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Microstructural and Phase Characterization of Vacuum-Brazed Inconel 718 Joints Used in PWR Spacer Grids

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1. Introduction

Brazing is a joining process in which a filler metal (FM) melts and flows between base materials (BM), forming the joint. In Ni–Cr–P brazed joints, the low solubility of phosphorus in nickel promotes the formation of brittle intermetallic phases, such as Ni_3P, which reduce ductility and mechanical strength. Previous studies [1-5] reported that phosphorus-rich phases and intermetallic compounds formed at the FM–BM interface can promote crack initiation and brittle fracture in nickel alloy joints. Therefore, this work aims to evaluate and identify the phases formed in brazed and aged filler metals, as well as at the FM–BM interface, using Energy Dispersive Spectrometry (EDS), Wavelength Dispersive Spectrometry (WDS), and X-Ray Diffraction (XRD) techniques.

2. Methodology

Annealed and stamped Inconel 718 strips (0.35 ± 0.01 mm) were used as the base material (BM), while a BNi-7 brazing paste (Nicrobraz 50-S) was used as the filler metal (FM). The nominal chemical compositions of the BM and FM are presented in Table 1. Brazing was performed in a vacuum furnace under around 10^{-3} mbar at 1060 °C for 10 min, followed by furnace cooling until room temperature. Part of the samples was aged for 18 h at 730 °C. The FM and FM–BM joints were characterized in both as-brazed and aged conditions. Microstructural and phase analyses were performed using Optical Microscopy (OM), Scanning Electron Microscopy (SEM)/EDS, WDS, and XRD. Elemental distribution was evaluated by EDS and WDS mapping, while phase identification was carried out by XRD using Cu-K_α radiation and open pattern diffraction databases (COD).

Table I: Chemical Composition of BM and FM (%wt.). Sources: [6-7].

Element	**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Co**	**Mo**
BM	0.08 (max)	0.35 (max)	0.35 (max)	0.015 (max)	0.015 (max)	17 - 21	1.0 (max)	2.8 - 3.3
FM	0.06 (max)			10		14		
Element	**Nb + Ta**	**Ti**	**Al**	**Fe**	**Cu**	**Ni**	**B**	**Ta**
BM	4.75 - 5.50	0.65 - 1.15	0.20 - 0.80	Bal.	0.30 (max)	50 - 55	0.006 (max)	0.05 (max)
FM						Bal.		

3. Results and Discussion

Fig. 1a shows images of the filler metal (FM) obtained by optical microscopy (OM), and Fig. 1b shows an image obtained by scanning electron microscopy (SEM) and the chemical composition determined by EDS at the indicated points.

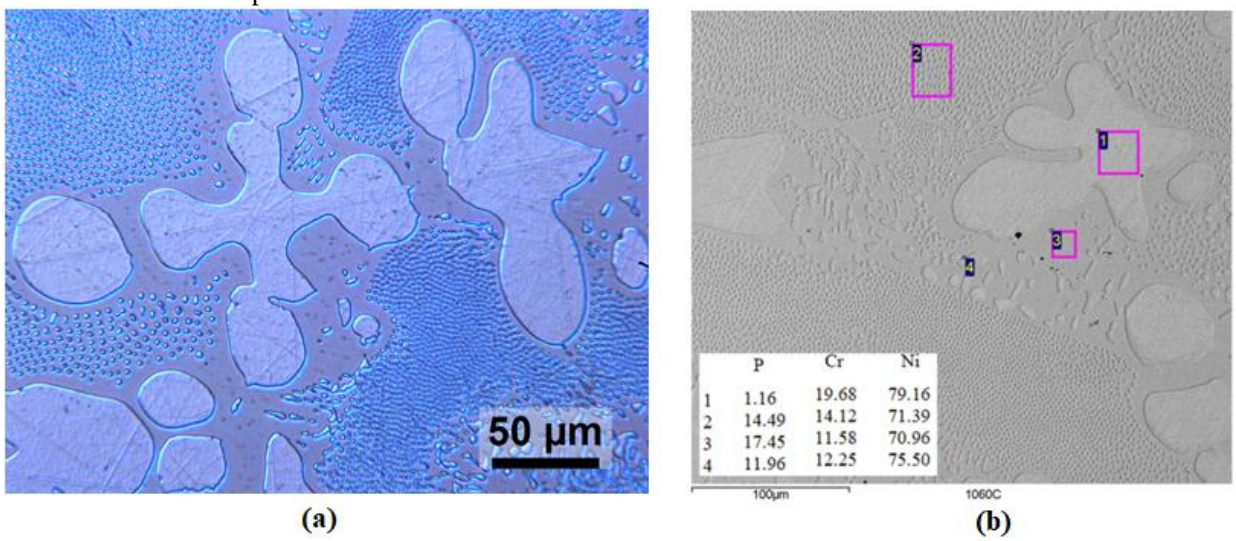

Figure 1. FM melted at 1060 °C: a) OM image; b) SEM image and EDS chemical composition.

Analysis of the FM melted reveals the formation of isolated regions ("islands"), indicating segregation of chemical elements. This segregation was confirmed by SEM and EDS, where the islands regions are rich in Ni and Cr, with depletion of P. The EDS chemical composition at point 1 confirmed a lower P content and a higher Cr and Ni concentration, whereas points 2, 3, and 4 exhibited higher P content, with lower Cr and Ni content. WDS analysis was performed on samples of the brazed joint (BJ) at 1060 °C and the aged joint (ABJ). Fig. 2 shows the intensity maps of main chemical elements measured with WDS for brazed joint (a – d) and aged brazed joint (f – i).

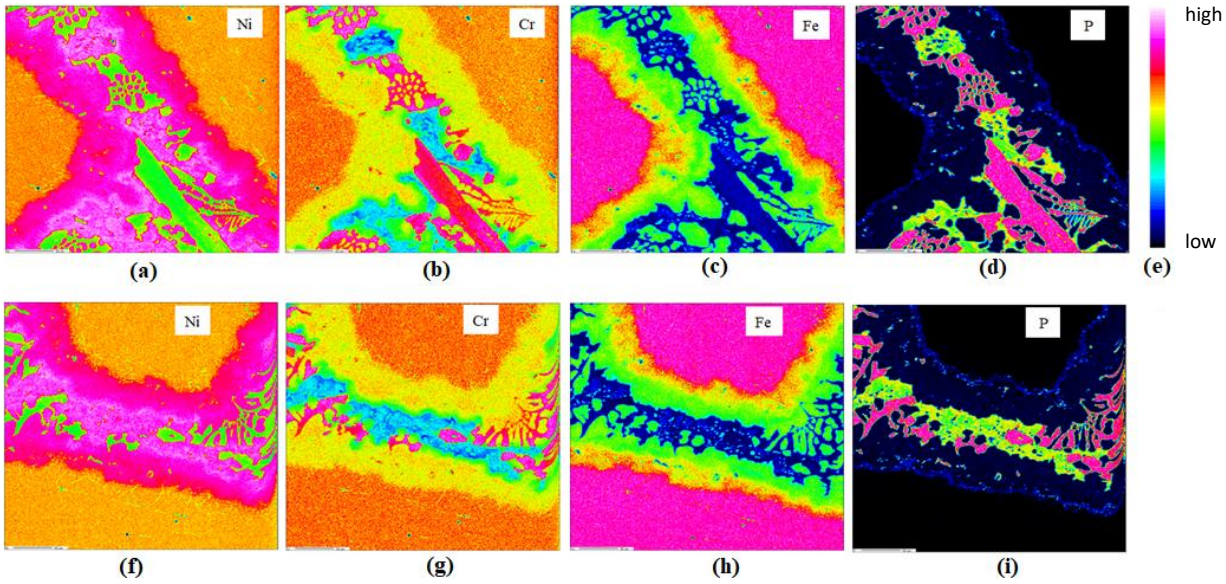

Figure 2. Elemental intensity maps of the: a – d) brazed joint (BJ) at 1060 °C, e) color intensity scale, and f – i) aged brazed joint (ABJ).

The WDS intensity maps for both as-brazed and aged conditions exhibited similar elemental distribution patterns. Ni showed higher concentration in the brazed region due to its high content in FM, while Cr

presented a heterogeneous distribution with Cr-rich islands. Regions enriched in P and depleted in Ni were also observed, indicating segregation phenomena associated with the low solubility of P in Ni and Cr bulk. Fe was uniformly distributed in the BM, with limited diffusion into the FM–BM interface region. The low solubility of P in Ni promotes the formation of phosphide phases. Intermetallic phases rich in Ni, Cr, and P were concentrated in the central region of the joint, which is consistent with the final solidification of low-melting phosphide-rich phases during brazing [2, 5]. To identify the phases formed at the joint between the base metal (BM) and filler metal (FM), four distinct samples were prepared. Two samples consisted of the filler metal melted at 1060 °C for 10 min (FM), one of which underwent additional aging at 730 °C for 18 h (Aged FM). The remaining two samples consisted of the filler metal deposited over the base metal and treated at 1060 °C for 10 min (BM+FM), with one subsequently aged at 730 °C for 18 h (Aged BM+FM). The resulting X-ray diffraction patterns, obtained using Cu-Kα radiation, are presented in Fig. 3 with respective phase identification employing the COD open database.

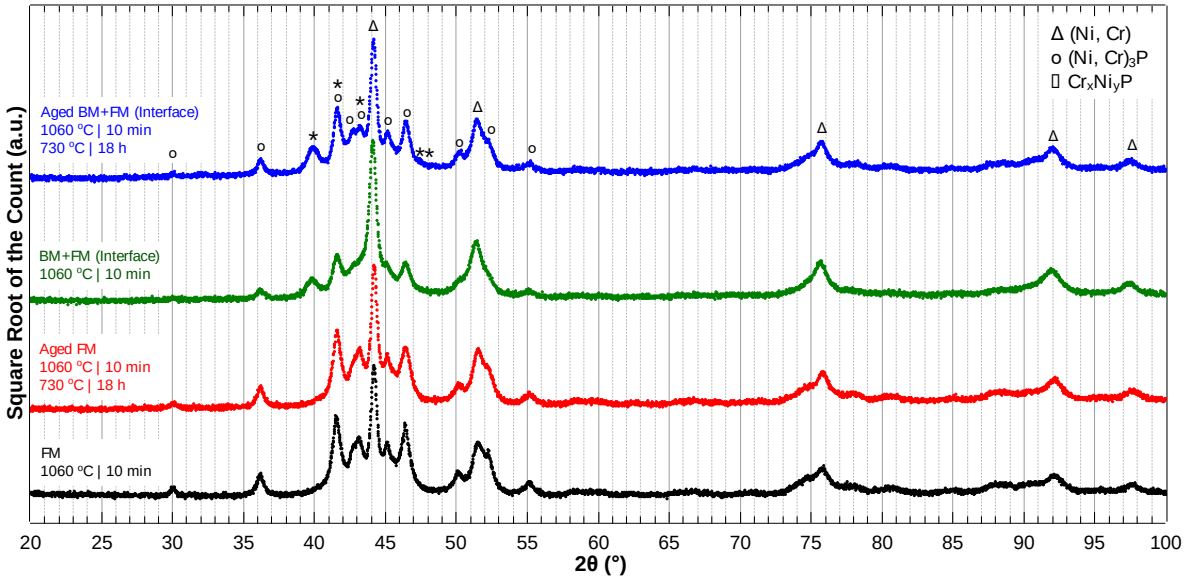

Figure 3. XRD patterns of the FM, aged FM, BM+FM (Interface), and aged BM+FM (Interface).

Both melted filler metal samples (FM and aged FM) comprised two phases: nickel–chromium phosphide $(Ni, Cr)_3P$ and a (Ni, Cr) solid solution. Conversely, in the samples where the filler metal was deposited over the base metal, the (Ni, Cr) phase remained stable, while $(Ni, Cr)_3P$ transformed into CrxNiyP. The subscripts x and y denote stoichiometric factors governed by the reactions between the liquid FM and the BM during brazing. WDS analyses confirmed the XRD findings, revealing regions enriched in Cr–Ni, Ni–P, and Ni–Cr–P phases. These transformations stem from diffusion-driven changes in elemental concentrations during brazing at 1060 °C. Similar phases have been reported previously [1, 3, 4] for the Ni–Cr–P phases filler metal system.

4. Conclusions

SEM/EDS analysis of the filler metal (FM) revealed that regions with lower P content exhibited higher Cr concentrations, indicating the formation of a Ni–Cr matrix. Additionally, WDS analysis revealed elemental segregation within the brazed zone, particularly involving Cr and P, along with the diffusion of Fe into the interfacial region. Similar elemental distributions were observed in both the as-brazed and aged conditions. Furthermore, XRD analysis identified two distinct phases within the FM: nickel–chromium phosphide $(Ni, Cr)_3P$ and a (Ni, Cr) solid solution. Notably, the aging heat treatment did not alter the phases formed in the brazed region.

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