Effect of Pulsed Current Gas Tungsten Arc Process on the Dissimilar Weldments between Nickel-based Superalloy/Austenitic Stainless Steel

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The present work aims at investigating the microstructural and mechanical properties of dissimilar welds between Superalloy C-276 and Grade 321 austenitic stainless steel sheets, fabricated by pulsed current gas tungsten arc welding. The microstructural examination was carried out using an optical microscope and scanning electron microscope (SEM) equipped with energy dispersive spectroscopy. The weld metal microstructures divulged finer equiaxed grains. SEM images revealed migrated grain boundaries adjacent to weld line on both Superalloy C-276 and Grade 321. In addition, the presence of Mo-rich phases was also observed in the weld metal and at the weld interface of Superalloy C-276, which needs further investigation. Mechanical tests were carried out with respect to microhardness, tensile and impact properties. Furthermore, the presence of finer dendritic structure and controlled distribution of elements obtained with PCGTAW contributed for higher corrosion resistance of WM compared to BMs. The results of the present study would help in obtaining high quality dissimilar joints. Moreover, Grade 321 being a low-priced material as compared to Superalloy C-276 would be an economical substitution and would facilitate in saving huge material costs.

KEY WORDS: pulsed current gas tungsten arc welding; dissimilar welding; elemental segregation; topologically closed packed phases; passivation.

1. Introduction

Multi-material parts have been more acquainted and frequently used in various industrial applications with a motive to meet various property requirements as well as for economical reasons.1) Nickel-based superalloys plays an important role in the development of various industries such as chemical, petrochemical, aerospace and nuclear power plant etc. due to high corrosion resistance and high strength.2–4) Among the various nickel-based superalloys, the demand for Superalloy C-276 in the manufacturing of components used in petrochemical, power generation and nuclear industries are enormous.5,6) This is due to the presence of Cr, Mo and Fe as major alloying elements which contribute to high strength as well as high corrosion resistance at elevated temperature applications.7,8) Owing to the high price of Superalloy C-276, it is economically viable to substitute them with a comparatively low priced material. Stabilized grade 321 austenitic stainless steel (ASS) has been recently employed as a tubing material in steam gas reformers and would be an excellent choice to replace Superalloy C-276 under lower risk conditions.9,10) Therefore, it is necessary to investigate the dissimilar joint of Superalloy C-276 and Grade 321 and has not been studied till now.

The joining of dissimilar materials is quite challenging and is greatly affected by the choice of welding process as compared to similar welding materials.11) Gas tungsten arc welding (GTAW) associated with continuous current mode is considered to be one of the most widely used welding process to join dissimilar materials.12,13) However, due to lower cooling rate associated with conventional GTAW process, problems such solidification cracking, microfissuring, increased micro-segregation and precipitation of intermetallic compounds may arise which lead to immense decrease in mechanical as well as corrosion resistance of such dissimilar weldments.14–20) In addition, slower cooling rate associated with such conventional welding techniques also results in coarser columnar dendritic structure and acts as a favorable site for segregation of elements while solidification.21,22) Therefore, it is essential to improve the welding process in order to obtain better microstructural and mechanical properties. A lot of research conducted in the recent past has shown the beneficial aspects of pulsed mode of GTAW over conventional GTAW process. Pulsed current gas tungsten arc welding (PCGTAW) which involves higher cooling rate results in minimized elemental segregation and consequently higher mechanical properties.2,5,23) M. Manikandan et al.24) obtained refined microstructure, enhanced mechanical properties and reduced segregation in

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welds of Superalloy C-276 by switching over to PCGTAW. K. D. Ramkumar et al. investigated the dissimilar joints of Superalloy C-276/Ni–Cu alloy 400 and showed absence of grain coarsening in HAZ and enhanced ductility. K. D. Ramkumar et al. showed reduced elemental segregation in dissimilar joints of Grade 304 and Alloy 625 due to controlled heat input associated with PCGTAW as compared to conventional GTAW. K. D. Ramkumar et al. investigated bimetallic combination of Ni–Cu alloy 400 and Grade 904 L using ERNiCrMo-4 and ERNiCu-7 fillers for marine applications. They concluded that the best performance could be achieved by employing ERNiCu-7 filler in combination with PCGTAW. Arivarasu et al. suggested employing PCGTAW technique for dissimilar joining of 4 340 Alloy steel/Grade 304 L as it provides controlled heat input which reduces the width of HAZ and secondary phase formation. Furthermore, R. Neissi et al. evaluated the quality of dissimilar joints between 2205 duplex stainless steel (DSS) to Grade 316 L weldments by employing both pulsed and continuous current mode. They showed refinement in microstructure and reduced micro-segregation which subsequently improved mechanical and corrosion properties as compared to continuous current mode.

From the above literature, it was observed that switching over to pulsed current mode of GTAW process improves the quality of dissimilar joints and subsequently forms the basis of present investigation. Therefore, the present work aims at investigating the quality of dissimilar joints with respect to microstructural and mechanical properties. The outcome of the present study would facilitate industries in obtaining high quality dissimilar joints as well as at reducing material cost.

2. Materials and Method

In the present investigation, the base materials (BMs) procured were 6 mm thick plates of Superalloy C-276 and Grade 321. The solution annealing of both Superalloy C-276 and Grade 321 were carried out at 1 067°C (1 h) and 1 100°C (1 h), respectively, followed by water quenching.6,30) The filler wire ERNiCrMo-4 was used to fabricate the dissimilar joint. The chemical compositions of both BMs and filler wire used in the present study are given in Table 1. The BMs were then cut into a dimension of 100 mm × 100 mm × 6 mm using a wire-cut electrical discharge machine (EDM) for dissimilar joining of materials. Prior to welding, the dissimilar plates were machined to provide single V-groove butt-joint configuration (with root gap and size of 2 mm and 1 mm, respectively) and included angle of 80°. To ensure proper gripping and reduced tension during solidification, a jig fixture was used with copper backup plates and the inter-pass temperature was kept as 150°C, accordingly.22,14) PCGTAW was carried out in four passes using polarity as direct current electrode negative (DCEN) and the heat input for each pass was calculated using Eq. (1) (see Table 2).

\[ HI = \eta I V / s \] (1)

Where, \( \eta \) represents the efficiency (considered as 60%), \( V \) corresponds to the voltage (V), \( s \) corresponds to the welding speed (mm/sec) and I represents the average current \( (I_{avg}) \), calculated using Eq. (2).

\[ I_{avg} = (I_p + t_p I_p) / (t_p + t_b) \] (2)

Where, \( I_p \) and \( t_p \) represents the peak current (A) and pulse current duration (ms), respectively. \( I_b \) and \( t_b \) represents the background current (A) and background current duration (ms), respectively.

After welding, a transverse section of weld (size 50 mm × 10 mm × 6 mm) was cut from the centre of dissimilar welded plate for microstructural characterization after electrochemical etching at 5 V for 25 s in chromic acid solution (100 cc H₂O + 10 g CrO₃) using Potentiostat (Solartron-1285). The microstructures were characterized using an optical microscope (Zeiss “AxioLab A1”) and scanning electron microscope (JEOL “6380 A”) equipped with energy dispersive spectroscopy (EDS) to evaluate the amount of segregation. Microhardness test in both horizontal and perpendicular direction of welding was carried out with a force of 4.90 N for a dwell period of 20 s (Simadzu

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**Table 1.** Chemical composition (wt.%) of base and filler materials.

| Materials     | Mo   | Cr   | W    | Co   | Mn   | Fe   | Si   | V    | Ti   | C  | Ni |
|---------------|------|------|------|------|------|------|------|------|------|----|----|
| C-276         | 16.36| 15.83| 3.45 | 0.05 | 0.41 | 6.06 | 0.02 | 0.17 | 0.005| Bal.|    |
| Grade 321     | 18.63|      |      |      |      |      |      |      |      | 0.33| 0.029| 10.61|
| ERNiCrMo-4    | 17.00| 16.50| 4.50 | 2.50 | 1.0  | 7.0  | 0.08 | 0.02 | 0.02 | Bal.|    |

**Table 2.** Process parameters employed in PCGTAW.

| No. of Pass | Current (A) | Voltage (V) | Pulse time (ms) | Frequency (Hz) | Speed (mm sec⁻¹) | Cumulative heat input (kJ mm⁻³) |
|-------------|-------------|-------------|-----------------|----------------|------------------|-------------------------------|
| Root        | Peak current \( (I_p) \) | Base current \( (I_b) \) | \( T_p \) | \( T_b \) |                  |                               |
| Filling pass 1 | 150          | 80          | 14              | 0.4            | 4                | 1.66                          |
| Filling pass 2 | 150          | 80          | 14              | 0.4            | 4                | 1.66                          |
| Cap         | 150          | 80          | 14              | 0.4            | 4                | 1.66                          |

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Microhardness tester) by microhardness tester (following ASTM E92-82 standard). Potentiodynamic polarization test to evaluate the corrosion behaviour of BMs and weld metal (WM) was carried out in a 0.5 M H₂SO₄ + 0.01 M NH₄SCN solution potentiostat “Solartron-1 285” according to in accordance with ASTM-G:5-94 standards. The test was carried out in a conventional three electrode cell using saturated calomel electrode as reference electrode, platinum as an auxiliary electrode. The working electrode was prepared from both BMs and WM. The sweep potential for anodic polarization was kept within the range of −0.5 V to 1.5 V at a scan rate of 1 mVs⁻¹.

3. Results and Discussion

3.1. Macrostructure Examination

Macrostructure examination was carried out on the dissimilar weldment of Superalloy C-276 and Grade 321 by employing PCGTAW and the macrograph is shown in Fig. 1. Improper choice of filler material and welding parameters often results in problems such as cracking, lack of fusion, penetration, pores and undercuts. However, no such defects were observed in the present investigation, which confirms that the selection of both filler materials as ERNiCrMo-4 and welding parameters were adequate to produce defect free dissimilar joint employing PCGTAW.

3.2. Optical Examination of Weldment

The optical microstructures containing various regions of dissimilar welded Superalloy C-276/Grade 321 is shown in Fig. 2.

3.2.1. Weld Metal Microstructures

Figure 2(a) showed that the WM predominantly consisted of fine equiaxed dendritic morphology (marked as (i) in Fig. 1). The WM microstructure has a prominent influence on the mechanical properties and hot cracking susceptibility of welded joints. In general, the appearance of equiaxed dendritic structure in conventional GTAW is considered to be difficult due to the remelting of heterogeneous nuclei/growth lies ahead of the solid-liquid (S-L) interface. This happened due to the higher temperatures prevailing in the liquid, thus making the survival of the nuclei intricate. Therefore, in conventional fusion welding methods, the WM mostly exhibits coarser columnar dendritic structure during solidification and hence results in inferior corrosion resistance, mechanical properties as well as higher susceptibility to solidification cracking. However, the reduced temperature gradients due to arc pulsation promote constitutional supercooling in shorter duration and consequently resulted in finer equiaxed morphology and thus improved properties.

3.2.2. Interfacial Microstructures

Microstructural examination at the weld interface region illustrated a clear defined weld line and epitaxial growth (perpendicular to fusion line moving towards WM) on both Grade 321 and Superalloy C-276 side as shown in Figs. 2(b) and 2(c). The reason for the occurrence of epitaxial growth could be due to the similarity in FCC crystal structure of both BMs and filler materials which might have favored this type of growth. The microstructure at the weld interface of Grade 321 showed presence of an unmixed zone (UMZ) close to the weld line (see Fig. 2(b)). This happens when the melting point of filler material (≈370°C) is similar or higher to that of BM (≈1400°C), only a small part of the BMs can be melted and no dilution occurs in the re-solidification stage; which results in the formation of UMZ between the two zones (marked as (ii) in Fig. 1). Moreover, the existence of δ-ferrite stringers was also observed at the HAZ, which has a beneficial effect of minimizing grain growth and decreasing propensity to HAZ liquidation cracking. On the other hand, interfacial microstructures showed slight presence of a partially melted zone (PMZ) characterized by grain boundary melting and thickening (marked as (iii) in Fig. 1). In addition, few grains had undergone grain coarsening in the HAZ due to heating cycles associated with different passes during welding as shown in Fig. 2(c).

3.3. SEM/EDS Examination of PCGTA Weldment

The extent of segregation occurred during solidification often results in the formation of deleterious intermetallic compounds which significantly affects the mechanical properties and corrosion resistance of joints. As discussed before (section 1 and 3.2.1), it has been reported in the literature that coarser dendritic structure associated with conventional GTAW results in high degree of segregation and are more prone to hot cracking phenomenon as compared to equiaxed dendritic structure. Therefore, SEM-EDS point analysis was carried out on the different regions in order to evaluate the severity of micro-segregation occurred within the PCGTA joints. The SEM image of WM confirmed the presence of finer equiaxed morphology as shown in Fig. 2(d). SEM images at the weld interface of both Grade 321 side and SuperalloyC-276side clearly revealed the existence of migrated grain boundaries (MGBs) as shown in Figs. 2(e) and 2(f). MGBs are commonly prevalent in fully austenitic welds or due to the reheating actions occurred during mul-

Fig. 1. Image showing macrograph of dissimilar welded Superalloy C-276 and Grade 321.
tipass welding. Further analysis indicated that both Mo and W segregated assertively (emerged as white in color) in the interdendritic region of both WM and at the interface of Superalloy C-276. This could be understood as both Mo and W have large radii as compared to other elements in the weld pool, resulting in the segregation of secondary phases at the terminal stage of solidification as shown in Figs. 2(g) and 2(h). However, the precipitation of harmful deleterious tetragonal closed packed phases (TCP) such as sigma, P and \( \mu \) were found to be totally absent due to controlled heat input and proper choice of filler material as confirmed by SEM-EDS analysis. The complete elimination of harmful secondary phase(s) in Superalloys\(^8\)\(^,\)\(^24\) and dissimilar combination of 4340 Alloy steel/Grade 304 L\(^28\) was also reported on switching over from conventional GTAW to PCGTAW. The reason for this could be explained in terms of the theory of distribution coefficient \( (k) \) which was applied to quantify the propensity to micro-segregation of different alloying elements during cooling of the welds. Perricone and DuPont\(^40\) evaluated “\( k \)” values for different elements in various alloys based on the Ni–Cr–Mo system employing the equation:

\[
k = \frac{C_{\text{core}}}{C_0}
\]

Where, \( C_{\text{core}} \) is the alloying elemental level in the core of dendrite. \( C_0 \) is the alloying element level in the liquid. They observed that the value of “\( k \)” moves towards unity for both Mo and W on switching from conventional GTAW to PCGTAW and thereby reducing the extent of micro-segregation. The similar tendency in which the “\( k \)” values lesser than one signifies higher micro-segregation and could be completely avoided by employing PCGTAW was also reported by many other researchers and the same phenomenon was believed to have occurred in the present study also.\(^8\),\(^41\)–\(^43\)

3.4. Mechanical Characterization
3.4.1. Microhardness Testing

Figure 3(a) showed the results of the microhardness test carried out in a plane perpendicular to the direction of welding. The microhardness curve showed an increasing trend in hardness when moving from Grade 321 BM (BM-1) to Superalloy C-276 BM (BM-2). The difference in chemical
composition between the BMs might be the reason for such variation in hardness. The average hardness value at the WM (255.5 HV) was found to be greater than the Grade 321 BM and 321 HAZ while it was observed to be lower than Superalloy C-276 HAZ and Superalloy C-276 BM. The rapid solidification due to PCGTAW resulted in enhanced undercooling (reduced the nucleation rate) which ended up in refined equiaxed dendritic structure (as compared to coarser structure associated with conventional GTAW process) and consequently increased the hardness. In addition, a sudden increase in hardness value was observed at the weld line (marked as fusion line-2 in Fig. 3(a)) on Superalloy C-276 side. The presence partially melted grains might have contributed for such sudden rise in hardness value. Figure 3(b) showed the vertical plot of microhardness taken out in each welding pass. The results revealed that among four passes, the maximum average hardness value was obtained at the root pass. This happened due to the higher cooling rate prevailing at the root pass by using Cu backup plates during welding. This subsequently resulted in finer dendritic structure at the root pass compared to other passes and enhanced hardness.

3.4.2. Impact Test

Figures 4(a) and 4(b) showed the images of the impact tested specimens before and after failure. The images revealed that the specimen had undergone sufficient notch deformation and did not break rapidly. The impact value was coming out to be 210 J. The reason for such enhancement in impact values could be attributed to the fully austenitic structure which results in improved toughness of welds. Moreover, the presence of finer equiaxed dendritic structure could also be the reason as they accommodate more contraction strains during solidification, therefore are more ductile as compared to columnar dendritic structure associated with conventional GTAW process. Furthermore, the SEM fractograph revealed ductile fracture consisted of micro-voids, finer dimple size along with tearing ridges as depicted in Fig. 4(c).

3.4.3. Tensile Test

Tensile test was carried out to evaluate the ultimate tensile strength (TS) of the dissimilar welded joint and also to predict the mode of failure. The TS of the pulsed current welded joint was found to be (579 MPa) which was higher than the Grade 321 BM (i.e. weaker parent metal). Therefore, the tensile specimen fractured in the BM of Grade 321 which is in agreement with the hardness plot such that Grade 321 BM experienced lower hardness as compared to other regions. As the fracture took place in the BM, it would be inconclusive to comment on the presence of finer equiaxed dendritic structure in case of tensile strength of dissimilar joints. However, the presence of finer equiaxed dendritic morphology might have increased the restraint of the FZ as compared to the Grade 321 BM. The fractured surface of the tensile specimen was characterized using SEM to determine the mode of failure. The fractograph showed the presence of micro/macro-voids and dimples confirming ductile mode of failure as shown in Fig. 4(d). The occurrence of macro-voids depicted that the specimen had absorbed sufficient energy before getting fractured, which also assured the absence of deleterious phases in the weldments.

3.5. Corrosion Test

The corrosion resistance of both the BMs and WM were
evaluated by performing potentiodynamic polarization test as shown in Fig. 5. Along with H₂SO₄, an acidified ammonium thiocyanate (NH₄SCN) was also added in the solution to simulate a moderately oxidizing medium in which the active to passive transition of the candidate materials could be easily studied. The polarization plots showed a wide range of passivation for both WM and Superalloy C-276 and this could be attributed to the presence of Mo and W in the matrix. However, the value of Eₚit was found to be lower for WM as compared to Superalloy C-276 BM. The lower Eₚit value of the WM could be attributed to the formation of secondary Mo-rich phases which led to the depletion of Mo and Cr in the matrix (as reported in section 3.3). These Mo and Cr depleted regions consequently acts as an anodic site for the pit formations (Fig. 6) and was found to be comparatively insignificant compared to conventional GTAW process which results in higher degree of segregation and hence reduced corrosion resistance. Moreover, the passivation behaviour in the anodic branch of polarization curve for Grade 321 BM could be attributed to the presence of higher content of Cr (compared to Superalloy C-276 and filler wire).

Although, Grade 321 being a cost-effective (lesser alloyed) material compared to Superalloy C-276, its anodic branch had shown considerable passivation behaviour. Therefore, the selection of Grade 321 in combination with PCGTAW process would be an economical substitution for Superalloy C-276 in industrial applications.

4. Conclusions

(1) Sound weld of Superalloy C-276 and Grade 321 could be obtained by employing multi-pass PCGTAW using ERNiCrMo-4 filler wire.

(2) Welds made by employing PCGTAW showed finer equiaxed dendritic structure in the WM. The existence of an UMZ along with δ-ferrite stringers was observed at the weld interface on Grade 321 side. Moreover, PMZ was also observed at the weld interface of Superalloy C-276.

(3) SEM images witnessed the presence of MGBs at the weld interface of both Superalloy C-276 and Grade 321 side. EDS point analysis results showed that some secondary phase formation had occurred in WM and at the weld interface of Superalloy C-276. However, no such formation of deleterious TCP phases was observed due to controlled heat input associated with PCGTAW.

(4) Tensile fracture occurred at the Grade321 BM, which clearly showed that the WM possessed sufficient strength, irrespective of the presence of secondary phases. Furthermore, the results of both the tensile and impact test confirmed ductile mode of failure.

(5) Polarization results showed that the WM displayed greater corrosion resistance as compared to BMs which could be attributed to the presence of finer dendritic structure and controlled distribution of alloying elements. Based on the present work, it is very much advised to utilize PCGTAW along with ERNiCrMo-4 filler wire to fabricate high quality dissimilar joint of SuperalloyC-276/Grade 321 with enhanced mechanical properties. In addition, Grade 321 being an economical grade would help in saving huge material costs.

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REFERENCES

1) J. Verma, R. V. Taiwade, R. K. Khatirkar, S. G. Sapate and A. D. Gaikwad: Trans. Indian Inst. Met., 70 (2017), No. 1, 225, DOI: 10.1007/s12666-016-0878-8.
2) D. Bhattacharyya, J. Davis, M. Drew, R. P. Harrison and L. Edwards: Mater. Charact., 105 (2015), 118.
3) V. A. Ventrella, J. R. Berretta and W. de Rossi: Phys. Procedia, 39 (2012), 569.
4) K. K. Mehta, P. Mukhopadhyay, R. K. Mandal and A. K. Singh: Metall. Mater. Trans. A, 45A (2014), 3493.
5) Y. Ma, Y. Xu, S. Zhang and C. Lu: Adv. Mater. Res., 941-944 (2014), 1483.
