Effect of Postweld Heat Treatment on Ductility of Ni-Co-Cr Based Alloy Welds

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Abstract

Properties of Gas Tungsten Arc weldments of a commercial, wrought alloy with nominal composition of 29Co-28Cr-2.75Si-Bal.Ni have been investigated. The weldments with a filler metal of matching chemistry are found to have a limited room temperature ductility in the as-welded condition. Metallographic evaluation revealed that the weld metal was characterized by a continuous eutectic phase, which was widely distributed along the dendrite microstructure. The eutectic phase is mainly consist of $(Si,Ti)_xNi_y$. Controlling welding parameters was not effective in improving the ductility of the weldments, whereas a proper Postweld Heat Treatment (PWHT) restored the ductility. The continuous eutectic phase in the as-welded deposit, which caused poor ductility of the weld metals, was considerably reduced or removed with a proper PWHT. The optimum PWHT "window" is proposed based on the experimental result.

Introduction

Increasing demands for industrial plants with higher efficiency proposed a new challenge in the materials engineering to come up with alloys which can meet more severe service condition, such as higher temperature, corrosive environment. This trend has led to a sharp increase in the use of high temperature alloys. For example, Ni-Co-Cr based superalloys have replaced the austenitic stainless steels for major components of various industrial boilers, incinerators.

Recently, a lot of industrial plants employed a new breed of burner, so called "low NO_x burner", which operated at higher temperature than the conventional one. This new design requires to re-place the austenitic stainless steels with the Ni-Co-Cr based alloys for the metallic components to withstand high temperature and corrosive environments of the fuel rich zone. The alloy is useful due to its combination of good high-temperature strength, thermal stability, high-temperature corrosion resistance against environments containing sulfur, chlorides and vandalism. Moreover, its excellent room temperature ductility provides superior fabricability.

Welding of this type of alloy, however, presented the same kind of problems as those frequently encountered in the welding of the austenitic stainless steels, such as solidification cracking, microfissuring.[1-3] The controlling factors responsible for the solidification cracking are both the chemical composition of the filler metals and the welding parameters. The solidification cracking of weldments, in principle, can be successfully

Superalloys 1996
Edited by R. D. Kissinger, D. J. Deye, D. L. Anton,
A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford
The Minerals, Metals & Materials Society, 1996

prevented by combination of the following two ways; selection of the filler metals with lower content of detrimental elements, such as P and S, and employment of low heat input and interpass temperature in the welding process.[1-6]

Another important issue in the welding of the alloy is degradation of the mechanical properties, such as drastic decrease of welds ductility in the as-welded condition.[1] The poor ductility resulted in a cracking during the guided bend test of the weldment, which has been attributed to the formation of a second phase with low melting temperature. The second phase, which was strongly affected by the segregation of alloying elements, are possibly minimized by a subsequent PWHT.[1]

In this study, therefore, the effects of PWHT on the properties of Gas Tungsten Arc (GTA) weldments of a commercial, wrought Ni-Co-Cr based alloy have been investigated focusing on the subsequent improvement in the mechanical properties of the weldments. The optimum condition of the PWHT, henceforth, is proposed for the application to the actual fabrication procedure, in which GTA welding of the alloy is required.

Experimental Procedure

Materials

The nominal chemical composition of the alloy and filler metal are shown in Table 1. Plate thickness was 6.4mm for bend test and tensile test, 12.7 mm for all-weld-metals tensile test. Matching filler metals are solid wires of 2.4mm diameter.

Welding & PWHT

Several batches of GTA weldments with different heat input were prepared. Microstructural examination of the weldments confirmed that neither fusion-zone solidification cracking nor microfissuring was encountered. GTA welding parameters are summarized in Table 2. For bend testing and tensile testing specimens, one side, flat position welding with a groove design of 60° single V with 4mm root gap was done, whereas a groove design of 20° single V with 12mm root gap with backing plate was used for all-weld-metal specimens.

Postweld heat treatment was carried out with a box furnace, monitoring temperature of the specimen surface with a K-type thermocouple attached on it. PWHT of the welds was conducted at the holding temperature in the range of 880℃ to 1095℃, followed by an air cooling.

Table 2. GTA Welding Parameters.

Current	115-140 A
Voltage	10-12 V
Heat Input	8.9-11.2 kJ/cm
Travel Speed	4.7-10.5 cm/min
Shielding Gas & Rate	Ar, 15 ℓ/min
Interpass Temperature	< 90 ℃

Table 1. Chemical Composition of Base Metal and Filler Metal (wt%).

	Ni	Co	Cr	Si	Mn	Ti	Fe	C	S	P
Base Metal	41.1	28.4	26.4	2.82	0.82	0.47	0.10	0.06	0.001	0.002
Filler Metal	39.4	28.7	27.5	2.81	0.71	0.49	0.10	0.06	0.001	0.002

Mechanical testing

Mechanical properties of the weldments were evaluated using an universal tensile tester with 100 ton capacity, and 2T guided bend tester (bending radius two times plate thickness). Before machining of the weldments to the final specimen configuration, specimens were heat treated for the specific PWHT conditions.

Microstructural evaluation

Representative samples of weldments having weld metal as well as the heat-affected zone were metallographically prepared to characterize micro-structural features. The specimens were polished through 0.05 ㎛ alumina and electroetched in a solution of (60㎖ HCl+35㎖ HNO_3+25㎖ Methanol) at 10~15V. Both an optical microscopy (for magnifications up to 500X) and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) were used for the examination. The SEM was also used to examine the fracture surfaces of tensile and bend test specimens. An electron probe microanalyzer (EPMA) was used for chemical analysis of different phases found in the SEM observations.

Results and Discussion

Mechanical properties

Results of tensile and bend tests on the as-welded GTA weldments are summarized in Table 3. All tensile test specimens were fractured at weld metal, and the bend testing of weldments yielded overall cracks in the weld metal regardless of their welding parameters. Tensile properties of the weldments obtained from the all-weld-metal specimens are compared with those of the base metal with solution-annealed conditions, as shown in Fig. 1. The tensile elongation is only 9% in the as-welded condition, whereas a fully solution-annealed alloy shows an elongation of 73%. This suggests a very brittle nature of the weld metal in the as-welded condition.

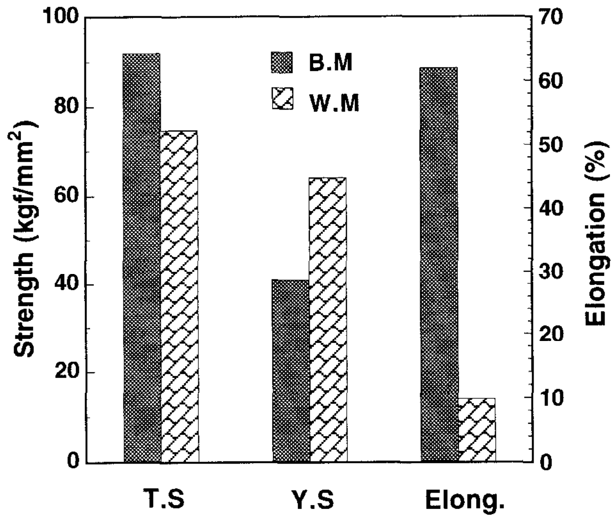

Fig. 1 Tensile properties of weld metal and base metal.

Table 3. Mechanical properties of the as-welded GTA weldments at RT.

Thickness (mm)	Tensile Strength[1)] (kgf/mm²)	Location of Rupture	2T Guided Bend Test[2)]	
6.4	74.4	Weld Metal	Face	Cracked
			Root	No Crack
12.7	69.4	Weld Metal	Side	Cracked

1) ASME SFA-5.11 (25.4mm gage length, 6.4mm dia.), for transverse tensile test.
2) ASME QW-462 (38W×240L×6.4ᵗmm)

In an attempt to improve the weld metal ductility, various welding conditions, such as heat input were applied. It was reported that lower heat input, as in the present study, resulted in faster cooling of the weld pool, which would suppress segregation of the alloying elements due to narrower interdendritic spacing.[8,9] However, the mechanical test result of the welds with different welding condition, as shown in Table 4, indicates that the weld metal still lacked a proper ductility, thus, resulting in cracks at the weld metals during the bend test. This suggests that controlling welding parameters alone cannot improve the ductility of the weld metal in the as-welded condition.

Microstructural Analysis

On the fracture surface of the bend test specimen in the as-welded condition shown in Fig. 2, a continuous, film like second-phase at the dendrite interface mixed with dimples was observed.

Metallographic evaluation of the interdendritic second-phase found on the fracture surface was carried out on the overetched, cross-sectional weld metal. SEM photos of the overetched weld metal's microstructure, as shown in Fig. 3(a) and (b), show a very aggressive "wetting" action of the liquid phase. In Fig. 3(b), the magnified view of the weld metal reveals that the weld metal can be characterized by a series of continuous eutectic phases with considerable liquation of the phase along with interdendritic boundaries. EDS analysis of the matrix and the eutectic phase, as shown in Fig. 3(c) and (d), respectively, strongly suggests that the eutectic phase is mainly consists of $(Si,Ti)_xNi_y$.

EPMA analysis of the eutectic phase, as shown in Fig. 4, confirms the EDS result that the eutectic phase was enriched with Si, Ti, Ni, C, as well as being depleted with Cr and Co. Therefore, rather brittle nature of the present, Ni-Co-Cr based weld metal in the as-welded condition could be originated by the formation of interdendritic eutectic phase of low melting temperature during solidification of the weld pool.

This type of eutectic phase with liquid film like nature can also promote the solidification cracking or microfissuring in the weld metal under highly stressed conditions.[10] Interdendritic micro-fissures of 30~80㎛ in length have been observed in the weldments deposited with high heat input in this study. In Fig. 5, the microfissuring is shown in the reheated zone of the weld, where the eutectic phase provided constitutional liquation reaction between the phase and matrix.[4,8,10]

Table 4. Bend test results with various welding heat Inputs.

Heat Input (kJ/cm)	Travel Speed (cm/min)	Interpass Temp. (℃)	Bend Test
8.9	10.5	< 90	Cracking
5	13.4	< 20	Cracking
10	7.3	< 185	Cracking

Fig. 2 Fracture surface of the bend test specimen.

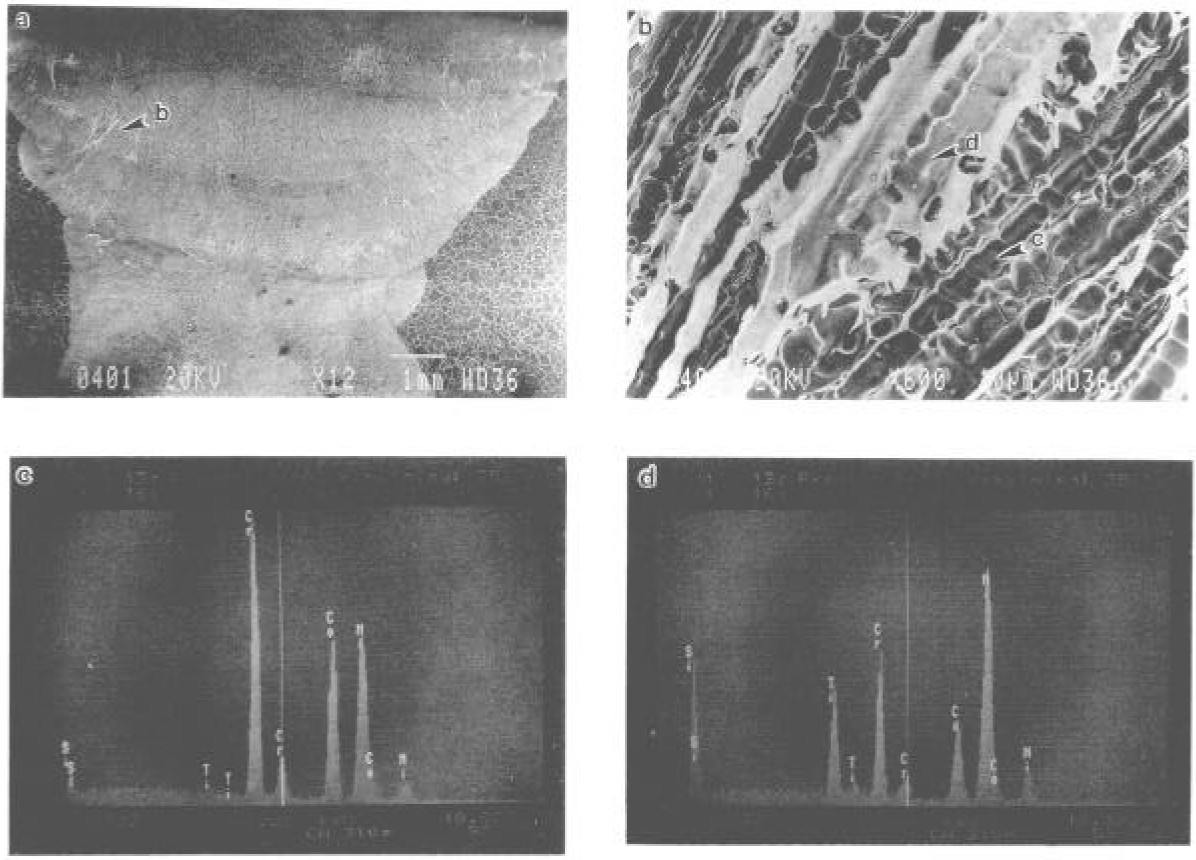

Fig. 3 (a), (b) SEM photos of the overetched weld metal's microstructure, (c), (d) EDS results of matrix and continuous eutectic phase, respectively.

PWHT

Based on the other reports that PWHT would enhance the ductility of the weld metal,[1] a proper condition for PWHT was investigated by varying holding temperature and time. To select proper range of PWHT temperature, previously reported transformation temperatures were reviewed from literatures.[1] The solution annealing temperature of the present Ni-Co-Cr based alloy is about 1100℃, whereas binary phase diagrams of Ni-Si and Ni-Ti suggested eutectic temperature of 1152℃ and 942 ℃, respectively.[1] Differential thermal analysis (DTA) on the weld metal, carried out previously by the authors, indicated the melting temperature of the eutectic phase was in the range of 940~1060℃.

These evaluations leaded to setting PWHT temperature of the weldments in the range of 880℃ to 1095℃. In Fig. 6, tensile properties of the all-weld-metals obtained before and after PWHT at 1095℃ for 1 hour are compared. PWHT has increased the room temperature elongation of the weld metal from 9% to about 44%. Fig. 6 also indicates that PWHT cause an increase in tensile strength as well as a decrease in yield strength of the weld metal.

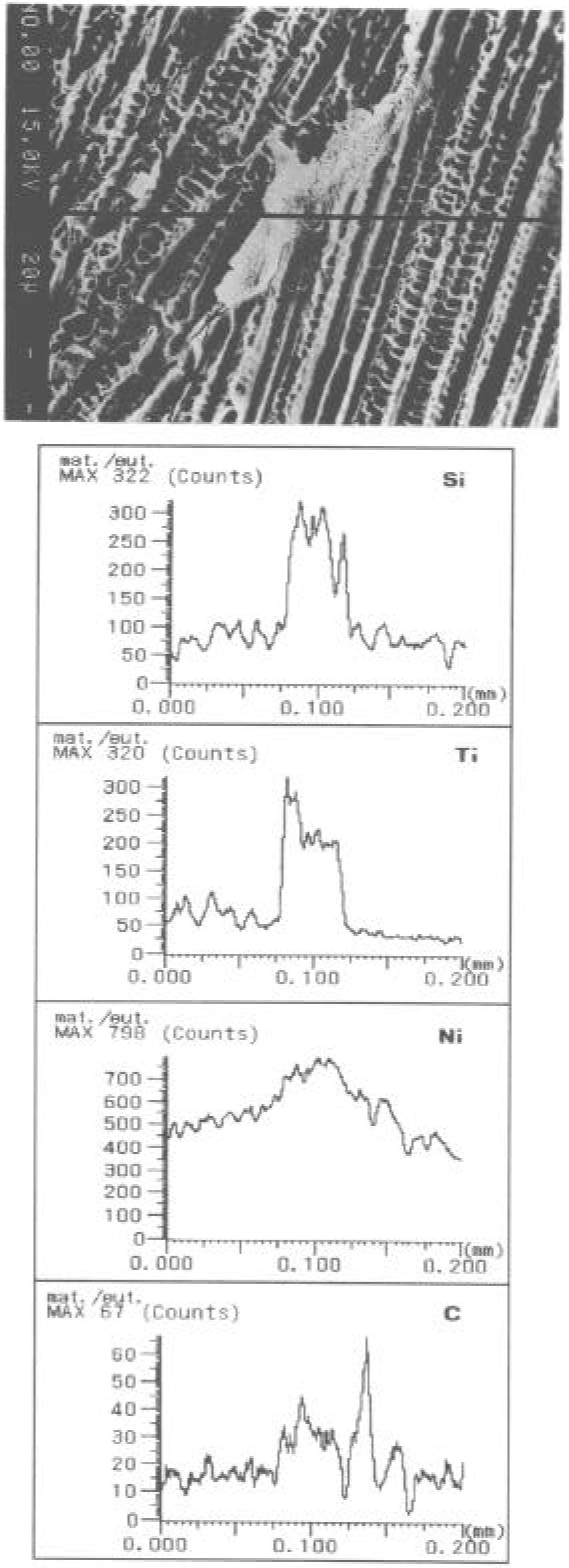

Fig. 4 SEM photos of the overetched weld metal's microstructure, and its EPMA results of line scanning of the eutectic phase.

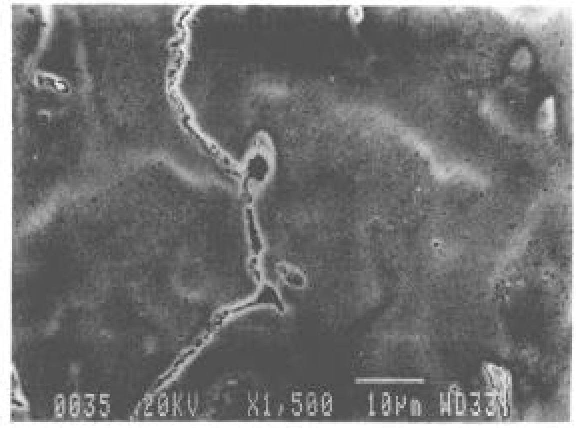

Fig. 5 Microfissuring in interpass region of weld metal.

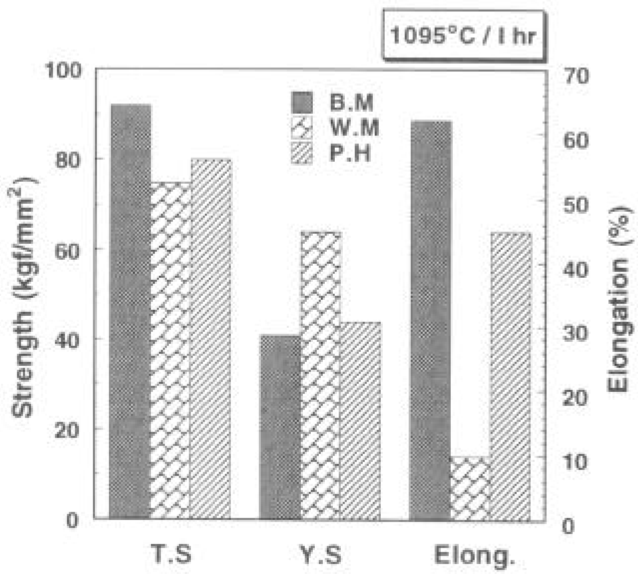

Fig. 6 Tensile properties of the as-welded and PWHT specimens.

A set of PWHT was also conducted for 1 hour at temperature in the range of 880℃ to 1095℃. In Fig. 7, the room temperature elongation of the weld metal is plotted as a function of PWHT condition. The elongation of the weld metal after PWHT is found to increase with PWHT temperature. Especially sharp increase in the elongation value after PWHT above 985℃ is quite noticeable.

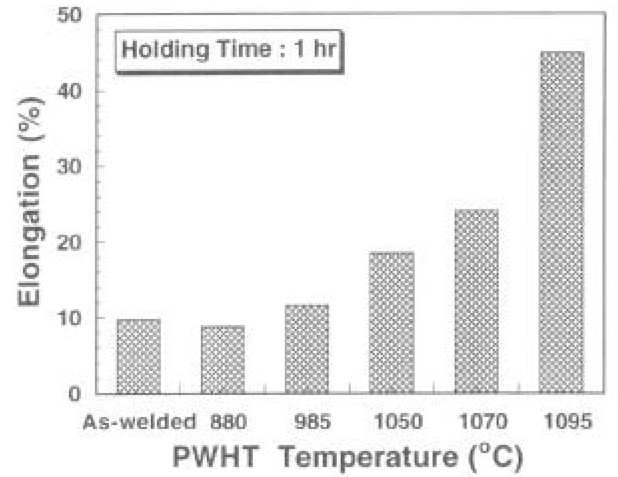

Fig. 7 Ductility change with various PWHT temperature (all-weld-metal tensile test).

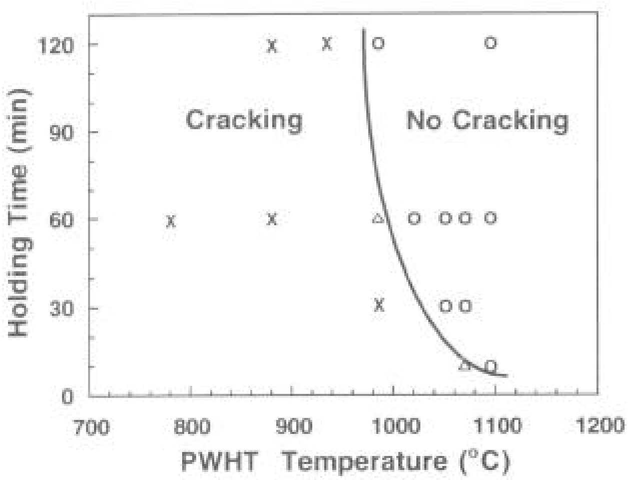

Fig. 8 2T guided bend test result with various PWHT conditions.

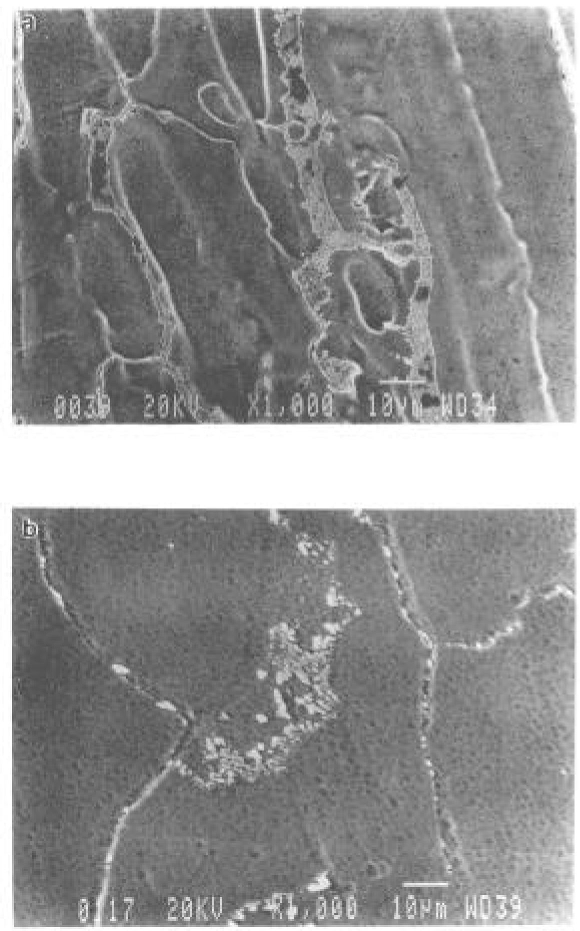

Fig. 9 SEM microstructure of weld metal in the as-welded (a) and PWHT (b) condition.

Bend test results obtained from the all-weld-metal specimens subjected to various PWHT conditions are plotted in Fig. 8, which indicates that higher temperature and longer time result in sounder weld metals without any crack during the bend test. Temperatures higher than 1200℃ should be avoided, however, due to the possibility of grain growth of the base metal and incipient melting. The melting range of the alloy is about 1225℃ to 1300℃ as determined by DTA. Lower temperature limit for the PWHT "window" is about 985℃, below which the longer holding time does not improve the weld metal ductility. Therefore, the optimum PWHT condition is 1050℃/1hr/AC, which enables the weld metal not to develope cracking during the bend test.

Microstructurally, the effect of PWHT is to break-up the continuous network of eutectic phase in the weld metal. SEM photos of the overetched weld metal observed before and after PWHT, as

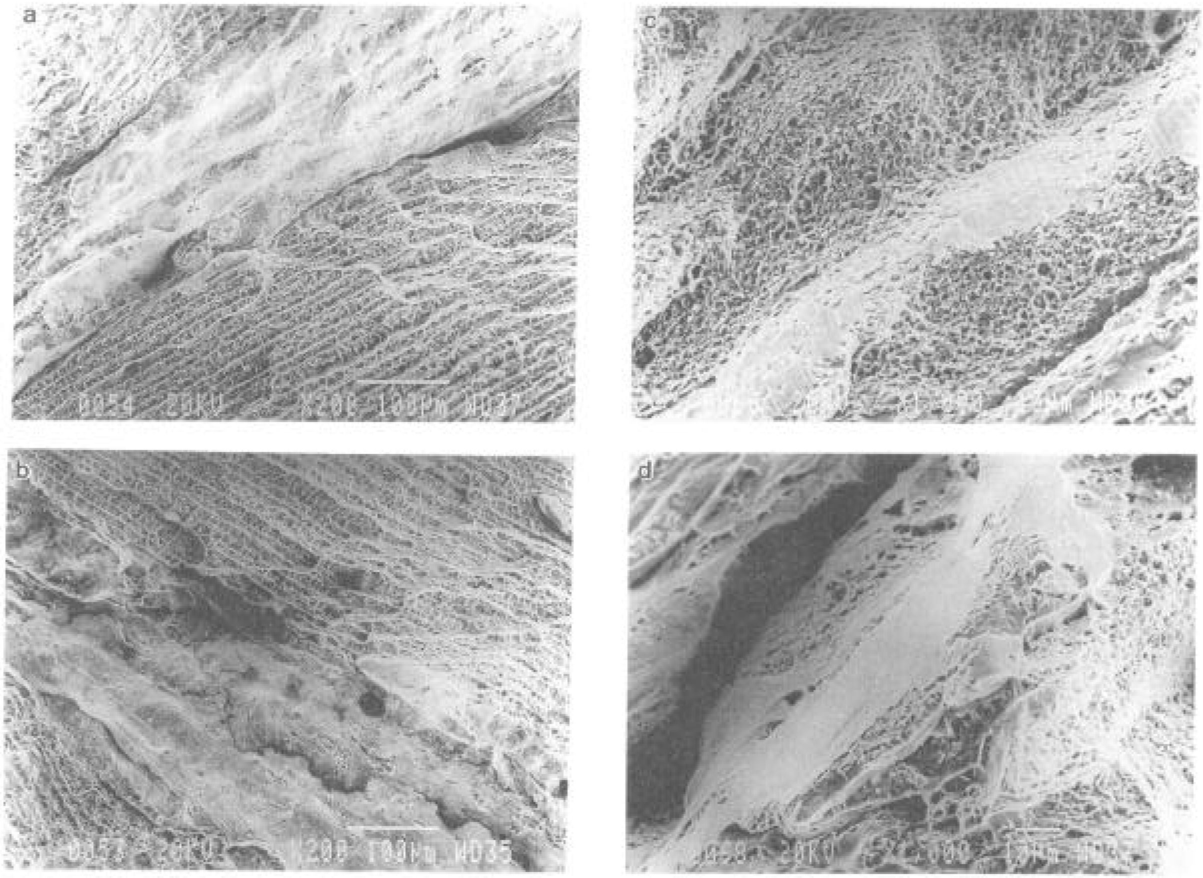

Fig. 10 Fracture surface of all-weld-metal tensile specimen in (a), (b) : as-welded and in (c), (d) : PWHT condition.

shown in Fig. 9(a) and (b), confirm this explanation. The continuous network of eutectic phase found in the weld metal in the as-welded condition is drastically reduced after PWHT at 1095℃ for 1 hour. On the other hand, a series of smaller carbides ($M_{23}C_6$) are formed along the interdendrite boundaries, which occurred during a rather slow, air cooling process.[11]

SEM fractographs of the tensile test specimens obtained before and after the PWHT, as shown in Fig. 10, also reveal the same kind of phenomenon as being observed in the micro-structural evaluation. Fracture surface (200×) of the as-welded specimen revealed a very aggressive "wetting" action of the eutectic phase, of which very flat fracture mode with no dimple suggests that the interface between the phase and matrix would be a source of the poor ductility. On the other hand, only small amount of the phase is noticeable in the fracture surface (1000×) of the weld metal subjected to PWHT at 1095℃.

Conclusions

1) Evaluation on the Gas Tungsten Arc weldments of a wrought, nickel-base alloy with nominal composition of 28Cr-29Co-2.75Si-Bal.Ni showed that the weld metals exhibited a poor ductility in the as-welded condition.

2) Poor ductility of the weld metal in the as-welded condition is caused by a continuous eutectic phase, which is mainly consist of $(Si,Ti)_xNi_y$,

3) The eutectic phase was successfully reduced or removed with a proper PWHT, whereas controlling welding parameters was not effective in improving the ductility of the weldments.

4) PWHT of the alloy is essential if cold forming of the weldment is required after welding, or if adequate joint ductility is a design requirement. The recommended PWHT condition is 1050℃/1hr/AC.

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