (Sudhakaran et al., 2012).

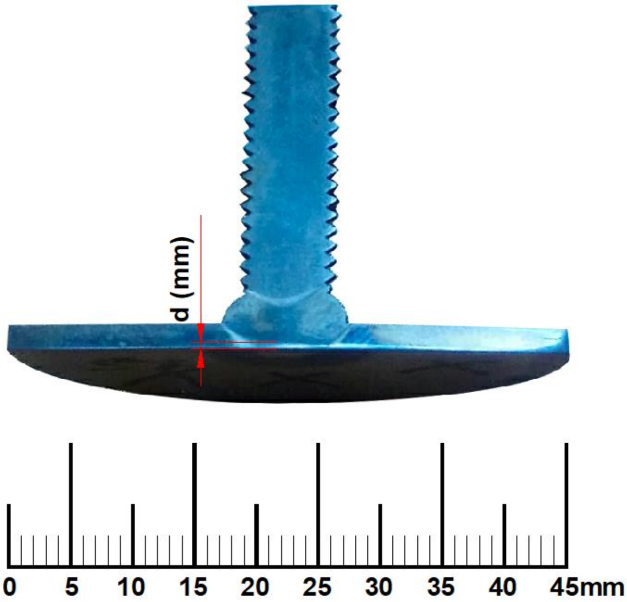


Figure 4.19 Measuring of Depth Penetration

4.8.4 Micro Hardness Test

Hardness testing is a crucial and widely used mechanical procedure for evaluating the properties of metals and other materials. Hardness is generally defined as the capacity of a material to resist permanent indentation. During this process, an indenter is pressed against the surface of the material with a specified load for a defined period, and the size or depth of the resulting indentation is subsequently measured.

The main aim of hardness testing is to assess whether a material is appropriate for a particular application or the specific process it will undergo. According to general application areas, hardness tests are divided into two main groups: micro-hardness and macro-hardness tests.

Macro-hardness testing involves applying a load of more than 1 kg to the indenter, while micro-hardness testing involves applying a load of 1 kg or less. Macro-hardness tests are used to test heavier gauges, molds, and sheet materials, while micro-hardness tests are used on extremely small parts, welded joints, thin superficially hardened parts, coated surfaces, and thin sheet metal (up to 0.0125 mm or 0.0005 in) (Chandler, 1999).

Vickers hardness is typically assessed by applying a load to an indentation created by a ball, cone, or pyramid. In our study, we employed the Vickers micro-hardness method to determine the hardness of the weld zone in our specimens. The device used for this testing features a diamond pyramid with a square base, a face angle of 136 degrees, a maximum load capacity of 1 kg, and a loading duration of 10 seconds. With the microscope of the micro-hardness tester, the initial point on the main sheet metal was chosen to be 1 mm above the base metal's bottom surface and then moved toward the stud metal.

Figure 4.20 Device of Micro-hardness Tester

4.8.5 Micro-Structure Examination

To understand the effects of microstructure on the mechanical performance of welds, it is important to recognize microstructural differences at the various weld regions. To grasp how microstructure influences the mechanical performance of welds, it's essential to acknowledge the variations in microstructure across different weld zones. When two distinct materials are joined through arc welding, the heat generated by the electric arc melts both the stud and the base metal in the weld zone and the heat-affected zone. This process results in differences in the microstructural characteristics and grain sizes of both the stud and the base metal (MI et al., 2008). In this investigation, a Nikon microscope with 500X magnification was used to show the changes in the microstructure of WM, interface zone, and HAZ.

Figure 4.21 Nikon Microscope with 500X Magnification

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 Introduction

The results section of this research outlines the analysis of the experimental findings and presents a discussion.

5.2 Evaluation of Tensile Test

Tensile testing is a destructive method commonly employed to assess the strength and ductility of WM, particularly in welded joints. This research examined the weldability of components made from two distinct material classes, utilizing various welding parameters and analyzing the resulting data. The results revealed that the tensile strength of the weld joint surpassed that of both the base metal and the stud metal. The study demonstrated that welding parameters have a significant impact on the performance and quality of the weld. While some specimens exhibited robust weld joints, others, welded with different parameters deviating from optimal values, displayed inadequate fusion and inferior performance.

These tests underscore the importance of using optimal welding parameters to achieve sound weld joints and enhanced tensile strength, which is essential for successful welding outcomes.

In this context, achieving improved performance and quality of welded joints is essential to attain higher joint strength values. Figure 5.1 depicts the fracture mode of the samples following the tensile test

Figure 5.1 Fracture Mode on Samples After Tensile Test

5.3 Evaluation of Bending Test

The bending test is a crucial mechanical experiment that provides insight into the strength of welded joints and assesses the ductility of the material. The bending strength is defined as the maximum bending stress experienced at the moment of fracture, which indicates the bending capacity of the sample. In other words, it reflects the material's resistance to bending forces. In our study, bending tests were conducted on samples with proper welding joins, achieved through optimal welding parameters, as well as on samples with weaker joints.

These tests were performed by the EN ISO 14555 International Standard. During the tests, appropriate forces were applied to the samples according to the standards, allowing us to observe their bending behavior. Notably, the samples with high joint strength, welded using optimal parameters, showed no fractures or defects during bending. However, slight cracks were identified in the samples with lower tensile strength due to different welding parameters. To confirm the presence of cracks and defects, a liquid penetrant test was conducted on the samples, which successfully verified the cracks.

Table 5.1 Results of Bending Test Performed on Samples

Sample No	**I (Amp)**	**t_w (sec)**	**P (mm)**	**L (mm)**	**Location of Fracture**	**Evaluation**
S1	500	0,220	3	5,9	no fracture	passed
S2	500	0,250	3	5,9	weld zone	failed
S3	350	0,280	3	5,9	no fracture	passed
S4	350	0,270	3	5,9	weld zone	failed
S5	500	0,200	3	5,9	no fracture	passed

Liquid Penetrant Testing (LPT) is employed to identify surface-connected discontinuities, including fatigue cracks, those caused by quenching and grinding, as well as fractures, porosity, incomplete fusion, and imperfections in joints. Figure 5.2 presents the results of the bending tests conducted on the samples.

Figure 5.2 Results of Bending Test on Samples

It was also observed in this experiment that cracks and defects occurred as a result of welding at a value close to the optimum welding parameter by automatically adjusting the amperage and holding time in samples with the same plunge (m) and lift (L) height. These defects may have been caused by incorrect manual sensitivity of the welding process. According to the bending test results, although no defects were detected in samples numbered (S2 and S4), fractures were detected according to the penetration test, and no cracks and fracture formation were observed in samples numbered (S1, S3, S5) and this was also confirmed by the penetration test.

5.4 Evaluation of Depth Penetration (DOP)

Weld penetration, also known as fusion depth, refers to how deep the fusion extends from the molten surface into the base material or previous weld pass. The welding current plays an important role in determining this penetration depth. In particular, the depth of weld penetration is directly affected by the welding current; increasing the current increases penetration, while decreasing it decreases penetration. Normally, under variable welding current, the depth penetration should vary at a certain rate according to the thickness of the base metal sheet. Due to the thickness of the base metal, which is only 2 mm, the welding current values used according to the optimum welding parameters caused almost equal penetration in all samples. In all well-welded samples, the penetration depth is approximately at the same level, and due to this observed situation, it can be said that all welds have full penetration. Below, the penetration depth and weld size in a best quality welded sample can be seen; (Sample No. S5).

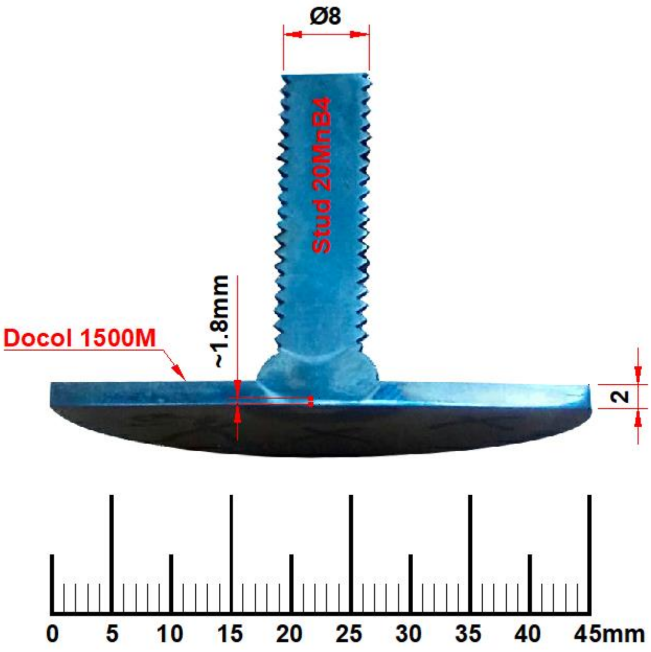


Figure 5.3 Measuring of DOP on Samples

5.5 Evaluation of Micro-Hardness Testing

Hardness refers to a material's resistance to permanent deformation, including indentation, wear, and scratching. Microhardness testing plays a crucial role in assessing structural changes during mechanical testing, particularly in welded joints. The heat involved in the welding process causes microstructural alterations, such as melting, cooling, and solidification in the welded areas, leading to variations in grain size and, consequently, differing hardness levels in these regions. In our study, we analyzed the hardness values of the weld sections in our samples, examining how temperature variations affected the hardness. In our experiments, we utilized two distinct samples: one exhibiting high-quality joint strength (S5) and the other demonstrating weaker joint strength (S4). The following figures illustrate our observations regarding hardness changes. Our results indicate that the hardness of the weld metal (WM) surpasses that of both the heat-affected zone (HAZ) and the base materials. Furthermore, an examination of the hardness distribution in the welded samples revealed a soft area at the bottom of the main material, as depicted in the accompanying figures. This soft region likely forms due to the accumulation of softer weld metal on the harder base metal during the welding process.

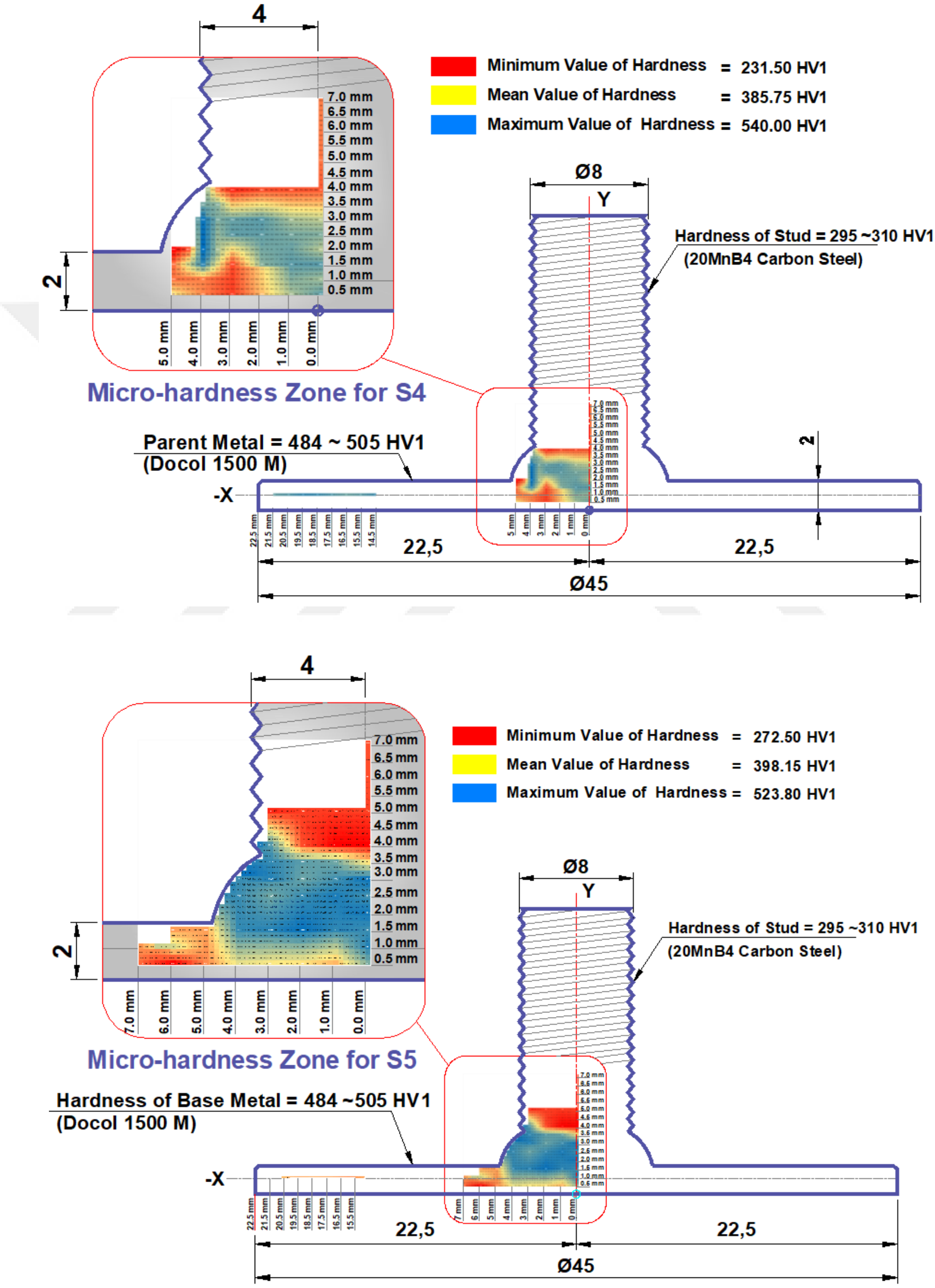


Figure 5.4 Distribution of Hardness on the S4 & S5 Samples

5.6 Finite Element Analyses Results

In addition, the failure situation and joint strength value that caused the damage was simulated using Deform FEM and Solidworks analysis software, and the resulting failure situation and the obtained joint strength values were verified. The results are shown in **Figure 5.5** and **Figure 5.6**

5.7 Microstructure Analyses Results

It is important to perform microstructure analysis to improve the strength, interface, and heat-affected zone properties of the weld metal. In another sense, significant changes in microstructural properties affect the mechanical properties of the weld joint. The change in grain size in the microstructure affects the weld joint quality (MI et al., 2008). At the bottom of **Figure 5.7**, the cross-sectional view and the selected microstructure region of the arc stud welding connection prepared at 350 A welding current and 0.20 s welding time are shown. **Figure 5.7.a** shows the microstructure of the left side view of the main material Docol 1500 martensite. These sections can be called parts whose internal structure does not change during welding. This means that these areas are not overly exposed to welding heat. **Figure 5.7.b** shows the microstructure of the upper side view of the main material Docol 1500 martensite. These regions are similar to the microstructure on the side surface of the plate in terms of internal structure change, except for close distances to the weld areas. **Figure 5.7.c** shows the microstructure of view of the stud material 20MnBn4. This region is not exposed to heat. **Figure 5.7.d** shows the microstructure view of the HAZ, which is the heat-affected zone of Docol 1500M, which is the melting zone of the main material. Generally, heat-affected zones are the most critical point of the welded connection, fractures occur more in these regions and the microstructures of these regions change depending on the heat input. It can be said that the microstructure also grows and increases in grain structure. **Figure 5.7.e** shows the microstructure view of the HAZ, which is the heat-affected zone of 20MnB4, which is the melting zone of the stud material. **Figure 5.7.f** shows the microstructure of the fusion zone of the weld joint produced at 350 A current and 0.20 second welding time.

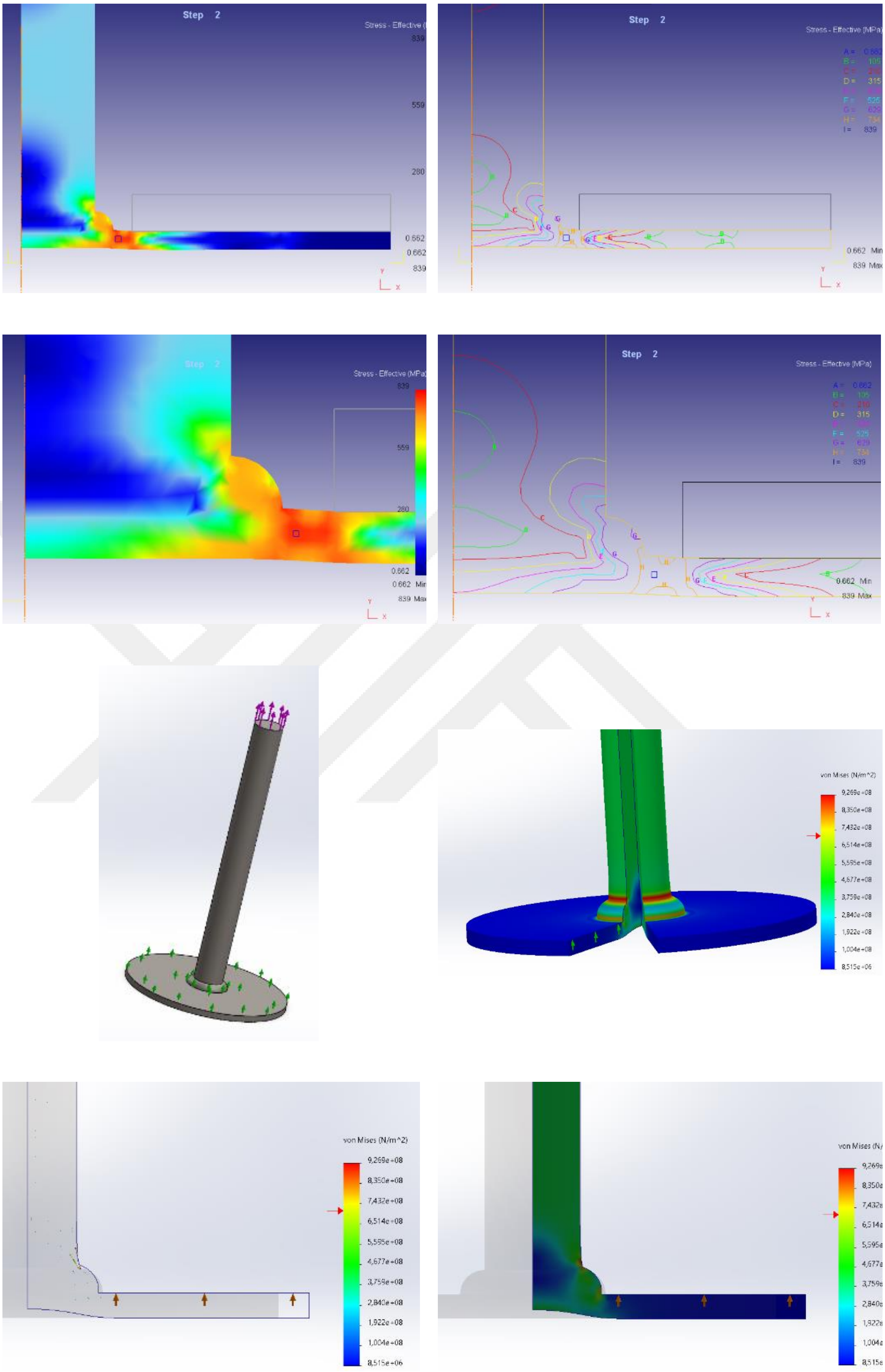


Figure 5.5 Results of FEA for S5 Sample

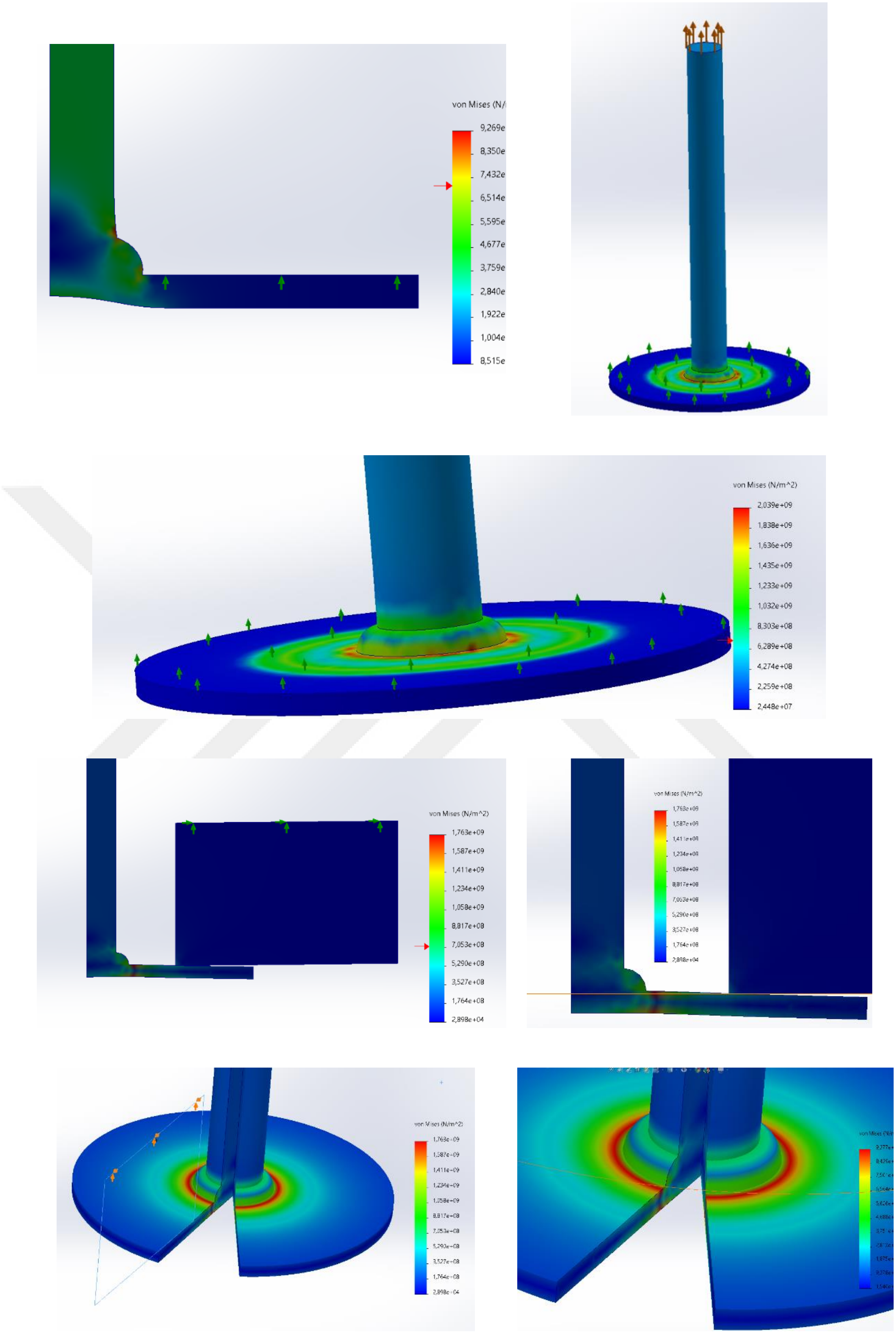


Figure 5.6 Results of FEA for S5 Sample

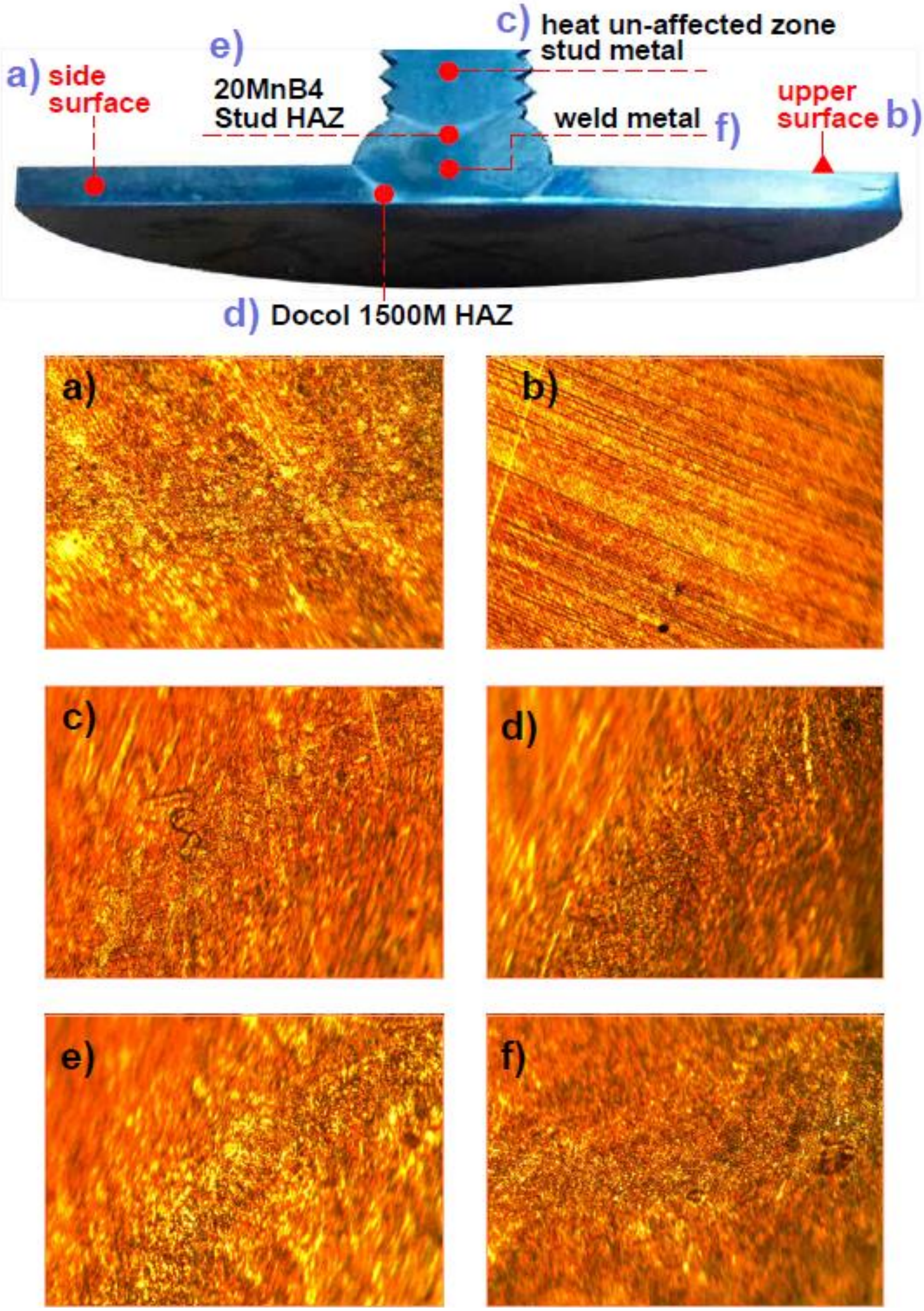


Figure 5.7 Microstructure images from different regions of Sample No. S5.

5.8 Discussion

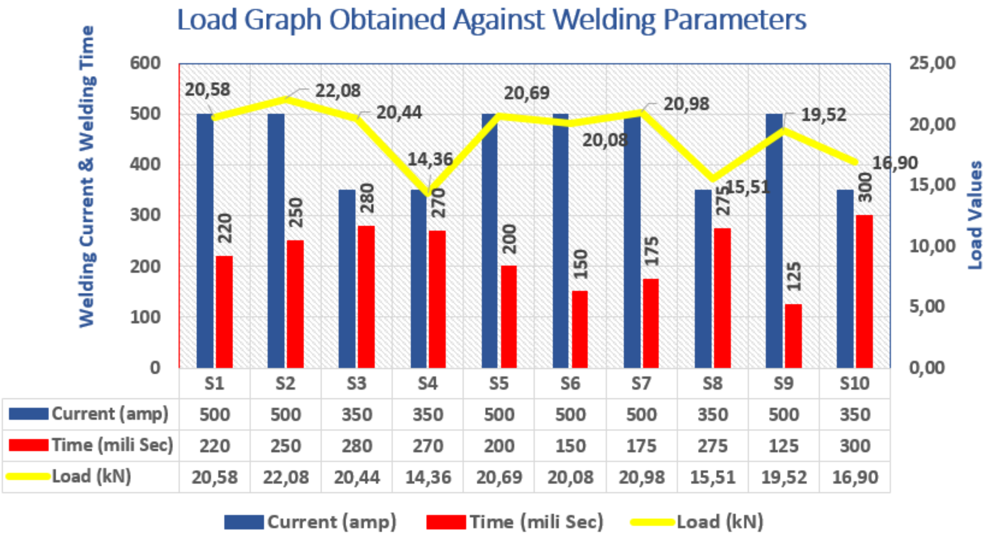
The Docol 1500 Martensite material and 20MnB4 quality materials can be successfully welded using the arc stud welding method. Proper adjustment of parameters, including welding amperage, welding time, plunge distance, and lifting distance, is crucial for conducting post-welding tests. The evaluation of these tests revealed that these parameters significantly influence the formation of a strong and high-quality welded joint. In summary, the study highlights the importance of parameter optimization in achieving optimal welding results.

Welding Time; The duration of the welding process is a critical factor, especially in techniques such as arc stud welding, which involves short welding times. Long welding times can lead to excessive fusion and penetration, which can cause weld build-up called overlap, while inadequate welding times can lead to inadequate heat input and penetration depth, which can result in poor joint strength. It is therefore important to adjust the welding time according to the stud materials' diameter.

Welding Amperage; Increasing the amperage value in the welding process increases the welding temperature and is the most important secondary parameter for the process after the welding time. It is necessary to choose a certain value depending on the stud diameter to be welded and the base metal (WM) thickness. If the amperage value is used at a higher value than it should be, it causes excessive fusion. If it is used at a lower value, it causes insufficient fusion, negatively affecting the quality of the weld joint.

Plunge Distance; The plunge distance refers to the length of the stud metal that extends a specified distance from the ceramic ring end of the stud. The plunge distance represents the end part of the stud that remains outside to form the weld fillet. Its effect on welding is that a short immersion distance may cause incomplete fillet formation, while a long immersion distance may cause irregular fillet formation and excessive spatter. In our study, we used the same diameter stud and the same base metal thickness in all examples, so we used 3 mm as a constant.

Lifting Distance; Lift distance refers to the space between the tip of the stud and the base metal. This air gap enhances the circuit's resistance, producing the heat necessary to melt both the stud and the base material for welding. If the gap is too large, the arc won't be able to form; conversely, if there is no gap, a direct short circuit may occur in the base material, resulting in insufficient heat generation. In our study, we used the same diameter stud and the same base metal thickness in all examples, so we used 5.9 mm as a constant. The effect of the welding parameters applied in joining high-strength steel to carbon steel using the arc stud welding method is reflected in the results of the tensile tests after welding. The graph below shows the distribution of breaking loads obtained from the tensile tests performed on welded joint samples created with various welding parameters. There are changes in the breaking load depending on the welding time of the joints. The breaking load values of 10 different welded samples obtained as a result of different welding times between 0.15 seconds and 0.300 seconds for 350A and 500A welding currents are given in the graph below;



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Current (amp)	500	500	350	350	500	500	500	350	500	350
Time (mili Sec)	220	250	280	270	200	150	175	275	125	300
Load (kN)	20,58	22,08	20,44	14,36	20,69	20,08	20,98	15,51	19,52	16,90

Figure 5.8 Load Graph Obtained According to Welding Parameters

The lowest breaking loads were observed to be 19,52kN and 20,08kN at 0.125 and 0.150 seconds of welding time, respectively, when using a welding current of 500A. These low breaking load values are attributed to inadequate melting of the base metal due to insufficient welding time. As the welding time increased, the joint strength also increased and the failure load reached 20,69 kN and 20,58kN at 0.200 and 0.220 seconds, respectively. The maximum breaking load was 22,08kN at a welding time of 0.250 seconds with a current of 500A. These findings indicate that the tensile strength of the weld surpasses that of both the base metal and the stud material, suggesting that some samples exhibit excellent joining capabilities. An increase in breaking load also implies a corresponding rise in grain size due to greater heat input. At a lower current of 350A, the breaking load values recorded at 0.270, 0.275, 0.280, and 0.300 seconds were 14,36kN, 15,51kN, 20,44kN, and 16,90kN respectively. Similar to low welding times, reduced current values resulted in lower breaking load measurements due to insufficient heat input and incomplete melting. These tests demonstrate that achieving optimal welding parameters is crucial for obtaining strong welds and enhanced joint strength. When the finite element analysis simulation of the weld area subjected to breaking loads is performed on the sample S5 with the highest breaking loads, the values obtained for the joint strength and hardness are as follows:

SAMPLE No.5	**Hardness HV1**	**Joint Strength Mpa**
HAZ-1	272	860
HAZ-2	395	1300
WELD METAL	**525**	**1800**
DOCOL 1500M	484 ÷ 505	1500 ÷ 1700
20MnB4	295 ÷ 310	930 ÷ 950

Table 5.2 Hardness and Joint Strength Values of S5

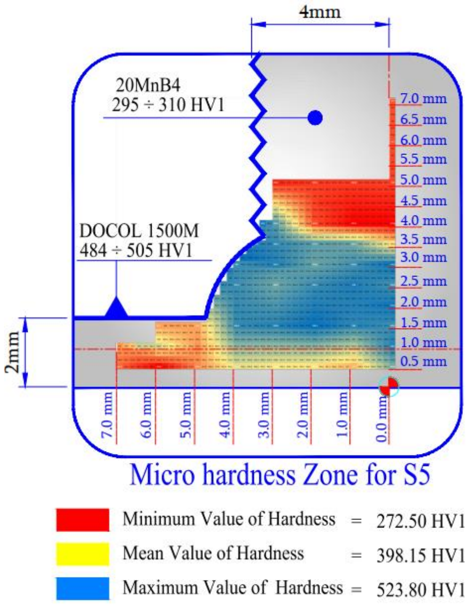


Figure 5.9 Hardness Change of Welding Area of Sample S5.

CHAPTER 6

CONCLUSIONS AND FUTURE WORKS

6.1 Introduction

This chapter discusses research findings on arc stud welding of high-strength steels, as well as potential future work in this field.

6.2 Conclusions

Among the welding methods, arc stud welding is a successful method for welding fully threaded low carbon steel studs with a diameter of 8 mm and a length of 75 mm, a diameter of 45 mm and a thickness of 2 mm to high strength martensitic steel plate. Stud welding application was performed on 10 different samples and parameters ranging from 350 ampere to 500 ampere welding current values and 0.125 seconds to 0.300 seconds welding time values, and 5 welded joints with the best welding parameters were determined among the 10 samples.

Tensile tests were applied to 10 different samples and the samples were examined by changing the duration according to the breaking load values. Bending tests were applied to 5 different welded joints with the best parameters, and then the hardness and microstructure examination of the welded joint with the best parameters was performed.

It was determined that the most successful welding among welded connections was the one with 500A electric current, 0.200 second welding time, 3mm plunge, and 5.9mm lifting distance.

As a result of the tensile strength test, it was determined that the rupture occurred under a maximum load of 20,695 N and the maximum joint strength was 1800MPa. The conclusions obtained as a result of the studies conducted are as follows;

1. In the S5 welding joint, which utilized a 500A electric current with a welding duration of 0.200 seconds, a plunge depth of 3mm, and a lift height of 5.9mm, a maximum strength of 1800MPa was achieved during the tensile

2. strength test. It was concluded that this strength measurement reflects the joint strength rather than the completed tensile strength.
3. During the tensile test of the S5 sample, welded at 500 amperes for 0.200 seconds, a failure mode was observed under a load of 20,695 N. The mode of failure was characterized by pull-out fracture, resulting in the formation of holes within the base material.
4. The bending test performed on the S5 sample, following EN ISO 14555 standards, revealed no indications of cracks or micro cracks in the welding area or the stud. In addition, samples S1 (500A and 0,22 sec) and S3 (350A and 0,28sec) successfully passed the bending test as well.
5. Hardness measurements from the sample revealed values of 272HV1 and 860MPa UTS in the HAZ-1 region, 395HV1 and 1300MPa UTS in the HAZ-2 region, and 525HV1 and 1800MPa in the welding zone. For the base material, Docol 1500 Martensite hardness was recorded at 484-505 HV1 and 1500-1700MPa, while the 20MnB4 stud displayed hardness values of 295-310 HV1 and 930-950MPa UTS. Notably, the melting zone exhibited higher hardness than both the base material and the stud. It can be said that the reason why the weld metal area has high hardness and strength is the rapid cooling conditions after excessive heating.
6. An examination of the microstructure reveals that the heat-affected areas experience the highest temperatures, leading to an increase in grain structure, which grows and elongates in this region. It is anticipated that these microstructural changes will influence the mechanical and physical properties of the affected areas. It can also be said that the reason for the HAZ region having a coarse grain structure is the excessive heating and slow cooling conditions.

6.3 Future Works On ASW Method On High-Strength Steels

This study serves as supplementary research for future work focused on evaluating the weldability of carbon and stainless steel studs with different diameters using the arc stud welding technique on high-strength steels with different properties.

Using an experimental design method such as Taguchi, we aim to determine the optimal welding parameters that will lead to high-quality welds.

In addition, the welded samples will be subjected to microstructural analysis and metallurgical tests, including bending tests, tensile strength evaluations, and hardness evaluations to evaluate their impact on weld quality.

REFERENCES

©2024 STANLEY® Engineered Fastening. (2024, July 30). Stud Welding Methods.https://www.Stanleyengineeredfastening.Com/En/Resources/ Stud-Welding-Methods.

A.C. ASSOCIATES, 2024. (2024, July 31). Ceramic Ferrules. https://www.Acassoc.Net/Post/Easy-Tips-to-Reduce-Waste-at-the-Jobsite. www.acassoc.net/post/easy-tips-to-reduce-waste-at-the-jobsite

Algodi, S. J. M., Salman, A. A., & Al-Helli, A. H. (2023). Microstructure and Mechanical Properties of AISI 1106 /AISI 1045 Steels Drawn Arc Stud Welded Joints. Advances in Science and Technology Research Journal, 17(5). https://doi.org/10.12913/22998624/171020

American Honda Motor Co., I. (2010, June 18). 2011 Honda CR-Z High-Strength Steel Application.h US/Releases/2011-Honda-Cr-z Body?Page=370.https://hondanews.com/en-US/photos/2011-honda-cr-z-high strength-steel-application

Anik, S., & Tülbentçi, K. (1980). Kaynak Tekniği. İstanbul Teknik Üniversitesi Kütüphanesi, 960. Aravinda, T. (n.d.). Advantages and Limitations of Welding. Concept of Lathe Machine and Welding Techniques, 37.

ASTM, E. (1999). 407-99: Standard Practice for Microetching Metals and Alloys. ASTM, West Conshohocken.

Cary, H. B. (2004). Modern Welding Technology 5/e. Industrial Robot: An International Journal,31(4),376. https://doi.org/10.1108/ir.2004.31.4.376.3

Chambers, H. A. (2001). Principles and practices of stud welding. Pci Journal, 46(5), 46–59.

Chandler, H. (1999). Introduction to hardness testing. Hardness Testing. USA: ASM International, 1–13. Crdcreighton. (2016, August 4). Welder Training Manual 2016.https://Www.Crdcreighton.Com/Wp-Content/Uploads/Welder-Training-Manual-2016.Pdf.

Cunat, P.-J. (2001). The welding of stainless steels. Euro Inox.

Davis, J. R. (2004). Tensile testing. ASM international.

Demeri, M. Y. (2013). Advanced high-strength steels: science, technology, and applications. ASM international.

Di Gianfrancesco, A. (2016). Materials for ultra-supercritical and advanced ultra-supercritical power plants. woodhead Publishing.

Eyercioglu, O., Alacaci, S., & Aladag, M. (2021). Experimental investigation of springback of locally heated advanced-high strength steels. Int. J. Res.-Granthaalayah, 9, 269–277.

Groover, M. P. (2010). Fundamentals of modern manufacturing: materials, processes, and systems. John Wiley & Sons.

Hamza, R. M. A. (2012). Optimized stud arc welding process control factors by Taguchi experimental design technique. Welding Processes, 369–394.

Hance, B. M. (2018). Advanced high-strength steel (AHSS) performance level definitions and targets. SAE International Journal of Materials and Manufacturing, 11(4), 505–516.

Harry A. Chambers PCI Journal. (2001). Harry Chambers' Article on Principles and Practices of Stud Welding (September-October 2001 PCI JOURNAL, pp. 46-58) Nelson Stud Welding , Inc. Elyria Ohio. Harry Chambers' Article on Principles and Practices of Stud Welding (September-Otober 2001 PCI JOURNAL, Pp. 46-58) , 2001, 1–15.

Heer Vohera. (2024, July 30). Advantages of Arc Stud Welding (SW). https://Blog.Thepipingmart.Com/Other/Advantages-and- Disadvantages-of-Arc-Stud-Welding-Sw/.

Horvath, C. D. (2021). Advanced steels for lightweight automotive structures. In Materials, design and manufacturing for lightweight vehicles (pp. 39–95). Elsevier.

Hsu, C., & Mumaw, J. (2011). Weldability of advanced high-strength steel drawn arc stud welding. Welding Journal, 90(3).

Image Industries Inc. (1993, March). IMAGE Welder's guide to Arc Stud Welding March 1993 Revision 1. https://www.Evansmetal.Com/Wp-Content/Uploads/2018/05/STUD_WELDING.Pdf.

ISO 14555:2017. (2017). ISO 14555:2017, Welding — Arc stud welding of metallic materials, Edition 4,2017.

Kahraman, N., & Gülenç, B. (2016). Modern kaynak teknolojisi.

Keeler, S., & Kimchi, M. (2017). AHSS Application Guidelines Version 6.0. World Auto Steel. World Steel Association.

Kou, S. (2003). Welding metallurgy. New Jersey, USA, 431(446), 223–225.

Küçüktürk, G., Tahta, M., Gürün, H., & Karaağaç, I. (2022). Evaluation of The Effects Of Local Heating On Springback Behaviour For Ahss Docol 1 400 Sheet Metal.Transactions of Famena, 46(3). https://doi.org/10.21278/TOF.463037821

Laber, K., & Koczurkiewicz, B. (2015). Determination of optimum conditions for the process of controlled cooling of rolled products with diameter 16.5 mm made of 20MnB4 steel. Proceedings of the 24th International Conference on Metallurgy and Materials-METAL, 364-370.

MI, K., ML, K., Biro, E., & Zhou, Y. (2008). Microstructure and mechanical properties of resistance spot welded advanced high strength steels. Materials Transactions, 49 (7), 1629 – 1637.

Miller Welds. (2016). The History of Welding. Miller Welds, 3.

Nelson. (2021, July). Operating manual Stud welding unit INTRA 2100/1400 for drawn arc and short-term drawn arc processes, Edition: 202107, Revision :A/07.2021/EN.https://www.Stanleyengineeredfastening.Com/-/Media/Web/SEF/Resources/Docs/Nelson/Operating Manual_INTRA-2100-Und-1400.Pdf.

Olson, D. L., Siewert, T. A., Liu, S., & Edwards, G. R. (Eds.). (1993). Welding, Brazing, and Soldering. ASM International. https://doi.org/10.31399/asm.hb.v06.9781627081733

Ramasamy, S. R., Gould, J., & Workman, D. (2002). Design-of- experiments study to examine the effect of polarity on stud welding. Welding Journal-New York-, 81(2), 19-S.

Samardžić, I., Ergić, T., & Klarić, Š. (2008). Analiza sprememb varilne napetosti pri elektroobločnem varjenju čepov s keramičnim obročem. Varilna Tehnika, 57(2), 35–41.

Samardžić, I., Kladarić, I., & Klarić, Š. (2009). The influence of welding parameters on weld characteristics in electric arc stud welding. Metalurgija, 48(3).

Sharma, A., Kumar, S., & Duriagina, Z. (2020). Engineering Steels and High Entropy-Alloys. BoD–Books on Demand.

Small, K. B., Englehart, D. A., & Christman, T. A. (2008). Etching specialty alloys. Adv. Mater. Process, 166, 32–37.

SOYER Branch. (2024, July 31). SOYER Arc Stud Welding Machines and Equipments. https://Soyer.de/En/Products/Stud-Welding-Guns/Ph-3n-Srm16/. https://soyer.de/en/products/stud-welders/

SSAB. (2024, August 1). Docol® 1500M Martensitic. https://www.Ssab.Com/Tr-Tr/Markalar-ve-Urunler/Docol/Otomotiv-Celigi-Snflar/Martensitli-Celik/1500m.

Sudhakaran, R., Vel-Murugan, V., & Sivasakthivel, P. S. (2012). Effect of process parameters on depth of penetration in gas tungsten arc welded (GTAW) 202 grade stainless steel plates using response surface methodology. TJER 2012, 9(1), 64–79.

Taylor, J. S. (2001). An Engineer’s Guide to Fabricating Steel Structures: Successful Welding of Steel Structures. Australian Institute of Steel Construction.

Valiulis, A. V. (2014). A history of materials and technologies development. VGTU leidykla „Technika “.

Vander Voort, G. F., & Handbook, A. S. M. (2004). Volume 9: Metallography and Microstructures. ASM International, Novelty (OH).

Weman, K. (2011). Welding processes handbook. Elsevier.

World Steel Association AISBL. (2024, August 1). Advanced High-Strength Steel (AHSS) Definitions. Https://Www.Worldautosteel.Org/Steel-Basics/Automotive-Advanced-High-Strength-Steel-Ahss-Definitions/. https://www.worldautosteel.org/steel-basics/automotive-advanced-high-strength-steel-ahss-definitions/

Yılmaz, N. F., Çakır, M. V., & Yılmaz, M. (2016). Saplama Kaynak Bağlantılarının Çekme Dayanımının ANFIS ile Modellenmesi. Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 31(ÖS1), 79–88. https://doi.org/10.21605/cukurovaummfd.311889

Yilmaz, N. F., & Hamza, A. A. (2014a). Effect of process parameters on mechanical and microstructural properties of arc stud welds. Materials Testing, 56(10), 806–811.

Yilmaz, N. F., & Hamza, A. A. (2014b). Effect of process parameters on mechanical and microstructural properties of arc stud welds. Materials Testing, 56(10), 806–811.

Yilmaz, N. F., & Hamza, A. A. (2014c). Effect of process parameters on mechanical and microstructural properties of arc stud welds. Mater Test 65 (19): 806–811.

CURRICULUM VITAE

PERSONAL DATA:

Name and Surname: Tamer UÇAR

EDUCATION:

Master’s Degree	Gaziantep University
2024	Mechanical Engineering - Construction and Manufacturing Department
Bachelor’s Degree	Gaziantep University
2015-2020	Mechanical Engineering - Faculty of Engineering
Bachelor’s Degree	Anadolu University
2008-2012	Faculty of Economy - Economics and Administrative Sciences
Associate's Degree	Gaziantep University
1999-2001	Mechanical Program – Gaziantep Vocational School

JOB (WORK) EXPERIENCE:

05/2005 –	Çiltuğ Isı San.ve Tic. A.Ş. – Gaziantep / Turkey
	Draftsman, Manufacturing Engineer, Site Chief, Project and Planning Manager
02/2003 – 02/2004	Turmak Metal Machine – Gaziantep / Turkey
	Manufacturing Department
01/2002 – 07/2003	Güven Mill Machine – Gaziantep / Turkey Draftsman

06/1999 – 07/1999 Pasabahce Glass Factory – Mersin / Turkey

Summer Internship