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Improvement in stress rupture properties of inconel 718 gas tungsten arc welds using current pulsing

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Weld fusion zones in Inconel 718 are known to exhibit poor mechanical properties in relation to the base metal as a result of extensive interdendritic Nb segregation and consequent formation of Nb-rich, brittle, intermetallic Laves phase ($(Ni, Fe, Cr)_2$ (Nb, Mo, Ti)) during weld metal solidification, which depletes the matrix of useful alloying elements and aids in easy crack initiation and propagation [1, 2]. Post-weld solution treatments cannot be entirely relied upon in dealing with the Laves problem as dissolution of Laves phase to any significant extent is not possible without simultaneously causing undesirable grain coarsening in the base metal [3, 4]. Therefore, there is a need to control Nb segregation and Laves formation during welding itself.

In an effort to control Nb segregation and Laves formation in gas tungsten arc (GTA) welds, current pulsing technique was used. Autogenous, bead-on-plate, full-penetration GTA welds were produced using constant current (CC) and pulsed current (PC) in Inconel 718 cold-rolled sheets (2 mm thick) in 980 °C solution treated condition (welding parameters given in Table I). The welds were given the following heat treatments: (i) direct aging (DA) (720 °C/8 hr/furnace cool to 620 °C/8 hr/air cool); (ii) solution treatment at 980 °C/20 min/air cool followed by aging as above (STA). Weld microstructures were characterized using optical and scanning electron microscopes (SEM). Studies on Nb segregation were performed using electron probe microanalysis (EPMA). Stress rupture tests (temperature: 650 °C, stress: 690 MPa) were conducted following standard procedures on transverse specimens (gauge length four times gauge width).

The use of current pulsing resulted in significant refinement of the fusion zone solidification structure (Fig. 1), with consequent improvement in Laves morphology, i.e., finer, discrete particles in the PC weld against long chains of coarser interconnected particles in the CC weld (Fig. 2). Current pulsing also reduced the extent of Nb segregation during weld metal solidification, as evidenced by a higher dendrite core Nb concentration in the PC weld in relation in the CC weld (Table II). Image analysis on SEM pictures showed that the amount of Laves phase in the PC weld (8.0 ± 1.2 vol.%) was considerably lower when compared to the CC weld (14.2 ± 1.5 vol.%). DA treatment was found to produce no change in weld microstructure with regard to Laves phase and Nb segregation. Post-weld solution treatment resulted in partial dissolution of Laves phase and in precipitation of needle-like δ-phase (orthorhombic Ni_3Nb precipitate) around Laves particles (Fig. 3). The treatment also reduced Nb segregation to some extent, as evidenced by an increase

TABLE I Welding parameters

Constant current welding	
Current (A): 110	
Speed (mm/sec): 6	
Voltage (V): 18	
Pulsed current welding	
Peak current (A): 150	
Background current (A): 45	
Speed (mm/sec): 4	
Pulse frequency (Hz): 8	
Pulse on-time: 20% of cycle time	
Voltage (V): 18 V	

TABLE II Results of EPMA quantitative analysis (average of there measurement)

	Element (wt%)							
Sample	Ni	Cr	Fe	Nb	Mo	Ti	Al	Si
CC, as-weld, Laves	44.52	14.34	13.72	19.54	4.12	1.74	0.64	0.94
PC, as-weld, Laves	47.50	14.83	14.94	14.62	3.98	1.54	0.67	0.86
CC, as-weld, dendrite core	52.54	21.62	20.47	1.41	2.02	0.76	0.88	0.06
PC, as-weld, dendrite core	52.32	20.75	20.02	2.18	2.44	0.72	0.86	0.06
CC, STA, dendrite core	52.74	20.31	19.88	2.04	2.31	0.81	0.66	0.07
PC, STA, dendrite core	52.80	19.92	19.62	3.14	2.75	0.85	0.60	0.08
Base metal	53.00	18.20	18.95	5.08	3.13	0.97	0.51	0.12

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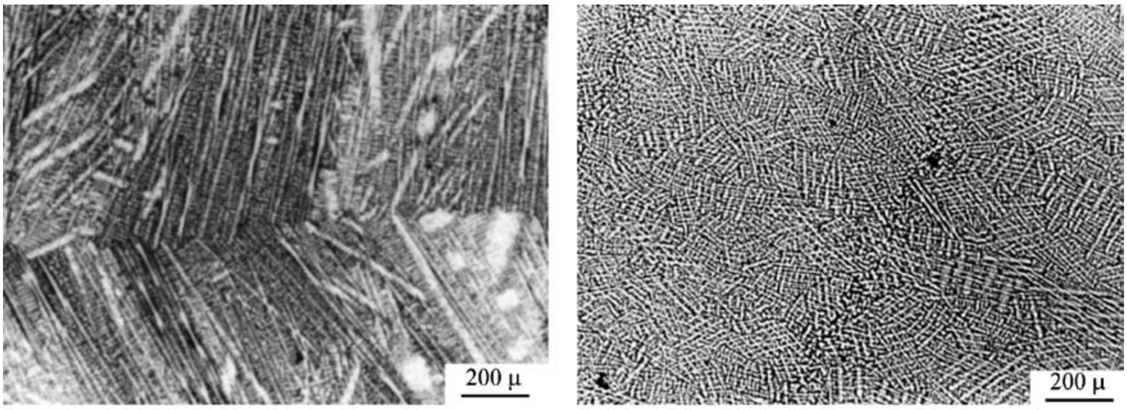
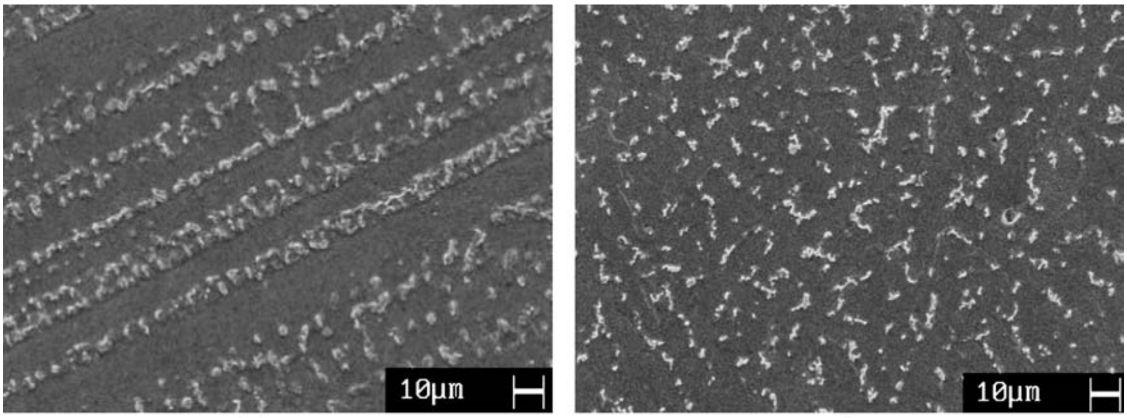


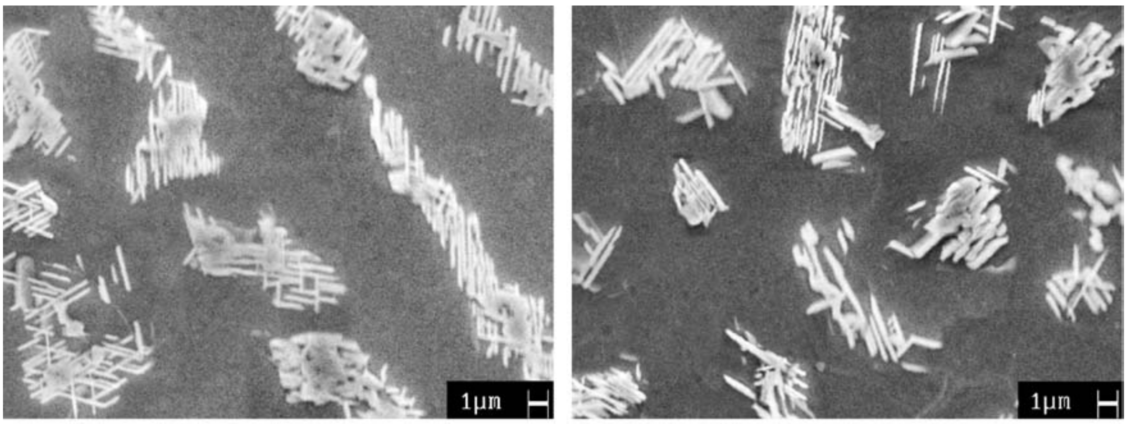
(a) (b)

Figure 1 Optical microstructures of as-weld fusion zones: (a) CC, (b) PC.



(a) (b)

Figure 2 SEM microstructures of as-weld fusion zones: (a) CC, (b) PC.



(a) (b)

Figure 3 SEM microstructures of STA weld fusion zones: (a) CC, (b) PC.

in dendrite core Nb concentrations after the treatment (Table II). While post-weld solution treatment did not eliminate Laves phase in both the welds, the extent of Laves dissolution appeared to be more in the PC weld (Fig. 3b), as also evidenced by a greater increase in dendrite core Nb concentration after solution treatment in the PC weld compared to the CC weld (Table II). More details on weld microstructures and the reasons for observed improvements due to current pulsing may be found elsewhere [5].

The results of stress rupture tests are given in Table III. All the weld specimens have failed in the weld metal. It may be seen that while rupture life and ductility of both the welds in both the heat treatment conditions are inferior in relation to the base metal, the PC weld properties are considerably higher in both the heat treatment conditions. The base metal exhibited typical intergranular fracture features with wedge-type cracks along the grain boundaries common in stress rupture failures (Fig. 4a). The CC welds showed (Fig. 4b and c) fracture along interdendritic regions with no signs of any plastic deformation. On the other hand, while the PC welds also exhibited interdendritic fracture features (Fig. 4d and e), the presence of dimples on certain regions of

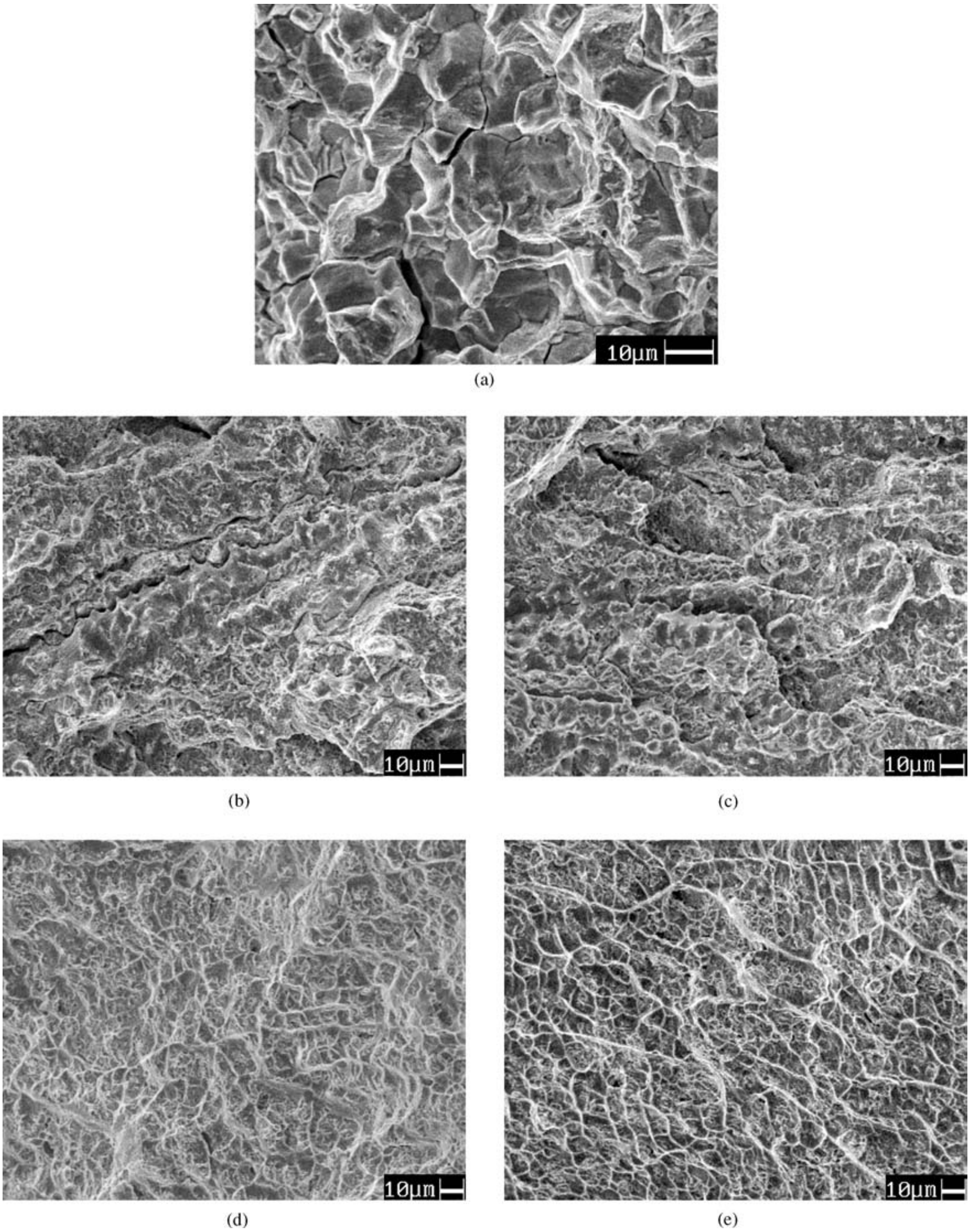


Figure 4 Stress rupture fracture surfaces: (a) Base metal, STA, (b) CC, DA, (c) CC, STA, (d) PC, DA, (e) PC, STA.

the fracture surfaces evidences considerable plastic deformation in the fracture process.

The low CC weld rupture life and ductility in DA condition is attributable to a large amount of interconnected Laves phase present in the weld microstructure. The brittle Laves particles aid in early initiation of cracks and provide a low energy fracture path. The detrimental role played by the Laves particles is evident on the weld fracture surface which showed fracture along chains of interconnected Laves particles with hardly any signs of plastic deformation. Further, it is expected that the weld metal would be weaker in relation to the base metal due to improper precipitation of strengthening phases γ'' (b.c.t. Ni_3Nb) and γ' ($Ni_3(Al,Ti)$) as a consequence of severe Nb segregation, which can also affect the rupture life.

TABLE III Results of stress rupture tests at 650 °C/690 Mpa (average of three tests)

Condition	Rupture life (h)	Rupture ductility (%)
Base metal, STA (transverse)	115	13
CC, DA	16	2
PC, DA	45	6
CC, STA	21	3
PC, STA	52	8

Use of current pulsing considerably improved the weld rupture properties. While both CC and PC welds exhibited interdendritic fracture features, the PC weld exhibited dimples, though some what coarser and shallower, on most of the fracture surface. This is attributable to the lower amount of Laves phase and its improved morphology (fine, discrete particles) in the PC weld, which present a less harmful situation to weld properties compared to a greater amount of highly interconnected coarser Laves phase in the CC weld. Also, the reduced segregation of Nb in the PC weld would automatically mean better precipitation of strengthening phases. The PC weld metal would thus be relatively stronger, which also contributes to the observed improvement in rupture life.

There is a slight improvement in properties in STA condition compared to DA condition in both the welds. The STA weld fracture surfaces also showed a greater evidence of plastic deformation in the fracture process. While this is attributable to partial Laves dissolution and some reduction in Nb segregation caused by solution treatment, it is believed that these effects would have resulted in even greater improvement in properties, had there been no δ-phase precipitation. The presence of needle-like δ-phase in excessive amounts was found to be detrimental for stress rupture properties in wrought alloy 718 [6]. It may be noted, however, that the property improvement due to current pulsing is greater than the property improvement due to post-weld solution treatment.

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References
1. W. J. MILLS, *Weld. J.* **63**(8) (1984) 237s.
2. C. RADHAKRISHNA and K. PRASAD RAO, *Materials at High Temperatures* **12**(4) (1994) 323.
3. *Idem.*, *J. Mater. Sci.* **32** (1997) 1.
4. G. D. JANAKI RAM, A. VENUGOPAL REDDY, K. PRASAD RAO and G. MADHUSUDHAN REDDY, Microstructural characterization of Inconel 718 GTA welds, communicated to Practical Metallography, March 2004.
5. *Idem.*, Control of Laves phase in Inconel 718 GTA welds through the use of current pulsing, accepted for publication, Science and Technology of Welding and Joining, September 2003.
6. W. CHEN and M. C. CHATURVEDI, *Acta Mater.* **45**(7) (1997) 2735.

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