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The effect of post-weld heat treatment on microstructure and tensile properties of alloy C-276 welded joints fabricated by pulsed current gas tungsten arc welding

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Abstract

The Mo-rich TCP phases P and μ are susceptible to hot cracking in the alloy C-276. These phases can be reduced by quashing the microsegregation of alloying element Mo in the weldment. The present study investigates the possibility of reducing the microsegregation by post weld heat treatment of the weldments. The joints were fabricated by pulsed current gas tungsten arc welding by employing different filler wires ERNiCrMo-3 and ERNiCrMo-4. The weld joints were characterized with respect to microstructure, Scanning Electron Microscope (SEM), Energy Dispersive Spectroscopy (EDS), and tensile test. The optical microstructure revealed the fine equiaxed dendrites were observed in the fusion zone. EDS analysis revealed the presence of Mo-rich segregation in the subgrain boundary in the ERNiCrMo-3 and absence in the later. The results show that selection of temperature to dissolve Mo segregation is not sufficient in the case of ERNiCrMo-3. The tensile result shows the improved strength in both weldments compared to base metal.

Keywords: alloy C-276; microsegregation; post weld heat treatment.

1. Introduction

Alloy C-276 is a nickel based superalloy derived from Ni-Cr-Mo ternary system [1]. The alloying elements Cr and Mo act as a solid solution strengthener and also help to resist corrosion in a wide range of application [2]. Alloy C-276 is a workhorse material for power plant, naval / marine environment due to excellent corrosion resistance in sea water. Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) are widely used to fabricate alloy C-276 in the industrial scenario [3]. Many literatures reported that welding of alloy C-276 complicated with the formation of intermetallic phases (P and μ) at the end of the solidification [1-11]. The composition of P phases is 34%Ni, 40%Mo, 16%Cr, 7%W and 4%Fe (wt%) and μ phase is 33%Ni, 41%Mo, 15%Cr, 6%W and 4%Fe. Cieslak et al. [1] reported that segregation of Mo and W-rich alloying elements leads a formation of intermetallic phases P and μ at the end of the solidification. The authors also indicated that these phases tend to prone to hot cracking during the solidification process. The researcher stated that proper selection of welding process and consumables might avoid the extent of microsegregation [3]. Manikandan et al. [10] and Guangyi et al. [11] reported that laser welding in pulsed and continuous mode reduced the microsegregation compared to arc welding during solidification in the alloy C-276. The authors also indicated that reduced microsegregation improved overall mechanical properties of the weld joint. Ahmad et al. [7] also reported that there is no evidence of intermetallic phases during the electron beam welding process. Manikandan et al. [2,3] also reported that Pulsed Current Gas Tungsten Arc (PCGTAW) welding of alloy C-276 with matching

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filler and autogenous mode resulted in reduced microsegregation and improved mechanical properties compared to under alloyed filler wire. Kun Yu et al. [12] studied the effects of post weld heat treatment on microstructure and mechanical properties of laser welds in GH3535 superalloy. The authors found that tensile strength of the weld joint is improved compared to the base metal and as-welded condition. Devendranath Ramkumar et al. [13] also studied that effect of post weld heat treatment on microstructure and tensile properties of ATIG weld of Inconel X750. The authors reported that the joint efficiency of post weld heat treatment is improved compared to the as-welded condition.

There is no literature reported on Post Weld Heat Treatment (PWHT) of alloy C-276. The present study articulates the PWHT of alloy C-276 by employing two different filler wires (i) ERNiCrMo-3 & (ii) ERNiCrMo-4 to bring down the extent of microsegregation of alloying elements in the fusion zone. The comparative studies on two different filler wires on microstructure and mechanical properties are discussed. The results of the study would be highly informative and directly applicable to the end users working alloy C-276 weldment.

2. Experimental

Alloy C-276 was procured in the form of 4 mm thick hot rolled solution annealed condition in the shape of a plate. The major chemical composition of the as received plate and filler wires are listed in Table 1. Welding was carried out with ERNiCrMo-3 and ERNiCrMo-4 filler wire with the diameter of 1.6 mm.

Table 1. Chemical composition of base metal and filler wires.

Base Metal / Filler wire	% Chemical Composition					
	Ni	Mo	Cr	W	Fe	Nb
Alloy C-276	Bal	16.36	15.83	3.45	6.0	--
ERNiCrMo-3	Bal	10.0	22.0	---	1.0	4.5
ERNiCrMo-4	Bal	17.00	16.5	4.5	7.0	--

Table 2. Process Parameter for PCGTAW welding ERNiCrMo-3 and ERNiCrMo-4.

Pulse Current (A)	150
Background Current (A)	75
% on time	60
Pulse frequency (Hz)	5

The weld coupons were prepared by electrical discharge machining (EDM) process in the dimension of 4mm X 55 mm X 220 mm. The edges were thoroughly cleaned with acetone to remove the oil and other contaminants. The welding was carried out PCGTAW mode using ERNiCrMo-3 and ERNiCrMo-4 filler wires by KEMPPI DWE. The weld joints photographs are shown in Fig. 1. The process parameters employed in the present studies are listed in Table 2.

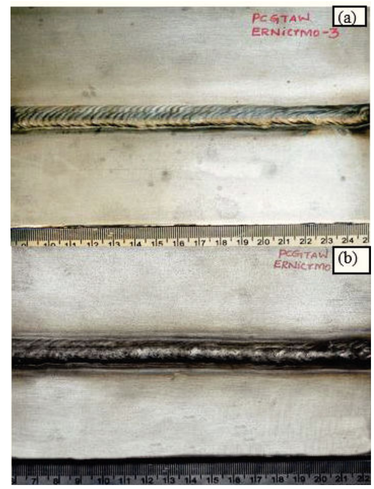

Fig. 1. Photographs of weld joints (a) ERNiCrMo-3 PCGTAW and (b) ERNiCrMo-4 PCGTAW.

Fig. 2 shows the macrograph of the weld joints. The weldments were exposed for a PWHT by direct aging at a temperature of 720 ºC, hold for 8h, furnace cool to 620 ºC, and hold for 8 hours, air cool until the temperature reached room temperature. Temperature has been selected based on early reports of the researcher for alloy 625 [15].

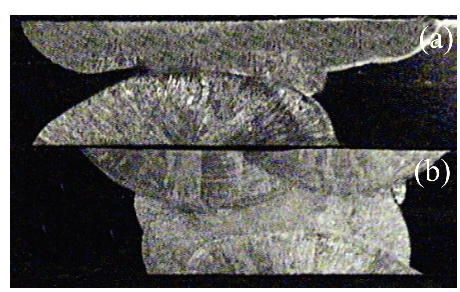

Fig. 2. Macrostructure of weld joints produced (a) ERNiCrMo-3 PCGTAW and (b) ERNiCrMo-4 PCGTAW.

Microstructure examination was carried out in the cross section of the weld joint consists of base metal, fusion zone and heat affected zone (HAZ). The standard metallographic procedure was adapted to polish the sample from 220 to 2000 grid SiC followed by followed by 0.5 μ alumina powder and water polish to achieved the fine finish. The microstructure was revealed by applying the etchant prepared in the mixture of 80 mL HCL, 4 mL HNO_3, 1 g $CuCl_2$, and 20 mL glycerol. The structural changes in the weldments were studied with the help of Optical and Scanning Electron Microscope (SEM). Microsegregation of alloying elements was examined with Energy Dispersive Spectroscopy (EDAX) analysis. Ni, Cr, Mo, W and Fe were given to emphasis. Tensile Strength of the weld joints was evaluated by a Universal testing machine (Instron make mode 8801) and a crosshead velocity of 2 mm/min was adopted for straining. The specimens were extracted as per ASTM E8/E-8M (subsize) standard. The tensile test was done in triplicate to ensure the repeatability of the test results.

3. Results and discussion

3.1. Macro examination

X-ray radiography and macrograph were done to evaluate the quality of the weld joints. Macrograph of weld joint produced by PCGTAW using ERNiCrMo-3 and ERNiCrMo-4 filler wire are shown in figure 2. There is no evidence in the presence of crack and lack of penetration in the weldments. In general, improper selection of welding consumables and process parameters leads to crack in the weldments [15]. The present study confirmed that selection of filler wire and process parameters are optimal.

3.2. Microstructure examination

Figures 3 and 4 show the optical microscope of PCGTAW welded alloy C-276 fabricated by ERNiCrMo-3 and ERNiCrMo-4 after the PWHT. The base metal microstructure consists of a well-defined austenitic structure with grain boundaries. Annealing twins can be seen in several grains. The plates were solution treated at 1120 ºC and rapidly quenched to room temperature in order to retain a single phase solid solution. In both cases, fusion zone consists of a fine equiaxed dendritic structure with austenitic phases in the center of the fusion zone (3a and 4a). The faster cooling rate attributed to PCGTAW welding leads to refined microstructure in the fusion zone. A similar observation was reported by Farahani et al. [16] for the alloy 617 PCGTAW. Fig. 3b and 4b represent the weld interface region of ERNiCrMo-3 and ERNiCrMo-4 filler wires. In the both cases, the microstructure is a change from columnar to fine equiaxed dendritic structure towards the weld center. It is believed to the thermal gradient. In the fusion zone, thermal gradients are steeper close to fusion boundary compared to weld interior [17]. The steep thermal gradients favor to columnar dendritic growth in a direction opposite to that of heat extraction. However, toward the weld center, the thermal gradients are not as steep which in a combination of rapid cooling leads fine cell structure/equiaxed dendrites in the PCGTAW.

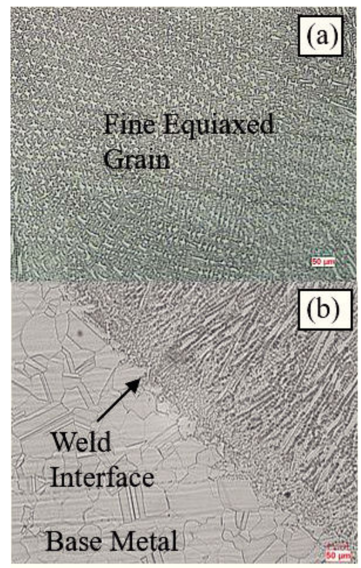

Fig. 3. Microstructure of ERNiCrMo-3 PCGTAW weld (a) weld center and (b) weld Interface.

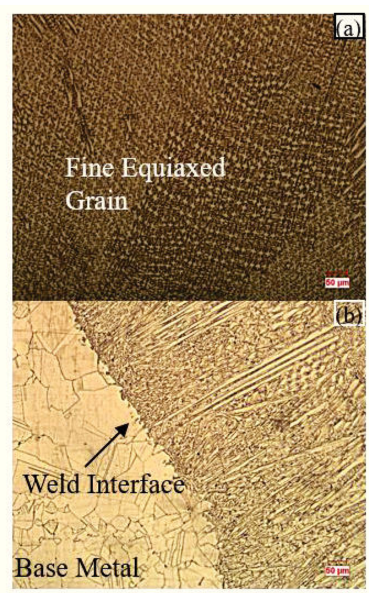

Fig. 4. Microstructure of ERNiCrMo-4 PCGTAW weld (a) weld center and (b) weld interface.

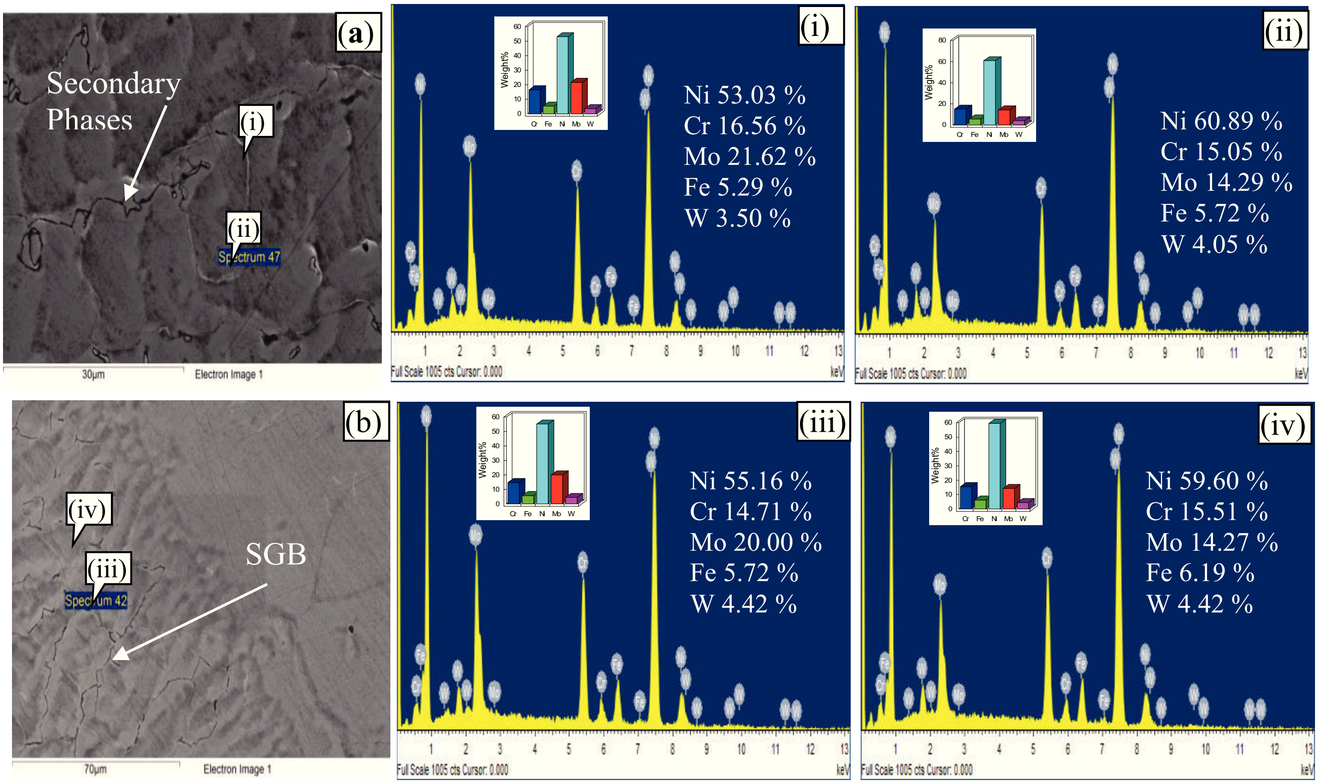

Fig. 5. SEM/EDS analysis of PWHT PCGTAW ERNiCrMo-3 (a) SEM – weld center; (b) SEM -weld Interface; (i) EDS analysis of weld center grain boundary; (ii) EDS analysis of weld center matrix; (iii) EDS analysis of weld interface grain boundary; (iv) EDS analysis of weld interface matrix.

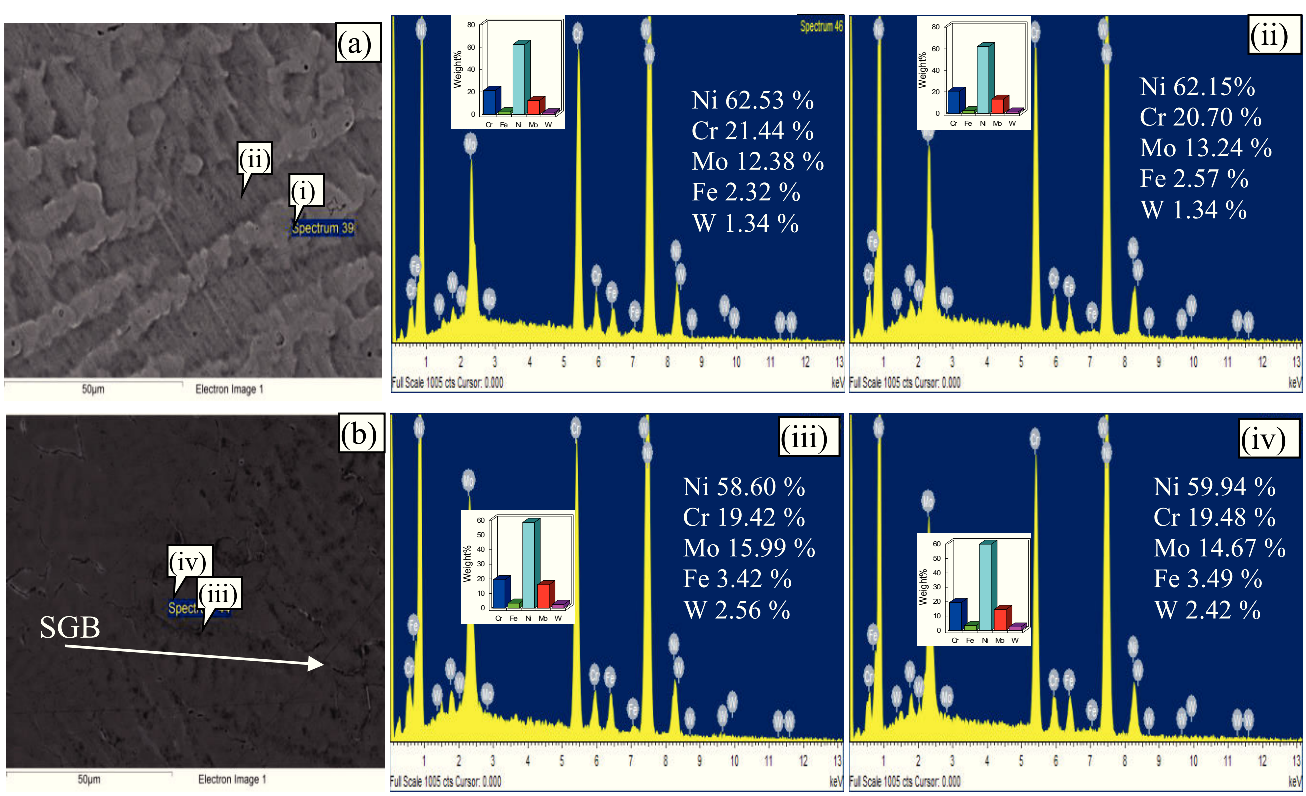

Fig. 6. SEM/EDS analysis of PWHT PCGTAW ERNiCrMo-4 (a) SEM – weld center; (b) SEM -weld Interface; (i) EDS analysis of weld center grain boundary; (ii) EDS analysis of weld center matrix; (iii) EDS analysis of weld interface grain boundary; (iv) EDS analysis of weld interface matrix.

3.3. SEM/EDS analysis

Figure 5 and 6 represented the SEM/EDS analysis of PWHT PCGTAW weldments. Figure 5a represents the higher magnification SEM micrograph of PWHT PCGTAW ERNiCrMo-3. It is noticed that secondary phases are precipitated (white color) in the weld grain boundary regions. Figure 6a shows the higher magnification SEM micrograph of ERNiCrMo-4 filler wire. In the fusion zone precipitates are absent. In both cases, weld interface regions revealed the presence of Solidification Grain Boundary (SGB). Figure 5(i-iv) represented the EDS analysis of PWHT PCGTAW ERNiCrMo-3. EDS analysis was carried out in subgrain boundary and matrix in both weld center and interface regions. Similarly, ERNiCrMo-4 is represented in Fig. 6(i-iv).EDS analysis was carried out to evaluate the microsegregation of Ni, Cr, Mo, W and Fe. These alloying elements are leads to the formation of P and μ phases during solidification. The early research carried out the same author represented the welding carried out by ERNiCrMo-3 shows the higher segregation of Mo in the subgrain boundary. In the present research, work aging was done to reduce the effect of microsegregation of alloying elements. The effect of microsegregation in ERNiCrMo-3 after heat treatment is represented in Fig. 5(i-iv). It is observed that the segregation of Mo in the subgrain boundary is noticed in the weld center and weld interface region. The similar observation is not noticed in the case of ERNiCrMo-4 filler wire. It is also well evident from the SEM micrograph the secondary phase precipitates are noticed in the subgrain boundary. It is well explained by the authors in his previous research work. Alloy C-276 has the nominal chemical composition Ni-16Cr-16Mo-5Fe-4W, whereas the nominal chemical composition of ERNiCrMo-3 is Ni-22Cr-10Mo-1Fe. In contrast, ERNiCrMo-4 filler wire is the base metal filler wire; the alloying elements are present at the same level as in the base metal. The segregation of Mo is also due to low diffusivity compared to other alloying elements in Nickel matrix. The higher segregation of Mo can be understood in terms of the larger difference of atomic radii of 9% compared to matrix element Ni. In the case of Cr and Fe, the difference is 1 %. The aging temperature was designed to dissolve the precipitation of Mo-rich intermetallic phases. However, the temperature is not high enough to dissolve the intermetallic phase in the present study. Similar observation was noticed in the alloy 625 by heat treatment on pulsed plasma arc deposition [15]. It is a witness from the present study the extent of microsegregation is not significantly altered from the as-welded condition for heat treatment temperature up to 720 ºC. El-Dasher et al. [18] reported that Mo-rich TCP phases in the Ni-based superalloy can be dissolved by heat treatment of about 1000 ºC.

3.4. Mechanical properties

3.4.1. Tensile test

Table 3 list the mechanical properties of PWHT of PCGTAW welded alloy C-276 using ERNiCrMo-3 and ERNiCrMo-4 weld metal.

Table 3. Cumulative mechanical properties of PCGTAW welded alloy C-276.

Type of Welding	UTS (MPa)	Average UTS (MPa)	Average % Elongation
Base Metal	750	750	75
PCGTAW	785		
ERNiCrMo-3	778	786	49.1
	795		
PCGTAW	824		
ERNiCrMo-4	812	813	60.08
	805		

Fig. 7 shows the tensile failure samples. Base metal strength and ductility also listed for comparison in table 3. The PCGTAW ERNiCrMo-4 shows 3 % improved ultimate tensile strength compared to ERNiCrMo-3 weld metal.

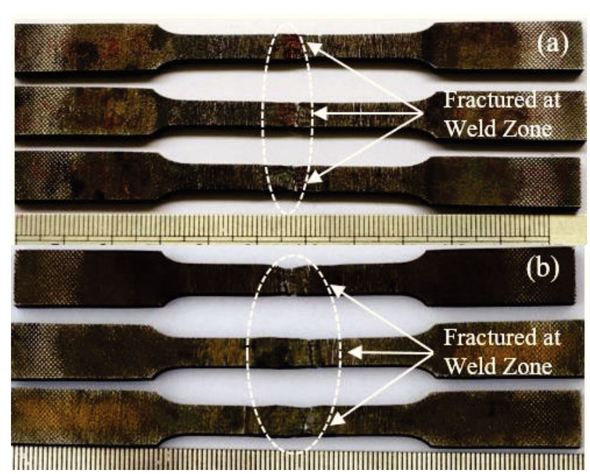

Fig. 7. Photographs of failed tensile test specimens (a) ERNiCrMo-3 PCGTAW weld and (b) ERNiCrMo-4 PCGTAW weld.

The PWHT improved 11.3 % tensile strength of ERNiCrMo-3 compared to the as weld condition reported by the same author in his earlier findings [2,3]. It is evident from the present study extent of the microsegregation (Mo) is reduced compared to the early findings [2,3]. During PWHT process the weldment hold for 720 ºC for 8 hours. The alloying elements like Fe, Cr are completely dissolved in the matrix, whereas molybdenum is not completely dissolved. The higher segregation of Mo in the subgrain boundary in ERNiCrMo-3 is largely responsible the lower tensile strength compared to other weldment. The formation of Mo-rich intermetallic phases is known to detrimental to weld mechanical property. A number of investigators have attributed the poor strength, ductility and fracture toughness in the Ni-Cr-Mo alloy during the welding process. The formation of Mo-rich intermetallic phases not only depletes the alloying elements in the matrix but also provides the favorable condition for crack initiation and propagation. Fig. 8 represents the SEM fractography of tensile failure.

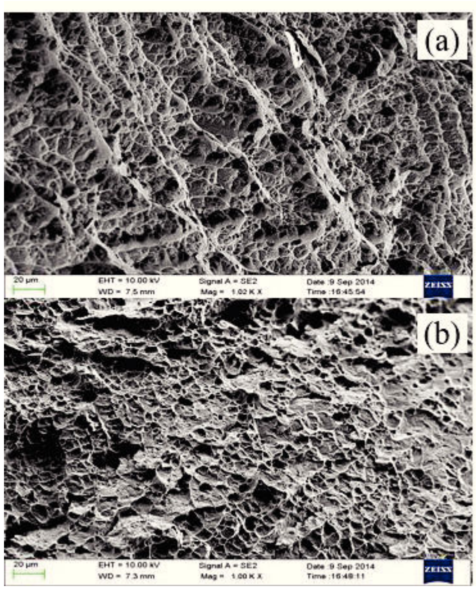

Fig. 8. Tensile Test SEM Fractograph (a) PCGTAW ERNiCrMo-3 weld and (b) PCGTAW ERNiCrMo-4 weld.

Figure 8a and 8b shows the SEM fractograph analysis of tensile failure samples. The fracture surface exhibit completely dimpled with microvoids. PCGTAW with ERNiCrMo-4 shows higher ductility compared to ERNiCrMo-3 filler wire. It is evident from the EDS observation the segregation of Mo-rich intermetallic phases is primarily responsible for the lower tensile ductile compared to other weldment. The formation of the Mo-rich intermetallic phases forms the complex crystal structure in the austenitic matrix and avoid the dislocation motion during the plastic deformation, and these phases make the favorable site for process fracture in the easier way by providing sites for excessive microvoid nucleation and propagation of macro voids leads to cracks along the interdendritic region resulting in lower tensile elongation [16]. The low diffusion rate of Mo during PWHT leads to extensive microsegregation in the interdendritic regions in ERNiCrMo-3 filler wire. Janaki Ram et al. [20] noticed the similar observations in the alloy 718 by continuous and pulsed current welding mode.

4. Conclusions

1. X-ray radiography and macroexamination confirmed that the defect free welding was achieved in the process parameters employed in the present study.
2. The fine equiaxed dendrites were achieved in the fusion zone of the both weldments.
3. SEM/EDS analysis revealed that segregation of Mo in the subgrain boundary is noticed in ERNiCrMo-3 filler wire. This indicates the temperature selected for the post-weld heat treatment is not sufficient to dissolve Mo.
4. The effect of post weld heat treatment with fine equiaxed microstructure improved the tensile strength of weldment compared to base metal.

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