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ORIGINAL ARTICLE

# Recycling of steel slag as a flux for submerged arc welding and its effects on chemistry and performance of welds

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**Abstract**
The slag generated by the steel plant has been utilized to produce submerged arc welding flux. The flux produced by recycling steel slag has been applied in the submerged arc welding process. The effects of recycled slag on the chemical composition, microhardness, and microstructure of weld metal have been evaluated. For chemical composition, weld pads were prepared and beads on plates for bead geometry were deposited. It has been found that the chemistry of welds deposited using recycled steel slag is acceptable in accordance with ASME specifications. It is further observed that the addition of 10% $CaCO_3$, 20% $SiO_2$, and 6% MnO to the steel slag during recycling provided 0.10% carbon, 0.11% Si, and 0.8% Mn, respectively, in the weld metal. The microstructure of welds produced using recycled steel slag contains acicular ferrite which is desirable for improved tensile and impact strength. The microhardness of weld metal prepared using recycled steel slag is 220.9 VHN, which is more than that of weld metal deposited with fresh flux. Smooth surface appearance and desirable bead profile having deeper penetration were obtained. It is interesting to note that the cost of recycled steel slag is economical by 62% in comparison with equivalent virgin flux available in the market. The developed technology after fine-tuning will be transferred to the industry for practical applications.

**Keywords** Recycling · Steel slag · Submerged arc welding · Element transfer behavior · Flux

## 1 Introduction

### 1.1 Recycling of steel slag

In a steelmaking plant, the raw material used in the form of steel scrap, which contains a large number of impurities (gangue). For converting steel scrap into useful steel billets, a flux is used to remove impurities present in it. Flux reacts with gangue and removes it in the form of slag, which is known as steel slag. The slag generated during this process is discarded as waste. Das et. al. estimated that approximately 4 tons of slag is generated for making one ton of steel [1]. Guo et al. found that 300 million tons of steel slag was dumped as waste in China alone, in the year 2016 [2]. According to Proctor et al. about 21 million tons of steel slag is produced every year in the USA [3]. Tiwari et al. revealed that in India around 12 million tons of steel slag is generated per year [4]. Due to stringent rules and regulations of government agencies, dumping of slag is very difficult. To mitigate the problem of dumping the researchers and scientists are striving hard to reduce, reuse, or recycle slag for various applications.

Wang et.al. (2019) have proposed that steel slag can be reutilized in the same steel-making process as well as in building constructions [5]. It was found that the slag produced by steel-making plants has not been applied for the manufacturing of welding fluxes so far. Therefore, an attempt was made by Saini & Singh [6] to utilize steel slag for producing welding flux. They established the feasibility of steel slag for the production of welding flux and opened a new area of research. In continuation with their previous research, they planned to investigate the effects of recycled slag on the element transfer behavior (gain/loss of alloying elements) of fluxes manufactured using steel slag. The effect of recycled slag on bead profile, metallurgical properties of weld metal, and operating characteristics like arc stability and slag detachability

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have been evaluated and presented. The economic viability of recycling slag as a flux has also been established. The plan of investigation has been shown as a flow diagram in Fig. 1. The details of various steps followed are given below:

**Table 1** Chemistry of parent metal and filler wire

| Chemicals (wt.%) | C | Mn | Si | S | P |
|---|---|---|---|---|---|
| Filler wire | 0.1–0.18 | 1.7–2.2 | 0.10 | 0.025 | 0.025 |
| Base plate | 0.1–0.22 | 1–1.17 | 0.6 | 0.03 | 0.03 |

## 2 Experimentation

The base material SA 516 grade 70 having 12-mm thickness was chosen for the present study since it is widely used for manufacturing pressure vessels, heat exchangers, and boilers which consume a huge amount of flux during welding. The electrode filler wire EH-14 was used in the combination with flux for welding. The chemistry of the parent metal plate and filler wire is presented in Table 1. A submerged arc welding machine manufactured by M/s Ador-Fontech was used for welding in the present research work. The machine has a maximum current of 1200 ampere at 100% duty cycle, and direct current electrode positive (reverse) polarity was used during experimentation. The welding variables selected after pilot runs are shown in Table 2.

### 2.1 Collection of steel slag

The slag used in this study was collected from the dumping yard of Vardhman Special Steels Ltd. Ludhiana, India. The chemistry of steel slag (given in Table 3) was analyzed by XRF at Spectro Analytical Limited New Delhi, India. The characterization of steel slag for determining the chemical compounds and phases was done on an X-ray diffraction spectroscopy (XRD) machine manufactured by Bruker, Model: D8 Advance DaVinci installed at SLIET Longowal, India. XRD analysis was performed in the continuous scanning mode over a range of 10-80° under X-ray source: Copper wavelength= 1.54 angstrom, Detector: LYNXEYE_XE, step size- 0.02°, time/step - 0.02°/sec.

The compounds and phases present in steel slag as revealed by XRD are shown in Fig. 2. The figure depicts XRD patterns and characterization of steel slag. It is interesting to note that the slag has profound potential to be used for making flux required for submerged arc welding. Because compounds such as Gehlenite ($Ca_2Al(AlSiO_7)$), Wustite ($Fe_{0.932}O$), Magnetite ($(Co_{0.19}Fe_{0.81})(Co_{0.14}Fe_{1.59})O_{4.082}$), Larnite ($Ca_2(SiO_4)$), and Harmunite ($CaFe_2O_4$) are already present in the slag which encourages the use of steel slag for manufacturing of welding fluxes.

### 2.2 Weld pad deposited using pure steel slag

The steel slag collected from industry was crushed using an electrically operated mechanical crusher and then sieved in a 10 mesh size sieve to get grain size similar to the original flux. The granular slag was applied as a flux to produce a weld pad

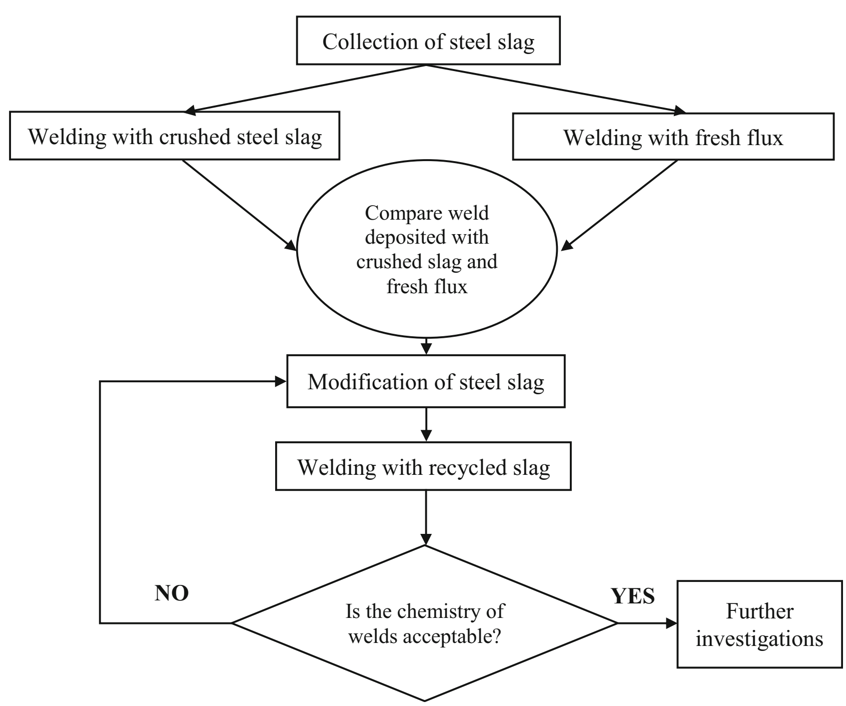


**Fig. 1** Flow diagram for recycling of steel slag

**Table 2** Welding parameters for weld pads

| Parameters | Units | Symbol | Value |
|---|---|---|---|
| Open circuit voltage | Volts | V | 33 |
| Current | ampere | I | 450 |
| Welding speed | m/min | S | 0.3 |
| NPD | mm | N | 20 |

in accordance with ASME specifications (Fig. 3). The chemistry of the weld pad was evaluated with the help of a spectrometer and recorded in Table 4. The chemistry of weld revealed by spectrometer gives an idea about the minerals/oxides already present in steel slag.

### 2.3 Weld pad deposited using fresh flux

A weld pad to know the chemistry of weld metal generally used in industry was prepared (Fig. 3) using fresh original flux. The chemistry of weld pads is shown in Table 4. The difference in the chemistry of welds prepared using fresh virgin flux and crushed steel slag will act as a light house for further processing of slag so that processed slag (recycled slag) will be able to produce welds having acceptable chemistry.

### 2.4 Comparison of chemical compositions

The chemistry of weldments deposited using pure steel slag, fresh original flux, and ASME requirements has been indicated in Table 4. The chemistry of welds was analyzed critically with ASME requirements and reached to the conclusion that what chemicals, oxides, compounds, and deoxidizers are required in the recycling of steel slag. The selection of ingredients and their functions play a vital role in the recycling of steel slag. The functions of some chemicals are discussed in the next section.

### 2.5 Selection of ingredients

The additives used for the recycling of slag were chosen based on the chemistry of the weld produced. The alloying elements adding to the flux enhance the mechanical behavior and crack resistance of the weld metal. Proper selection of ingredients affects the strength and bead geometry of weld [7]. Based

**Table 3** Chemical composition of steel slag

| Chemicals | CaO | $SiO_2$ | MnO | $Al_2O_3$ | MgO | $Na_2O$ | $Cr_2O_3$ | $MoO_3$ |
|---|---|---|---|---|---|---|---|---|
| Wt.% | 18.2 | 12.1 | 5.01 | 5.77 | 4.10 | 1.22 | 1.38 | 1.00 |

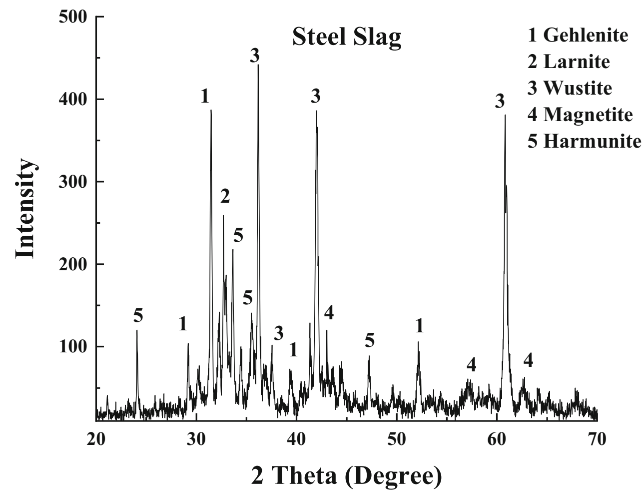


**Fig. 2** XRD analysis showing compounds present in steel slag

upon the ability to generate certain specific mechanical/metallurgical properties to the weld metal, the main ingredients generally used are calcium carbonate, Ferro-Mn, Ferro-Si, Ferro-Ti and silica, etc. Due to the hygroscopic nature of calcium oxide, calcium carbonate was added [8]. Generally, potassium silicate and sodium silicate are used as a binder [9]. For better arc stability potassium silicate binder (20% solution) was used in the present study.

To increase manganese content in the weld, metal Ferro-manganese was added. Titanium powder, Ferro-manganese, and Ferro-silicon were added as deoxidizers [10–14]. The various minerals/oxides used for modification of steel slag as a welding flux and their functions are given below:

**Calcium Oxide (CaO)** Calcium oxide is chemically basic and hygroscopic in nature [15]. It is used to increase the basicity index, improve arc stability, decrease the viscosity by providing desired fluidity in the weld pool, and reduce oxygen from the weld pool [16]. In weld metal, CaO is the most influencing factor for controlling acicular ferrite content [17].

**Manganese Oxide (MnO)** The nature of manganese oxide is basic, and it is used to improve the arc stability and reduce the viscosity and sulphur content from the weld pool [18].

**Silica (Silicon Dioxide)** Silica is chemically acidic in nature and it is used to improve weld appearance which gives a sound weld bead with good slag detachability [19, 20] and increases viscosity and current-carrying capacity. Silica also gives good arc stability with better penetration of weld [16]. The silicon dioxide and carbon reactivity create a balance between oxygen and sulphur [21].

**Calcium Fluoride ($CaF_2$)** This alloying element is also known as Fluorspar. It is chemically basic in nature; it is used to protect the weld pool from atmospheric contamination and

**Table 4** Chemistry of weld pads and ASME requirements

| Chemical composition (wt.%) | C | Mn | Si | P | S |
|---|---|---|---|---|---|
| ASME requirements | 0.05–0.15 | 0.80–1.50 | 0.10–0.30 | 0.03 | 0.03 |
| Pure steel slag | 0.03 | 0.12 | 0.0005 | 0.027 | 0.041 |
| Fresh virgin flux | 0.18 | 0.90 | 0.19 | 0.041 | 0.029 |

lower the melting range of slag. It provides the maximum fluidity to the flux hence maximum weld coverage and helps to escape the gases from the weld pool and reduce dissolved $H_2$. The optimum amount of $CaF_2$ should be used since too much amount of fluoride affects the arc stability, increases the tendency to undercut, and reduces the silicon content. $CaF_2$ reduces the oxygen content from the weld pool and increases the hardness of the weld metal [22, 23]. The increased amount of $CaF_2$ in the flux increases the impact strength of the weld [24].

**Rutile ($TiO_2$)** The main source of titanium dioxide is rutile [25]. It is chemically neutral in nature. It promotes the formation of acicular ferrite and refined grained structure which is helpful in the increment of notch toughness and ductility of weld metal [26, 27]. According to the classical theory of heterogeneous nucleation, $TiO_2$ inclusions nucleate acicular ferrite by acting as inert substrates [28]. It also provides good slag detachability and reduces oxygen content. The ultimate tensile strength increases with an increase in $TiO_2$ content in the flux [25].

**Aluminum oxide ($Al_2O_3$)** The nature of aluminum oxide is acidic, and it is used to improve the weld's physical appearance and slag detachability after welding. It also enhances the formation of acicular ferrite and refined grain structure which results in improving notch toughness and ductility. $Al_2O_3$ must be added in the manufacturing of flux for improving the reduction efficiency [29].

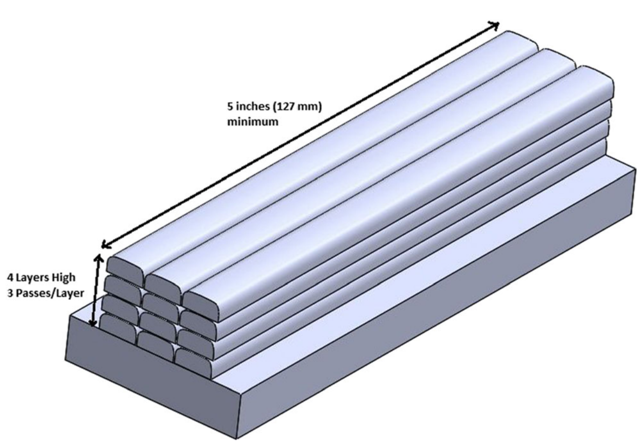


**Fig. 3** Weld pad (ASME SFA-5.17)

### 2.6 Recycling of slag

The steel slag collected from industry was crushed using an electrically operated crusher and then used a ball mill to make it a fine powder. Based upon the information provided by chemical pads produced using crushed steel slag, fresh flux, and ASME requirements, alloying elements and deoxidizers in powdered form were added. The milled powder of slag along with deoxidizers and chemicals were mixed in a ball mill for 20 min to get a homogeneous dry mixture. The potassium silicate binder was added to bind and wet the dry mixture. The agglomeration of the wet mixture was done by passing it through a 10-mesh size sieve to generate small pellets. The pellets were placed in an open atmosphere to dry in the air for 24 h and sintered at 800 °C for 3 h in an electric muffle furnace. After sintering, the solid mass was then crushed accompanied by a sieving process to achieve desired grain size which is known as "recycled steel slag." The recycled steel slag was utilized as a flux for further investigations as planned in the flow diagram shown in Fig. 1. To evaluate the chemistry of weld prepared using recycled steel slag, a weld pad was prepared as presented in Fig. 3. The chemical composition of the weld pad deposited using recycled steel slag was analyzed with a spectrometer and correlates with ASME standards. This process was repeated until the chemistry of weld metal satisfies ASME requirements. The chemistry of welds achieved at various trials has been presented in Table 5. It is given in Table 5 that the 7th trial run satisfies the ASME requirements.

## 3 Results and discussions

### 3.1 Element transfer behavior

For element transfer behavior (loss or gain of alloying elements), weld pads as shown in Fig. 3 were deposited using recycled slag along with EH-14 filler wire. The chemical composition of weld pads was evaluated with a spectroscope. The load-bearing capacity and strength of the welded joint depend upon mechanical properties which are further dependent on the chemistry and microstructure of weld metal [30]. Metallurgically, the flux is used to alter the chemical composition of the weld by adding alloying elements. The alloying elements may also be reduced through burning, oxidation, or

**Table 5** Weld metal chemistry for various slag trials during recycling

| Trial No. | Chemicals added (in wt.%) | Chemical composition of weld metal (wt.%) | | | | |
|---|---|---|---|---|---|---|
| | | C | Mn | Si | P | S |
| 1 | $CaCO_3$=10%, $SiO_2$=6%, Fe-Mn=6%, Fe-Si= 4% | 0.04 | 0.30 | < 0.01 | 0.019 | 0.017 |
| 2 | $CaCO_3$=12%, $SiO_2$=7.2%, Fe-Mn=8%, Fe-Si= 6% | 0.063 | 0.295 | 0.014 | 0.024 | 0.022 |
| 3 | $CaCO_3$=10%, $SiO_2$=8%, $CaF_2$=5%, MnO=5%, FeO=5%, $Al_2O_3$=5%, Fe-Mn=4%, Fe-Si= 6% | 0.056 | 0.394 | 0.017 | 0.033 | 0.112 |
| 4 | $CaCO_3$=15%, $SiO_2$=10%, $CaF_2$=5%, MnO=10%, FeO=5%, $Al_2O_3$=5%, Fe-Si=2%, Fe-Mn=2%, $Cr_2O_3$=12%, $TiO_2$=3% | 0.07 | 0.61 | 0.06 | 0.03 | 0.09 |
| 5 | $CaCO_3$=10%, $SiO_2$=15%, $CaF_2$=5%, MnO=5%, $Al_2O_3$=5%, Fe-Si=5%, Fe-Mn=5%, $Cr_2O_3$=20%, $TiO_2$= 5% | 0.09 | 0.46 | 0.06 | 0.04 | 0.11 |
| 6 | $CaCO_3$=10%, $SiO_2$=15%, $CaF_2$=5%, MnO=4%, $Al_2O_3$=5%, Fe-Si=10%, Fe-Mn=4%, $Cr_2O_3$=10%, $TiO_2$=5% | 0.11 | 0.69 | 0.07 | 0.033 | 0.06 |
| 7 | $CaCO_3$=10%, $SiO_2$=20%, $CaF_2$=5%, MnO=6%, $Al_2O_3$=5%, Fe-Si=10%, Fe-Mn=5%, $Cr_2O_3$=12%, $TiO_2$=5% | 0.10 | 0.80 | 0.11 | 0.03 | 0.05 |

volatilization. The slag composition is deciding factor of slag oxidation [31]. Therefore, it is necessary to know the element transfer behavior of recycled slag. It will help to find out whether the recycled slag is capable to deposit weld metal having desired chemistry and in accordance with ASME requirements. The chemistry of weld metal along with the additives added for each trial has been discussed in Table 5.

### 3.1.1 Transfer of carbon

The tensile strength of weld metal increases with an increase in the percentage of carbon [23]. It promotes desirable acicular ferrite at the expense of grain boundary ferrite which further improves the toughness [17]. In this research, the carbon content in welds prepared using pure slag is 0.03% (Table 4) which is lower than that of the parent metal and filler electrode wire used. This can be attributed to the fact that the carbon is oxidized to form carbon monoxide as given in Eq. (1);

$$C + O = CO\,(g) \tag{1}$$

Moreover, alloying elements had already been exhausted from the steel slag during steelmaking and is unable to provide alloying elements. The chemistry of weld metal deposited with pure crushed steel slag and fresh virgin flux along with an acceptable range of ASME specifications have been recorded in Table 4.

As revealed by 1st trial (Table 5), the addition of $CaCO_3$ (10 wt.%) to the steel slag, amount of carbon in weld metal has increased to 0.04%, which further increased up to 0.063% with 12% addition of $CaCO_3$ (trial number 2, Table 5).

Further addition of $CaCO_3$ (15%) results in increased carbon 0.07% which is within the acceptable range of ASME specifications.

These observations conclude that carbon is picked up by weld metal from $CaCO_3$ during welding. On heating, $CaCO_3$ disassociates into CaO and yields $CO_2$. At high temperatures, $CO_2$ further splits into carbon monoxide and oxygen. The complete reactions are given in Eqs. 2 to 4.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2}$$

$$CO_2 \rightarrow CO + O \tag{3}$$

The element having high reactivity reacts with oxygen. The carbon monoxide present in the molten pool, due to high temperature splits into carbon and carbon dioxide gas as given in Eq. 4.

$$2CO \rightarrow C + CO_2 \tag{4}$$

This free carbon is dissolved in the molten pool by diffusion process, hence adding carbon content to the weld.

It is clear from Table 5 that Trial No. 4 provided 0.07% carbon which satisfies ASME specifications, but other elements like manganese and silicon are still less compared with ASME specifications; therefore more trials were conducted.

### 3.1.2 Transfer of manganese

The amount of manganese in the weld metal depends upon the percentage of manganese present in filler wire. The ferromanganese and MnO present in the welding flux also contribute in increasing the manganese content in the weld metal. In the present investigation, it is observed that the manganese content in weld prepared with pure crushed steel slag is 0.12% which is lower than the Mn content in filler wire and base metal and does not satisfy ASME requirements. The loss of Mn can be represented as:

$$2[Mn] + \mathrm{Si}O_2 = 2(MnO) + [Si] \tag{5}$$

The loss of manganese may also be due to evaporation as revealed by Bourgette et. al. [32]. Some of the researchers found that the addition of ferromanganese increases the manganese content of weld metal apart from deoxidizing the weld pool. Therefore, Ferromanganese 6% and 8% were added in trials 1 and 2 which increase manganese content by 0.3% and 0.295% respectively. The increment of manganese in weld metal was not significant. The Ferro-Mn acts as a deoxidizer by removing oxygen from the weld pool and a lesser amount of manganese picked up by the weld metal. Mitra and Eagar found that the manganese content can be increased by adding MnO to the flux [33]. Hence 5% and 10% MnO was added in trial 3 and 4 resulting increase in manganese content by 0.394% and 0.61% respectively. The increase in manganese content may be represented as:

$$(MnO) = [Mn] + [O] \tag{6}$$

No doubt the amount of manganese in the weld metal has been improved by adding Ferro-Mn and manganese oxides, but the content of manganese is still lower than the required amount. That is why $Cr_2O_3$ was added, the addition of $Cr_2O_3$ can increase the amount of manganese in the weld metal. The addition of 12% $Cr_2O_3$ provided 0.8% manganese (Trial number 7) in weld metal which is within the acceptable range of ASME specifications. The increase in manganese due to the addition of $Cr_2O_3$ can be represented as;

$$Cr_2O_3 + MnO = 2CrO_2 + Mn \tag{7}$$

### 3.1.3 Transfer of silicon

Table 4 revealed that the amount of silicon present in the weld prepared using crushed steel slag is 0.0005% which is negligible in comparison to that of weld deposited using fresh virgin flux (0.19%). The oxidation process is responsible for the silicon loss from the weld produced with pure crushed slag which can be represented as:

$$[Si] + 2O = (SiO_2) \tag{8}$$

According to the reference [34], silicon content in weld metal increases with the addition of $SiO_2$ in the flux. Therefore, to increase the amount of silicon in the weld, $SiO_2$ was added to the steel slag during recycling. It was found that the percentage of silicon in the weld increased to 0.01, 0.014 and 0.017% by adding 6, 7.2 and 8% of $SiO_2$ respectively, which are still lesser than the required amount. The silicon transfer from silica can be represented as:

$$(SiO_2) \rightarrow [Si] + 2[O] \tag{9}$$

$$K = \frac{a_{Si} \cdot a^2 o}{a_{SiO_2}} \tag{10}$$

$$\log K = \frac{-28360}{T} + 10.61 \tag{11}$$

where $a_{Si,}$ $a_{O,}$ $a_{SiO2,}$ K, and T are the activity of Si and oxygen in the weld, activity of silica in the slag, reaction constant, and temperature of the molten pool in Kelvin, respectively.

With the application of Eqs. 9-11, Chai and Eagar have given the following equation [35]:

$$aSiO_2 = 73.6[wt\%Si][wt\%O] \tag{12}$$

This equation concludes that the addition of silica in welding flux improves the activity of silica causing the pick up of silicon by the weld metal from flux [36].

Mitra and Eager found that the addition of $Cr_2O_3$ decreases the flux basicity resulting increased amount of Si in the weld [33]. The research carried out by [37] suggested that the reduction of silicon and manganese takes place by the addition of aluminum. Taking the advantage of their research, aluminum oxide was added which acted as a chief reducing agent. This resulted not only increase in silicon but also the manganese content in the weld metal. Further addition of aluminum oxide decreases the basicity index of flux which leads to an increase in silicon content. By adding 12% $Cr_2O_3$ and 5% $Al_2O_3$ (trial number 7), the silicon content increased up to 0.11% which is in the acceptable range of ASME Standards.

### 3.1.4 Transfer of sulfur

Sulphur is an impurity that adversely affects the impact strength of weld metal. It combines with iron to form iron sulphide which consists of low melting point eutectics that lead to liquidation crack in the heat-affected zone around the grain boundaries. Higher contents of sulphur promote porosity in the weld metal. Therefore, it should be less than 0.05%. To mitigate the effect of sulphur, manganese is added which reacts with sulphur contents to form manganese sulphide (MnS) as follows:

$$Mn + S = MnS \tag{13}$$

The present investigation revealed that the amount (in wt.%) of sulphur in weld deposited using crushed steel slag is 0.041 which is within the acceptable range. By adding $CaCO_3$ and $SiO_2$ which is necessary to increase carbon and silicon in the weld metal, sulphur content unintentionally increased. Trial 7 revealed that adding 10% $CaCO_3$ and 20% $SiO_2$ result in an increased amount of sulphur up to 0.05% in the weld. As the weld pads prepared were 4 layers high, the dilution effect is negligible, and the only source of sulphur is flux. The transfer of sulphur content to the weld metal can be presented as:

$$[S] + \left(O^{2-}\right) = \left(S^{2-}\right) + [O] \tag{14}$$

The equilibrium constant for the above equation as follows:

$$Ks = \frac{(a_{s2-})[a_o]}{(a_{o2-})[a_s]} \quad (15)$$

From which the sulphur distribution ratio can be derived as:

$$\frac{(a_{s2-})}{[a_s]} = Ks\frac{(a_{o2-})}{[a_o]} \quad (16)$$

If Henrian behavior for all the components is assumed [38]:

$$[Wt.\%S] = Ks\frac{(n_{o2-})}{(Wt.\%S)[Wt.\%O]} \quad (17)$$

where (Wt.% S), [Wt.%S], Ks, ($n_{o2-}$), and [Wt.%O] are the wt.% of sulphur content in slag, wt.% of sulphur in the weld metal, equilibrium constant, number of oxygen ion in the 100 grams of slag, and wt.% of oxygen in the weld, respectively.

From the above discussion, it is concluded that the amount of sulphur in weld depends upon various factors such as sulphur content in slag, oxygen ions and dissolved oxygen in the molten pool. Dissolved oxygen in weld metal increases with increasing $SiO_2$ in slag.

### 3.1.5 Transfer of phosphorus

This element is also an impurity that reduces the ductility of weld metal due to temper and intergranular embrittlement [39]. In the present study, it was found that phosphorus in weld prepared using pure crushed slag is 0.027.

However, a small amount of phosphorus was picked up by the weld produced using recycled steel slag which can be explained through the following equations:

$$2[P] + 5[O] + 3(O^{2-}) = 2(PO_4^{3-}) \quad (18)$$

or by

$$[2P] + [5O] = (P_2O_5) \quad (19)$$

the equilibrium constant is:

$$Kp = \frac{(wt.\%P_2o_5)(aP_2O_5)}{[a_p]^2[a_O)^5} \quad (20)$$

where (wt.%$P_2O_5$) and (a$P_2O_5$) are mole fraction and activity coefficient of phosphorus pentoxide in the slag.

$$[a_P] = \frac{(wt.\%P_2O_5)(aP_2O_5)}{k_p[a_O]^5} \quad (21)$$

The increased amount of phosphorus is due to adding $CaCO_3$ and silica to the slag, which increases the amount and activity of phosphorus pentoxide. The higher amount of phosphorus in the weld could also be due to the higher amount of ferromanganese added [40]. Because manganese ore contains some amount of phosphorus [33], finally, the amount of phosphorus is acceptable in accordance with ASME codes.

## 3.2 Weld bead profile

The load-carrying capacity of welded joints depends upon the bead geometry and shape relationships [30]. The bead geometry and dimensions of weld influence the service performance of the welded joint [35]. Weld bead morphologies also affect the cooling rate of the weld which influences the microstructure and grain size of weld metal [41]. Generally, bead profile is influenced by the welding parameters and welding flux. Flux having higher basicity index results in deeper penetration [38]. Hence to investigate the bead profile obtained using a particular flux is very essential. To compare weld bead profiles, three beads on plates were produced using fresh virgin flux, recycled steel slag, and crushed slag keeping all other parameters constant. The weld specimen of 20 mm were extracted from the center of the test plates. The schematic diagram of the cutting plan of the test specimen for measuring the bead geometry has been given in Fig. 4.

Srinath found that the welds produced having shape factors from 1.3 to 2.0 are preferred as they are free from ingotism defect and have better mechanical properties [42]. From Table 6 and Fig. 5, it is observed that weld penetration shape factor (WPSF) achieved utilizing crushed slag, fresh virgin flux, and recycled steel slag are 1.45, 2.34, and 2.06 respectively. The value of WPSF of the weld bead prepared by recycled steel slag is 2.06 which is very near to the value recommended by [42]. This proves that recycled slag is capable to produce welds having the preferred weld penetration shape factor.

Weld reinforcement form factor (WRFF) is the ratio of weld width to reinforcement. The value of the form factor should be between 2.0 and 7.0 for better mechanical properties [43]. From Table 6 and Fig. 5, it is observed that weld reinforcement form factor obtained with pure steel slag, fresh virgin flux, and recycled steel slag are 1.41, 3.42, and 3.99, respectively, which are desirable. The results obtained are comparable with the results achieved by Srinath who obtained a form factor having a value of 2.0 [42]. The weld bead

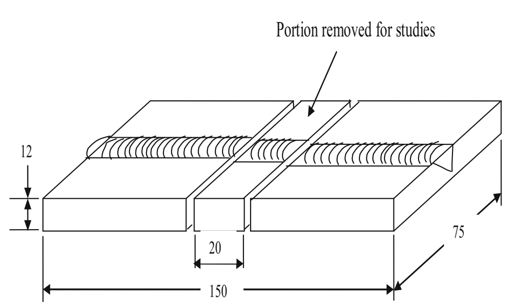


**Fig. 4** Cutting plan for bead geometry

**Table 6** Weld bead profile and shape factor

| Weld deposited with | p (mm) | w (mm) | r (mm) | WPSF | WRFF |
|---|---|---|---|---|---|
| Pure slag | 5.61 | 8.13 | 5.76 | 1.45 | 1.41 |
| Fresh flux | 6.67 | 15.62 | 4.56 | 2.34 | 3.42 |
| Recycled slag | 8.71 | 17.96 | 4.50 | 2.06 | 3.99 |

dimension is recorded in Table 6, and the bead profiles are shown in Fig. 5. From this table and Fig. 5, it is clear that penetration of the weld deposited with recycled steel slag is 8.71 mm which is higher than that achieved with crushed steel slag and fresh flux. This further encourages the use of recycled slag.

### 3.3 Visual inspection

Before removing the specimens for bead geometry, microhardness, and microstructure, the test plates were subjected to visual inspection. Irregular and uneven weld bead having a flat top surface was obtained using crushed slag because deoxidizers and alloying elements have already been exhausted. Ripples were not visible on the top surface (Fig. 5(a)). The convex-shaped top surface of welds prepared using fresh virgin flux as well as recycled steel slag was obtained which are similar. No undercuts, porosity, and pockmarks were detected, and smooth beads were achieved (Figs. 5(b and c)).


**Fig. 5** Profile of welds deposited with pure slag (**a**), fresh flux (**b**), and recycled slag (**c**)

### 3.4 Microstructure

The mechanical behavior of weld metal depends upon the chemistry and microstructure of weld metal [40]. Therefore, metallurgical investigations are extremely important to predict the mechanical properties and performance of welded joints during service life. The metallurgical investigations consist of the study of microstructure and microhardness. For metallurgical investigation specimens were extracted from the center of test plates. The specimens were polished using various grades of emery papers followed by lapping with velvet cloth and then etched using 2% Nital. An optical micrograph of different welds produced using crushed steel slag, fresh virgin flux, and recycled steel slag was captured by metallurgical microscope made by Qualitech Systems at 200X and 500X. The micrographs of base metal and weld metals are shown in Figs. 6–9.

#### 3.4.1 Microstructure of base material

The microstructure of base material SA516 Grade 70 is presented in Fig. 6. It consists of alternate layers of ferrite and pearlite in a rolling direction. The approximate ferrite content is 54.49%, while pearlite content is 45.51% as revealed by ImageJ software.

#### 3.4.2 Microstructure of weld prepared using crushed slag

The microstructure of weld prepared using pure crushed steel slag has been presented in Fig.7. It is clearly shown that columnar structure having grain boundary ferrite (GBF) and isolated colonies of polygonal ferrite (PF) is g present. Widmanstatten ferrite side plates and a small amount of acicular ferrite (AF) are also visible. It is further noted that the amount of grain boundary ferrite and polygonal ferrite is much

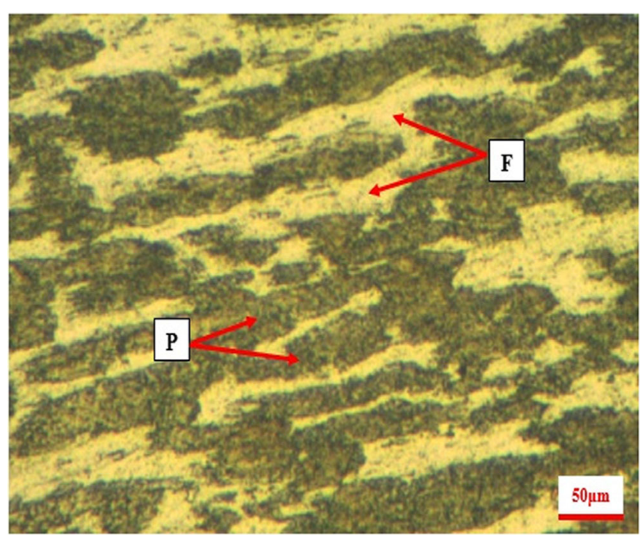


**Fig. 6** Microstructure of base material ASME SA 516 Grade 70 at 500X

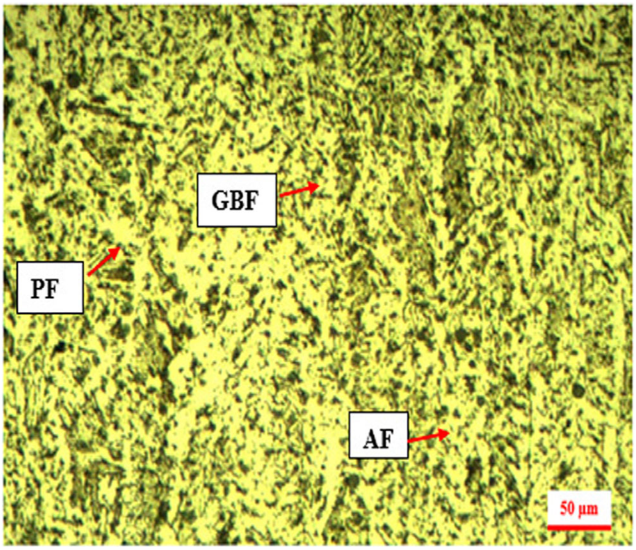


**Fig. 7** Microstructure of weld metal deposited with pure slag at 200X

more than acicular ferrite. Ferrite provides high tensile strength and excellent impact toughness [44]. Chemical composition control is important for increasing acicular ferrite volume fraction [45]. The significant amount of grain boundary ferrite and polygonal ferrite is due to less amount of carbon (0.03%) and manganese (0.12%) present in weld metal as pure slag is not able to add the alloying elements to the weld metal [6]. The further relatively low hardness of weld metal (Fig. 11) supports the observations.

#### 3.4.3 Microstructure of weld metal deposited with fresh flux

The microstructure of weld metal prepared using fresh virgin flux has been shown in Fig. 8. This figure indicates a columnar structure having grain boundary ferrite and acicular ferrite. Acicular ferrite is formed in a randomly oriented short needle structure with a basket weave feature and interlocking together with its fine grain size [45].

Some stray colonies of polygonal ferrite and Widmanstatten ferrite side plates are also visible. It is interesting to note that the amount of acicular ferrite is more than grain boundary ferrite. The acicular ferrite is desirable for improved strength and toughness [26]. The increased amount of carbon (0.18%) and manganese (0.9%) in the weld metal is responsible for the increased amount of acicular ferrite since CaO is the most influencing factor to form acicular ferrite [16].

#### 3.4.4 Microstructure of weld metal deposited with recycled slag

Figure 9 indicates the microstructure of weld deposited using recycled steel slag. This figure reveals the presence of grain boundary ferrite, Widmanstatten ferrite side plates, and acicular ferrite. It is further observed that amount of acicular ferrite is more than that of grain boundary ferrite which is desirable.

The microstructure is comparable with the microstructure of weld prepared with fresh virgin flux. The increased amount of carbon (0.1%) and manganese (0.8%) are responsible for the increased contents of acicular ferrite [45]. The addition of chromium content in the flux promotes the formation of acicular ferrite [46]. The microstructure of weld metal prepared using recycled slag has been presented in Fig. 10 at higher magnification (500X) for better understanding.

### 3.5 Microhardness survey

Hardness measurement can provide information about the metallurgical changes that occurred during welding. It is a representative for ascertaining the strength, toughness,b and ductility of a material [47]. In the present study, the

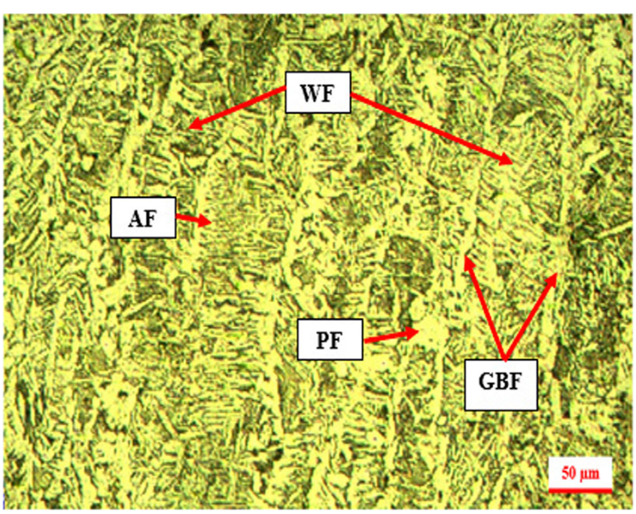


**Fig. 8** Microstructure of weld metal deposited with fresh flux at 200X

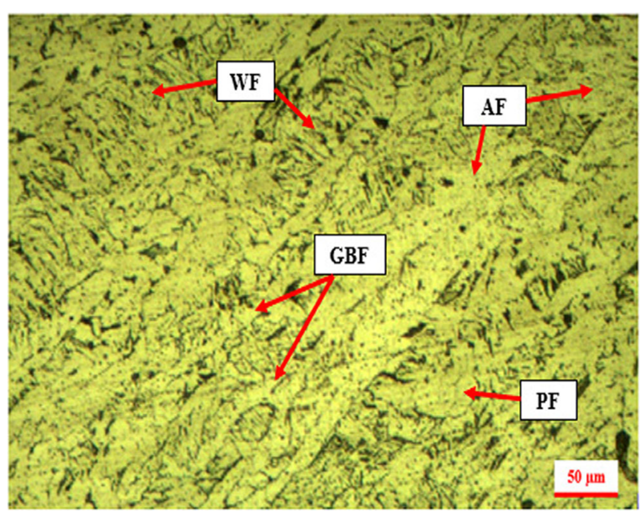


**Fig. 9** Microstructure of weld metal deposited with recycled slag at 200X

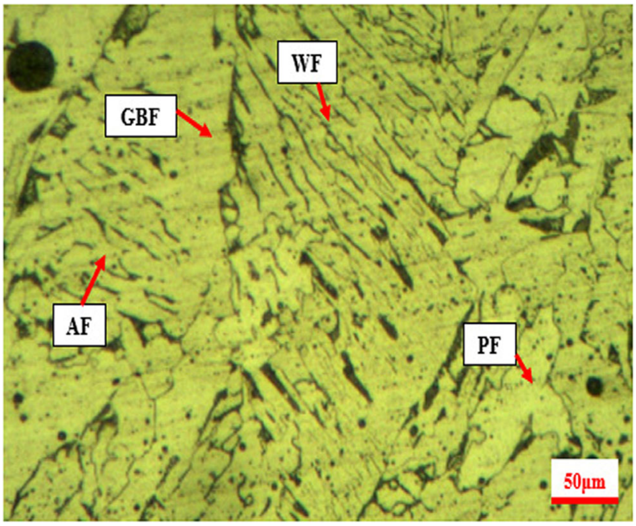


**Fig. 10** Microstructure of weld metal deposited with recycled slag at 500X

microhardness test was conducted on the cross-section of weld beads prepared using pure crushed slag, fresh virgin flux, and recycled steel slag. Microhardness was measured at the cross-section of weld bead starting from uppermost to the downward direction at a suitable interval of 0.5 mm as shown in Fig. 11. It depicts that the hardness of weld deposited with recycled steel slag is higher than that obtained with crushed slag and is comparable with fresh virgin flux. Because the concentration of C, Mn, and Si in weld metal deposited with fresh virgin flux and recycled steel slag is more than that of crushed slag. The microhardness is high at HAZ (heat affected zone) as compare to other regions due to grain refinement.

### 3.6 Arc stability

The molten metal transferred through the arc from electrode to molten pool directly influences the quality and appearance of welds [48]. Arc stability is an indication of regular, smooth, and evenly distributed ripples on the top surface of the weld bead. It was noted during welding from the oscillations shown by the pointer of the voltmeter mounted on the SAW machine [49]. An unstable arc was observed during welding with crushed slag because the chemicals having ionization potential are absent in it. The addition of various chemicals like MnO and CaO during recycling increases the ionization potential of recycled slag resulting in improved arc stability. Similar results have been presented by Kumar et.al. [50].

### 3.7 Slag detachability

Slag detachability was noted during the cleaning of the weld bead produced. It is the ease with which solidified slag can be removed from the weld bead. Poor slag detachability will increase the chances of slag inclusions in the weld metal, particularly in multi-pass welds. Hence self-lifting slag is desirable. The difference between the linear expansion coefficient of slag and weld is directly proportional to the slag detachability. The lower linear expansion coefficient promotes the sticking of slag to the weld metal [31]. Slag detachability was observed during post-weld cleaning using a wire brush and chipping hammer. Poor slag detachability was observed in the case of bead deposited with pure slag. It was due to irregularities on the top surface of the weld. FeO film is the main reason for poor slag detachability [31]. Self-peeling of slag was obtained in the case of fresh flux and recycled slag. The addition of $Al_2O_3$ and $TiO_2$ during the recycling of slag is responsible for the improvement in slag detachability due to an increase in the coefficient of thermal expansion. Similar results have been reported by Wittung [51].

### 3.8 Economic analysis

The economic viability of a product is a paramount parameter for a product designer. The use of recycled slag is considered

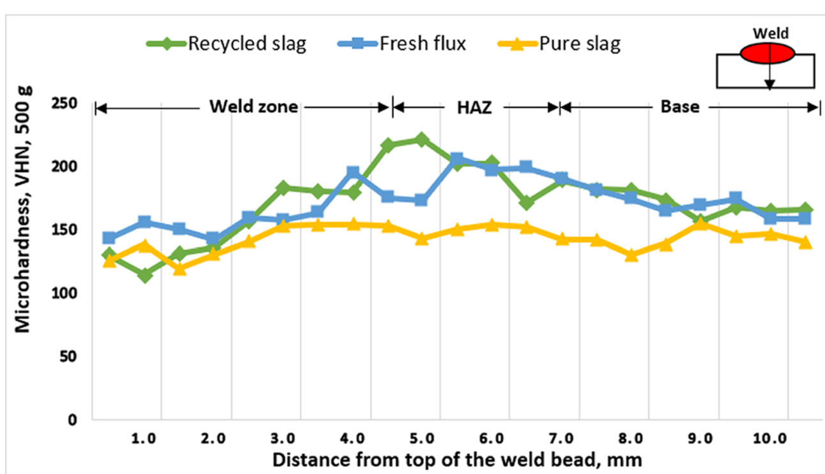


**Fig. 11** Microhardness survey of various weld beads

Table 7 Economical analysis

| S. No. | | | | Cost (in Rs.) |
|---|---|---|---|---|
| **1.** | Material cost | a | Cost of steel slag used | Rs 80.00 (Transportation cost only) |
| | | b | Cost of $CaCO_3$ and $SiO_2$ | Rs 30.00 |
| | | c | Cost of $CaF_2$ and MnO | Rs 62.50 |
| | | d | Cost of $Al_2O_3$ | Rs 35.00 |
| | | e | Cost of Ferro-Mn and Ferro-Si | Rs15.00 |
| | | f | Cost of $Cr_2O_3$ and $TiO_2$ | Rs 427.50 |
| | | g | Cost of Potassium Silicate (Binder) | Rs 450.00 |
| | | | Total Material cost | 1100.00 |
| **2.** | Processing cost | a | Baking cost | Rs 1080.00 |
| | | b | Labour cost | Rs 100.00 |
| | | c | Crushing and milling cost | Rs 90.00 |
| | | | Total processing cost | Rs 1270.00 |

to be economical and technically viable if it is capable to produce an acceptable quality of the weld and at the same time be economical also [52]. Technical viability has already been proved, and for economic viability, the cost of recycled steel slag per 100 kg has been calculated and compared with the cost of commercial fresh flux. It helps to establish the efficacy of using recycled slag. Economic analysis has been given in Table 7.

Prime cost = Material cost + Processing cost = Rs1100 + Rs 1270 = Rs 2370/-

Considering 10% of the prime cost as overhead charges and 10% as profit,

The total price of recycled slag per 100 kg = Rs 2370 + Rs 474 = Rs 2844/-

Price of equivalent fresh flux available in the market per 100 kg = Rs 7500.00

$$\text{Percentage saving} = \frac{\text{Market price} - \text{recycled slag price}}{\text{Market price}} \text{X } 100$$

$$\text{Percentage saving} = \frac{7500 - 2844}{7500} \text{X } 100$$

$$= 62.08\%$$

## 4 Conclusions

1. The recycled steel slag is capable to produce the chemistry of weld within the acceptable range of ASME specifications.
2. The amount of carbon, silicon, and manganese in the weld metal increases with the addition of $CaCO_3$, $SiO_2$, and MnO, respectively, to the steel slag during processing.
3. As per ASME specifications, 0.10 weight percent of carbon is required in the weld metal which is achieved by adding 10% $CaCO_3$ in steel slag.
4. Similarly, 0.11% silicon was achieved in the weld metal by the addition of 20% $SiO_2$ to the steel slag during processing.
5. The addition of 6% MnO and 5% Ferro Mn provided 0.80% Mn content of weld metal.
6. Good arc stability and excellent slag detachability were observed.
7. The bead appearance was good and free from surface defects.
8. The use of recycled steel slag is economical by 62.08%.

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## Declarations

**Ethics approval (include appropriate approvals or waivers)** The manuscript has only communicated to one journal only. And has not submitted to more than one journal for simultaneous consideration.

**Additional declarations for articles in life science journals that report the results of studies involving humans and/or animals** Not applicable

**Consent to participate** The authors have given their consent to participate.

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