Effect of heat input on TIG welding of hastelloy C-276

Vasareddy Mahidhar¹, Sampreet K R¹, Chiguluri Shai Vinay¹, C B Maheswaran², T Deepan Bharathi Kannan*¹

¹Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, India
²School of Mechanical Engineering, Sastra Deemed to be University, Thanjavur, India

E-mail: tdbk23@gmail.com

Abstract. In this work, an attempt is made to study the effect of heat input on mechanical and metallurgical properties of Tungsten Inert Gas (TIG) welded Hastelloy C-276 sheets. Hastelloy C-276 sheets of thickness 1.6mm were used throughout this study. Three butt joints were made by varying the values of welding current in the steps of 1 Ampere. The weld quality was assessed by measuring bead geometry, tensile strength and microhardness. From the experimental results, it was found that the hardness proportionally varied with the change in welding current whereas tensile strength first increased and then decreased with increase in welding current. The weld property variation is discussed with the aid of microstructures taken from Scanning Electron Microscope (SEM), Energy Dispersion Spectroscopy (EDS) and X-ray Diffractometer (XRD).

1. Introduction

Hastelloy C-276 (UNS N10276) is an alloy with main constituents as Nickel, Molybdenum and Chromium along with little amounts of Iron and Tungsten which makes the material corrosion resistant. The presence of Nickel and Molybdenum makes the material resistant to pitting/crevice corrosion. Some of the other fascinating properties of Hastelloy C-276 are good resistance to various acids such as nitric, sulphuric, chromic, hydrofluoric and hydrochloric acids and high strength at elevated temperatures. Due to its excellent corrosive resistant properties, Hastelloy C-276 is widely preferred in the fabrication of critical components in marine, nuclear and chemical industries [1]. Welding plays an important role in the manufacturing of components like gas pipelines, pressure vessels, oil tankers and chemical reactors which are required in the abovementioned industries. Among all the available welding techniques, TIG welding which is also called Gas tungsten arc welding (GTAW) is found to be one of the suitable welding processes for joining high temperature materials as it produces high quality, clean welds. Stable arc due to constant arc length helps to achieve cleaner welds during TIG welding process. TIG welding is preferred in joining almost all non-ferrous and ferrous metals owing to its simplicity in operating and it is also comparatively inexpensive. In welding, the output parameters like bead width and depth of penetration mainly depend on the welding current, welding speed used. A few authors explored TIG welding of Hastelloy plates by varying some of the welding parameters. Sumitra Sharma et al. [2] welded AISI 321 ASS and Hastelloy C-276 using conventional TIG and Pulsed TIG welding process. The authors found that the pulsed TIG welding process helped in achieving narrower and deeper weld compared to that of continuous TIG welding process. Chao Chen et al. [3] utilized TIG and pulsed ultrasonic TIG (PU-TIG) welding processes for joining Hastelloy C-276. The authors concluded that PU TIG weld had
depth of penetration 46% more than conventional TIG welding. Similarly, PU TIG weld bead width was 27% more than that of TIG welding process. In addition to the TIG welding process, few authors also explored other welding processes for joining Hastelloy C-276. Kalinga et al. [4] utilized fiber laser welding source for welding Hastelloy C-276 and authors achieved full penetration in all welding trials. The authors also stated that heat input supplied during the process had control over the depth of penetration and bead width. Ashutosh et al. [5] investigated pulsed Nd: YAG welding of Hastelloy C-276 and authors were able to achieve full penetration and lesser bead width. HAZ bead width was very less and the authors cited higher power density of the laser source helped in reducing the bead geometry. Mechanical Properties such as tensile strength and hardness play a crucial role in the selection of materials for chemical, oil & gas industries.

Sathish Kumar et al. [6] welded Hastelloy C-276 plates using TIG and Pulsed TIG welding process. The authors compared the hardness values of both processes and found that Pulsed TIG welding resulted in better hardness and the difference in the hardness value was around 8.05%. The authors also concluded that absence of micro segregation of Mo, Cr rich elements as the main reason for the better hardness value in pulsed TIG Welded Samples. In order to get higher hardness value in the weld, Mahidhar et al. [7] recommended to select welding parameters in such a way that it results in the formation of dendrite grains in the fusion zone. The authors also recommended using laser welding for joining Hastelloy C-276 sheets. The tensile strength of the welded Hastelloy C-276 is highly affected during the welding process due to the formation of brittle phase and defects. Tensile strength of the weld plays a key role in all the structural applications. Most of the works related to welding of Hastelloy C-276 reported weld with lesser tensile strength. Kalinga et al. [4] joined Hastelloy C-276 using laser welding process and the authors reported that the weld had lower strength than the base metal. Elemental Segregation was found to be a major cause of the reduced tensile strength. Sathish Kumar et al. [6] compared conventional TIG and Pulsed TIG welding processes with respect to tensile strength. The authors found that Pulsed TIG welded samples had better tensile strength and it was around 4.18% higher. TIG welded samples had lower strength owing to the presence of embrittlement precipitates. Tensile strength was found to increase with increase in current for the MIG welded Hastelloy C-276 plates [8]. The authors reported that the presence of defects such as pores, incomplete penetration, incomplete fusion would decrease the tensile strength.

In any welding process, the variation of input parameters plays an important role. The correct combination of parameters plays a vital role in getting properties suitable for specific applications. Among the various welding parameters, welding current and welding speed have significant effects on bead geometry and mechanical properties. Kamlesh Kumar et al. [9] in their work studied the influence of welding current on mechanical properties of TIG welded Aluminium 1050 sheets and stated that with increase in welding current from 110 A to 150 A the fusion zone width was increased from 4.93 mm to 9.216 mm and also penetration width increased from 0.815 mm to 3 mm. Increase in welding current also had considerable effects on microstructure. Columnar dendrites were observed in the fusion zone (FZ), while heat affected zone (HAZ) contained both equiaxed and columnar dendrites. Sridhar et al. [10] conducted submerged arc welding by varying welding current on AISI 304 austenitic stainless steel and stated that with the increase in welding current, depth of penetration, penetration area and bead overlap area were enhanced. Kalinga Simant Bal et al. [11] carried out electron beam welding in joining Hastelloy C-276 and authors stated that interaction volume of the substrate with beam increased with increase in accelerating voltage which resulted in increase in melt zone area.

From the above literatures, it can be understood that Hastelloy C-276 is one of the suitable candidate for the oil and gas industry. Welding plays a crucial role in the fabrication of components used in oil and gas industries. It is also understood that only a few attempts are made in joining Hastelloy C-276. Even in those attempts, the properties didn’t meet the demands of the industries. Considering that, an attempt is made to identify the correct heat input that has to be supplied during welding process in order to get properties suitable for chemical, oil and gas industries.
2. Experimental Procedure
Butt joints were made on 1.6 mm thick Hastelloy C-276 sheets using the TIG welding machine which is shown in Fig. 1

![Figure 1.TIG welding setup.](image)

The composition of Hastelloy C-276 alloy is Ni-57, Co-2.5, Cr-15.5, Mo-16, W-4, Fe-5.5, Si-0.08, Mn-1, C-0.01, P-0.025.

TIG welding parameters and their ranges used for this work are presented in Table 1. Voltage was kept constant and the welding current was varied in the steps of 1 Amp. The heat input was calculated using the following formula.

\[
\text{Heat input} = \text{current} \times \text{voltage} / \text{welding speed}
\]

| Sample No | Voltage (V) | Speed (mm/sec) | Welding Current (Amps) | Heat input (J/mm) |
|-----------|-------------|----------------|------------------------|-------------------|
| 1.        | 4.1         | 1.23           | 42                     | 140               |
| 2.        | 4.1         | 0.97           | 43                     | 181.75            |
| 3.        | 4.1         | 0.71           | 44                     | 254.08            |

To prevent the weld zone (WZ) from contamination by environmental gases, Argon was used for shielding. SiC sandpapers were employed to polish and HCl + Oxalic powder in the fraction of 10:1 was used as an etchant to carry out the microstructural analysis. OLM Vision Measuring setup with a magnification of 5 X was utilized to capture the bead geometry. Field Emission Scanning Electron Microscope (FESEM) equipped with an Energy Dispersive Spectrometer (EDS) was used for capturing the high-resolution microstructure and the elemental composition of the weld. Vicker’s Microhardness Tester (Matsuzawa) was employed for determining the microhardness (HV) based on the standard ASTM E384-11. To determine the microhardness, the dwell time and load used were 10 seconds and 500 grams respectively. Tensile strength was investigated by using a load cell of 20kN and the test was conducted based on the standard ASTM A370-E8.
3. Results and Discussion

3.1. Macrostructure

The macrostructures of the welded samples were captured using OLM measuring setup with a magnification of 5X and are shown in Fig.2.

![Macrostructure Image](image1)

![Macrostructure Image](image2)

![Macrostructure Image](image3)

**Figure 2.** Macrostructure

| Sample No. | Bead width (mm) | Depth of Penetration (mm) |
|------------|-----------------|--------------------------|
| 1.         | 5.80            | 1.569                    |
| 2.         | 7.361           | 1.851                    |
| 3.         | 6.026           | 1.74                     |

The attributes of the bead geometry i.e., depth of penetration and bead width values are given in Table 2. The characteristics of a good quality weld are high depth of penetration and low bead width. Whereas in this case, it was observed that the sample 2 had the highest value of depth of penetration and bead width as well. Similarly, the sample 1 with the lowest depth of penetration value also has the least bead width. With increase in heat input from sample 1 to sample 2 both depth of penetration and bead width increased. For further increase in heat input in sample 3 the bead width and depth of penetration got reduced.

3.2. Microstructure

![Microstructure Image](image4)

![Microstructure Image](image5)

![Microstructure Image](image6)

**Figure 3.** Microstructure.
FESEM images of the welded samples are given in Fig. 3. In the sample 1, the microstructure was predominated by columnar dendrites with some defects (pores and blowholes), whereas in the sample 2 equiaxed dendrites were clearly visible and defects such as blow holes, pores were not present. Sample 3 contained columnar dendrites along with cellular grains in different regions. The weld had pores and blowholes (defects) similar to the first sample. The grain size was found to be similar in all the three welds. Cooling rate had a significant control over the grain size. It was observed that heat input of 181.75 J/mm resulted in favourable microstructure. This trend is similar to that observed in the work of Subhas Chandra Moi [12].

3.3. EDS (Energy-dispersive X-ray Spectroscopy).

Table 3. Comparison of mass percentage of the elements in the base metal and welds.

| Element | Base metal | Sample 1 | Sample 2 | Sample 3 |
|---------|------------|----------|----------|----------|
| Ni      | 51.75      | 53.01    | 51.07    | 48.83    |
| Mo      | 15.84      | 16.89    | 15.11    | 16       |
| Cr      | 18.95      | 17.47    | 18.08    | 17.41    |
| C       | 3.82       | 3.11     | 5.29     | 7.02     |
| W       | 3.65       | 2.95     | 3.26     | 3.64     |
| Fe      | 5.98       | 6.32     | 6.55     | -        |
| Mn      | -          | 0.06     | -        | 0.52     |
| S       | -          | -        | 0.65     | 0.21     |
| Co      | -          | 0.18     | -        | -        |
| Si      | -          | -        | -        | 0.20     |
| O       | -          | -        | -        | 6.17     |

EDS technique was utilized to study the elemental composition in the base metal and weld zone of all the three samples. The results obtained from EDS are tabulated in Table 3. Significant variations in the elemental compositions were observed in the weld zones on comparing with the base metal. In sample 1, the mass % of Ni increased by slightly more than 1%, whereas in sample 3, Ni mass % was reduced by about 3%. In Hastelloy C-276 Molybdenum (Mo) and Chromium (Cr) configuration plays a vital role in pitting and crevice corrosion. The percentage composition of Chromium in sample 2 was comparable to the base metal but decreased in the samples 1 and 3. Meanwhile, the percentage composition of Molybdenum in samples 1 and 3 was higher than that of base metal whereas it was similar to the base metal in sample 2. Thus, it is observed that sample 2 had the elemental composition which was almost similar to that of base metal.
3.4. XRD (X-Ray Diffraction)

![Figure 4. XRD.](image)

**Table 4.** Peak Intensity and FWHM values.

|                | Intensity (Counts) | FWHM    |
|----------------|--------------------|---------|
|                | γ (43.7°)          | M7C3 (50.8°) | γ (74.5°) |
| Base Metal     | 130969.54          | -       | 17964.05  |
| Sample 1       | 52668.57           | 60741.81| 25169.23  |
| Sample 2       | 48858.25           | 233544.97| 48822.25  |
| Sample 3       | 62968.49           | 82149.51| 23961.53  |
|                | FWHM               |         |
| γ (43.7°)      | M7C3 (50.8°)       | γ (74.5°) |
XRD analysis was performed on all the three samples along with the base metal. In Table 4, the values of peak intensity and FWHM (Full Width at Half Maximum) are tabulated. In all the three welded samples, similar phases were observed at 2θ values of 43.7°, 50.8° and 74.5° respectively. In base metal there were only two phases present at 43.7° and 50.8°. The peak intensities for γ phase (43.7°) of the base metal and the samples 1, 2 and 3, were found to be 130969.54, 52668.57, 48858.25 and 62968.49 respectively. Peak intensity for inter metallic phase M₇C₃ (50.8°) of samples 1, 2 and 3 were found to be 60741.81, 233544.97 and 82149.51 respectively. Similarly, the peak intensity values for γ phase (74.5°) of base metal and samples 1, 2 and 3 were 17964.05, 25169.23, 48822.25 and 23961.53 respectively. Thus it can be inferred that, in all the welding trials similar peak intensities were obtained with a little variation from that of base metal. For the base metal the highest peak was observed at γ phase (43.7°), whereas for the samples 1, 2 and 3 the highest peak intensity was observed at intermetallic phase M₇C₃ (50.8°).

FWHM values indicate the nature of grains. If the FWHM value is small, grains will be coarser whereas, if the FWHM value is large, the grains will be finer. From Table 6 it can be observed that, for γ phase (43.7°) of base metal the FWHM was high (0.5196) which resulted in finer grains and the lowest value (0.3385) was observed for sample 1 which contained coarser grains. For M₇C₃ (50.8°) intermetallic phase of sample 2, least value of FWHM (0.3385) was observed which resulted in coarser grains. Samples 1 and 3 had comparably higher value of FWHM (0.5077) owing to which finer grains were obtained. Whereas γ phase (74.5°) of samples 2 and 3 which contained coarser grains had FWHM value of about 0.4231; base metal and sample 1 with finer grains had FWHM values of about 0.5196 and 0.5077 respectively.

3.5. Microhardness

Microhardness measurement was carried out on both WZ and HAZ and the values are interpolated in Fig. 4. It was observed that for sample 1, the hardness value increased from WZ to HAZ. On the contrary, in the sample 2 the hardness value gradually decreased from WZ to HAZ. In the sample 3 the hardness value was almost same in both HAZ and WZ. In addition to this when hardness values were lower in WAZ and HAZ compared to that of base metal (191HV). There was no proper trend observed.
in variation of hardness among HAZ and WZ. With increase in heat input the hardness value first increased and was almost the same with further increment of heat input. Due to the presence of equiaxed grains, sample 2 had the highest hardness value among all the three samples. These variations in the hardness can be approved from the conclusions drawn from XRD analysis.

3.6. TENSILE STRENGTH

Tensile testing was carried out on Gas Arc welded Hastelloy C-276. The results of the tensile tests showed that the Ultimate tensile strength (UTS) tends to increase at first and then decrease as the welding current increases. Due to differences in thermal conductivity, fusion temperature and solubility of the materials, brittle phases can appear and deteriorate the tensile strength of the joint. The specimen welded with heat input of 181.75 J/mm (sample 2) attained the maximum tensile shear strength (400 MPa approx). With the increase in heat input the tensile strength and elongation percentage increases upto a threshold value, then it gets reduced. The reason for attaining maximum tensile strength is due to the presence of equiaxed grains and also due to the higher intensity of M7C3 phase which was observed from XRD analysis. Similar results were observed in Sarvanan et al. [13] work.

3.7. Fractography

Figure 6. Tensile strength for various specimen.

Figure 7. Fractography images of various samples.
In all the samples dimples were observed on the fractured specimen through which it was confirmed that ductile mode of fracture has occurred.

4. Conclusion
In this work, Hastelloy C-276 sheets were joined using TIG welding process and the following conclusions were made.

- Full penetration was achieved in two of the welds.
- Mid range heat input had higher bead width as well as higher depth of penetration.
- With increase in heat input the tensile strength and hardness increased up to a threshold value and then reduced.
- Elemental composition of the sample with heat input of 181.74 J/mm (sample 2) was almost similar to that of base metal. From the XRD results it was observed that, in all the samples only three phases were present.
- From the fractography results it was confirmed that ductile mode of fracture was observed in all the specimens.

5. References
[1] Manikandan M, Hari P R, Vishnu G, Arivarasu M, Devendeanath Ramkumar K, Arivazhagan N, Nageswara Rao M and Reddy G. M2014 Procedia. Mate. Sci. 5 2233-2341
[2] Sumitra Sharma, Ravindra V. Taiwade and Himanshu Vashishtha 2017 JMEPEG 26 1146–1157
[3] Chao Chen, Chenglei Fan, Xiaoyu Cai, Sanbao Lin, ZengLiu, Qingkai Fan and Chunli Yang2019 J. Manu. Proc. 46241-247
[4] Kalinga Simant Bal, Jyotsna Dutta Majumdar and Asimava Roy Choudhury 2018 Optics and Laser Tech. 108392-403
[5] Ashutosh Bagchi, S. Saravanan, G. Shanthos Kumar, G. Murugan and K. Raghukandan 2017 Optik 14 680-89
[6] M. Sathishkumar and M. Manikandan 2019 J. Manu. Proc. 459-21
[7] Vasareddy Mahidhar, K. R. Sampreet, Rajesh Kannan and T. Deepan Bharathi Kannan 2020Mater Tod: Proc 21 595-600
[8] Raja Subramanian, Balaji Natarajan, Balasubramanian Kaliyaperumal and Rajendran Chinnasamy https://doi.org/10.1088/2053-1591/ab093a
[9] Kamlesh Kumar, Prakash Mohan and Manoj Masanta 2018 Mater Tod: Proc 5 24141-24146
[10] P. V. S. Sridhar, Pankaj Biswas and Pakeswar Mahanta Mater Tod: Proc
[11] Kalinga Simant Bal, Jyotsna Dutta Majumdar and Asimava Roy Choudhury 2019 Optik- Int. J. Ligh and Elec. Opti 183 355-366
[12] Subhas Chandra Moi, Pradip Kumar Pal, Asish Bandyopadhyay and Ramesh Rudrapati 2019 J. Mech. Engi. 16 29-40
[13] S. Saravanan, N. Sivagurumanikandan and K. Raghukandan2019 Optik- Int. J. Ligh and Elec. Opti. 185 447-455