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Investigation of the Hardness of Submerged Arc Welding Slag in the Recycling Process for Stainless Steel Welding

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ABSTRACT
Submerged arc welding (SAW) generates a granular flux that turns into slag during the welding process. This slag, which contains mineral residues, is non-biodegradable and poses significant environmental challenges, requiring safe disposal. This process incurs substantial land usage and costs. To tackle these issues, research was conducted to find ways to recycle SAW slag. In the study, agglomerated fluxes were created by blending various alloying elements and deoxidizers (determined through trial and error) with milled slag, while potassium silicate was used as a binder. The optimal combination included SiO2 (8%), Cr2O3 (4%), TiO2 (3%), and MnO (2%), which achieved the desired weld chemistry in line with ASTM A 240 specifications for stainless steel type 304.The weld quality was evaluated after achieving the necessary chemistry through various tests, including tensile strength, Charpy impact, and microhardness assessments. The ferrite structure was analyzed using optical microscopy, and the ferrite content was measured with a Feritscope FMP-30. The findings indicated that the recycled slag maintained arc stability and slag detachability comparable to that of fresh flux.The ultimate tensile strength of the weld using the recycled flux reached 559.36 MPa, exceeding the tensile strength of the base metal (SS 304) and showing similar performance to that with fresh flux. Additionally, the cost of recycling the slag was 54.62% lower than that of using new flux. Thus, it can be concluded that recycled flux presents a viable and cost-effective alternative to fresh flux in industrial applications.
Keywords- *Submerged arc welding, Flux, Filler material, Hardness*

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I. Introduction

Submerged arc welding (SAW) is a fusion welding technique that involves a continuously advancing electrode directed at the workpiece. This process utilizes granular flux, which is stored in a hopper and dispensed through a nozzle just ahead of the weld pool. When the electrode creates an arc with the workpiece, the flux melts and produces molten slag. This slag, being less dense than the weld metal, rises to the top and acts as a barrier against contaminants from the atmosphere. It's important to remove this slag after the welding process is complete. Submerged arc welding can be performed using mechanized equipment or handheld tools. With a remarkable duty cycle of 100%, it can operate at an impressive current of up to 2000A, with arc voltages ranging from 25 to 40 volts (Phillips, 2016). SAW also has the capability to use multiple electrode wires simultaneously, leading to a significantly high deposition rate. This characteristic makes it particularly useful for welding thicker materials, typically between 3mm and 100mm, in fewer passes. (Sridhar,Biswas, &Mahanta, 2019). The quantity of molten slag and the weld pool produced during the welding process limits submerged arc welding (SAW) to a horizontal position. It's essential to choose the process parameters with care to achieve a proper weld. A schematic representation of the submerged arc welding process is illustrated in Figure 1.1.

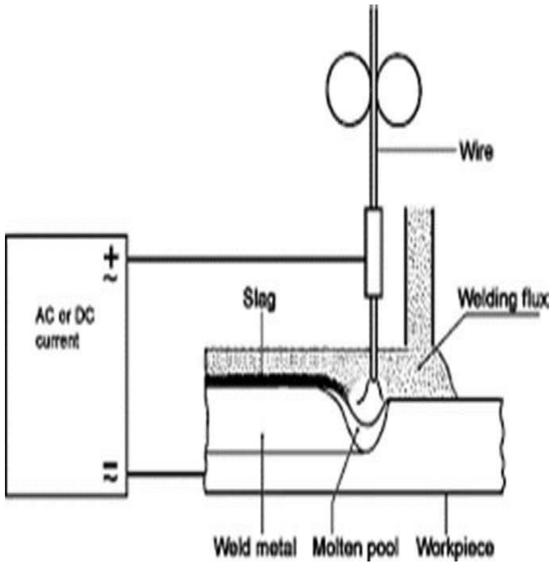

Figure1.1Schematicdiagramofsubmergedarcwelding

1.1 Advantages of Submerged arc welding

The welding process boasts a high weld deposition rate while minimizing the amount of smoke and fumes produced. A notable advantage is the absence of arc radiation, which enhances safety during the operation. Additionally, modifying the properties of the weld is simplified by adjusting the flux composition. The availability of automatic SAW machines means that even less skilled workers can perform welding tasks effectively. Moreover, when working with thick metal, it is possible to achieve strong joints with a minimum number of passes.

1.2 Limitations of Submerged arc welding

Welding can only be performed in a flat position, which limits its versatility. Additionally, the setup is not very portable, making it less convenient for various work environments. After completing the welding process, there is a necessity to remove the slag, adding an extra step to the procedure. This method is suitable primarily for thicker sections of material and is not recommended for thinner ones. Furthermore, the flux used in this process has a tendency to absorb moisture, potentially resulting in weld defects.

A flux recovery system is needed, which adds a layer of complexity to the process.

1.3 Applications of SAW

SAW is commonly utilized for welding thick metals in various contexts, such as pressure vessels, marine constructions, and offshore structures (Choudhary, Kumar, & Unune, 2019). It is also applied in welding ship structures and thick-walled stainless-steel piping (Nam et al., 2018).

Equipment for submerged arc welding
The main components involved in automatic submerged arc welding include the welding power supply, which provides the necessary energy for the process, along with the welding nozzle that directs the arc. The flux container holds the flux material, while the wire feeder and its regulation system ensure a consistent supply of wire for welding. Additionally, the travel system enables the movement of the welding apparatus, and the control interface allows the operator to manage various settings throughout the welding operation.

II. Literature review

To effectively understand past research findings and identify gaps in knowledge, it is essential for researchers to conduct a detailed literature review. Slag, a byproduct of submerged arc welding, poses a recycling challenge due to its non-biodegradable nature, making complete recycling imperative. Developing a suitable methodology to achieve this goal has been a focus for researchers over the past few years. Various approaches have been explored, including the use of SAW slag in manufacturing bricks and ceramics, utilizing pure slag for welding and cladding applications, mixing slag waste with virgin flux during welding, and striving for comprehensive recycling of SAW slag to enhance welding operations.

A comprehensive overview of the literature reviewed in the previously mentioned subcategories will be provided under the following headings: Using SAW slag as a building material, Reusing SAW slag for welding, Employing a slag-flux mixture in welding, and Complete recycling of SAW slag for welding applications.

2.1 Utilization of SAWsla gasabuilding material

(Ramesh, Gandhimathi, Nidheesh, Rajakumar, &Prateepkumar, 2013) explored the use of welding and furnace slag in low-cost construction, highlighting its good compressive strength. In their research, they replaced fine aggregates in concrete blocks with waste materials like welding slag and furnace slag at various percentages: 5%, 10%, and 15%. The amounts of cement, concrete, and slag remained constant for the initial tests. The building materials underwent compressive strength testing in accordance with IS code, revealing that the use of slag in the concrete blocks led to increased compressive strength. After 28 days, the optimal compressive strength recorded was 41 N/mm² with 5% welding slag and 39.7 N/mm² with 10% furnace slag. The results indicated that replacing sand with 5% welding slag or 10% furnace slag is highly effective for practical applications.

Ananthi and Karthikeyan (2015) explored the use of industrial byproducts, specifically bottom ash and welding slag, as substitutes for fine aggregates in concrete production. They analyzed the chemical makeup of these materials using X-ray diffraction and examined their structure with a scanning electron microscope. To evaluate the strength of the resulting concrete, a compression test was performed. The findings revealed that concrete mixtures containing up to 10% industrial waste exhibited significantly greater compressive strength compared to traditional concrete.

In a study conducted by Ganga and Rajkohila (2015), various percentages of fused submerged arc welding (SAW) slag were used to replace sand in concrete mixtures. They focused on creating M25 grade concrete by using a mix of SAW slag, fine aggregate, coarse aggregate, cement, and water in specific proportions. The SAW slag was substituted for coarse aggregate at ratios of 10%, 20%, 30%, and 40% across different samples. To evaluate the mechanical properties, samples were prepared in three forms: 150 mm cubes for compressive strength tests, cylindrical specimens measuring 300 mm in length for tensile strength, and flexural beams sized at 500×150×150 mm. The samples were assessed for strength after curing periods of 7 days and 28 days for each level of SAW slag substitution. Upon comparison at the 28-day mark, it was found that using 30% SAW slag led to a 12.85% reduction in compressive strength compared to the original concrete without any slag.

Separately, Francis and Abdel Rahman (2016) explored the potential of combining various metallurgical and agricultural wastes, including SAW slag and rice husk, with glass cullet to create lightweight porous glass-ceramics for technical applications. They investigated the impact of different concentrations of rice husk—up to 20%—as well as temperature variations on the resulting materials' porosity and water absorption. The findings indicated that when glass cullet was mixed with SAW slag and 20% rice husk at a temperature of 100 degrees, the resulting glass-ceramics exhibited a porosity of 67.76% and a water absorption rate of 42%. This provided a promising method for repurposing SAW slag into functional and efficient porous glass-ceramic products through a straightforward process of powder technology and sintering.

2.2 Reutilization of SAW slag for welding

In a study by Singh, Singh, and Gargan (2011), the researchers attempted to reuse slag by crushing it without any additional treatment. They prepared two different specimens using fresh flux and the crushed slag, while keeping all other conditions consistent. After the welding process, they compared the quality of the welds and noted that the weld made with crushed slag showed no significant changes in its physical appearance. However, a chemical composition analysis revealed that its composition did not meet the standards set by the AWS code. To further their investigation, Garg (2011) examined the bead geometry and microhardness of welds made with fresh flux versus crushed slag, discovering notable differences in both the bead shape and the microhardness of the samples.

2.3 Use of Slag-fluxmixture for welding

In a study conducted by Dobránszky, Németh, and Biczó (2014), researchers experimented with a slag-flux mixture that varied the slag content from 0% to 40%. They performed submerged arc welding on a specimen with dimensions of 55×10×7.5 mm using these different slag-flux mixtures. The results from spectroscopy indicated that mixtures with up to 40% slag could produce welds with excellent properties, without compromising the quality of the weld metal. The study also pointed out that a slag-flux mixture of this percentage exhibited good detachability and stability of the arc.

Following the spectroscopy analysis, Charpy impact toughness was measured at -20 degrees Celsius, along with tensile testing on the welded metal, revealing that these slag-flux mixtures contributed to robust mechanical properties. Additionally, the researchers noted that utilizing this slag-flux mixture could effectively reduce waste and lower costs.

In another research effort by Somal, Singh, Singh, and Singh (February 2016), the impact of various proportions of slag and fresh flux mixtures on bead appearance, slag detachability, microstructural characteristics, and chemical composition was analyzed to ensure compliance with standards. The team started their trials with a fresh flux containing 20% slag and then proceeded to use a 40% slag mix, followed by experiments with 60%, 80%, and ultimately, 100% slag to create weld beads on mild steel plates measuring 200×100×12 mm. They discovered that a mixture of 60% slag with fresh flux resulted in a quality weld bead. Moreover, it was found that the slag flux significantly lowered the sulfur and phosphorus content, which enhanced the impact toughness. The microstructure analysis revealed similar characteristics in the beads produced with the various slag-flux mixtures.

In a study by Gupta, Sapra, Singla, and Gora (2013), researchers investigated how a mixture of slag and flux affects the mechanical properties and microstructure of materials. They created three types of fresh flux—labeled A, B, and C—by combining various chemicals such as CaF2, CaO, Na2O, MnO, SiO2, Al2O3, MgO, TiO2, and FeO in different ratios using an agglomeration technique. These fluxes had basicity indices of 1.2, 1.3, and 1.5, respectively. The researchers then mixed the slag with these fluxes in amounts of 10%, 20%, and 30%. A total of 16 beads were deposited on a mild steel plate using these mixtures. The team conducted tensile, impact, and microhardness tests, along with microstructural analyses on all 16 beads. The findings revealed that both ultimate tensile strength and hardness decreased as the basicity index increased. Additionally, it was noted that mixing slag with flux led to a reduction in tensile strength, microhardness, and impact strength.

Similarly, Thirunavukkarasu, Kavimani, Gopal, and Das (2020) aimed to determine the ideal percentage of slag in virgin flux without sacrificing the weld bead's quality. In their experiments, they incorporated slag into the virgin flux at varying rates of 20%, 30%, 40%, and 50% to create weld beads on low carbon steel using welding wire EM12K at a current of 450A. They performed various non-destructive tests (NDT), including ultrasonic and radiographic inspections, to assess the weld's integrity. Mechanical testing, including hardness, tensile, and impact tests, was conducted to ensure the welds met the required standards. The results showed that the combination of flux and slag yielding the best results fell between 20% and 30%. Deviating from this range led to poorer weld quality, prompting the recommendation that for optimal cost-effectiveness, a slag-flux ratio of 20% to 30% should be maintained during weld deposition.

2.4 Thoroughre cycling of SAW slag for welding

Garg and Singh (2016) successfully repurposed submerged arc welding slag for stainless steel cladding. They analyzed the weld chemistry of the cladding material using spectroscopy, confirming it met ASME specifications. They conducted various tests on the cladding, including corrosion, bend, and microhardness tests, to ensure it would fulfill its intended function. The corrosion tests indicated that the cladding materials created with both fresh and recycled flux offered similar resistance to corrosion. The bend test showed that the weld exhibited good ductility and a strong bond with the base metal. The microhardness of the cladding proved satisfactory up to a certain plate number. The essential characteristics of the flux, such as arc stability and slag detachability, were found to be comparable to those of fresh flux. A noteworthy conclusion from their study was the significant cost savings, with recycled flux costing 73% less than fresh flux available on the market. For this process, Subinox-309L served as the electrode on the base metal SA 516 Grade 70.

In another study, Nimker and Wattal (2020) explored recycling submerged arc welding slag by incorporating various deoxidizers into it. They used the resulting flux to weld mild steel, alongside fresh F7AZ and EH 14 wires. The weld chemistry was analyzed to ensure it matched the AWS A 5.17 composition requirements. After confirming the desired chemical composition, a series of tests were conducted to assess the quality of the weld bead produced. The weld beads obtained from the recycled slag successfully passed all tests, including tensile and impact tests, and demonstrated properties nearly identical to those created with fresh flux.

III. EXPERIMENTATION

Thecurrentchaptersdealwiththeprocessusedintherecyclingof SAWslagandthetestperformed for evaluating the performance of weld deposited using fresh and recycledslag.Theapproachadoptedforrecyclinghasalsobeenpresentedinformofflowchat.

3.1 Welding Equipment used for experimentation

The TORNADO SAW M 800, produced by AdorFontech Ltd., was the submerged arc welding machine utilized during the experiment. This machine operates automatically and boasts a 100% duty cycle, featuring an IGBT (Insulated Gate Bipolar Transistor) inverter power source.

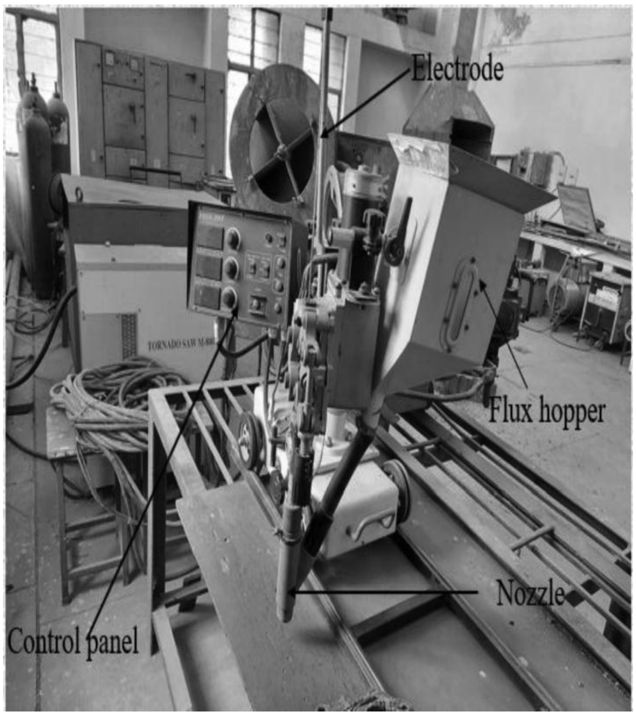

Figure3.1TORNADO SAW M-800

The TORNADO SAW M-800, depicted in Figure 3.1, is located in the advanced welding lab at SLIET and was utilized for all welding tasks during the experiment. The control panel features three knobs that allow adjustment of key parameters such as voltage, current, and welding speed based on specific needs. This machine can perform both forward and reverse welding simply by toggling the switches on the control panel. As shown in Figure 3.1, the flux hopper and the wire feed are positioned at the nozzle, which ensures the correct flux feed around the electrodes to safeguard the weld bead. Additionally, the trolley operates on rails while the welding process is underway.

3.2 Methodology

A thoughtful and well-structured experimental plan was implemented to ensure positive outcomes, which helped shorten the project's completion time. Below is a schematic representation of the methodology used to achieve the desired results.

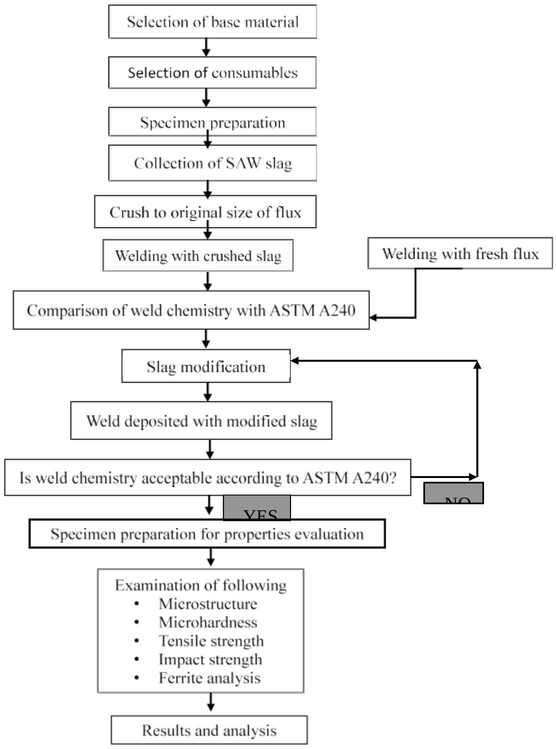

Figure3.2Flow chart of use methadology

3.3 Selection of base material

The literature review indicates that the recycling of SAW slag specifically for stainless steel welding has not been thoroughly investigated. Therefore, the experiment selected austenitic steel SS 304 as the base material for the recycling process. SS 304 is versatile, being used in applications that range from cryogenic settings, like LNG transmission and storage, to high-temperature environments in the petrochemical sector, as well as in both corrosive and normal conditions. By developing a recycling process for SAW slag in relation to SS 304, we can achieve significant cost savings and reduce the amount of slag waste generated. The SS 304 used in the experiment was sourced from M.R. Metal in Ludhiana, and its chemical composition was analyzed at Accurate Metallurgical Laboratories, also located in Ludhiana.

3.4 Specimen Preparation

The SS 304 stainless steel was sourced from M.R. Metal in Ludhiana and came as a large plate measuring 2400mm x 100mm x 12mm. To meet our specifications, it was trimmed down to the required size of 200mm x 100mm x 12mm using a power hacksaw found in the Fitting Shop at SLIET, Longowal, as illustrated in Figure 3.3.

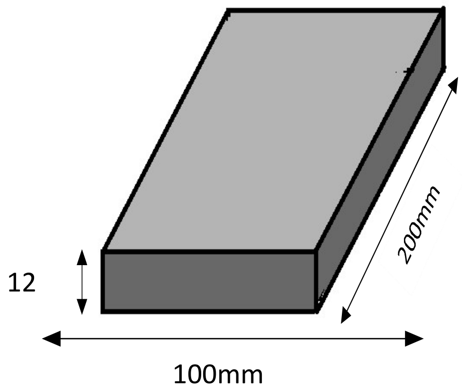

Figure3.3Schematicdiagramof theworkpiece withdimensions

Once the piece was cut to the specified size of 200×100×12mm³, any burrs were removed during the edge finishing process. After that, a groove angle was created on the plate as illustrated in Figure 3.4.

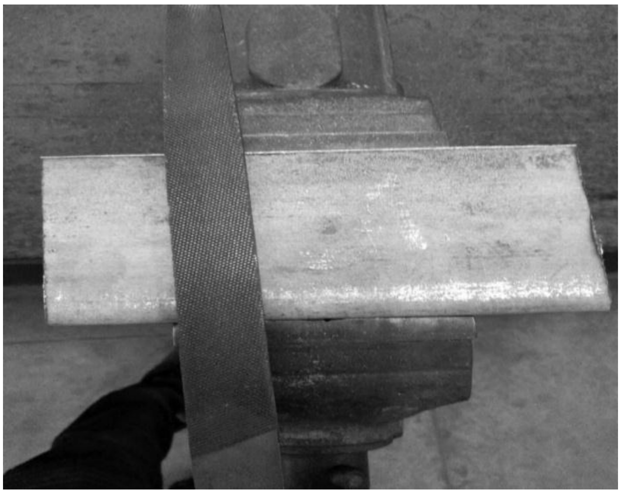

Figure3.4Edgefinishing

IV. RESULTSANDDISCUSSION

Welding was carried out using the filler wire ER 308L, maintaining consistent process parameters throughout all trial runs. The only change made in each trial was the composition of the agglomerated flux, as detailed in Table 3.2, to align with the composition requirements specified by ASTM A240. Prior to conducting the actual trial runs, several preliminary tests were executed to determine the optimal root face that would minimize melt-through, as illustrated in Figure 4.1, ensuring proper fusion to the root. It was determined that a root face of 2 mm, under the chosen process parameters, resulted in less melt-through while still achieving sufficient fusion at the root, making it the selected choice.

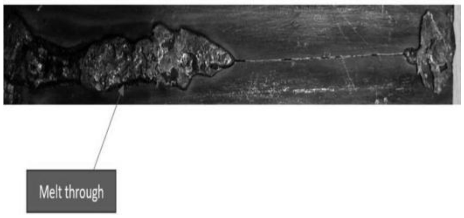

Figure4.1Meltthrough

Once the goal related to the root face was met, the trials began to focus on fulfilling the chemical composition standards outlined in ASTM A240. The chemical makeup of the weld joint using new flux and clean slag is shown in Table 4.2, while the results from each trial conducted during the recycling process, as mentioned earlier, can be found in Table 4.3.

4.1 TENSILETESTRESULTSANDANALYSIS

The tensile testing of specimens made with both recycled flux and fresh flux was performed following the ASTM E8M standards. According to ASTM A 240, the minimum tensile strength needed for SS 304 is 515 MPa, while the catalog for GEEFLUX 303 X GEE SAW 308L indicates that the tensile strength should range from 560 to 670 MPa. The results from the tensile tests show. ity(68%)arepresentedinTable

A total of six tensile test samples were taken, with three samples sourced from the weld using recycled flux and three from the weld using fresh flux, as illustrated in Figure 4.1. The average results, calculated from the highest and lowest measurements, are displayed in the table and graph below.

Table4.1 Tensiletest results

SampleTypes	Ultimatestrength	Breakingstrength	%Elongation
Recycledflux testpiece	559.36 MPa	246.44 MPa	25
Fresh flux testpiece	576.94 MPa	198.28 MPa	21.87

The data in the table indicates that the tensile strength of specimens made from recycled and fresh flux exceeds that of the base metal, as specified by ASTM A 240. However, there is a noticeable reduction in percentage elongation. This reduction might result from the austenite grains being increasingly divided by ferrite dendrites, which hinders shear deformation. Consequently, this leads to higher strength but lower ductility, along with a greater likelihood of phase-boundary failures (Gugelev, 1969). The experiment involved two passes to fill the groove, which might also contribute to the decreased percentage elongation, as it has been observed that increasing the number of passes typically results in a lower percentage elongation (Gowrisankar, Bhaduri, Seetharaman, Verma, &Achar, 1987).

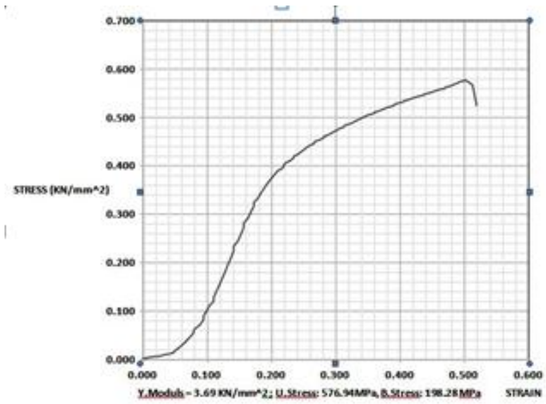

Figure- 4.2 Stress-strain curve

V. CONCLUSIONSANDFUTURESCOPE

A method for recycling slag generated during submerged arc welding for stainless steel has been developed and proved successful. The recycled slag weld's composition included C at 0.025%, Si at 0.390%, Mn at 1.49%, S at 0.020%, P at 0.028%, Cr at 18.36%, and Ni at 8.98%, all of which fall within the acceptable limits set by ASTM specifications.

The ultimate tensile strength of the weld produced with the recycled flux reached 559.36 MPa, surpassing the minimum tensile strength criteria established by ASTM standards. The average ferrite content in the fusion zone using the recycled flux was recorded at 5.14%, indicating good resistance to solidification cracking.

Both arc stability and slag detachability with the recycled flux were found to be satisfactory, comparable to those achieved with fresh flux. The micrographs of samples indicated a dual-phase microstructure comprising both austenite and ferrite for both fresh and recycled flux welds.

Economically, the recycled flux was 54.62% cheaper than the fresh flux available on the market, demonstrating the economic viability of recycling slag from submerged arc welding of stainless steel. Additionally, the joint efficiency of welds using recycled flux reached 108.61%, suggesting these welds are stronger than the base metal. The bead geometry achieved with the recycled flux was satisfactory, although it produced a slightly wider bead compared to that made with fresh flux.

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