ANALYSIS OF THE EFFECT OF ELECTRODE TYPE VARIATION AND PWHT TEMPERATURE VARIATION ON SMAW WELDING ON THE IMPACT STRENGTH AND BENDING OF ST 42 STEEL

Muhammad agung nadjmi nasution[1], **Kisto**[2]
[1]Teknik Mesin, Universitas Mangku Wiyata, Cilegon, 42411, Indonesia
[2]Teknik Mesin, Universitas Mangku Wiyata, Cilegon, 42411, Indonesia
*Email Corresponding Author: agungnasution88@gmail.com

ABSTRAK

Baja ST 42 merupakan baja karbon menengah yang banyak digunakan dalam industri konstruksi dan perkapalan karena memiliki kekuatan tinggi serta kemampuan menerima perlakuan panas. Namun, proses pengelasan dengan metode Shielded Metal Arc Welding (SMAW) sering menimbulkan tegangan sisa yang dapat menurunkan kualitas sambungan las. Untuk mengatasi hal tersebut, diperlukan perlakuan Post Weld Heat Treatment (PWHT) guna mengurangi tegangan sisa, memperhalus struktur mikro, dan meningkatkan sifat mekanik hasil lasan. Penelitian ini bertujuan untuk menganalisis pengaruh variasi jenis elektroda (E7016 dan E7018) serta temperatur PWHT (500°C dan 600°C) terhadap kekuatan lentur dan ketangguhan sambungan las baja ST 42. Proses pengelasan dilakukan pada posisi 1G, kemudian spesimen diberi PWHT selama 60 menit. Pengujian dilakukan menggunakan uji tekuk untuk menilai kekuatan lentur dan uji impak untuk mengukur ketangguhan sambungan. Hasil penelitian menunjukkan bahwa PWHT berpengaruh signifikan terhadap peningkatan sifat mekanik. Pada uji tekuk, kekuatan tertinggi dicapai oleh elektroda E7016 dengan PWHT 600°C sebesar 940,808 MPa, sedangkan nilai terendah ditunjukkan oleh elektroda E7018 tanpa PWHT sebesar 572,607 MPa. Pada uji impak, ketangguhan tertinggi diperoleh pada elektroda E7018 dengan PWHT 600°C sebesar 1,72 J/mm², dan nilai terendah terdapat pada elektroda E7016 tanpa PWHT sebesar 1,20 J/mm². Dengan demikian, PWHT terbukti meningkatkan kekuatan lentur dan ketangguhan sambungan, sedangkan pemilihan elektroda harus disesuaikan dengan kebutuhan aplikasi, baik untuk ketahanan lentur maupun ketangguhan terhadap beban dinamis.

Kata kunci: SMAW ; Elektroda E7016 ; Elektroda E7018 ; PWHT

ABSTRACT

ST 42 steel is a medium carbon steel that is widely used in the construction and shipping industries because it has high strength and ability to accept heat treatment. However, the welding process using the Shielded Metal Arc Welding (SMAW) method often causes residual stress that can reduce the quality of the weld joint. To overcome this, Post Weld Heat Treatment (PWHT) is needed to reduce residual stress, refine the microstructure, and improve the mechanical properties of the weld. This study aims to analyze the effect of variations in electrode types (E7016 and E7018) and PWHT temperatures (500°C and 600°C) on the flexural strength and toughness of ST 42 steel weld joints. The welding process was carried out at position 1G, then the specimen was given PWHT for 60 minutes. Testing was carried out using a bending test to assess flexural strength and an impact test to measure the toughness of the joint. The results showed that PWHT had a significant effect on improving mechanical properties. In the bending test, the highest strength was achieved by the E7016 electrode with PWHT 600°C of 940.808 MPa, while the lowest value was shown by the E7018 electrode without PWHT of 572.607 MPa. In the impact test, the highest toughness was obtained by the E7018 electrode with PWHT 600°C of 1.72 J/mm², and the lowest value was found in the E7016 electrode without PWHT of 1.20 J/mm². Thus, PWHT is proven to increase the flexural strength and toughness of the connection, while the electrode selection must be adjusted to the application needs, both for flexural resistance and toughness against dynamic loads..

Keywords: SMAW ; E7016 Electrode; E7018 Electrode; PWHT

INTRODUCTION

Technological developments in the shipping industry require innovation in the use of steel materials, especially ST 42 steel. This steel is often used for shipbuilding, engine components, and construction due to its mechanical properties as well as its ability in heat treatment. ST 42 steel is excellent for postheat (heat treatment), especially at higher temperatures, as it increases toughness. With a carbon content of around 0.5012%, ST 42 steel is a medium carbon steel that is suitable for heat treatment [1]. According to the American Welding Society (AWS), welding is the process of metallurgically joining metals or metal alloys that occurs in a melted or liquid state. This process essentially harnesses heat energy to fuse two metals into a single unit [2]. The Electric Arc Welding (EAW) method is classified into two types based on the electrode, namely consumable electrodes that are melted and function as filler metals such as in the SMAW, GMAW/MIG, SAW, and FCAW processes, and non-consumable electrodes that do not melt, such as in the GTAW/TIG process. Among these methods, SMAW (Shielded Metal Arc Welding) is one of the most widely used techniques. This process uses flux-coated electrodes and electric arcs to melt the electrodes as well as some of the base metal so that a permanent connection is formed. The electrical voltage in this process also affects the melting speed and the quality of the welding results. In welded construction, welded metal must have at least the same strength and ductility as the parent metal. However, the welding process can change the mechanical properties of metals, depending on the welding conditions, methods, and procedures. The selection of the right electrodes is very important because electrodes are sensitive to moisture, dust, and oil, so they should be stored in a dry, clean place to avoid defects in the welds. In addition, proper welding current tuning is also crucial. Too low a current can cause the electric arc to be difficult to ignite and not enough heat to melt the electrode and base metal, resulting in uneven weld rigs and poor penetration [2]. Low-carbon steels such as ST 37, ST 40, and ASTM A106 Grade B are common choices due to their easy-to-weld, strong, and relatively economical properties. The steel joining process is generally carried out by the Shielded Metal Arc Welding (SMAW) method, which is a welding process by utilizing heat from the electric arc between the end of the feeded electrode and the base metal to be joined [3]. According to the research of Bawazir et al, the variation of electrodes E6013, E7016, and E7018 in the welding of ST 37 steel with ST 40 resulted in significant differences in mechanical properties. The E7016 electrode produces the highest hardness value of 77.40 HRC, while the E7018 electrode provides the highest toughness value with an impact energy of 252 Joules or 3.15 Joules/mm². This shows a correlation between hardness and toughness, where the higher the hardness value, the material's ability to withstand shock loads tends to decrease [3]. Based on this description, it can be concluded that the variety of electrode types in the SMAW welding process plays an important role in determining the quality of the weld joint. The study of the influence of electrode type on mechanical properties and microstructures is important to determine the most suitable electrode to use, so that the weld has optimal strength, hardness, and toughness. The use of different electrodes, including current variations and tensile test standards, affects the strength of SMAW weld joints, where the E7016 and E7018 electrodes—although they are the same low-hydrogen type according to the AWS A5.1 standard—have differences in flux layers, current polarity, arc stability, and deposit efficiency that affect the mechanical properties, quality, and durability of structural steel welds [4]. In the welding process, residual stress arises which can affect the quality of welding results. To reduce this, PWHT (Post Weld Heat Treatment) heat treatment is carried out. This study examines the effect of PWHT on the mechanical properties of S275J2 steel welding using the SMAW technique. After welding, PWHT is carried out at a temperature of 600°C for 1 hour, then tested for microstructure and Charpy impact (toughness). The results of the microstructure test showed ferrite and perlite structures with fine grain sizes, but the grain structure in welding with PWHT was more uniform and even. The Charpy impact test showed an increase in fracture power after PWHT, which was 8.98% in base metal, 26.13% in HAZ, and 52.78% in weld metal. This result is in line with the PWHT's goal, which is to improve material toughness [5]. The development of modern manufacturing technology and the construction industry demands materials with high strength, toughness, and good weldability. Low-carbon steels such as SS400 and ASTM A36 are widely used in a wide range of engineering applications, including the shipping, construction, and machining industries, due to their malleable, weldable, and combination of strength and ductility. The metal joining process in low-carbon steel is generally carried out by welding methods, including Shielded Metal Arc Welding (SMAW) and Gas Metal Arc Welding (GMAW), which are able to produce permanent joints with high efficiency. However, the welding process can cause various problems in the joints, such as the appearance of residual stress, changes in microstructure, and decreased mechanical properties due to non-uniform heating and cooling cycles. High residual stresses can cause distortion, cracking, and reduce the resistance of the connection to dynamic loads or corrosion. To overcome this, Post Weld Heat Treatment (PWHT) is carried out which aims to improve the mechanical properties and microstructure of the welded results. PWHT is done by reheating the welded results at a certain temperature below the melting point of the material, holding them for a certain time, and then cooling them in a controlled manner. Various studies have shown that PWHT exerts a significant influence on the mechanical and microstructural characteristics of low-carbon steels. Hazazi and Lubis reported that PWHT at 500°C was able to increase the hardness and improve the microstructure of SMAW welded SS400 steel [6]. Meanwhile, Oladele et al. stated that in the low-carbon steel of MMAW welding, the PWHT process causes a change in grain size from smooth to somewhat coarse, thereby reducing tensile strength but improving the homogeneity of the microstructure [7]. Aprianto and Pranoto's research found that increasing PWHT temperature in the GMAW process can increase the toughness and ductility of the material, although it decreases tensile strength due to reduced dislocation density [8]. Meanwhile, Wahab et al. explained that in non-similar metal joints (A36 316L), PWHT at a temperature of 400°C gives optimal results for hardness values and impact energy [9]. Based on this description, it can be concluded that PWHT has an important role in improving the quality of weld joints, especially in balancing the hardness, strength, and toughness of the material. Therefore, the study of PWHT temperature and time variations is important to determine the optimal conditions that can produce welds with the best mechanical and microstructural performance. Heat treatment is a process that aims to change the microstructure and mechanical properties of a metal by heating it to a certain temperature range, then regulating its cooling rate in a controlled manner without changing its chemical composition. The initial heating stage is carried out by raising the temperature of the base metal before the welding process, which serves to adjust the microstructure and increase the initial temperature of the material to suit the welding needs. This heating also affects the cooling rate which becomes slower in the welded metal area and HAZ (Heat Affected Zone). The post heating process has an important role in reducing the risk of cold cracks and cracks due to hydrogen that arise due to high residual stress in the weld results. In addition, this treatment is also able to increase the ductility of the HAZ (Heat Affected Zone) area and improve the weldability of base metals and around the HAZ. ST 42 steel is categorized as a medium carbon steel with a carbon content ranging from 0.3% to 0.6%, and has a minimum tensile strength of about 60 kg/mm², as reflected by its designation. This type of steel generally has a lower hardness rate compared to cast iron. Based on the results of previous research, postheat treatment at temperatures of 550°C and 600°C has a significant influence on the hardness and microstructure of AISI 1045 steel welded using the GMAW method. At 550°C, the hardness of the HAZ area reached 184.9 HV with a welding speed of 2.5 mm/s, which was the lowest value in the study. Meanwhile, when the postheat temperature is raised to 600°C, the hardness value increases to 263.6 HV at HAZ with a welding speed of 3 mm/s. These results show that the increase in postheat temperature is able to improve the microstructure while improving the mechanical properties of the weld joint. The SMAW welding process is one of the most widely used methods, with E7016 and E7018 electrodes being the main choices. However, the mechanical properties of the weld can be affected by the selection of electrodes and post-weld heat treatment. Based on these problems, this study aims to analyze the effect of electrode type variation and postheat temperature variation on the impact strength and bending of ST 42 steel.

RESEARCH METHODS

2.1. Research Object

The object in this study is ST 42 Steel. Medium carbon steel (ST 42) is one type of steel that is included in the group of medium carbon steel. This carbon content allows it to undergo a heat treatment process, which aims to produce hardened steel [10]. Carbon steel is a type of alloy steel that is composed of two main components, namely iron (Fe) as the basic element and carbon (C) as the main alloy element. In the manufacturing process, in addition to iron and carbon, various other chemical elements such as sulfur (S), phosphorus (P), silicon (Si), manganese (Mn), and other additional elements are often added according to the characteristics and properties of the steel to be produced. The carbon content in carbon steel varies, generally in the range of 0.2% to 2.14%. The role of carbon in steel is very important, namely as a hardening element that strengthens the structure of steel by preventing dislocation shifts in the crystal lattice of iron atoms [11].

Table 1 Composition of ST 42 Steel [10].

No	*Element*	*Content*
1	Carbon	0.5085%
2	Silicon	0.2726%
3	Mangan	0.6703%
4	Fosfor	0.0114%
5	Sulfur	0.0038%

2.2 SMAW Welding

According to the American Welding Society (AWS), welding is the process of joining metals or metal alloys through metallurgical bonding that occurs when a material is in a liquid or melting state. In other words, welding can be interpreted as a method of joining metals that uses heat energy as the primary source to hold and bond materials.

[12]. Common Shielded Metal Arc Welding (SMAW), or so-called shielded electrode welding, is a welding process that utilizes an electric arc as a heat source to melt metal. Based on the definition of the American Welding Society (AWS), the SMAW method is performed using a flux-coated electrode that creates an electric arc between the electrode and the parent metal, resulting in a strong and permanent metal connection. [12]. During welding, the electrode coating layer burns up and produces a protective gas that protects the electrode, electric arc, molten metal, and work area from outside influences. The flux formed adds protection, while the electrode wire core melts as a filler. In some electrodes, the iron powder in the protective layer also increases the supply of metals.

2.3 1G welding conditions

The situation during the welding process or welding posture refers to the placement and direction of movement of the electrodes when connecting metals. The 1G weld position (Flat Welding Position) is the welding position where the electrode moves horizontally on a flat surface. This position is often used in construction because it is easy to perform and results in a strong and consistent joint [13]. Flat conditions (1G) allow welding to be carried out more easily as gravity helps maintain the stability of the molten metal and reduces the risk of welding defects.

2.4 Electrode Identification Code System

The electrode consists of two main components, namely a metal core without a coating that functions as a current conductor and handle on the welding tool, and an outer layer in the form of flux. The flux layer plays an important role in the welding process, as it functions to protect molten metals from atmospheric influences, form a shield, stabilize the electric arc, and add alloy elements to the welded metal. In the welding process, electrodes are used to produce an electric arc that melts the parent metal and the filler metal so that a fused weld joint is formed. Each type of electrode has a different chemical composition, which affects tensile strength, yield strength, and weld quality [14]. The coding of welding electrodes can be described as follows. Electrode E7018 indicates that the letter E means arc electrode for the SMAW process, the number 70 indicates a tensile strength of 70 ksi, the number 1 indicates that this electrode can be used at all welding positions, while the number 8 indicates that the electrode has a flux layer with a high potassium titanium content. Meanwhile, the E7016 electrode also has the same meaning for the letter E, the number 70, and the number 1, but the number 6 indicates that this electrode uses a flux layer with a low potassium titanium content.

2.5 Post Welding Heat Treatment (PWHT)

Postheat is a heat treatment process that is carried out after the welding stage, and is often referred to as post-weld heat treatment (PWHT). This process aims to stabilize and improve the microstructure of the metal, while improving the mechanical properties of the weld joints [15]. Post Weld Heat Treatment (PWHT) or post-welding heat treatment in this journal refers to the controlled heating process carried out after friction stir welding (FSW) welding on dissimilar metal joints AA2014-AA5083. This process aims to assess the thermal stability of microstructures and their effect on the mechanical properties of joints [16]. Postheat is generally applied to materials that are at risk of cracking due to the influence of hydrogen (hydrogen-induced cracking) or to materials that require strict control of mechanical properties after the welding process. Therefore, postheat is an important stage in the welding process series to ensure the integrity and performance of weld joints in various industrial applications.

Figure 1 PWHT Tool

2.6 Impact Test

The impact test aims to assess the ability of the material to absorb sudden load energy and reveal the properties of the fragility and weakness of the weld joint. In this study, the test was carried out using the Charpy method on ST42 steel, covering the welding area and HAZ. Specimens measuring 10×10×55 mm with a V notch (45°, 2 mm) were tested with load in the opposite direction of the notch. The test results show the toughness of the material in units of J/mm², where the greater the energy absorbed, the tougher the material is [17]. According to AWS, impact testing is important to ensure weld joints meet toughness standards, especially on steel structures and pressurized components. Specimens are taken from a critical area (weld metal, HAZ, or base metal) with a standard size of 10×10×55 mm, and tested at a specific temperature, e.g. -20°C or -40°C. AWS D1.1 requires a minimum energy of 27 J at the test temperature. In addition to absorption energy, these tests also indicate types of faults (ductile or brittle) that can identify cracks, hydrogen brittleness, or microstructural changes [12]. Thus Impact Tests are an important component of the welding process to ensure that weld joints have adequate toughness and meet safety and performance standards, especially in structural and high-pressure applications.

Figure 2 Impact Test Equipment

2.7 Test Bending Test

Bending is a test to assess the strength of a material when subjected to bending loads. The goal is to measure the ability of a material to resist deformation or fracture under pressure. This test is performed by applying a slow load until the specimen reaches a certain point, and the results are used to evaluate the bend strength of the material. In this study, bending tests were performed on ST42 steels with strong variations in preheat current and temperature, following the ASTM E19014 standard. Visual evaluation of the quality of a material can be done through bending or bending testing. This test aims to assess the strength of the material after receiving the load and determine the level of elasticity of the weld joint, both in the heat-affected zone (HAZ) and in the area of the welded metal itself.

$$\sigma b = \frac{3pl}{2bd} \quad (1)$$

expressed in megapascals (MPa), P is the load given in Newton units (N), L denotes the span length or distance between two supports in millimeters (mm), while b and d represent the width and thickness of the specimen respectively which are also expressed in millimeters (mm) [18]. This study applies the face transverse bending method. The face bend method was chosen because in this process, the weld surface is subjected to tensile stress, while the bottom of the weld is subjected to compressive stress. The focus of observation is directed at the area of the weld surface that is subjected to tensile stress to detect the possibility of cracking. Furthermore, a more in-depth analysis was carried out to determine the location of the cracks, whether they occurred in weld metal, heat-affected zones (HAZ), or in the fusion line which is the boundary between welded metal and HAZ[16].


Figure 3 Bending Test Equipment

2.8 Standard Deviation

Standard deviation is a commonly used spread metric. It covers the entire data group, thus providing better stability than other metrics. However, if there are extreme values in the data group, the standard deviation can lose its sensitivity, similar to the mean. The formula can be expressed as follows.

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (2)$$

2.9 Research Stage

This research includes several stages, including the following:

A. Material Collection The material used is ST 42 steel which is included in the category of medium carbon steel, with specimens measuring 800 mm long, 400 mm wide, and 10 mm thick.

B. Plate Cutting The ST 42 steel material is cut into two parts from its original size, which are 800 mm long, 400 mm wide, and 10 mm thick.
C. ST 42 Steel Welding The ST 42 steel material that has been cut is then welded using the SMAW (Shielded Metal Arc Welding) method. This welding process is carried out at INLASTEK Welding Institute with the following stages:
    a. Type of Classification : SMAW
    b. Welding Machine : Krisbow 450W
    c. Electrode Type : Elektrda E-7016 and E-7018
    d. Parent Metal : ST 42 Steel
    e. Voltage : 20 to 30 V
    f. Current (amperes) : 70 to 100A
D. Specimen Manufacture 24 bend test specimens with dimensions of 60x20x10, and 24 impact test specimens with dimensions of 55x10x10. The process of making both types of specimens.
E. Heat Treatment Process After the specimen manufacturing process is completed, heat treatment is carried out which consists of two temperature variations, namely 500°C and 600°C. The postheating process is carried out by placing the test specimen into the furnace machine for 60 minutes.

RESULTS AND DISCUSSION

3.1. Heat Input

Heat input is the amount of heat energy that enters the metal during the welding process, which is generated by the combination of current, voltage, and velocity Fill supported by the presence of image data, tables, and calculation analysis results from the equations referenced in the manuscript [6]. Typed at 10pt, Times New Roman is in Justify writing condition (left-right aligned). welding. The amount of heat input is usually calculated in units of kJ/mm with the equation:

$$HI = \frac{V\,x\,I\,x\,60}{S\,x\,1000} \quad (3)$$

Using the E7016 and E7018 electrodes, heat input plays an important role because it directly affects the width of the Heat Affected Zone (HAZ), changes in the microstructure, and the mechanical properties of the welded results. Too high an input heat can cause metal grains to grow larger thereby lowering toughness and increasing the risk of heat cracking. Conversely, too low an input heat can lead to imperfect weld penetration, reducing the strength of the joint.

The results showed that the post-weld heat treatment (PWHT) setting at temperature variations of 500–600°C was able to improve mechanical properties, both in bending and impact tests. This is related to the effect of heat input combined with heat treatment, so that the heat distribution is more controlled and the microstructures formed are more homogeneous. Therefore, heat input control is one of the important factors in maintaining the quality of ST 42 steel welding results.

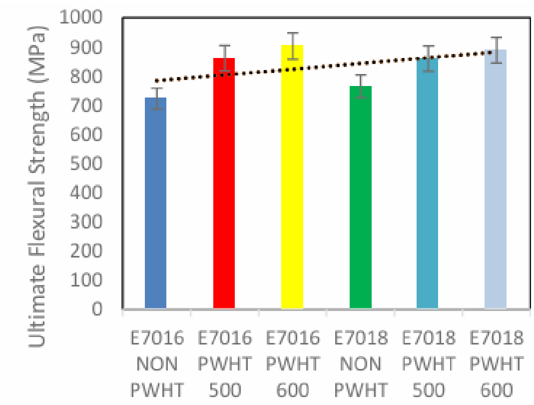
$$HI = \frac{30\,x\,100\,x\,60}{150\,x\,1000} = 1{,}2\ Kj/cm$$

3.2. Results

Bending Test =1.2 Kj/cm This bending test on ST 42 steel is performed based on the ASTM E190-14 standard using two types of electrodes and two PWHT temperature variations. A total of 24 specimens were prepared with uniform test dimensions, where each variation was tested through four repetitions. The purpose of this test is to assess the material's ability to withstand bending loads. The following is the process of work and the results before and after the work. This study uses the surface transverse bend test method (face bend) to evaluate the weld results. This method was chosen because it places the weld surface at tensile condition and the base at the compressive condition. Observations are focused on identifying crack surfaces as well as tensiles to determine their location, whether in weld metal, HAZ, or fusion lines [16].

Figure 4 Specimens Before Bending Test

Figure 5 Specimens After Bending Testing



Gambar 6 Ultimate Flexural Strength (Mpa)

Table 2 Ultimate Flexural Strength (Mpa)

Variations	*L(mm)*	*B(mm)*	*D(mm)*	P(Kn)	Strong Flexor	Average Strong Bending (Mpa)
E7016 NON PWHT	60	20	10	143 54,48 3	724,161 723,731 720,971	722,9
E7016 500°	60	20	10	179,3 3	849,738 867,889 865,5,72	861,0
E7016 600°	60	20	10	2192 5,18	898,757 906,55 901,858	902,3
E7018 NON PWHT	60	20	10	1849 0, 43	768,734 767,755 758,211	764,9
E7018 500°	60	20	10	2023 6, 022	867,832 854,609 857,885	860,1
E7018 600°	60	20	10	156 94,56	879,067 898,569 891,901	889,8

Based on Figure 6, the Yield Flexural Strength value shows a tendency to increase along with the application of PWHT and the increase in heat treatment temperature. Specimens with electrode E7016 at PWHT 600°C had the highest bending stress value of 850.588 MPa, indicating that heat treatment at high temperatures is able to improve the ability of weld joints to withstand bending loads before undergoing plastic deformation. In contrast, the E7016 specimen without PWHT showed the lowest yield flexural strength value, which was 689.838 MPa. This condition shows that welding joints without PWHT are still affected by high residual stress, which reduces the material's ability to withstand bending loads. In specimens with E7018 electrodes, a similar upward trend was also seen, where the yield value of flexural strength increased from 684.584 MPa (non-PWHT) to 824.801 MPa at 600°C PWHT. These results confirm that PWHT plays a significant role in improving the mechanical quality of weld joints through residual stress relaxation and homogenization of microstructures. Based on the Ultimate Flexural Strength graph, there is an increase in maximum flexural strength due to PWHT treatment. Specimens with E7016 electrodes at PWHT 600°C showed the highest ultimate flexural strength value, which was 902.390 MPa, while the lowest value was obtained in the E7016 Non PWHT specimen, which was 722.936 MPa.

This increase indicates that higher PWHT temperatures are able to improve the weld's ability to withstand maximum bending loads before failure occurs. In the E7018 electrode, the ultimate flexural strength value also increased from 764,900 MPa (Non PWHT) to 889,846 MPa at 600°C PWHT, although the value was slightly lower than that of the E7016 electrode at the same temperature. These results are also supported by the journal S. E. Susilowati and D. Sumardiyanto, that the tensile strength value of 617 MPa and a higher toughness of 1.8564 Joule/mm² on the E 7016 electrode indicates better plastic deformation ability and resistance to bending failure, so that this electrode is considered superior in facing bending loading conditions [19]. Overall, the results of the bending test showed that the application of PWHT, particularly at 600°C, had the most significant effect on the increase in the bending strength, ductility, and energy resistance of ST 42 steel weld joints. The E7016 electrode exhibits the best performance in terms of maximum bending strength, while the E7018 electrode provides a more stable deformation character. These findings confirm that the selection of the right electrode type and PWHT temperature is critical to improving the reliability of weld joints in structural applications that accept bending loads. Post Weld

Heat Treatment (PWHT) does not have a significant effect on the mechanical and microstructural properties of electrically welded mild steel welds [20]. The E7016 electrode produces higher bending strength because it has a low hydrogen content and a base flux layer that is able to produce a finer weld metal microstructure and lower the potential for weld defects, thereby improving ductility and resistance to bending deformation [19]. Based on the Rules for Classification and Construction of the Indonesian Classification Bureau (BKI) Volume VI on welding, low hydrogen type electrodes are recommended for welding of the main structure of vessels that use medium carbon steel and receive a high bending load with a minimum bending strength of 400 Mpa [18]. The results of this study show that the use of E7016 electrodes in SMAW ST 42 steel welding with Post Weld Heat Treatment (PWHT) treatment at 600°C results in the highest bending strength, which is 902,390 MPa, which far exceeds the minimum limit of bending strength required by BKI. Therefore, the E7016 electrode with a PWHT of 600°C is very suitable for application to the main structure of the ship such as the hull plate, deck, main girder, as well as longitudinal and transverse anchors that function to withstand the global bending load of the ship due to the influence of sea waves.

3.3. Impact Tests

Impact testing was carried out to determine the resistance of SMAW welding ST 42 steel under sudden load. The specimen is given a punch load on a hammer of a certain weight that is swung from a certain angle.

Figure 7 Specimens before Impact Testing

Figure 8 Specimens after impact testing

Table 3 Impact test results

Variation	*A (mm2)*	*Energy Impact (J)*	*Power of Impact (J/ mm²)*	Average Strength of Impact (J/mm²)
E7016 NON PWH T	88	97,00	1,10	1,20
	88	116,00	1,32	
	90,4	106,00	1,17	
E7016 500°	88,8	114,00	1,28	1,26
	90,4	117,00	1,29	
	88	106,00	1,20	
E7016 600°	90,4	120,00	1,33	1,32
	92	130,00	1,41	
	91,2	112,00	1,23	
E7018 NON PWH T	85,6	142,00	1,66	1,52
	82,4	119,00	1,44	
	84,8	124,00	1,46	
E7018 500°	88,8	144,00	1,62	1,66
	86,4	151,00	1,75	
	85,6	138,00	1,61	
E7018 600°	88	168,00	1,91	1,72
	88	148,00	1,68	
	96	151,00	1,57	

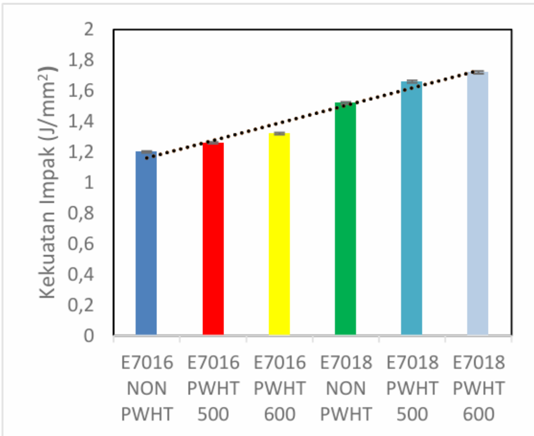


Figure 9 Average Diagram of the Impact Test

Based on the results of impact testing on ST 42 steel with electrode variations and Post Weld Heat Treatment (PWHT) treatment, material toughness values were obtained that varied between 1.20 J/mm to 1.72 J/mm. In general, the results showed that PWHT had an effect on increasing impact energy values, especially in specimens welded using the E7018 electrode. The highest average impact price value was obtained in the E7018 specimen with a PWHT temperature of 600°C, which was 1.72 J/mm, while the lowest value was found in the NON PWHT E7016 specimen with a value of 1.20 J/mm. The increase in impact price after PWHT treatment shows that the heating process is able to reduce residual stress and improve the microstructure in the HAZ (Heat Affected Zone) area, so that the material becomes more resilient to shock loads. In addition, comparisons between the two types of electrodes showed that E7018 produced a higher impact price than E7016 across treatment variations. This is due to the content of deoxidizer elements and low hydrogen 48 in the E7018 electrode which is able to produce welded metal with better ductility and toughness. Overall, the test results showed that PWHT treatment at 600°C had the most significant effect on improving material toughness, both in the use of E7016 and E7018 electrodes. These findings support the theory that PWHT can refine grain structure and reduce residual stress due to the welding process, thereby improving the material's ability to absorb impact energy before breaking. The test results are also in accordance with previous research According to the research of F. Bawazir, Bukhari, and A. S. Ismy, the variation of electrodes E6013, E7016, and E7018 in the welding of ST 37 steel with ST 40 produced a significant difference in mechanical properties. The E7016 electrode produces the highest hardness value of 77.40 HRC, while the E7018 electrode provides the highest toughness value with an impact energy of 252 Joules or 3.15 Joules/mm² [3]. Post Weld Heat Treatment (PWHT) does not have a significant effect on the mechanical and microstructural properties of electrically welded mild steel welds [20]. Based on the effect of heat input on grain growth and the mechanical properties of weld joints, it is hypothesized that the AWS E7018 electrode produces higher impact toughness than the E6013 and E7016 electrodes. This is due to the characteristics of the E7018 electrode which is able to produce effective and stable heat input at certain welding currents, thereby triggering the recrystallization process and the formation of a relatively more uniform and ductile grain size in welded metals and HAZ regions [3]. It can be concluded that the E7018 electrode type variation has the advantage of withstanding shock loads. According to BKI regulations, ship structures located in areas with high dynamic loads, shocks, and vibrations require welded joints with a good level of toughness to prevent brittle failures with a minimum impact force of 27 J [21]. The results of this study show that the welding of ST 42 steel using E7018 electrodes with PWHT treatment at 600°C produces the highest impact toughness, which is 1.72 J/mm² or converted to Joules of 172 J, which shows the ability of the weld joint to absorb impact energy optimally. Thus, the E7018 electrode with a PWHT of 600°C is recommended to be applied to areas of the vessel that receive dynamic loads and shocks, such as structures around the engine room, the main engine mount, the stern area, as well as the area near the propulsion system, so as to meet the requirements for weld joint toughness according to BKI regulations.

CONCLUSION

This study shows that the variation of electrode type and Post Weld Heat Treatment (PWHT) treatment exerts a significant influence on the mechanical properties of ST 42 steel weld joints. In bending testing, the highest bending strength was obtained by using the E7016 electrode fed PWHT at 600°C, reaching 902.3 MPa, while the lowest strength was demonstrated by the E7016 electrode without PWHT with a value of 722.9 MPa. In impact testing, the highest toughness was achieved by electrode E7018 with a PWHT of 600°C of 1.72 J/mm², while the lowest value was achieved by electrode E7016 without PWHT with an average of 1.20 J/mm². These results prove that PWHT in the temperature range of 500–600°C is effective in lowering residual stress, smoothing microstructures, and improving the bending strength and toughness of joints, so that the welding quality of ST 42 steel can be significantly improved. In addition, the results of the study confirm that the selection of electrode type plays an important role in determining the mechanical performance of the joint. The E7016 electrode is superior in improving flexural strength due to its flux characteristics that result in deep penetration and stable arcs, making it suitable for structural applications that demand resistance to static or high bending loads. In contrast, the E7018 electrode showed better performance in increasing resistance to dynamic loads, especially after PWHT treatment at 600°C. This is due to the higher iron powder content in the E7018 flux layer, which improves the deposition of welded metals and improves the metal's ability to absorb impact energy. Thus, the selection of electrodes should be tailored to the characteristics of the application, whether it emphasizes more on flexural strength (E7016) or toughness to impact loads (E7018).

References

[1] G. Y. Pratama and Y. Yunus, "Pengaruh Post Weld Heat Treatment (PWHT) Dengan Variasi Media Pendinginan Hasil Pengelasan SMAW Pada Pipa Kilang ASTM A 106 Grade B Terhadap KekuatanBending Dan Struktur Mikro," J. Tek. Mesin, vol. 10, no. 03, pp. 69–76, 2022.

[2] H. Nasution, "Pengaruh Variasi Elektroda Pengelasan SMAW Pada Baja AISI SS201 Terhadap Hasil Uji Tarik," Pros. Semin. Nas. Tek. UISU, pp. 1–3, 2023.

[3] F. Bawazir, Bukhari, and A. S. Ismy, "Pengaruh Variasi Elektroda Las Pada Sambungan," J. Mesin Sains Terap., vol. 5, no. 2, pp. 1–6, 2021.

[4] S. Wahyudi, R., Nurdin., "Analisa Pengaruh Jenis Elektroda Pada Pengelasan SMAW Penyambungan Baja Karbon Rendah Dengan Baja Karbon Sedang Terhadap TYensile Strenght," J. Weld. Technol., vol. 1, no. 2, pp. 43–47, 2019.

[5] K. A. Nasra, Zuldesmi, and J. C. Kewas, "Pengaruh Post Weld Heat Treatment Terhadap Sifat Mekanik dan Struktur Mikro Baja Karbon ST42 dengan Pengelasa SMAW (Shielded Metal Arc Welding)," ACTUATOR J. Tek. …, vol. 1, no. 1, pp. 26 36, 2020, [Online]. http://ejurnal-mapalus Available:unima.ac.id/index.php/actuator /article/vie w/115

[6] D. S. W. Hermawan Yudha Prasetya Taufik Wisnu Saputra, "Jurnal Pendidikan Teknik Mesin Undiksha," J. Pendidik. Tek. Mesin Undiksha, vol. 10, no. 2, pp. 14–21, 2022, [Online]. Available: http://10.0.93.79/jptm.v10i2.51606

[7] O. Oladele, D. B. Alonge, T. O. Betiku, E. O. Igbafen, and B. O. Adewuyi, "Performance Evaluation of the Effects of Post Weld Heat Treatment on the Microstructure, Mechanical and Corrosion Potentials of Low Carbon Steel," Adv. Technol. Mater., vol. 44, no. 1, pp. 41–47, 2019, doi: 10.24867/atm-2019-1-007.

[8] E. Aprianto and H. Pranoto, "Literature Review on Microstructure and Mechanical Properties of Ss400 Steel Due To Variations in PWHT Temperature in the GMAW Welding Process," Int. J. Adv. Technol. Mech. Mechatronics Mater., vol. 06, no. 2, pp. 107–118, 2025, doi: 10.37869/ijatec.v6i2.129.

[9] Wahab, L. H. Arma, H. Arsyad, and R. Bin Othman, "Effect of Temperature Variation PWHT Dissimilar Welding Low Carbon Steel ASTM A36 with ASTM A240 Type 316L," EPI Int. J. Eng., vol. 7, no. 1, pp. 33–37, 2024, doi: 10.25042/epi ije.022024.05.

[10] Y. Miranda and A. M. Bade, "Analisa Perbedaan Temperatur Pada Material Baja Karbon Rendah S355Jo Terhadap Distorsi Pada Pengelasan Smaw," Zo. Mesin, vol. 9, no. 1, pp. 10–18, 2018.

[11] N. W. L. Rd, Seventh Edition , Volume 5. American Welding Society, 550, 1997.

[12] D. R. Nero and Suheni, "Pengaruh Pengelasan SMAW Menggunakan Beda Elektroda dan Posisi Pengelasan 1G , 2G , 3G Berbahan Baja ASME SA36 terhadap Pengujian Kekerasan Vickers dan Struktur Makro," Pros. Semin. Nas. Teknol. Ind. Berkelanjutan III, vol. 3, no. Senastitan Iii, pp. 1–7, 2023, [Online]. Available: http://ejurnal.itats.ac.id/senastitan/article/vi ew/4192

[13] V. Ayu Setyowati, E. Wahyu Restu Widodo, and T. Mesin -Institut Teknologi Adhi Tama Surabaya Jl Arief Rahman Hakim, "Analisa Pengaruh Jenis Elektroda Pengelasan Smaw Terhadap Kekuatan Stainless Steel 304," Pros. Semin. Nas. Sains dan Teknol. Terap., vol. 0, no. 0, pp. 179–184, 2016, [Online]. Available: http://ejurnal.itats.ac.id/sntekpan/article/v ie w/1339

[14] N. Ashok G.S et al., "Effect of pre- and post-weld heat treatments on the microstructure and mechanical properties of the rotatory friction welded martensitic steel-soft magnetic alloy joints," Mater. Sci. Eng. A, vol. 929, no. February, p. 148121, 2025, doi: 10.1016/j.msea.2025.148121.

[15] V. Sharma, M. P. Sharma, and A. K. Jain, "Journal of Alloys and Metallurgical Systems Effect of post-weld heat treatment on dissimilar AA2014-AA5083 friction stir welded joints," J. Alloy. Metall. Syst., vol. 10, no. December 2024, p. 100177, 2025, doi: 10.1016/j.jalmes.2025.100177.

[16] B. K. Indonesia, "Rules for Classification and Construction Part 1 Seagoing Ships RULES FOR WELDING," vol. VI, 2024, [Online]. Available: www.bki.co.id

[17] S. E. Susilowati and D. Sumardiyanto, "JURNAL KAJIAN TEKNIK MESIN

Vol 9 No1 Hal 25-34 PENGARUH JENIS ELEKTRODA E 6010 DAN E 7016 TERHADAP SIFAT MEKANIS DAN STRUKTUR MIKRO PIPA API 5L GRADE X 52," vol. 9, no. 1, pp. 25–34, 2024.

[18] R. K. Aninda, S. M. Karobi, R. Shariar, and M. Rahman, "Effect of post-weld heat treatment on mechanical properties and microstructure in electric arc welded mild steel joints," J. Eng. Res., vol. 12, no. 2, pp. 210–215, 2024, 10.1016/j.jer.2023.10.012.

[19] B. K. INDONESIA, "RULES FOR THE CLASSIFICATION AND RULES FOR WELDING 2018 EDITION BIRO KLASIFIKASI INDONESIA," vol. VI, 2018.

[20] Ramadhan, M. H. N. (2024). Pengaruh Perbedaan Ayunan Pengelasan Dengan Metode SMAW Terhadap Kekuatan Tarik Pada Baja ST 37 Strip 5 MM. *AL-MIKRAJ Jurnal Studi Islam dan Humaniora (E-ISSN 2745-4584)*, *5*(01), 312-319.