

# Nickel-Induced Microstructural Evolution and Its Impact on the Mechanical Properties of Welded Joints

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## Research Article

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# **Nickel-Induced Microstructural Evolution and Its Impact on the Mechanical Properties of Welded Joints**

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## **ABSTRACT**

Nickel is widely used as an alloying element to improve the performance of welded joints, particularly in structural steels. In the present work, the influence of controlled nickel additions on the mechanical and microstructural properties of mild steel welded joints fabricated using manual metal arc welding (MMA) was investigated. Nickel concentrations of 1.3 wt.% and 1.5 wt.% were introduced through nickel-based filler metals, and their effects were compared with nickel-free welds.

Mechanical characterization was carried out using Charpy V-notch impact testing and Vickers hardness measurements, while microstructural features of the weld metal and heat-affected zone (HAZ) were examined using field emission scanning electron microscopy (FESEM). The results showed a notable improvement in impact toughness and hardness with nickel addition. Compared to nickel-free welds, impact energy increased from 160 J to 187 J, while hardness improved by approximately 15–31%. Microstructural analysis revealed refined grain structures and reduced porosity in nickel-containing welds, which contributed directly to the observed mechanical enhancement.

The novelty of this study lies in the systematic evaluation of narrow nickel additions (1.3 & 1.5 wt.%) and their correlation with impact energy partitioning and microstructural refinement under controlled welding conditions. The findings indicate that moderate nickel additions significantly enhance weld integrity and can be effectively employed to improve the reliability of mild steel welded structures.

**Keywords:** Mild steel, Nickel, Hardness, Toughness, Strength, Welding, Microstructure.

## 1. INTRODUCTION

Mild steel, sometimes referred to as low carbon steel or plain carbon steel, is a kind of steel with a comparatively low carbon content (usually less than 0.25%). Because of its price, adaptability, and ease of manufacture, it is the most widely utilized type of steel [1]. Good mechanical qualities including strength and ductility make mild steel appropriate for a wide range of uses. It is extensively utilized for constructions, machinery, automotive parts, and general fabrication in the construction, manufacturing, automotive, and other industries. Mild steel's low carbon content makes it malleable and weldable, making it simple to shape, mold, and weld [2]. However, mild steel could be less durable and resistant to wear than steels with higher carbon content. Additional coatings or finishes can increase its resistance to corrosion [3].

Welding is a fabrication technique that joins metallic elements, usually by applying pressure, heat, or both. Whether or not a filler material is included, it entails heating the base metals and letting them fuse together. Between the materials being joined, welding produces a strong, long-lasting, and permanent bond. However, a number of flaws and inconsistencies brought on by poor welding methods, insufficient process control, or material impurities can lower the quality of welded joints [4]. These flaws, which include deformation, porosity, lack of fusion, and cracks, can seriously weaken weld connections and impair the manufactured structure's overall functionality [5].

Researchers have looked into adding nickel to mild steel weld joints in order to address these problems and improve their mechanical qualities. When added in controlled amounts during the welding process, nickel has demonstrated promising results in improving several key mechanical properties, including increased strength, hardness, and toughness, which are crucial for applications requiring robust weld joints capable of withstanding higher mechanical loads and harsh operating conditions [6-8]. By refining the microstructure and modifying the hardenability of mild steel, nickel facilitates the formation of fine-grained structures and borides that improve the mechanical performance in welded joints [9-13]. In order to shed light on the processes by which nickel improves weld joint integrity and performance, this study investigates the impact of nickel incorporation on the mechanical characteristics of mild steel weld joints [14]. This work improves our understanding of how to optimize welding procedures to produce better mechanical qualities and increased dependability in mild steel applications by thoroughly reviewing the body of research and experimental results [15]. Previous studies have demonstrated that alloying elements such as nickel can significantly improve weld metal toughness, hardenability, and resistance to brittle fracture. Nickel acts as an austenite stabilizer, lowers the ductile-to-brittle transition temperature, and suppresses the formation of coarse and brittle phases in the HAZ (Heat affected zone) [16-21]. Recent studies have reported that nickel additions in the range of 0.5–5

wt.% significantly influence the microstructural evolution and mechanical performance of steels. The addition of nickel reduces transformation temperatures, promotes grain refinement, and enhances low-temperature toughness by stabilizing austenite and suppressing brittle fracture mechanisms. Furthermore, Ni alloying contributes to an improved strength–ductility balance through microstructural modification and precipitation control [22]. It has been reported that addition of 2 % wt. Ni reduces ferrite transformation temperature, refines grains, and significantly improves impact toughness. Also it been found that Ni-containing steels show improved toughness due to optimized grain boundary characteristics and phase distribution [ 23-25]. These findings confirm the beneficial role of nickel in enhancing the mechanical reliability of structural steels. While the beneficial role of nickel in weld metallurgy is well established, most reported studies focus on either high nickel concentrations or alloyed steels, with limited emphasis on narrow nickel additions in mild steel welds produced by flux-cored arc welding. Moreover, a detailed correlation between impact energy components (crack initiation and crack propagation) and microstructural refinement resulting from controlled nickel additions has not been sufficiently addressed. This represents a clear gap in the existing literature. The present study addresses this gap by investigating the effect of 1.3 wt.% and 1.5 wt.% nickel additions on the mechanical performance and microstructural characteristics of MMA mild steel welded joints. The aim of this work is to evaluate the effect of controlled nickel additions on impact toughness and hardness of mild steel welds and to correlate mechanical performance with microstructural features observed through FESEM and identify investigated compositions of Ni that provides a balance between strength and toughness for structural applications.

## 2. EXPERIMENTALPROCEDURE

### 2.1 Materials and methods

Sheets of mild steel were purchased locally. The specimen was sliced into several sizes. Different ambry paper grit sizes (600-2000) were used to clean the specimens. Ethanol was used to clean the specimens in order to eliminate any impurities that might have been present [17]. The mild steel specimen and nickel powder specifications are displayed in Table 1.

Table 1. Specification of Mild Steel and nickel.

|                               |           |
|-------------------------------|-----------|
| Thickness (Mild Steel)        | 5mm       |
| Number of pieces (Mild Steel) | 10        |
| Size (Mild Steel)             | 50x100 mm |
| Purity (Nickel)               | 99.5%     |

|                                      |                |
|--------------------------------------|----------------|
| Nickel particle size                 | 100 mesh       |
| Maximum limit of impurities (Nickel) | Fe..... 0.1%   |
|                                      | Co..... 0.005% |
| HSN code                             | 75040000       |

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## 2.2 Chemical Composition

The base metal and weld joints were chemically examined using a Baird Emission Spectrometer. The chemical makeup of the base metal and weld metal, respectively, is shown in Tables 2. All the other elements in the alloy were unchanged except for nickel.

Table 2. Chemical composition of mild steel.

| S.No.    | Element   | Mass%       |
|----------|-----------|-------------|
| 1        | Mn        | 0.52        |
| 2        | Si        | 0.5         |
| 3        | S         | 0.25        |
| <b>4</b> | <b>Fe</b> | <b>98.2</b> |
| 5        | C         | 0.20        |
| 6        | Ni        | 0.019       |

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## 2.3 Welding flux powder

The welding addition powder was procured from Nano-Shel, USA. To prevent moisture absorption and eliminate the possibility of gas entrapment during welding, the powder was first homogenized using a convective mixer and subsequently heat-treated in an autoclave. The nickel-based micropowder used in this study had a particle size in the range of 40–50  $\mu\text{m}$  and a nominal purity of 99.5%. This pre-treatment ensured uniform dispersion and stable behavior of the powder during welding operations.

## 2.4 Making Nickel electrodes for welding of mild steel joints

American Welding Society standard A5.1/A5.1M was followed for fabrication of Nickel-alloyed filler electrodes (1.3 wt% and 1.5 wt.%). The electrode consists of a mild steel core with flux coating. The flux coated electrode was initially blended and dried at 240  $^{\circ}\text{C}$  for 2.5 h to remove residual moisture. These ingots were later machined and wire-drawn to produce filler rods of the required dimensions suitable for arc welding applications. The electrode wire was prepared via cold drawing

following ASTM A510. Diameter of wire electrode is 3.15 mm. Table 3 gives fabrication and standards of electrode wire. Table 4 gives chemical composition of bare and nickel coated electrode.

Table 3 gives specification of electrode wire

| <b>Parameter</b>    | <b>specification</b> |
|---------------------|----------------------|
| Preparation method  | Cold drawing         |
| Standard compliance | ASTM A-510           |
| Wire diameter       | 3.15 mm              |

Table 4 gives chemical composition of bare and Nickel electrode

| <b>Element</b> | <b>Base composition %<br/>(without nickel)<br/>electrode</b> | <b>Final composition<br/>(1.3% wt)Nickel<br/>electrode</b> | <b>Final composition<br/>(1.5% wt) Nickel<br/>electrode</b> |
|----------------|--------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------------|
| Carbon         | 0.08                                                         | 0.07                                                       | 0.06                                                        |
| Manganese      | 0.45                                                         | 0.42                                                       | 0.44                                                        |
| Silicon        | 0.82                                                         | 0.79                                                       | 0.77                                                        |
| Nickel         | -                                                            | 1.30                                                       | 1.50                                                        |
| Phosphorous    | 0.012                                                        | 0.012                                                      | 0.011                                                       |
| Sulphur        | 0.008                                                        | 0.008                                                      | 0.007                                                       |
| Iron           | 98.522                                                       | 97.40                                                      | 97.212                                                      |

## 2.5 Welding setup

For the experimental program, three different welding consumables were prepared, corresponding to nickel concentrations of 1.3 and 1.5wt.% in the filler material. Welding was carried out using a manual metal arc (MMA) welding machine (Model: MMA-250) equipped with an automatic travel carriage to ensure consistent welding speed and heat input. The detailed welding parameters employed in the study are listed in Tables 5 and 6. Fig. 1 presents the actual welded joint produced under the optimized welding conditions. Fig 1 depicts irregularities in weld bead attributed due to MMA process. Multiple samples ensured repeatability and reliability. The elemental mapping and elemental analysis of weld bead after welding are illustrated in Fig. 2. Reduced heat input in later passes was done to control residual stresses and prevent thermal accumulation.

Table 5. Welding parameters.

| PASS NO | Current<br>(A) | Voltage<br>(V) | HEAT INPUT<br>(J/mm) | TRAVEL<br>VELOCITY<br>(mm/min) |
|---------|----------------|----------------|----------------------|--------------------------------|
| 1-2     | 250            | 25             | 25                   | 15                             |
| 3-4     | 300            | 30             | 22                   | 20                             |

$$HI = \eta \times \frac{V \times I \times 60}{v \times 1000} \quad (i)$$

Where

HI = heat input (J/mm)

V= voltage (Volts)

I= current (Ampere)

v= travel speed (mm/min)

$\eta$ = thermal efficiency factor (0.8 for MMA)

Table 6. Welding machine and flux specifications.

|                      |            |                  |         |                             |
|----------------------|------------|------------------|---------|-----------------------------|
| Welding process      | Flux cored | Welding position | Flat.   | Filler metal specification. |
| Arc welding.         |            |                  |         |                             |
| Filler metal         |            | classification   | DS85-K4 | Shielding gas/flowrate      |
|                      |            |                  |         | CO2                         |
|                      |            |                  |         | (100%)                      |
| Electrode extension  |            | (mm)             | 26-31   | Polarity                    |
|                      |            |                  |         | DCRP                        |
| Preheating/interpass |            | temp.            | 55°C    |                             |



Fig 1. Photograph of the flux-cored arc welded mild steel joint produced using nickel-based filler metal.

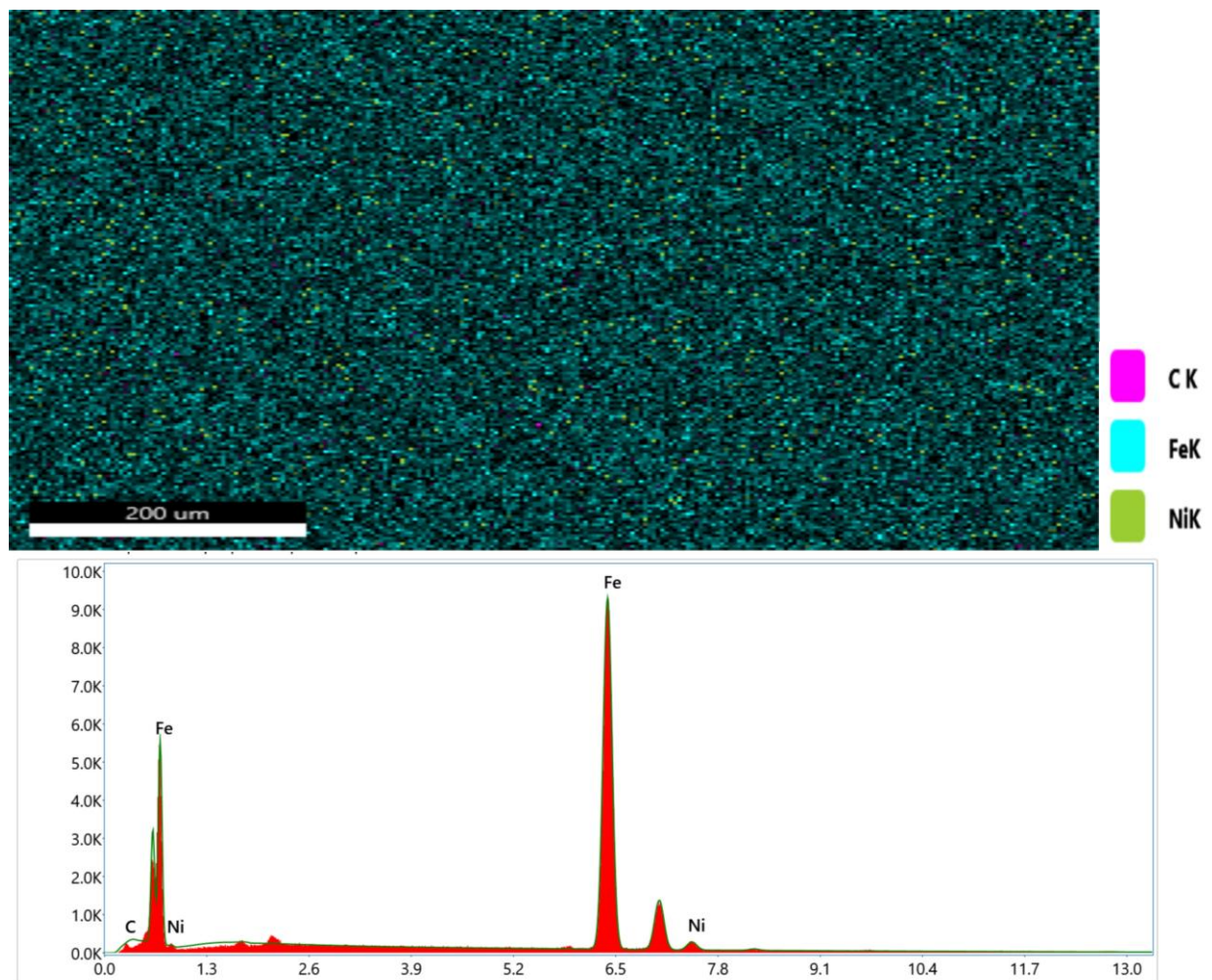


Fig 2. Shows EDS and Elemental mapping of Ni weld for 1.3% Ni specimen

### 3. Mechanical testing of samples

#### 3.1 Impact test

Tensile testing was carried out to evaluate the effect of nickel addition on the strength and ductility of the welded joints as per ASTM E23 standard. The standard tensile specimens required for testing were prepared from the welded plates in accordance with ASTM E8/E8M standards, with the weld metal positioned at the center of the gauge length. Testing was performed at room temperature using a impact testing machine. For each condition, three specimens were tested and average values were reported. Table 7 gives specification of testing specimen. Fig 3 shows the schematic specimen geometry. Table 8 shows the result values. Fig 4, fig 5 and fig 6 shows the graphical result for total energy , crack initiation energy and crack propagation energy respectively.

Table 7. gives specification of testing specimen for impact testing

| Parameter            | Value             |
|----------------------|-------------------|
| D (diameter)         | 10 $\pm$ 0.1 mm   |
| R (radius of fillet) | 2 mm              |
| A (reduced section ) | 24 mm             |
| G (gauge length)     | 55.0 $\pm$ 0.1 mm |

Table 8. impact test with and without nickel.

| Sample No. | Nickel wt<br>% | Impact Total<br>energy(J) | Crack<br>initiation<br>energy(J) | Crack<br>propagation<br>energy(J) |
|------------|----------------|---------------------------|----------------------------------|-----------------------------------|
| S1         | 0              | 160 $\pm$ 3               | 50 $\pm$ 1                       | 125 $\pm$ 2                       |
| S2         | 1.3            | 172 $\pm$ 4               | 58 $\pm$ 2                       | 129 $\pm$ 4                       |
| S3         | 1.5            | 187 $\pm$ 2               | 62 $\pm$ 1                       | 134 $\pm$ 5                       |

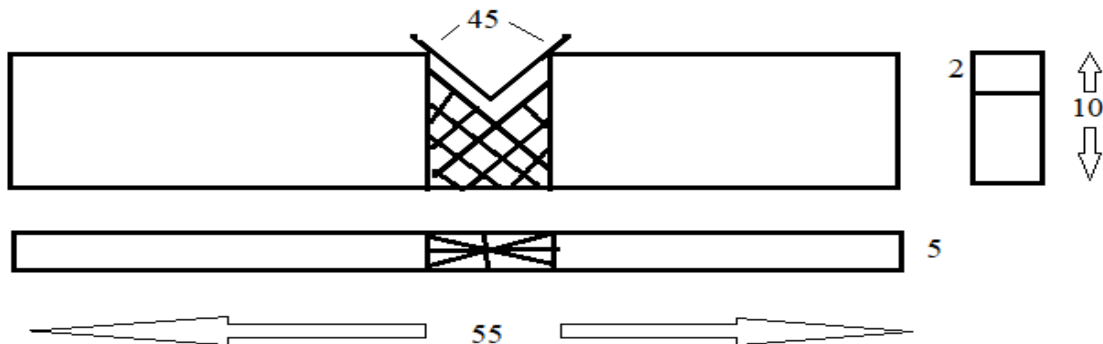


Fig 3 shows the schematic specimen geometry.

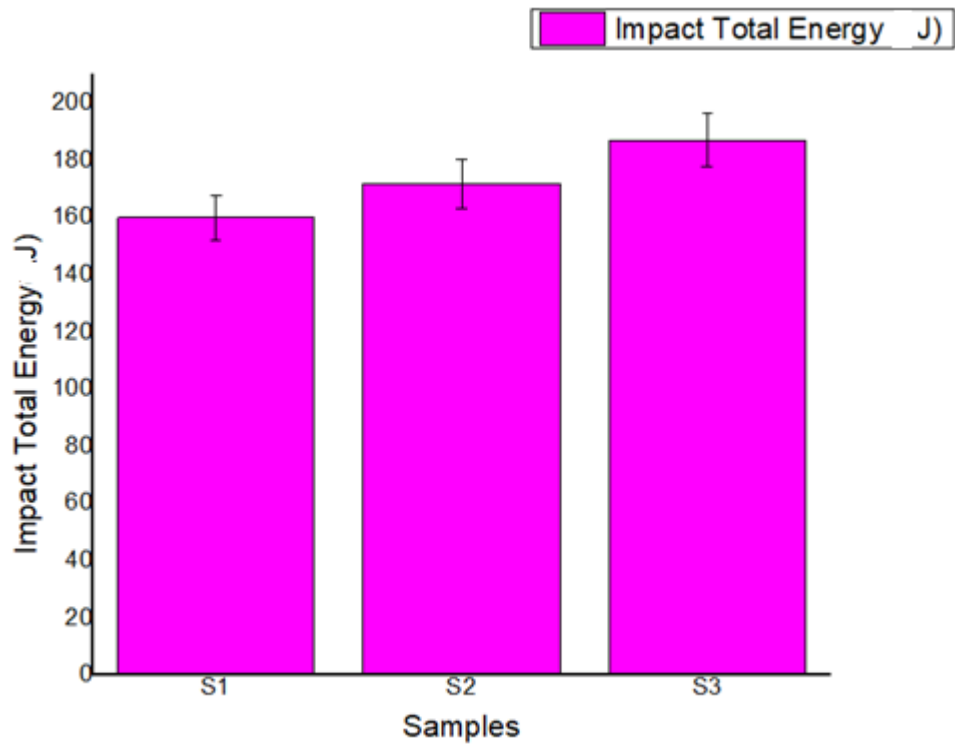


Fig 4. Variation of total absorbed impact energy without /with nickel content in welded joints.

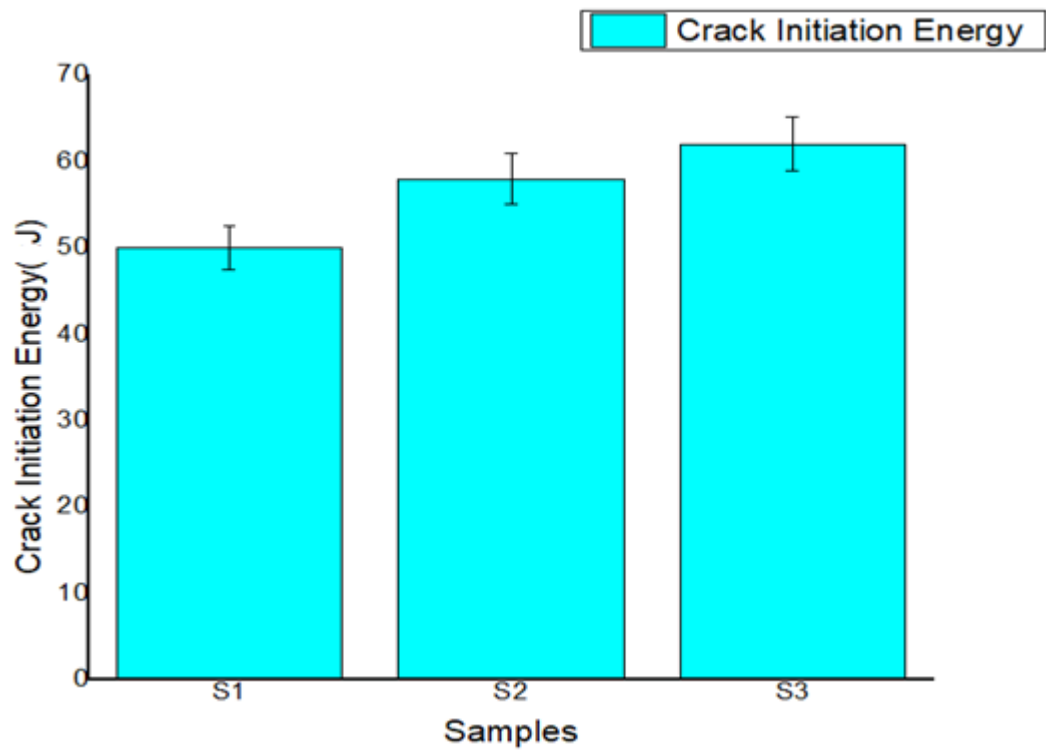


Fig 5. Variation of crack initiation energy for without /with Nickel weld specimens obtained from Charpy impact testing.

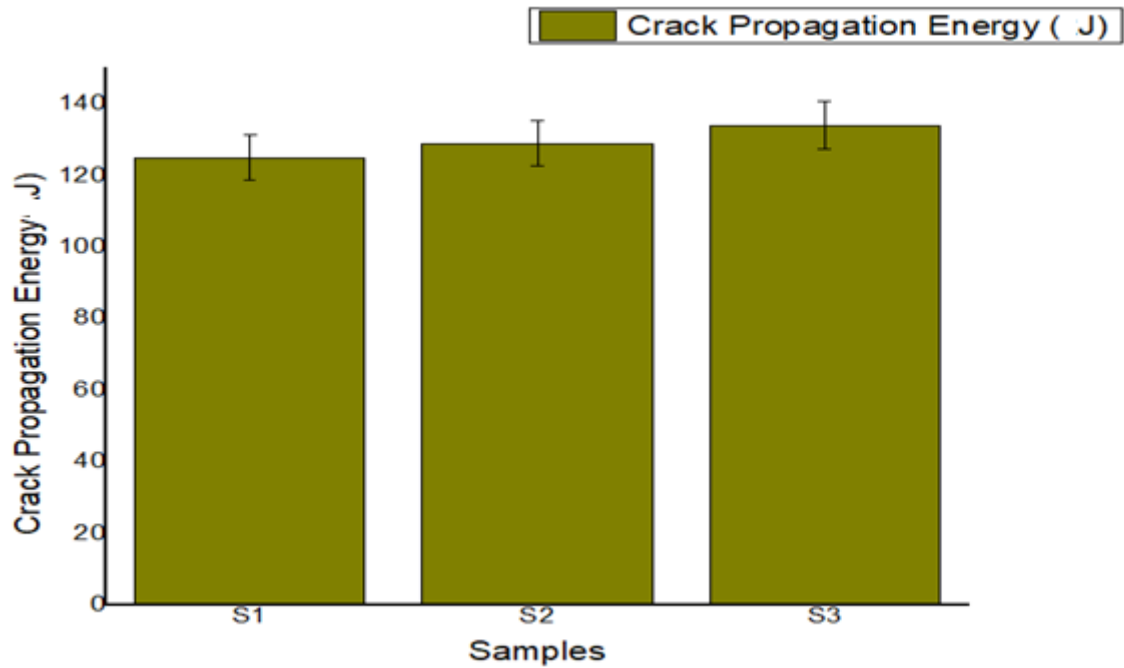


Fig 6. Variation of crack propagation energy for without /with Nickel weld samples obtained from Charpy impact testing..

### Mixed-Mode Fracture Behavior (1.3% and 1.5% Ni vs Non-Ni Welded Joints)

In welded joints, fracture rarely occurs under purely opening mode (Mode I); instead, it usually involves a combination of opening (Mode I) and sliding (Mode II), referred to as mixed-mode fracture. The presence of nickel significantly alters how cracks initiate and propagate under such combined loading. For **non-nickel welded joints**, the microstructure near the weld zone—particularly in the heat-affected zone (HAZ)—tends to be relatively coarse and less tough. Under mixed-mode loading, cracks initiate more easily at microstructural discontinuities such as inclusions or grain boundaries. Crack propagation is typically more brittle in nature, showing cleavage facets with limited plastic deformation. The crack path is relatively straight, indicating poor resistance to shear components of loading. Fig 4 shows results for non-nickel weld.

When **1.3% Ni is added**, the fracture behavior improves noticeably. Nickel promotes grain refinement and enhances toughness in both the weld metal and HAZ. Under mixed-mode loading, crack initiation is delayed due to better energy absorption capacity. The fracture surface begins to show a combination of ductile dimples and some cleavage features, indicating a transition toward ductile behavior. Crack propagation becomes more tortuous, reflecting increased resistance to both opening and shear stresses. Fig 5 shows results for 1.3% nickel weld.

With **1.5% Ni**, these effects become more pronounced. The microstructure becomes even more refined and homogeneous, leading to higher toughness and improved resistance to crack growth. Under mixed-mode conditions, the material accommodates deformation more effectively, resulting

in a dominant ductile fracture mechanism characterized by fine and uniformly distributed dimples. Shear lips and microvoid coalescence features are more evident, showing strong resistance to Mode II components. Crack propagation is significantly deflected and slowed, indicating enhanced fracture toughness. Fig 6 shows results for 1.5% nickel weld.

### 3.2 Micro hardness Mapping Across Weld Zone

To better understand the local mechanical response of the welded joints, micro hardness measurements were carried out across the base metal, heat-affected zone (HAZ), and weld metal. Indentations were made at regular intervals using a Vickers micro hardness tester under a load of 500 g with a dwell time of 10 s.

The hardness profile revealed a gradual increase from the base metal towards the weld metal in nickel-added joints, while the nickel-free weld exhibited noticeable hardness variation within the HAZ. The addition of nickel resulted in a more uniform hardness distribution and suppressed excessive softening in the HAZ, indicating improved thermal stability and grain refinement. Table 9 gives the values of results obtained along with fig 7. Error bars were incorporated in graphical representations to indicate data variability.

Table 9. Vickers hardness test with and without nickel.

| Sample | Nickel % | HV    | HV    | HV    | Average |
|--------|----------|-------|-------|-------|---------|
| No.    |          | 1     | 2     | 3     | Value   |
| S1     | 0        | 200.8 | 198.9 | 194.7 | 198.13  |
| S2     | 1.3      | 234.8 | 226.2 | 221.6 | 227.35  |
| S3     | 1.5      | 254.4 | 269.1 | 254.8 | 259.43  |

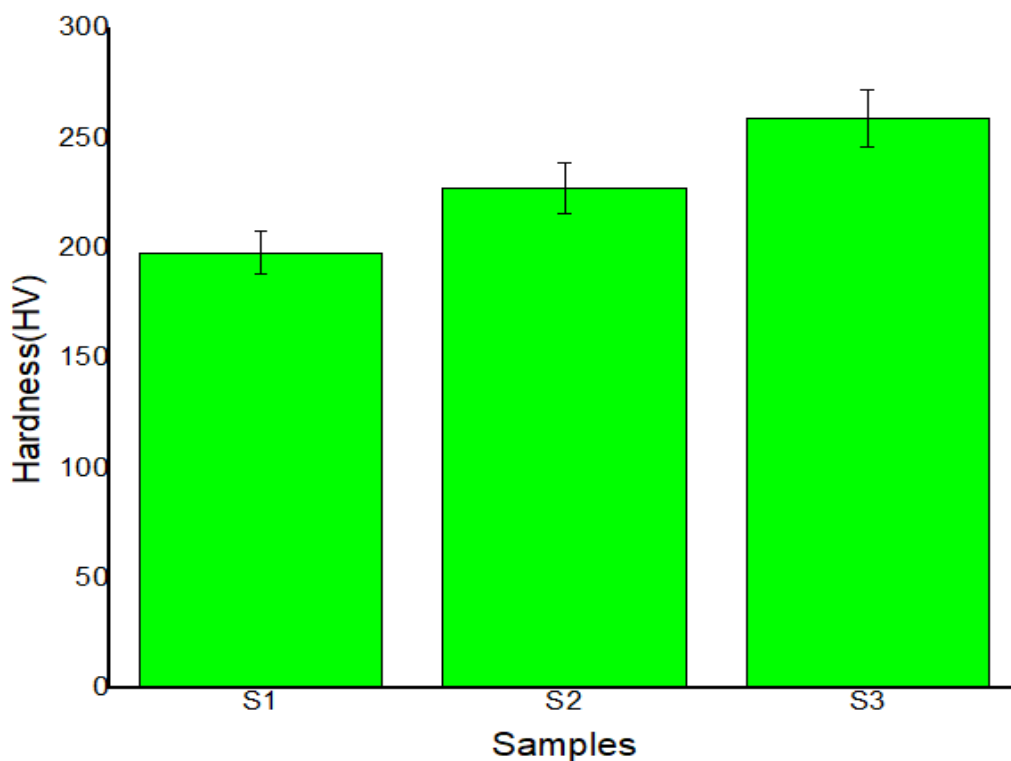


Fig 7. Comparison of average Vickers hardness values for welded joints with and without nickel.

From the above table the average hardness value of samples without nickel is 198.13HV. While as hardness value of samples with nickel is between 227.35-259.43 HV. Also, the percentage increase in hardness is 15-31%.

### 3.3 Fractographic Analysis

Fractographic examination of the Charpy impact-tested specimens was conducted to identify the fracture mechanisms associated with different nickel contents. The fracture surface of nickel-free welds was characterized by cleavage facets and river patterns, indicating a predominantly brittle fracture mode.

In contrast, welds containing 1.3 wt.% nickel displayed a mixed fracture mode, with the presence of shallow dimples alongside limited cleavage features. At 1.5 wt.% nickel, the fracture surface was dominated by fine and uniformly distributed dimples, suggesting a ductile fracture mechanism. These observations are consistent with the increased impact energy and improved crack propagation resistance observed in nickel-containing welds using FESEM model Gemini SEM (500 349599-9001- 180). Fig. 8 shows Fractographic analysis of non-boron weld sample. Fig 9 shows Fractographic analysis of 1.3 wt % nickel weld. Fig 10 shows Fractographic analysis of 1.5% nickel weld.

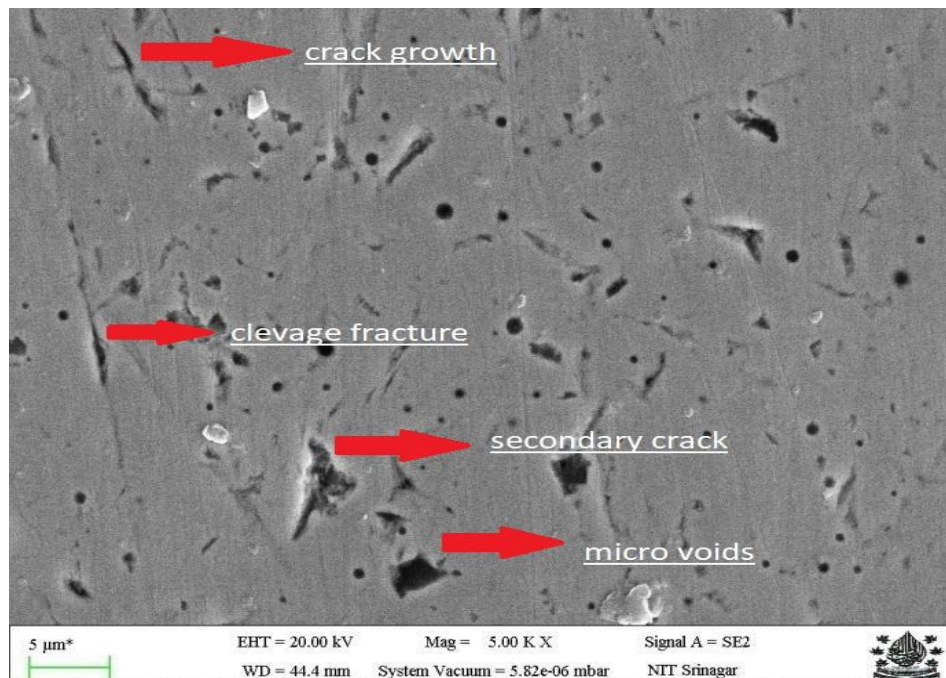


Fig 8. FESEM micrograph of weld metal without nickel

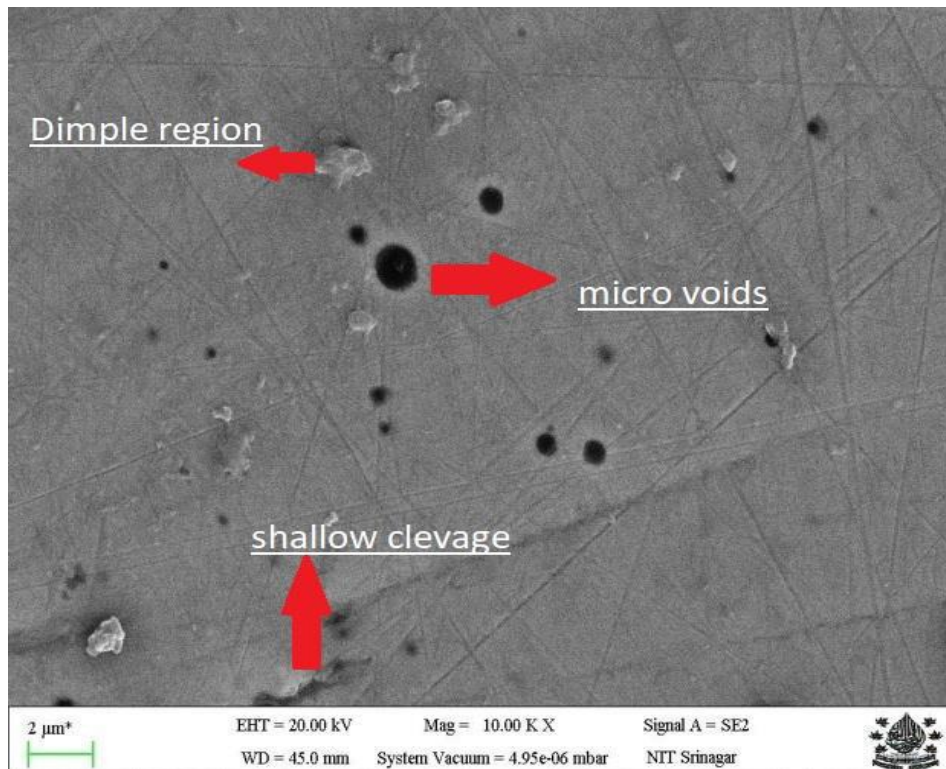


Fig 9. FESEM micrographs of weld metal with 1.3 wt.% nickel.

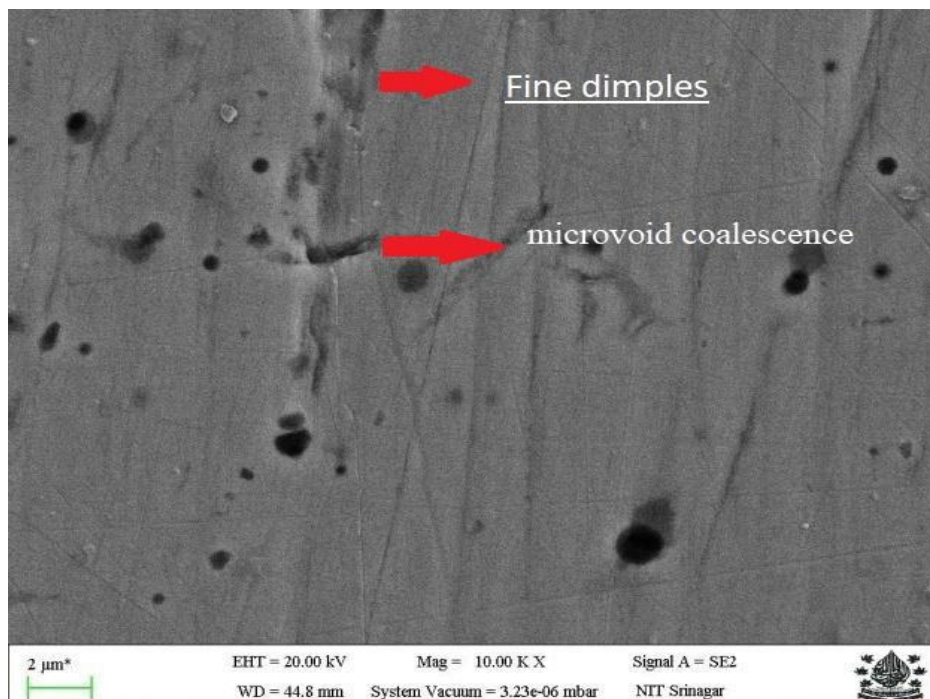


Fig 10. FESEM micrographs of weld metal with 1.5 wt.% nickel

### 3.4 Optical Metallography

The average grain size of the base metal, heat affected zone, and weld fusion zone was determined using the linear intercept method in accordance with ASTM E112. Metallographic samples containing nickel additions of 1.3 wt.% and 1.5 wt.% were prepared using standard grinding, polishing, and etching procedures to reveal the microstructure. Optical and scanning electron

micrographs were captured at appropriate magnifications, and multiple random fields were selected to ensure unbiased measurements. The number of grain boundary intercepts was recorded along test lines, and the mean intercept length was converted into average grain size values. A minimum of five measurements were obtained for each condition, and the reported values represent mean grain size along with standard deviation.

Quantitative phase analysis was carried out to determine the volume fraction of microstructural constituents present in the weld regions. High-resolution micrographs from nickel-modified welds (1.3 wt% and 1.5 wt%) were analyzed using digital image processing techniques. Image contrast and thresh holding were applied to distinguish phases based on morphology and grayscale variation. The measured area fractions from multiple regions were converted to volume percentages assuming uniform phase distribution. At least five images per sample were evaluated to improve accuracy, and the resulting phase fractions were expressed as percentage values with corresponding standard deviation. These quantitative data were correlated with hardness and mechanical performance to establish structure–property relationships.

Fig 11 shows optical micrograph of non –nickel weld. Fig 12 shows optical micrograph of 1.3% nickel weld. Fig 13 shows optical micrograph of 1.5% nickel weld.

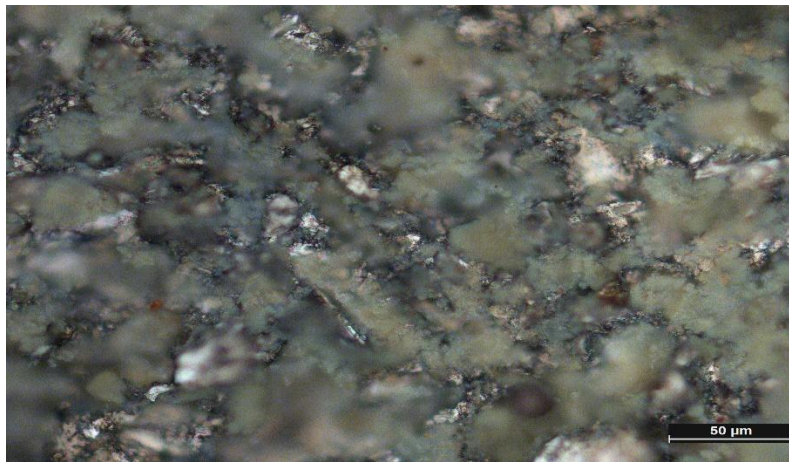


Fig. 11. shows optical micrograph of non -nickel weld

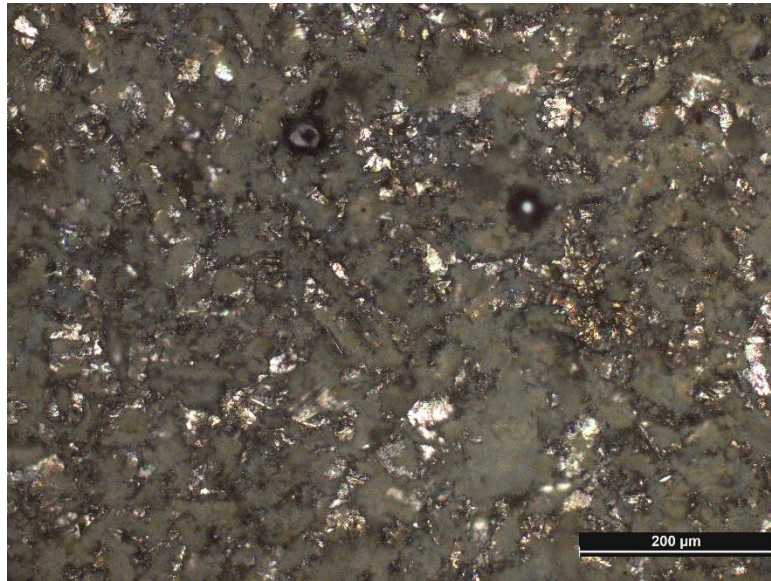


Fig . 12. shows optical micrograph of 1.3% nickel weld

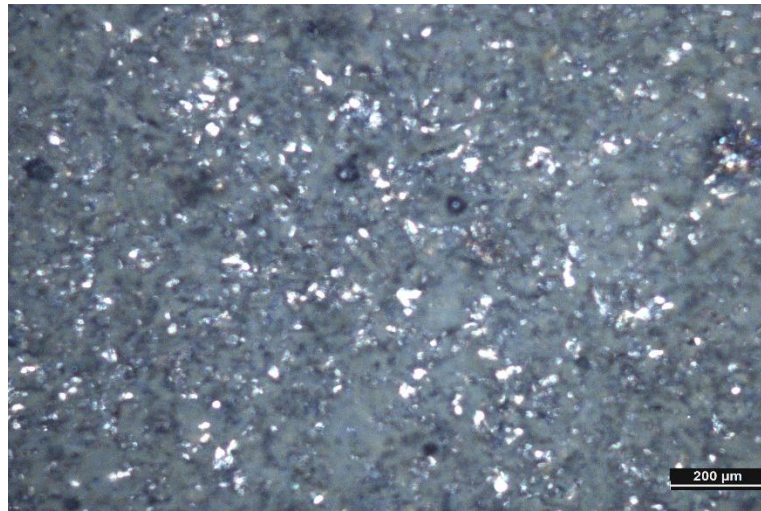


Fig. 13 shows optical micrograph of 1.5% nickel weld

### 3.5 Tensile Testing

Tensile testing of the welded joints was carried out to evaluate the effect of nickel addition on strength and ductility. Standard round tensile specimens were prepared from the welded plates in accordance with **ASTM E8/E8M**. Fig 14. shows the schematic geometry of specimen tested. Table 10 gives values of geometric values of tested sample.

The specimens were extracted transverse to the weld direction, ensuring that the weld metal was located at the gauge length center. The tensile tests were performed at room temperature using a **universal testing machine (UTM)** with a constant crosshead speed of **2 mm/min**. For each condition (without nickel, 1.3 wt.% Ni, and 1.5 wt.% Ni), **three specimens were tested**, and the average values were reported. Yield strength, ultimate tensile strength, percentage elongation, and fracture location were recorded for all samples. The tensile properties of the welded joints exhibited

a clear dependence on nickel content. The nickel-free welds showed a yield strength of approximately 285 MPa and an ultimate tensile strength of 435 MPa, with fracture occurring within the weld metal. This behavior indicates comparatively lower weld metal strength and reduced resistance to plastic deformation. With the addition of 1.3 wt.% nickel, a significant improvement in tensile performance was observed. The yield strength and ultimate tensile strength increased to 325 MPa and 482 MPa, respectively, accompanied by an increase in elongation to 20.1%. Notably, fracture shifted from the weld metal to the base metal, indicating that the weld zone became stronger than the surrounding material. Further increase in nickel content to 1.5 wt.% resulted in the highest tensile strength values, with a yield strength of 348 MPa and an ultimate tensile strength of 515 MPa. Although a marginal reduction in elongation was observed compared to the 1.3 wt.% nickel welds, the ductility remained higher than that of the nickel-free sample. This slight reduction in elongation can be attributed to increased solid-solution strengthening and microstructural refinement caused by higher nickel content. The observed improvement in tensile properties correlates well with hardness measurements and FESEM observations. Nickel addition promotes grain refinement and stabilizes the austenitic phase, leading to enhanced strength without a severe loss in ductility. These findings confirm that moderate nickel additions (1–2 wt.%) are effective in improving the load-bearing capacity and structural reliability of mild steel welded joints. Table 11 shows the values of geometric values of tested sample.

Table 11. gives values of geometric values of tested sample

| Parameter              | Value (mm) |
|------------------------|------------|
| G (Gauge Length)       | 50         |
| D (Gauge Diameter)     | 5.0        |
| R (Fillet Radius)      | 10         |
| Reduced Section Length | 57         |
| Grip Section Diameter  | 20         |
| Overall Length (L)     | 100        |

The mechanical performance of the welded joints exhibited a clear dependence on nickel content. The incorporation of nickel significantly enhanced strength, hardness, and impact toughness, demonstrating its effectiveness as an alloying element for improving weld integrity in mild steel. Impact testing revealed a consistent increase in total absorbed energy with nickel addition. Nickel-free welds absorbed 160 J, whereas welds containing 1.3 wt.% and 1.5 wt.% nickel absorbed 172 J and 187 J, respectively. Both crack initiation and crack propagation energies increased with nickel content, indicating improved resistance to crack nucleation and growth. This behavior is attributed to nickel's ability to stabilize the austenitic phase and suppress brittle microstructural constituents [21-33].

Hardness measurements showed a progressive increase with nickel addition. The average hardness

increased from approximately 198 HV in nickel-free welds to 227 HV and 259 HV for 1.3 wt.% and 1.5 wt.% nickel welds, respectively. Microhardness mapping further confirmed a more uniform hardness distribution across the weld metal and heat-affected zone (HAZ) in nickel-containing joints, suggesting improved thermal stability and reduced HAZ softening. Fig 14 shows the schematic geometry of specimen tested .Fig. 15 shows graphical results of test. Fig. 16 shows non nickel weld specimen before testing having cracks beforehand. Error bars were incorporated in graphical representations to indicate data variability. Fig 17(a,b,c,d) shows the Macroscopic fracture surfaces of non-Ni, 1.3% Ni, and 1.5% Ni welded joints showing increasing ductility and crack tortuosity with nickel addition.

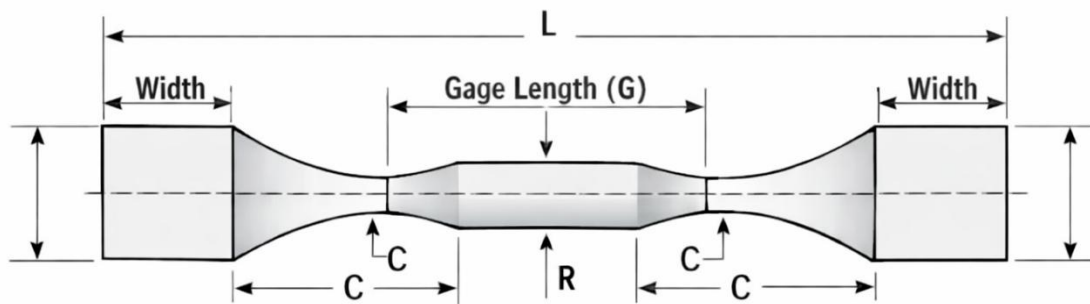


Fig 14. shows the schematic geometry of specimen tested

Table 11 shows the results obtained from Tensile testing of weld samples

| Sample | Nickel content (wt.%) | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Elongation (%) | Fracture Location |
|--------|-----------------------|----------------------|---------------------------------|----------------|-------------------|
| S1     | 0                     | $285 \pm 6$          | $435 \pm 8$                     | $18.2 \pm 0.6$ | Weld metal        |
| S2     | 1.3                   | $325 \pm 5$          | $482 \pm 7$                     | $20.1 \pm 0.5$ | Base metal        |
| S3     | 1.5                   | $348 \pm 7$          | $515 \pm 6$                     | $19.4 \pm 0.4$ | Base metal        |

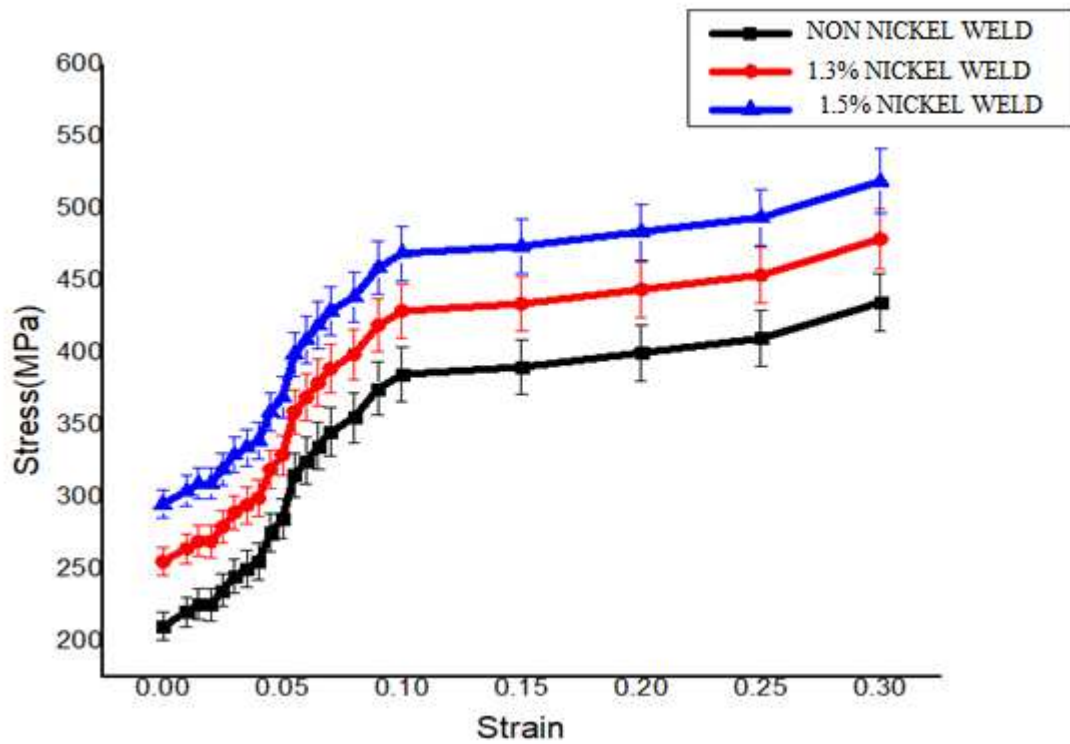


Fig. 15 shows graphical results of test



Fig .16. Macro photograph of welded joint showing crack initiation before impact testing.

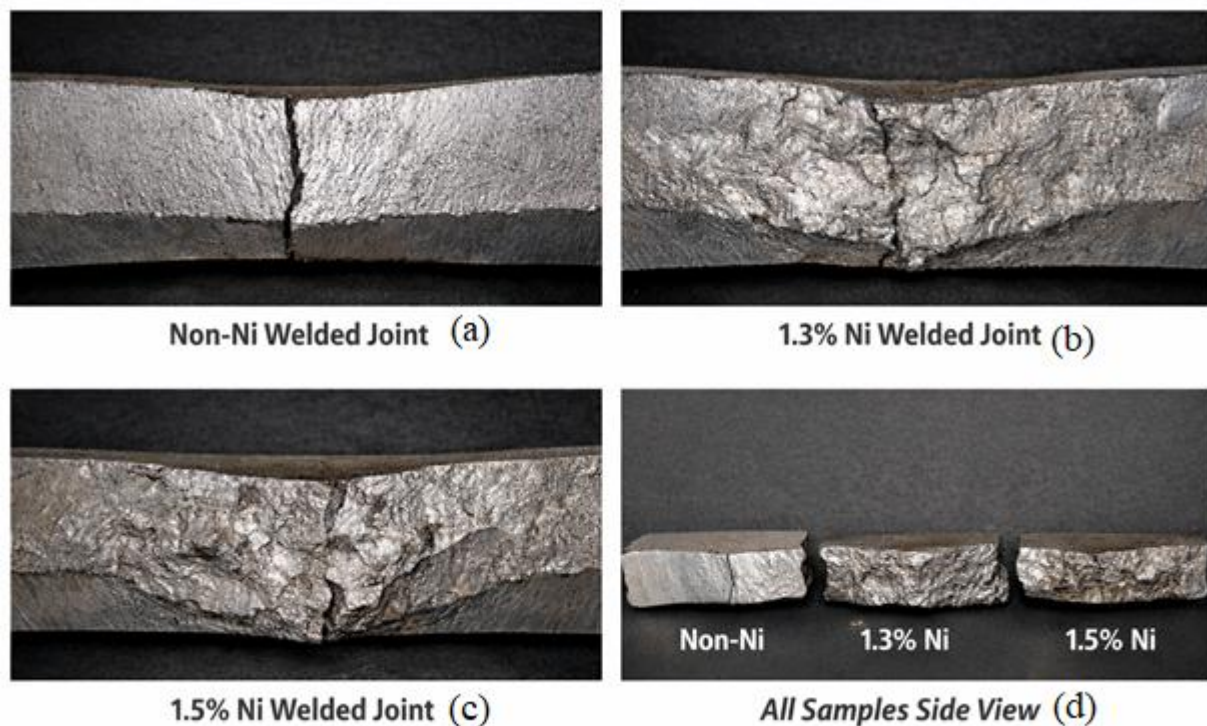


Fig 17 shows the Macroscopic fracture surfaces of non-Ni, 1.3% Ni, and 1.5% Ni welded joints showing increasing ductility and crack tortuosity with nickel addition

### 3.6 X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was conducted to examine the crystalline phases present in the weld metal and to understand the phase transformations induced by nickel addition. The XRD patterns of the welded joints with 0% Ni (Non-Ni), 1.3% Ni, and 1.5% Ni are presented in Fig. 18. The XRD results reveal that the non-nickel welded joint predominantly exhibits peaks corresponding to the BCC ferrite phase. With the addition of 1.3% and 1.5% Ni, additional peaks corresponding to FCC austenite and martensite phases become evident. The austenite phase is identified by characteristic peaks such as (111) and (200), while martensite is associated with peaks such as (101) and (200). An increase in nickel content leads to an increase in the intensity of these peaks, indicating the stabilization of the austenitic phase and the formation of martensite. This suggests that nickel plays a significant role in modifying the phase balance and refining the microstructure.

The presence of these phases contributes to a more complex and refined microstructure, which enhances the mechanical properties of the welded joints. In particular, the improved phase distribution is associated with increased toughness and strength, especially in the 1.5% Ni welded joint. Fig. 18. XRD patterns of welded joints for Non-Ni, 1.3% Ni, and 1.5% Ni content.

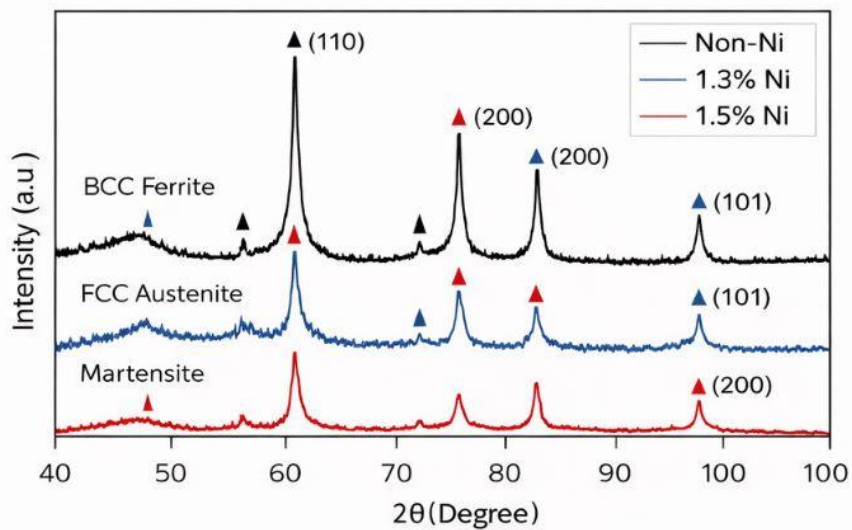


Fig. 18. XRD patterns of welded joints for Non-Ni, 1.3% Ni, and 1.5% Ni content.

## Results and discussions

Tensile testing results supported the hardness and impact data. Nickel-free welds fractured within the weld metal, indicating comparatively lower weld strength. In contrast, nickel-added welds exhibited higher yield and ultimate tensile strength, with fracture shifting to the base metal. This shift confirms that nickel addition strengthens the weld zone beyond the surrounding material.

Microstructural examination using optical microscopy and FESEM revealed significant grain refinement in nickel-containing welds. Nickel-free joints showed coarser grains and visible porosity, particularly in the heat-affected zone. The addition of nickel resulted in finer, more homogeneous grain structures with reduced pore density. These microstructural improvements directly correlate with the observed enhancement in mechanical properties.

Fractographic analysis of Charpy impact specimens further validated the mechanical trends. Nickel-free welds exhibited cleavage facets and river patterns, indicative of brittle fracture. Welds containing 1.3 wt.% nickel showed a mixed fracture mode, while 1.5 wt.% nickel welds displayed fine, uniformly distributed dimples characteristic of ductile fracture. This transition in fracture mechanism explains the increased impact energy and improved crack propagation resistance.

## CONCLUSION

In the present study, the influence of controlled nickel addition in welding consumables on the quality of mild steel arc-welded joints was systematically investigated. Nickel-containing filler electrodes were successfully fabricated using an in-situ mixed-salt reaction route, ensuring uniform chemical composition and good metallurgical stability during welding. The adopted fabrication and pre-treatment procedures for the flux and filler materials effectively minimized moisture uptake and gas entrapment, contributing to defect-free weld formation. Welding carried out using nickel-modified electrodes resulted in improved weld integrity and consistent bead geometry under the

selected processing conditions. The presence of nickel in the weld metal promoted a more refined microstructure, attributed to its austenite-stabilizing effect and its ability to suppress excessive grain coarsening during solidification and subsequent cooling. This microstructural refinement is expected to enhance mechanical performance by improving strength–ductility balance and resistance to crack initiation in the welded joints.

The study demonstrates that small, controlled additions of nickel in welding consumables can be an effective approach for tailoring the microstructure and overall performance of mild steel weldments without significant changes to conventional arc welding parameters. The findings provide useful insights for the development of cost-effective nickel-alloyed electrodes for structural and industrial applications. Future work may focus on detailed mechanical testing, fracture behavior, and corrosion performance to further establish the long-term reliability of nickel-modified welded joints.

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**Data availability's statement**

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**Code Availability**

In this study, no codes were employed. Therefore, code availability is not necessary.

**Ethics Approval**

This study did not contain any instances of plagiarism. The material is properly cited.

**Consent to participate**

The relevant author consents to take part in any debate or review procedure.

**Consent to publication**

The corresponding author consents to this manuscript's publication in your esteemed journal.

**Authors contribution**

The article and experiments were written by the corresponding author.

**Conflict of interest**

We certify that the results presented in this publication are entirely original and have not been submitted to any other journal. Regarding this study, the authors have no conflicts of interest.

**Use of AI**

No AI was used to write any part of this manuscript

**Declaration:****Data Availability Statement (DAS):**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**Ethical Approval**

*Response:* Not applicable.

This study does not involve human participants, animals, or any biological samples. The research is entirely based on materials processing, mechanical testing, and microstructural analysis of metallic specimens.

**Consent to Participate**

*Response:* Not applicable.

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