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Microsegregation Studies on Pulsed Current Gas Tungsten Arc Welding of Alloy C-276

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Abstract— Alloy C-276 prone to the formation of Topologically Closed Phases (TCP) at the end of the solidification. The formation of the TCP phases is known to the elemental segregation of Mo and W at the end of the solidification. The present research investigated the possibility of suppressing the elemental segregation by employing current pulsing technique. The weldment was fabricated by Pulsed Current Gas Tungsten Arc (PCGTA) Welding mode. The weld joint was studied with respect to microstructure, microsegregation and mechanical properties. Optical and Scanning electron microscopy were employed to study the microstructural changes in the fusion zone. The extent of microsegregation was studied by Energy-Dispersive Spectroscopy (EDS). Tensile test and bend tests were carried out to evaluate the strength and ductility of the weld joint. The results showed that refined microstructure with narrow Heat Affected Zone (HAZ). Energy-Dispersive Spectroscopy analysis showed that reduced Microsegregation. The tensile results showed that 20 % improved strength compared to the base metal. Bend test didn't result in any cracking.

.**Index Terms**— Alloy C-276, Pulsed Current Gas Tungsten Arc Welding, Microstructure, Scanning Electron Microscope, Segregation, Tensile test, Impact test

1 INTRODUCTION

Alloy C-276 is a single-phase Ni-based superalloy derived from Ni-Cr-Mo ternary system. It is a solid solution strengthening; there is no precipitation hardening operating in this alloy [1]. It offers excellent resistance to localized corrosion in both oxidizing and reduction environment. Alloy C-276 widely used in chemical processing and allied industries due to its higher resistance to corrosion [2]. Because of its resistance to corrosion in sea water especially under crevice corrosion conditions the alloy offers wide range of application in naval / marine environment. This environment induces attacks in other commonly used materials such as 316 stainless steel, MONEL alloy 400, and INCONEL alloy 625 [3]. Due to its excellent resistance to a wide spectrum of corrosive environments and superior mechanical properties, the alloy finds application in a variety of industries – nuclear sector, chemical processing, aerospace, marine engineering etc. [4], [5]. Welding of this alloy is carried out using GTAW as well as GMAW methods. Many researchers carried out welding on the alloy C-276 and concluded the formation of TCP phases such as P and μ at the end of the solidification. These phases are generally brittle in nature. For example, "Ahmed et al. [4]" studied the effect of microstructure and hardness studies of the electron beam welded zone of Hastelloy C-276 and concluded that the formation of μ phase was observed in the fusion zone after a tempering treatment at 950 ^{o}C. A study by "Guangyi et al. [6]" indicated that the laser welding using current pulsing resulted in absence of segregation as compared to other arc welding process and also observed that no macrosegregation was noticed in the weld joint.

"Cieslak et al. [7]" carried out arc welding studies on alloys C-4, C-22 and C-276. All these grades are highly corrosion resistant Ni-base alloys derived from Ni-Cr-Mo ternary system. The author found that elemental segregation occurs during welding, leading to the formation of brittle TCP phases P and μ in alloys C-22 and C-276. The authors reported that the alloy C-276 shows the highest susceptibility to hot cracking among the three alloys. They established that weld metal hot cracks are associated with inter-metallic secondary solidification constituents P and μ. "Hashim et al. [2]" studied the improvement of wear resistance of Hastelloy C-276 through laser surface melting. The authors inferred that the cooling rate was found to be more influential than the thermal gradient in determining the micro-structural features and it was also noticed that the laser treatment resulted in the absence of elemental segregation or new phase formation. "Manikandan et al. [8]" studied the continuous Nd: YAG laser welding of alloy C-276 and showed the reduced segregation with improved mechanical property. The core issue associated with the alloy C-276 is the formation of the secondary phases such as P and μ due to extend of micro segregation. In this context, the pulsed current gas tungsten arc welding (PCGTAW) has shown some improvement. For example, "Farahani et al. [9]" studied the weld joints produced in superalloy 617; they concluded that PCGTAW resulted in finer grain size in fusion zone and superior mechanical properties of weld joints compared to continuous current GTAW. "Janakiram et al. [10]" studies the effect of pulsing on weldments produced in superalloy 718; their finding was that pulsing brought down the severity of microsegregation with consequent reduction in the amount of Laves phase formed in the fusion zone during cooling. "Janakiram et al. [10]" reported refinement of microstructure in fusion zone and improvement in mechanical properties of weld joints when current pulsing was done. "Manikandan et al. [11]" compared the quality of weldments produced by GTAW and PCGTAW in superalloy 718 and concluded that pulsed current mode achieved maximum instantaneous cooling rate with consequent reduction in the amount of deleterious Laves

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phase in the fusion zone. The earlier attempts by the authors on the welding of alloy C-276 by autogenous PCGTA carried out with the non-optimized weld parameters yielded low strength compared to the present study and is reported elsewhere [12]. The process parameters were optimized by design of experiment and ANOVA technique [13]. In the present the study the weld joint of alloy C-276 was fabricated by autogenous PCGTAW process. It is proposed to examine in detail the effect of pulsing on the microsegregation in the weld zone. Metallurgical and mechanical evaluation of weldments produced by PCGTA shall be carried out using different characterization methods and will be documented.

2. Experimental Procedure

2.1 Material and Welding Procedure.

The base metal for this study was alloy C-276 nickel based super alloy. Alloy C-276 was procured in the form of hot rolled plate and was in solution annealed condition. The chemical composition of the base metal is listed in Table 1.

Table 1 Chemical Compostion of Base Metal Alloy C-276

Chemical Composition (% Wt.)								
Ni	Mo	Cr	W	Co	Mn	Fe	V	Others
Bal	16.36	15.83	3.45	0.05	0.41	6.06	0.17	0.005(P) 0.002(S) 0.02(Si) 0.005(C)

The material was cut into plates with dimensions 4 x 70 x 220 mm for carrying out welding trials. A square butt join was prepared. The welding was carried out manually by KEMPII DWE TIG welding machine. The welding parameters were presented in the Table 2.

Table 2 Process Parameter for PCGTA welding

Pulse Current (A)	165
Background Current (A)	77
% on time	60
Pulse frequency (Hz)	5

Other details related to the process and a procedure used in the present study includes the type and size of the non consumable for the joint investigated in this study. Thoriated tungsten electrodes (2.4 mm in diameter) were used to carry out the welding process. Argon was used as the shielding gas; the flow rate was 15 L/min, Polarity- DCEN. A special welding jig fixture is designed and fabricated with copper back plate so as to hold parts in alignment and to ensure that there is proper gripping and no bending during welding. After welding, the weld joint was cooled down to room temperature

2.2 Metallography Examination

To examine the microstructure and macrostructure of the weld joint, the specimens were machined out from the weld joint by EDM process. Figure 1 shows the photograph of the weld joint made by PCGTA autogenous mode of welding process. The microstructure and macrostructure specimens were mounted by molding epoxy, polished by SiC paper from 320 to 2000 grades, followed by 0.3 µm Al2O3 power and water. The etchant used to reveal the microstructure was made of 80 ml HCl, 4 ml HNO_3, 1 gm $CuCl_2$, and 20 ml glycerol. The macroexamination carried out in the cross sections of the weld joint were captured with the help of image analyzing software coupled with a Mac scope –Z macroscope fitted with WAT 202 D camera at a magnification of 1.25 X to facility the cross section area of the weld joint. The microstructure of different zone of interest like base metal, HAZ and fusion zone were viewed and captured with a CarelZesis optical microscope coupled with an image analyzing software

2.3 Tensile Test

Tensile coupons were cut with axis perpendicular to weld line and test was carried out as per ASTM: E8/E8M-13a.Universal testing machine (Instron make Model 8801) was used with a cross head velocity of 2 mm/min. Tensile tests were done in triplicate to check the reproducibility of the test results.

2.4 Bend Test

Bend test was carried out on the specimens which were cut into transverse section i.e. perpendicular to the weld direction 152 × 38 × 4 mm (ASTM E190-92(2008)). The test was carried out using a universal tensile test machine (UTM) by fixing the plunger (16 mm dia) and shoulders in the UTM machine. The load was applied continuously on the root of the weld joint up to the maximum bending angle of 180 degrees.

3. Results and Discussion

3.1 Macro Examination

The photograph of weld joint is shown in (Fig. 1) and the macrostructure is shown in (Fig. 2). The macrograph conform that the welding was carried out in two passes in both side in order to obtain the adequate penetration of the weld joint.

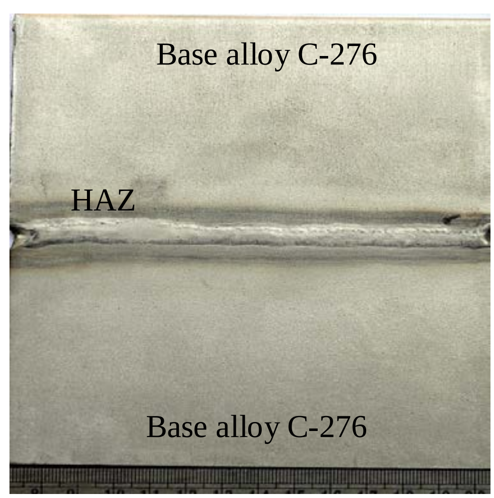

Fig. 1 Photograph of weld joint produced by Autogenous PCGTA

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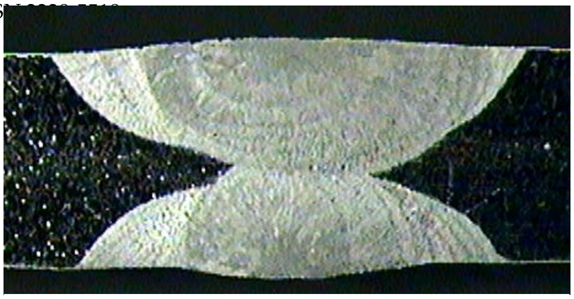

Fig. 2 Macrostructure of Autogenous PCGTA Weld joint Magnification: 1.25

The macrograph also indicatessteady fluid flow in the weld pool and good weld pool morphology and there is no problem of lack of penetration. The macrograph conform that the defect free welding was obtained in the fusion zone and HAZ. Improper selection of weld consumables and non-optimal choice of heat input during welding can cause problems of cracking in fusion zone/HAZ in Ni-Cr- Mo alloys [14]. No such cracking was noticed in the present study indicating that the parameter adopted to carry out the welding was optimal.

3.2 Microstructure Examination

3.2.1 Base Metal Microstructure

Figure 3 shows the microstructure of base metal and its annealing twins in as received condition. Alloy C-276 plates were normally solution treated at 1120 ^{o}C and rapid quenching in order to dissolve the precipitates. Therefore, annealing twins clearly existed in the base metal microstructure. The twin boundaries can prevent the dislocations movement during the deformation; they will have good effect on the strength of cubic materials [9], [10], [11], [12], [13], [14], [15].

Fig.3 Microstructure of alloy C-276 in as received condition.

3.2.2 Fusion Zone Microstructure

Figure 4 shows the microstructure of weld joint from weld interface to weld centre produced by PCGTA autogenous. Figure 4a represents the micrograph of weld interface. No grain coarsening was noticed in the HAZ region. It is believed that the controlled/reduced heat input associated with PCGTA leads to reduced grain coarsening of HAZ next to the fusion boundary. Near to the fusion boundary competitive growth was observed in fig 4b. During weld metal solidification grains tend to grow in the direction perpendicular to weld pool boundary of the maximum temperature gradient and hence maximum heat extraction. In general, face centered cubic (fcc) or body centered cubic (bcc) crystal structure the easy growth direction is <100>. The columnar dendrites or cells within each grains tend to grown in the easy growth direction perpendicular to the weld pool boundary will grow more easily and crowd out those less favorably orientation grains [16]. Figure 4b represents the fusion zone microstructure next to the weld interface and close to the weld centre. The micrograph shows the dominant in the columnar dendrite structure with few cellular structures. Figure 4c represents the micrograph of the weld center. The microstructure shows the equiaxed dendrite structures. The occurrence of cellular structure in the weld interior and columnar dendrites close to the fusion boundary can be explained on the basis of prevailing thermal gradient. Thermal gradients in a weld pool are steeper at regions close to fusion boundary than in weld interior [17]. The steep thermal gradients prevailing at the fusion boundary favor columnar dendritic growth in a direction opposite to that of heat extraction [10]. Towards the weld centre, however, the thermal gradients are not as steep, which in combination with the very rapid cooling rates lead to the formation of fine equiaxed dendrites.

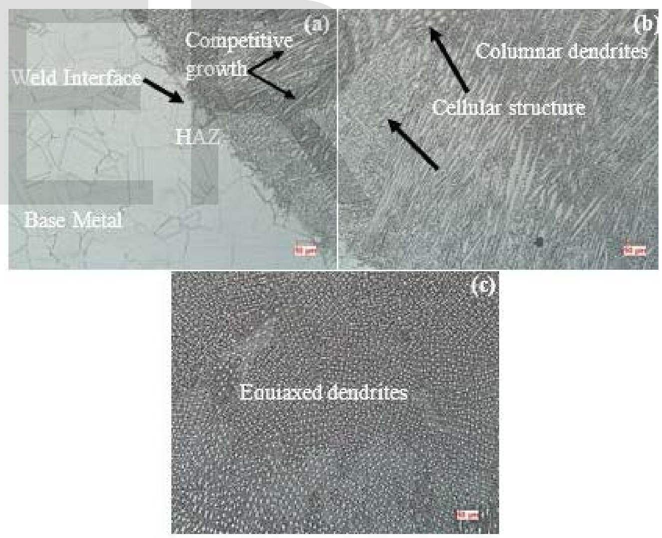

Fig. 4 Microstructure of alloy C-276. (a) Weld interface, (b) fusion boundary and (c) weld center

3.2.3 SEM/EDAX Analysis

SEM/EDAX point analysis was carried out across the weldments. EDAX analyses were done on subgrain boundary and subgrain body of the weld centre and weld interface regions (Fig. 5). Table 3 is a compilation of Ni, Cr, Mo, Fe and W. The result shows that the weld subgrain boundaries are enriched with the Mo and impoverished in Ni compared to the subgrain body (Fig. 5a&C). “Cieslak et al. [7]” reported that the segregation of Mo and W leads to the formation of intermetallic phases in the alloy C-276.

Table 3 Elements levels in different zones of autogenous PCGTAW joints, determined by EDAX
.

Zone	Ni	Cr	Mo	W	Fe
Weld subgrain boundary	50.09	16.50	23.99	3.89	5.52
Weld subgrain body	56.04	15.78	16.82	4.43	6.19
Weld interface-subgrain boundary	52.44	16.51	21.63	3.98	5.44
Weld interface-subgrain body	57.44	15.73	15.87	4.96	6.00

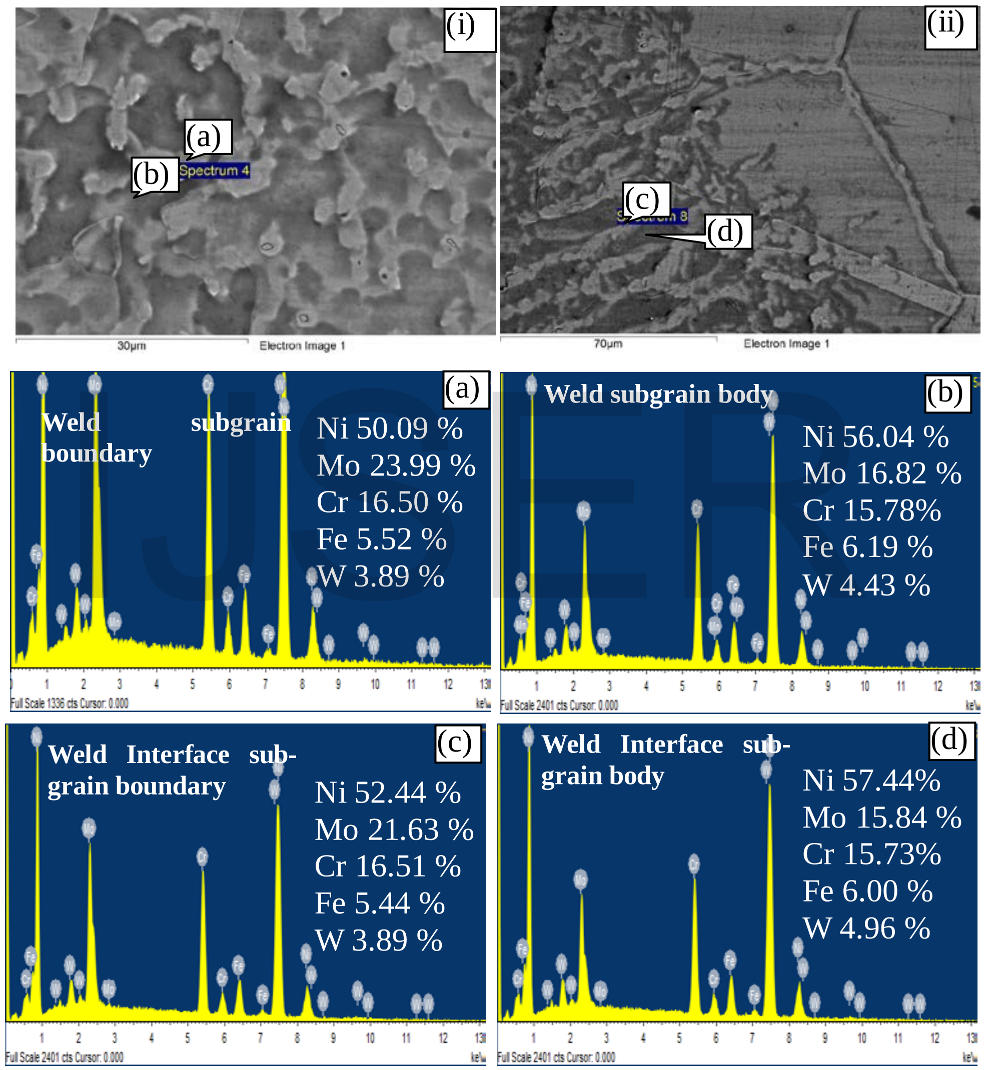

Fig. 5. SEM/EDAX analysis of autogenous PCGTA welded alloy C-276 for different region of the weldment. (i) SEM- Weld Centre; (ii) SEM-Weld Interface; (a) Weld sub-grain boundary; (b) Weld subgrain body; (c) Weld interface-subgrain boundary and (d) Weld interface-subgrain body.

The present result shows that the elemental segregation was found in the autogenous PCGTA welding process. The observed results were not matching with composition of P and μ phases reported by "Cieslak et al. [7]". The elemental segregation was suppressed in the present study compared to the other arc welding process. As reported by "Devendranath Ramkumar et al. [18]" PCGTA welding involves lower heat input and faster cooling rate and hence the Mo segregation becomes much lower and resulted in the fine microstructure in the fusion zone in the present study.

3.3 Mechanical Characterization

3.3.1 Tensile Test

Tensile test was carried out on the weldment fabricated by PCGTA mode. Figure 6 show the broken tensile failure samples. It was observed that tensile failure was occurred in the base metal region. The average tensile result was observed to be 780 MPa and ductility was found to be 60 %. The tensile result improved 20 % in received base metal of 750 MPa. The tensile result confirmed that the weld joints are stronger than the base metal. The tensile photograph clearly showed that the fracture occurred in the base metal. The ductility of the weld joint was also inline matching with the SEM fractrograph analysis. Figure 7 shows the SEM fractograph of tensile failure samples. The micrograph shows the presence of micro void coalescence, in line with the good ductility exhibited by the joints produced by PCGAT welding. Microstructure examination and EDS analysis also shows good agreement with tensile result. The coarser microstructure observed in the base metal leads to the tensile failure. The finer microstructure observed in the fusion zone shows the good strength and ductility of the weld joint in the present study.

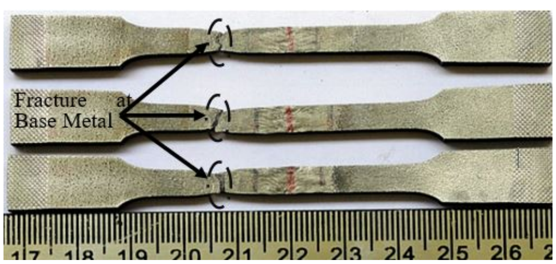

Fig. 6 Photographs of tensile failure specimens

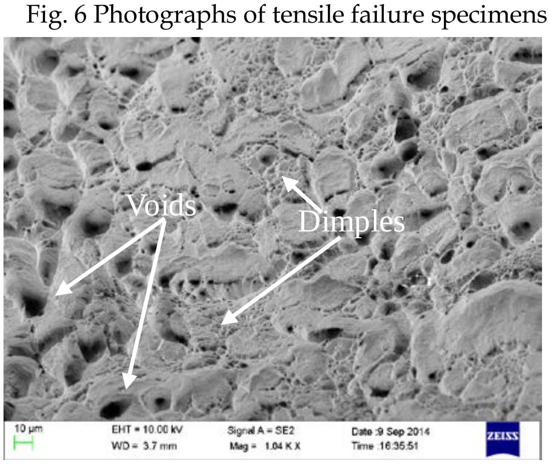

Fig. 7 SEM Fractograph of Tensile failure sample

3.3.2 Bend Test

Root Bend test was carried out to evaluate the ductility of the weld joint. Fig. 8 shows the photograph of bend test specimen. There was no cark noticed on the fusion zone. This confirmed that the ductility of the weld joint was good.

Fig. 8 Bend test specimen

4. Conclusion

This study reports the successful welding of autogenous PCGTA process. The major outcomes of the present study are given below:

1. Macrograph confirmed the defect free welding was obtained in pulsed current mode
2. Microstructure examination shows that refined microstructure were obtained in the fusion zone with narrow HAZ in the weld interface region. The controlled heat input along with faster cooling rate in the PCGTA welding leads to refined microstructure with narrow HAZ.
3. EDS analysis confirmed the absence of intermetallic phases in the fusion zone.
4. Tensile fracture occurred in the base metal. The result confirmed that the weld joint would have probably higher strength compared to the base metal
5. Bend test didn't show any crack in the surface of the fusion zone. This confirmed that the ductility of the weld joint was good

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Fig. 8 Bend test specimen