CHAPTER 11 - EXPERIMENT 9

MICROPROBE ANALYSIS OF INTERMETALLIC PHASES

11.1) Introduction

Previous chapters revealed a discrepancy between the equilibrium intermetallic phase predicted by the Ni-Hf binary phase diagram (i.e. Ni_5Hf) for the novel braze alloys, and the intermetallic phase provisionally identified in the Ni-Hf braze joints on the basis of SEM-EDS and preliminary microprobe analyses (Ni_7Hf_2). The SEM-EDS technique is, at best, semi-quantitative, and an attempt was therefore made to determine the chemical make-up of the intermetallic phases in modified Ni-Hf and Ni-Zr braze joints using more detailed electron microprobe analysis (EMPA) techniques. This experiment also aimed at assessing the effect of chromium additions to the Ni-Hf and Ni-Zr braze alloys on the microstructure of the wide gap braze joints.

11.2) Experimental procedure

MarM247/Ni-Hf and MarM247/Ni-Zr braze joints in In738 base metal were produced using two experimental ternary braze alloys with compositions of Ni-7Cr-31Hf and Ni-7Cr-13Zr (wt.%). Brazing was performed using the procedure described in §4.2. The joints were examined, either in the as-brazed condition (without applying an extended diffusion cycle), or after a diffusion treatment to facilitate the diffusion of the melt point depressant into the parent metal.

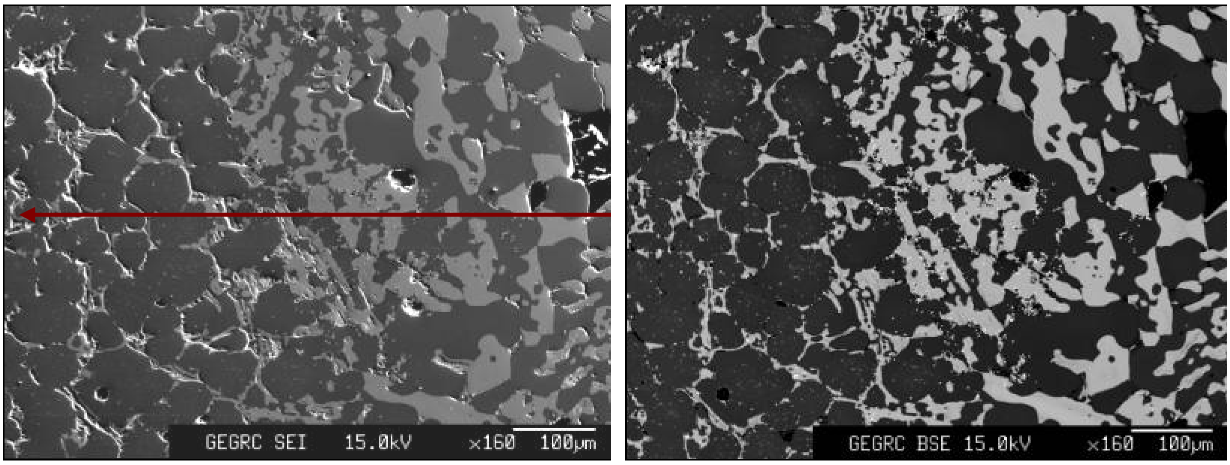
The brazed samples were mounted in resin and prepared using conventional metallographic techniques before being subjected to microstructural examination using microprobe analysis techniques. The mounted samples were carbon coated using a sputtering technique and electrically grounded with copper tape to minimize charging of the specimens by the microprobe electron beam. Calibration was performed using polished pure element standards.

Analysis conditions were established for either a 15 or 20 keV focused electron beam, adjusted to provide 35 nA of specimen current on pure nickel. Desired locations for analysis were selected by generating a backscatter electron (BSE) image before placing the instrument in "spot mode", during which the focused beam was directed to selected locations within the area shown in the BSE image. The BSE images were annotated to highlight the features subjected to elemental characterization by energy dispersive x-ray spectroscopy (EDS). The EDS peak identifications were verified using a wavelength dispersive x-ray spectrometer (WDS), tuned to the elements of interest. X-ray intensity data were collected in triplicate at each selected location. Measured x-ray counts were then converted to elemental weight percentages using commercially available algorithms.

11.3) Results and discussion

11.3.1 The MarM247/Ni-Hf braze joint produced using Ni-7Cr-31Hf braze filler (as-brazed condition):

Secondary and backscatter electron images of the MarM247/Ni-Hf joint produced using the experimental Ni-7Cr-31Hf braze filler metal are shown in **Figure 144** in the as-brazed condition. The arrow indicates the location and direction of the 5 μm stepped EPMA line scan. The results of the EMPA scan are shown in **Table 46**.



(a) (b)

Figure 144 – Secondary (a) and backscatter (b) electron images of the MarM247/Ni-7Cr-31Hf joint in the as-brazed condition.

Table 46 – The results of the EMPA scan of the MarM247/Ni-7Cr-31Hf braze joint in the as-brazed condition. (All compositions given in wt.%).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
74.213	64.158	11.067	4.40	1.71	68.70	9.30	0.30	0.58	3.40	1.04	7.15	2.65	0.01
74.218	64.158	11.067	4.48	1.72	69.15	9.18	0.28	0.58	3.16	1.03	7.14	2.54	0.00
74.223	64.158	11.067	4.48	1.66	68.69	9.25	0.30	0.58	3.43	1.09	7.11	2.59	0.00
74.228	64.158	11.067	4.45	1.64	68.40	9.13	0.30	0.60	3.42	1.03	7.12	2.83	0.00
74.233	64.158	11.066	4.54	1.69	68.41	8.99	0.34	0.57	3.33	1.06	7.08	2.86	0.00
74.238	64.158	11.066	4.55	1.67	68.13	9.07	0.31	0.58	3.23	1.00	7.03	2.66	0.00
74.243	64.158	11.066	4.74	1.64	68.00	8.72	0.30	0.60	3.05	1.00	6.96	2.78	0.01
74.248	64.158	11.068	0.40	27.68	56.16	0.72	9.57	0.09	3.08	0.13	2.98	0.00	0.00
74.253	64.158	11.068	0.63	26.18	56.43	1.41	8.81	0.14	2.61	0.23	3.28	0.00	0.00
74.258	64.158	11.068	4.68	1.69	68.03	8.77	0.31	0.59	3.09	1.07	7.02	2.55	0.00
74.263	64.158	11.068	4.52	1.66	68.11	8.98	0.31	0.61	3.13	1.06	7.16	2.76	0.00
74.268	64.158	11.068	4.50	1.63	67.83	9.03	0.31	0.61	2.97	1.07	7.17	2.75	0.00
74.273	64.158	11.068	4.22	13.37	58.87	7.35	1.30	0.48	5.22	0.86	5.69	1.15	0.01
74.278	64.158	11.066	4.56	1.64	67.57	8.92	0.31	0.62	2.87	1.04	7.17	2.85	0.00
74.283	64.158	11.068	4.64	1.64	68.17	8.84	0.32	0.61	3.00	1.04	7.16	2.66	0.00
74.288	64.158	11.068	4.59	1.60	67.68	8.87	0.32	0.65	2.92	1.01	7.17	2.66	0.00
74.293	64.158	11.066	4.54	1.76	67.77	8.66	0.32	0.60	3.00	1.02	7.12	2.67	0.00
74.298	64.158	11.068	0.88	24.80	57.35	1.81	8.08	0.17	2.92	0.26	3.48	0.00	0.00
74.303	64.158	11.068	0.29	28.34	55.23	0.59	9.36	0.08	2.78	0.16	2.96	0.00	0.00
74.308	64.158	11.068	0.29	28.36	55.77	0.54	9.44	0.06	2.91	0.17	2.96	0.00	0.01
74.313	64.158	11.068	0.29	28.45	55.56	0.57	9.36	0.07	2.76	0.14	2.90	0.00	0.00
74.318	64.158	11.066	3.04	11.30	63.34	5.83	3.30	0.40	2.91	0.76	5.58	1.32	0.01
74.323	64.158	11.068	4.54	1.70	68.45	8.56	0.35	0.56	2.92	1.03	7.17	2.26	0.00
74.328	64.158	11.068	4.53	1.59	68.39	8.69	0.33	0.60	2.81	1.04	7.23	2.55	0.01
74.333	64.158	11.068	4.55	1.63	68.18	8.71	0.29	0.59	2.69	1.08	7.19	2.64	0.01
74.338	64.158	11.067	4.61	1.74	68.19	8.58	0.31	0.56	3.08	1.04	7.05	2.38	0.00
74.343	64.158	11.067	4.47	1.61	68.41	8.86	0.26	0.60	3.07	1.02	7.20	2.47	0.00
74.348	64.158	11.067	4.60	1.77	68.11	8.67	0.36	0.61	3.22	1.03	7.18	2.23	0.00
74.353	64.158	11.067	4.55	1.74	68.08	8.72	0.29	0.59	3.29	1.03	7.16	2.66	0.01
74.358	64.158	11.067	4.52	1.66	68.61	8.67	0.34	0.57	3.24	1.06	7.23	2.35	0.00
74.363	64.158	11.067	4.64	1.73	67.96	8.58	0.32	0.60	3.22	1.05	7.17	2.37	0.00
74.368	64.158	11.067	5.68	3.56	68.87	7.46	0.63	0.51	3.34	0.85	6.36	1.07	0.02
74.373	64.158	11.066	4.81	1.59	67.81	8.58	0.32	0.59	3.09	1.02	7.10	2.43	0.00

Table 46 – (continued).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
74.378	64.158	11.066	4.55	1.71	67.21	8.65	0.29	0.58	3.12	1.05	7.17	2.79	0.02
74.383	64.158	11.066	4.60	1.70	67.51	8.60	0.32	0.59	3.36	1.05	7.08	2.43	0.00
74.388	64.158	11.066	4.68	1.75	67.72	8.76	0.37	0.58	3.20	1.02	7.11	2.29	0.00
74.393	64.158	11.066	4.40	3.13	66.37	9.22	0.60	0.61	2.46	1.05	7.33	1.89	0.01
74.398	64.158	11.066	4.72	1.62	68.42	8.81	0.34	0.57	3.12	1.02	7.14	2.38	0.00
74.403	64.158	11.066	4.88	1.61	68.42	8.69	0.35	0.55	3.01	1.04	7.07	2.05	0.00
74.408	64.158	11.068	4.88	1.71	68.67	8.73	0.35	0.54	3.30	1.03	7.10	2.12	0.01
74.413	64.158	11.068	4.87	2.40	68.59	8.63	0.37	0.59	3.03	0.99	6.97	2.11	0.02
74.418	64.158	11.066	4.87	1.71	68.70	8.70	0.35	0.57	3.41	1.00	7.00	1.65	0.00
74.423	64.158	11.068	3.53	9.56	65.11	6.64	3.03	0.44	2.68	0.78	5.90	0.94	0.00
74.428	64.158	11.066	0.32	28.28	55.10	0.69	9.34	0.09	2.99	0.15	2.90	0.00	0.01
74.433	64.158	11.066	0.34	28.32	55.65	0.68	9.21	0.05	2.53	0.15	2.83	0.00	0.00
74.438	64.158	11.066	0.37	26.67	56.91	0.92	9.85	0.11	1.75	0.17	3.07	0.00	0.01
74.443	64.158	11.068	3.03	16.92	62.22	1.44	9.70	0.13	2.14	0.25	3.20	0.00	0.00
74.448	64.158	11.068	0.32	29.43	55.77	0.58	8.15	0.06	2.83	0.12	2.91	0.00	0.00
74.453	64.158	11.068	0.97	45.68	34.07	2.84	5.77	0.22	9.53	0.30	2.80	0.00	0.01
74.458	64.158	11.068	5.33	1.66	69.66	8.51	0.40	0.55	2.95	0.93	6.84	1.39	0.01
74.463	64.158	11.068	5.32	1.62	69.86	8.50	0.35	0.59	2.74	0.98	6.84	1.53	0.01
74.468	64.158	11.066	5.43	15.67	60.91	4.16	3.19	0.30	4.50	0.46	4.10	0.25	0.01
74.473	64.158	11.066	1.63	17.51	58.98	2.26	8.42	0.17	2.10	0.25	3.54	0.00	0.00
74.478	64.158	11.003	2.20	3.35	37.04	7.31	0.76	0.24	5.20	0.73	2.91	1.37	0.00
74.483	64.158	11.067	5.81	5.41	68.75	7.04	0.80	0.46	2.92	0.80	5.89	0.70	0.00
74.488	64.158	11.067	5.06	1.60	69.21	8.59	0.35	0.57	2.61	0.95	6.86	2.51	0.00
74.493	64.158	11.065	5.48	2.09	70.60	8.20	0.49	0.50	2.81	0.91	6.51	1.46	0.01
74.498	64.158	11.067	1.86	16.95	62.21	3.76	8.91	0.25	1.53	0.43	4.36	0.00	0.01
74.503	64.158	11.067	7.86	6.11	71.63	3.87	1.42	0.27	3.64	0.45	4.10	0.29	0.02
74.508	64.158	11.067	0.67	43.17	37.81	1.04	7.89	0.09	9.41	0.15	2.04	0.00	0.01
74.513	64.158	11.066	0.29	34.25	50.08	0.58	8.76	0.06	4.81	0.12	2.54	0.00	0.01
74.518	64.158	11.066	0.35	29.23	55.59	0.74	8.58	0.09	3.02	0.18	2.93	0.00	0.01
74.523	64.158	11.066	0.29	27.62	55.05	0.76	9.13	0.08	2.91	0.16	2.90	0.00	0.00
74.528	64.158	11.064	4.46	1.79	67.89	8.56	0.43	0.53	3.30	1.05	6.85	3.06	0.00
74.533	64.158	11.064	4.69	1.57	68.33	8.52	0.33	0.53	3.02	1.05	6.85	2.77	0.01
74.538	64.158	11.062	3.00	23.04	50.75	6.71	2.44	0.44	6.71	0.73	4.93	0.19	0.00
74.543	64.158	11.064	2.55	27.62	45.92	6.57	2.10	0.36	7.45	0.65	4.84	0.00	0.01
74.548	64.158	11.066	0.29	27.04	55.63	0.63	9.62	0.07	2.61	0.17	2.92	0.00	0.00
74.553	64.158	11.064	0.29	28.52	54.53	0.57	9.16	0.05	2.63	0.16	2.87	0.00	0.00
74.558	64.158	11.064	0.28	28.40	54.96	0.56	9.31	0.07	2.40	0.12	2.83	0.00	0.00
74.563	64.158	11.062	0.28	26.58	53.92	0.62	9.28	0.05	2.32	0.16	2.83	0.00	0.01
74.568	64.158	11.062	0.28	27.48	53.96	0.69	9.39	0.07	3.07	0.14	2.80	0.00	0.02
74.573	64.158	11.066	3.49	21.00	53.49	6.96	0.88	0.46	6.58	0.76	5.35	0.58	0.00
74.578	64.158	11.066	4.49	1.63	68.45	9.00	0.35	0.56	2.82	1.04	7.10	2.25	0.00
74.583	64.158	11.064	4.45	1.72	67.62	8.97	0.35	0.56	3.14	1.01	6.94	2.74	0.00
74.588	64.158	11.066	4.45	1.69	68.66	9.09	0.32	0.55	3.06	1.02	7.01	2.31	0.01
74.593	64.158	11.064	4.30	1.64	67.67	9.16	0.35	0.56	2.99	1.04	6.95	2.76	0.00
74.598	64.158	11.068	4.99	4.13	65.68	9.99	0.74	0.62	2.80	1.13	7.50	2.95	0.00
74.603	64.158	11.066	4.36	1.65	67.84	9.01	0.33	0.57	3.15	1.04	7.08	2.76	0.00
74.608	64.158	11.068	4.37	1.65	68.21	8.98	0.33	0.58	2.86	1.03	7.17	2.89	0.01
74.613	64.158	11.066	4.34	1.66	67.18	8.97	0.32	0.55	3.04	1.02	7.09	3.13	0.01
74.618	64.158	11.068	4.37	1.70	67.58	8.88	0.33	0.59	2.87	1.04	7.15	3.11	0.00
74.623	64.158	11.065	4.34	1.70	67.05	8.88	0.36	0.54	2.72	1.04	7.09	3.04	0.02
74.628	64.158	11.065	4.27	1.60	66.69	9.10	0.31	0.52	2.82	1.05	7.06	3.24	0.01
74.633	64.158	11.067	4.36	1.64	67.42	8.98	0.33	0.57	2.67	1.03	7.17	2.90	0.00
74.638	64.158	11.067	4.36	1.65	67.84	9.01	0.33	0.57	3.15	1.04	7.08	2.76	0.00
74.643	64.158	11.065	4.37	1.65	68.21	8.98	0.33	0.58	2.86	1.03	7.17	2.89	0.01
74.648	64.158	11.065	4.34	1.66	67.18	8.97	0.32	0.55	3.04	1.02	7.09	3.13	0.01
74.653	64.158	11.067	4.37	3.05	67.15	8.49	0.75	0.50	3.01	0.97	6.95	2.38	0.00
74.658	64.158	11.066	0.29	28.76	54.29	0.67	8.10	0.08	2.91	0.13	2.93	0.00	0.00
74.663	64.158	11.066	0.34	29.19	54.49	1.02	8.40	0.09	2.97	0.20	3.05	0.00	0.00
74.668	64.158	11.066	4.00	5.23	64.01	8.40	0.69	0.45	3.95	1.00	6.80	2.53	0.01
74.673	64.158	11.066	1.01	23.28	57.27	2.47	7.48	0.15	3.32	0.35	3.83	0.00	0.01

Table 46 – (continued).													
X (mm)	**Y (mm)**	**Z (mm)**	**Al**	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**
74.678	64.158	11.064	3.92	5.53	62.65	8.56	0.50	0.42	4.78	1.00	6.87	3.25	0.00
74.683	64.158	11.066	3.17	16.43	54.78	7.06	1.27	0.36	6.96	0.81	5.90	2.15	0.01
74.688	64.158	11.066	3.94	6.32	62.13	8.40	0.67	0.41	4.26	0.97	6.93	3.36	0.01
74.693	64.158	11.066	4.17	1.61	66.17	9.04	0.32	0.40	3.35	1.07	7.44	3.60	0.00
74.698	64.158	11.066	4.17	1.63	66.09	9.14	0.30	0.40	3.38	1.07	7.55	3.69	0.00
74.703	64.158	11.066	4.13	1.61	65.62	9.28	0.27	0.41	3.20	1.08	7.57	3.74	0.01
74.708	64.158	11.066	3.69	6.97	60.67	8.77	0.41	0.38	4.89	0.97	7.01	2.93	0.01
74.713	64.158	11.066	4.19	1.66	65.97	9.19	0.29	0.39	3.29	1.06	7.56	3.50	0.00
74.718	64.158	11.066	3.70	9.69	59.90	8.38	0.72	0.37	5.49	0.99	6.76	2.70	0.00
74.723	64.158	11.066	4.21	1.68	65.99	9.07	0.29	0.40	3.44	1.10	7.56	3.39	0.00
74.728	64.158	11.066	0.82	21.49	56.85	2.30	6.85	0.14	3.42	0.27	3.97	0.00	0.01
74.733	64.158	11.066	4.16	1.61	66.51	9.31	0.32	0.38	3.34	1.01	7.69	3.25	0.00
74.738	64.158	11.066	4.24	1.71	66.33	9.23	0.30	0.36	3.48	1.03	7.52	3.20	0.00
74.743	64.158	11.066	4.19	1.64	66.16	9.36	0.29	0.37	3.51	1.09	7.63	3.40	0.00
74.748	64.158	11.066	4.16	1.62	66.64	9.42	0.29	0.38	3.46	1.08	7.71	3.60	0.00
74.753	64.158	11.066	4.26	1.70	66.61	9.33	0.32	0.35	3.76	1.06	7.55	3.20	0.00
74.758	64.158	11.066	4.19	1.69	66.65	9.38	0.27	0.37	3.63	1.09	7.70	3.27	0.00
74.763	64.158	11.065	4.16	1.69	67.08	9.43	0.29	0.37	3.65	1.11	7.67	2.93	0.00
74.768	64.158	11.065	4.26	1.74	66.54	9.20	0.30	0.37	3.57	1.00	7.60	2.90	0.00
74.773	64.158	11.065	3.67	7.10	62.84	7.89	1.43	0.31	4.24	0.95	6.75	2.47	0.00
74.778	64.158	11.065	2.13	7.05	60.67	6.54	2.10	0.26	3.50	0.58	6.08	1.85	0.02
74.783	64.158	11.063	4.10	1.70	65.52	9.27	0.30	0.35	3.83	1.05	7.39	3.69	0.00
74.788	64.158	11.069	4.03	3.81	65.13	9.14	0.32	0.37	4.32	1.05	7.56	3.44	0.00
74.793	64.158	11.067	4.17	1.67	66.26	9.40	0.29	0.37	3.54	1.09	7.81	3.69	0.00
74.798	64.158	11.064	4.11	1.72	65.84	9.40	0.28	0.35	3.90	1.09	7.73	3.64	0.00
74.803	64.158	11.064	3.45	10.86	58.52	8.52	0.45	0.34	6.31	0.98	6.84	3.03	0.01
74.808	64.158	11.017	1.73	2.65	40.95	9.97	0.38	0.23	6.43	1.01	4.53	5.29	0.00
74.813	64.158	11.066	4.21	1.76	66.03	9.32	0.27	0.35	3.57	1.06	7.74	3.56	0.01

The line scan results shown in **Table 46** revealed the presence of three possible Hf-rich intermetallic phases, with a phase containing between 24% and 28% Hf being most prevalent. Other Hf-rich phases detected during the scan contained between 11 and 13% Hf, and 34 to 45% Hf. In order to perform a more detailed analysis of the intermetallic phases observed in the braze joint, three spot chemical analyses were performed within the intermetallic compound in the braze joint. Two backscatter electron images of the MarM247/Ni-Hf braze joint are shown in **Figure 145**, with the location of the three phase analyses highlighted. The results of the microprobe phase analyses, shown in **Table 47**, suggest that the intermetallic phase within the braze alloy contained between 31 and 36% Hf (wt.%). The binary Ni-Hf phase diagram, shown in **Figure 49**, indicates that the Ni_5Hf intermetallic phase contains approximately 38 wt.% Hf, whereas the Ni_7Hf_2 intermetallic compound contains about 46 wt.% Hf. The results shown in **Table 47** therefore suggest that the intermetallic phase in the braze joint is Ni_5Hf, rather than Ni_7Hf_2. It is, however, interesting to note that the Hf-rich phase identified in **Table 47**, as well as the phase containing between 24% and 28% Hf in **Table 46**, contained high levels of Zr (between 7.4% and 9.6%), probably present as a contaminant that segregated preferentially to the intermetallic phase on solidification, and approximately 3% Ta, which may be present as a result of dilution with the MarM247 powder particles during brazing. The presence of Zr and Ta may shift the composition of the Hf-rich intermetallic phase away from the equilibrium composition predicted by the phase diagram. If it is assumed that the intermetallic compound contains between 7.4% and 9.6% Zr in solution, as well as 3% Ta, its composition may well approach that of the Ni_7Hf_2 (or rather $Ni_7(Hf,Zr,Ta)_2$) intermetallic compound.

In order to study the distribution of various elements within the Ni-Cr-Hf braze microstructure, EMPA maps were constructed. These maps are shown in **Figure 146** (for Al, C, Ni and Cr), **Figure 147** (for Zr, Hf and Si), **Figure 148** (for Ru, Ta, Ti and W) and **Figure 149** (for Fe and Mo).

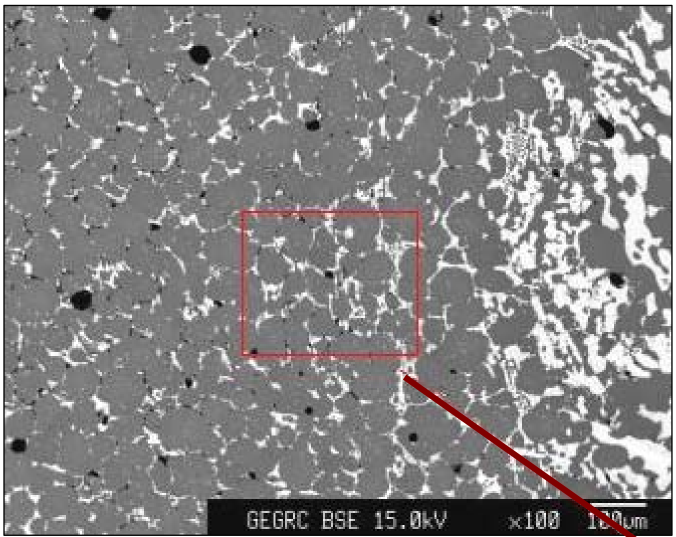


Figure 145(a) – Secondary electron image of the Ni-Cr-Hf alloy in the as-brazed condition.

Figure 145(b) – Enlarged view of the secondary electron image of the Ni-Cr-Hf braze shown in Figure 145(a), highlighting the location of three spot chemical analyses of the intermetallic compound within the braze.

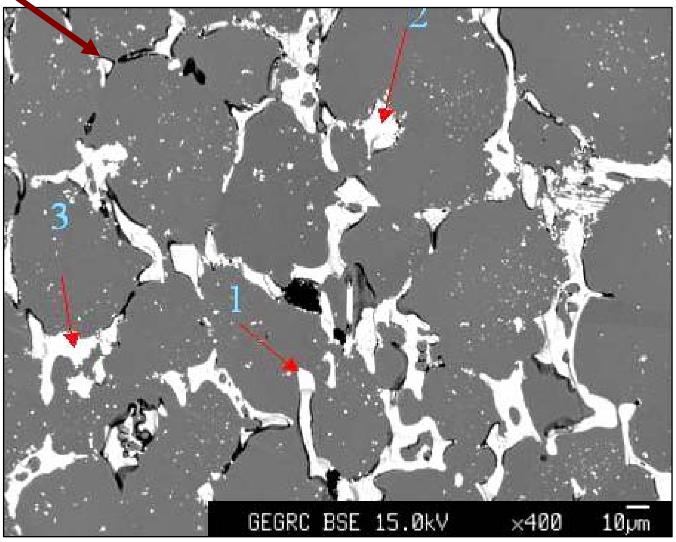


Table 47 - Quantitative EPMA data (taken at 15 keV and 80 nA with a focused spot beam) at three locations (indicated in Figure 145(b)) within the intermetallic phase. (Percentage by weight).

	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti	Si
Phase 1	0.29	31.53	55.16	0.84	8.43	0.06	3.35	0.15	3.37	0.07	0.00	0.21
Phase 2	0.29	31.09	55.37	0.71	8.54	0.05	3.39	0.18	3.10	0.08	0.01	0.25
Phase 3	0.29	36.34	53.02	0.62	5.30	0.05	3.91	0.15	3.62	0.13	0.00	0.21

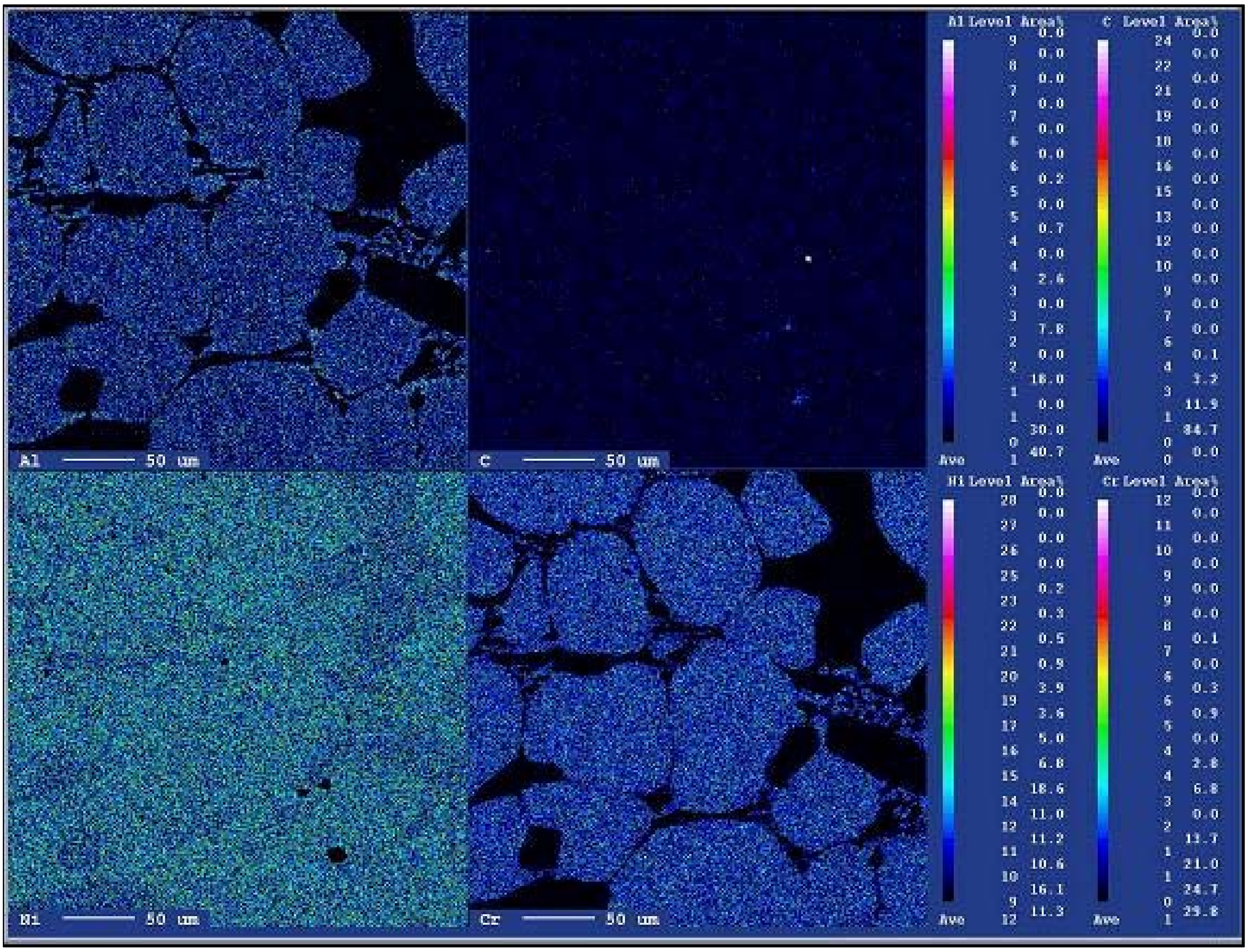


Figure 146 – EMPA maps displaying the distribution of Al, C, Ni and Cr within the MarM247/Ni-Cr-Hf braze microstructure (as-brazed condition).

The EMPA results shown in **Figure 146** indicate that Al and Cr partitioned strongly to the MarM247 powder particles during brazing. Given that the braze alloy contains 7% Cr and that a diffusion cycle was not applied, the low Cr concentration measured in the braze alloy between the MarM247 particles was surprising. Ni and C appeared to be fairly uniformly distributed between the braze alloy and the matrix, with a slightly higher Ni concentration measured in the MarM247 particles.

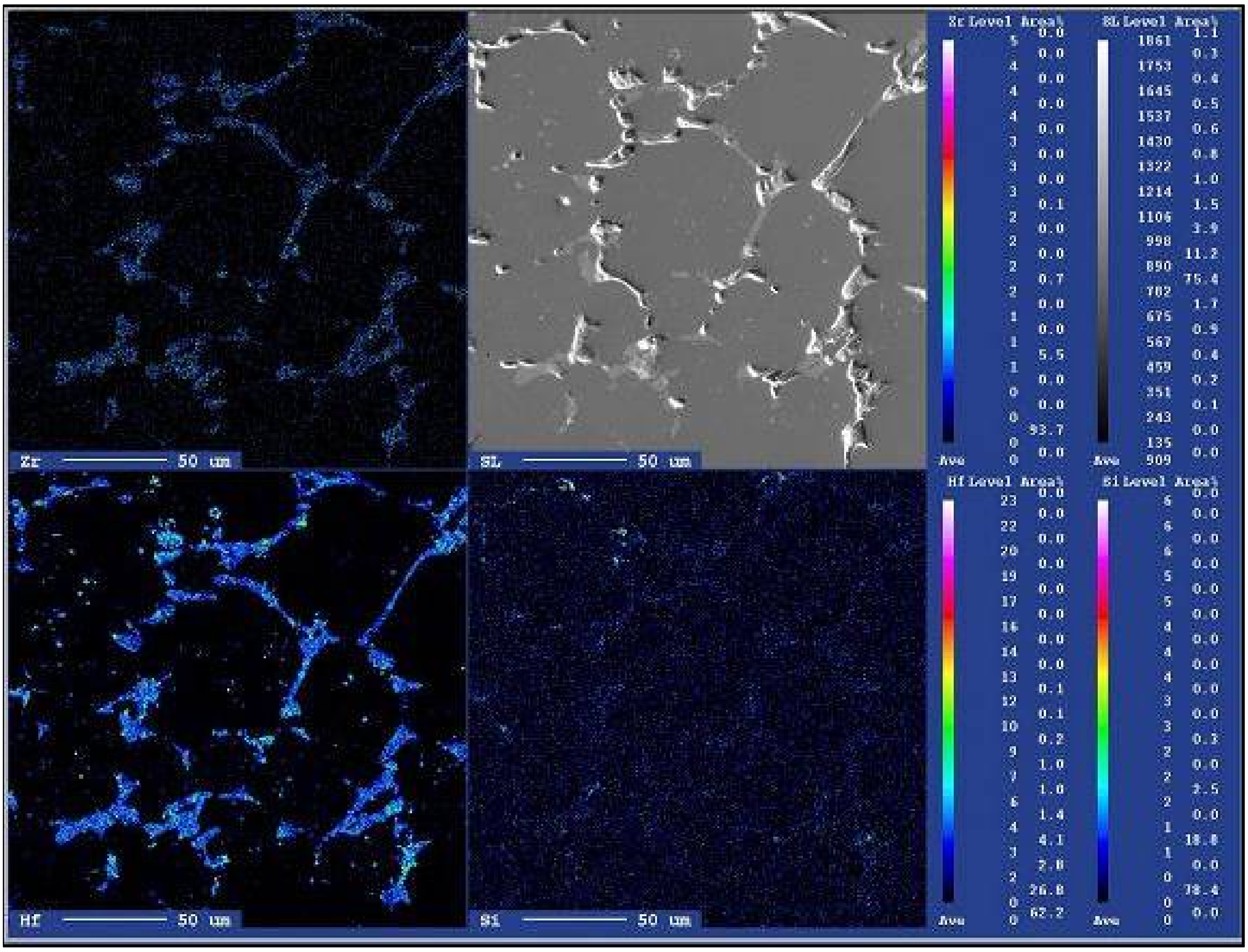


Figure 147 – EMPA maps displaying the distribution of Zr, Hf and Si within the MarM247/Ni-Cr-Hf braze microstructure (as-brazed condition).

The results shown in **Figure 147** suggest that both Hf and Zr partitioned strongly to the braze alloy, which confirms the results of the line and spot scans shown in **Tables 46 and 47**. Zr was not intentionally added to the braze alloy, and is almost completely absent from the MarM247 matrix particles (MarM247 has a nominal Zr content of 0.05 wt.%). A Zr content of 0.7 wt.% was measured in the binary Ni-Hf braze alloy as a result of contamination (see **Table 9**), but this is not considered high enough to cause the high Zr levels shown in **Tables 46 and 47**, and **Figure 147**. It is possible that the Cr powder used to make up the ternary Ni-Cr-Hf braze alloy contained a significant amount of Zr as contaminant. The Hf EMPA map confirms that the intermetallic phase within the braze joint is Hf-rich.

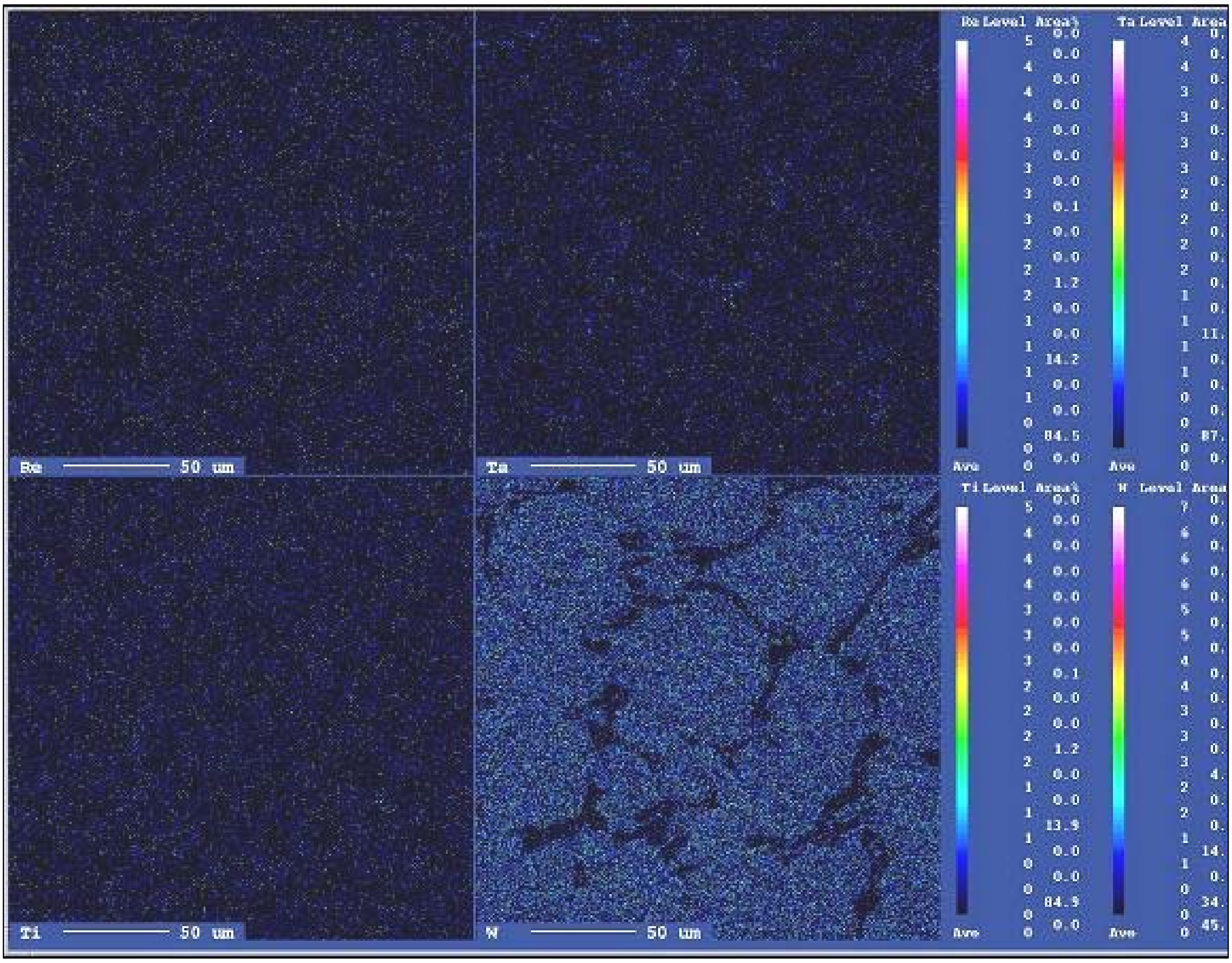


Figure 148 – EMPA maps displaying the distribution of Ru, Ta, Ti and W within the MarM247/Ni-Cr-Hf braze microstructure (as-brazed condition).

As shown in **Figure 148**, Ru, Ta and Ti were distributed fairly evenly between the braze alloy and the matrix. Tungsten, however, partitioned strongly to the MarM247 powder particles, suggesting low solubility within the intermetallic phase. The W appeared to be distributed evenly throughout the matrix particles, implying adequate solubility and little driving force for the precipitation of W-rich carbide particles or Laves phase.

The EMPA maps for Fe and Mo, shown in **Figure 149**, display preferential partitioning to the matrix particles, but due to the low levels of these elements within the MarM247 particles and the braze alloy, partitioning was weak.

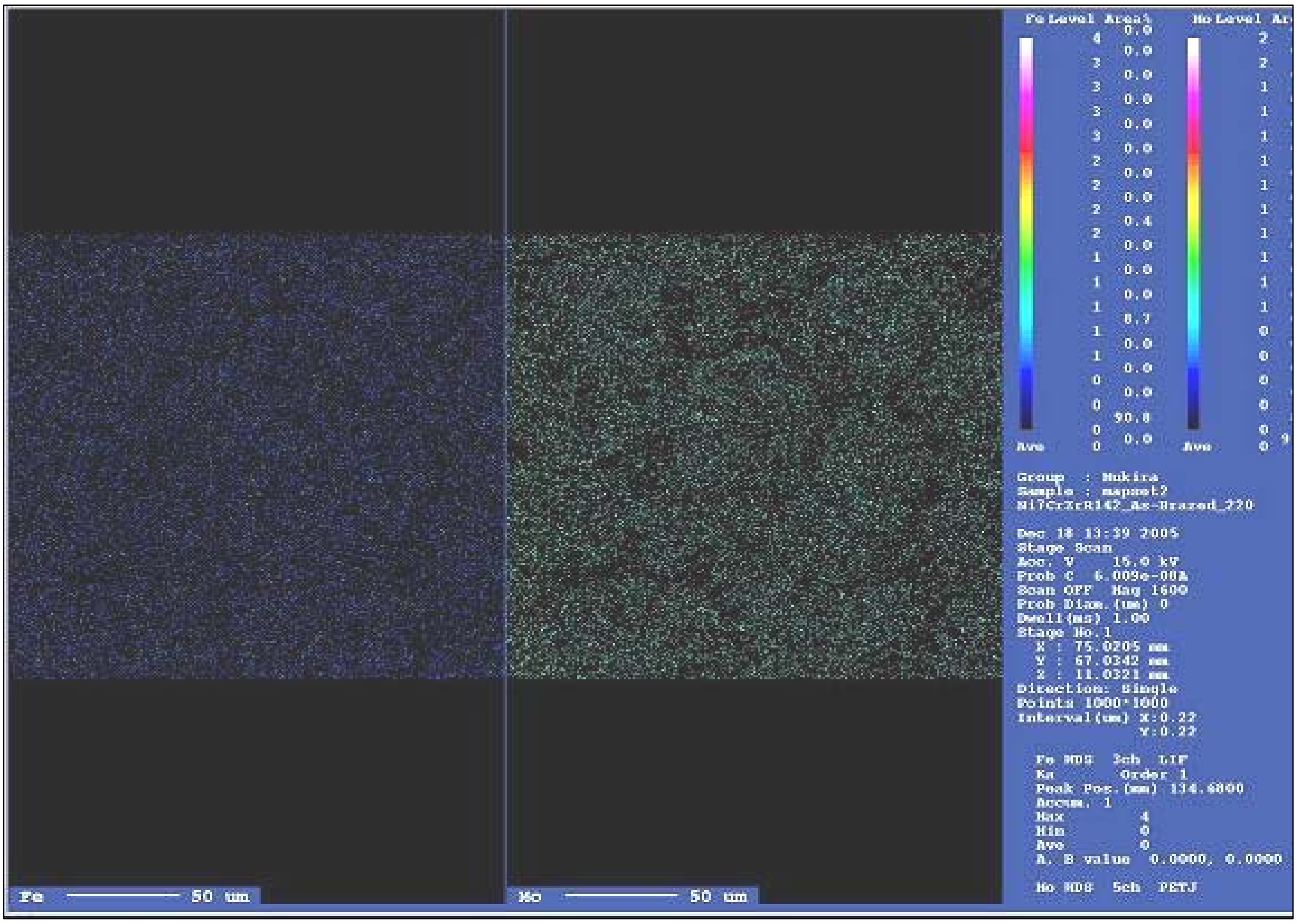
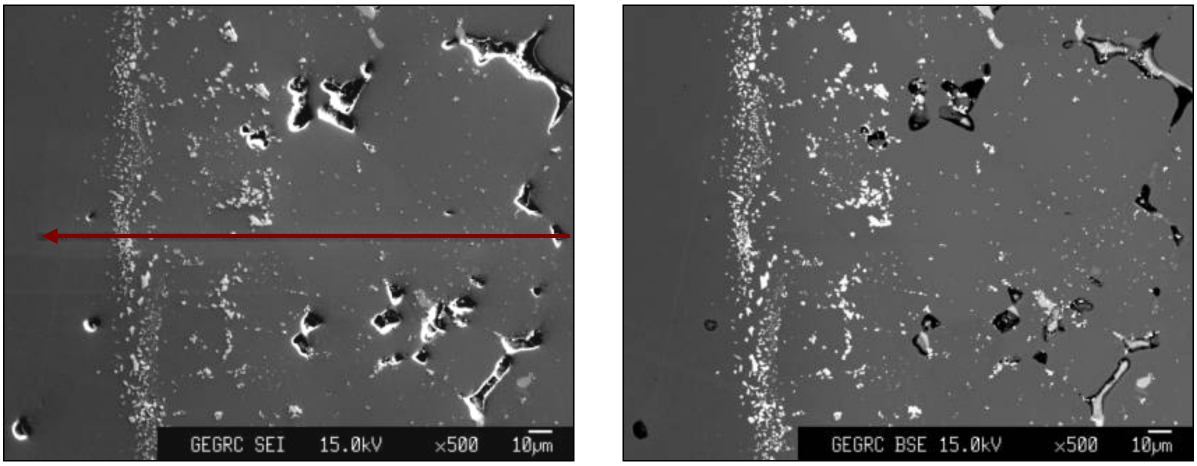


Figure 149 – EMPA maps displaying the distribution of Fe and Mo within the MarM247/Ni-Cr-Hf braze microstructure (as-brazed condition).

11.3.2 The MarM247/Ni-Zr braze joint produced using Ni-7Cr-13Zr braze filler (as-brazed condition):

Secondary and backscatter electron images of the MarM247/Ni-Zr joint produced using the experimental Ni-7Cr-13Zr braze filler metal are shown in **Figure 150** in the as-brazed condition. The arrow indicates the location and direction of the 2 μm stepped EPMA line scan. The results of the EMPA scan are shown in **Table 48**.

The line scan results shown in **Table 48** revealed the presence of a Zr-rich intermetallic phase, containing between 23% and 28% Zr. In order to perform a more detailed analysis of the intermetallic phase observed in the braze joint, four spot chemical analyses were performed within the intermetallic compound in the braze joint. Two backscatter electron images of the MarM247/Ni-Zr braze joint are shown in **Figure 151**, with the location of the four spot analyses highlighted. The results of the microprobe phase analyses, shown in **Table 49**, suggest that the intermetallic phase within the braze alloy contained between 27 and 29% Zr. The binary Ni-Zr phase diagram, shown in **Figure 50**, indicates that the Ni_7Zr_2 intermetallic phase contains approximately 30 wt.% Zr, whereas the Ni_5Zr intermetallic compound contains between 21 and 26 wt.% Zr. The results shown in **Table 49** are therefore inconclusive, suggesting that the intermetallic phase in the braze joint could be either Ni_5Zr or Ni_7Zr_2. Phase 3, shown in **Figure 145(b)**, is most likely the Ni-rich γ phase (with a composition shown in **Table 49**).



(a) (b)

Figure 150 – Secondary (a) and backscatter (b) electron images of the MarM247/Ni-7Cr-13Zr joint in the as-brazed condition (adjacent to the interface).

Table 48 – The results of the EMPA scan of the MarM247/Ni-7Cr-13Zr braze joint in the as-brazed condition. (All compositions given in wt.%).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
76.613	65.076	11.043	4.45	2.01	64.25	7.85	0.21	0.62	4.39	1.34	8.94	3.84	0.00
76.615	65.076	11.043	4.46	2.22	64.32	7.71	0.25	0.66	4.31	1.30	8.91	4.08	0.00
76.617	65.076	11.043	4.37	2.30	64.17	7.81	0.29	0.67	4.26	1.32	8.99	3.75	0.00
76.619	65.076	11.043	4.46	2.00	64.08	7.77	0.24	0.67	4.48	1.37	8.76	4.02	0.00
76.621	65.076	11.043	4.48	2.06	63.94	7.71	0.27	0.68	4.41	1.31	8.75	3.86	0.00
76.623	65.076	11.045	4.40	3.48	63.34	7.48	0.55	0.70	5.15	1.32	8.60	3.73	0.00
76.625	65.076	11.043	4.14	4.85	60.39	7.44	0.89	0.69	6.02	1.30	8.34	3.61	0.00
76.627	65.076	11.043	4.32	2.58	63.11	7.80	0.36	0.75	4.23	1.43	8.81	3.91	0.00
76.629	65.076	11.043	4.54	2.04	64.22	7.74	0.24	0.72	4.02	1.33	8.61	4.03	0.00
76.631	65.076	11.043	4.41	1.95	63.21	7.94	0.22	0.81	3.95	1.37	8.76	4.19	0.00
76.633	65.076	11.043	4.46	2.06	63.96	7.94	0.27	0.84	4.09	1.38	8.71	4.02	0.00
76.635	65.076	11.043	4.41	1.87	64.25	7.99	0.24	0.85	4.21	1.36	8.84	3.82	0.00
76.637	65.076	11.045	4.18	4.88	61.14	7.61	0.59	0.83	5.57	1.28	8.40	3.56	0.01
76.639	65.076	11.043	4.44	2.25	63.61	7.78	0.28	0.83	4.32	1.34	8.71	3.94	0.00
76.641	65.076	11.045	4.52	1.99	64.14	7.80	0.25	0.86	3.86	1.38	8.84	4.04	0.00
76.643	65.076	11.043	4.47	2.01	63.15	7.73	0.24	0.88	4.07	1.35	8.66	3.87	0.00
76.645	65.076	11.043	4.41	1.91	63.34	7.82	0.23	0.89	3.77	1.42	8.84	3.87	0.00
76.647	65.076	11.043	4.36	1.91	63.75	7.84	0.24	0.91	4.09	1.35	8.81	4.07	0.00
76.649	65.076	11.043	4.45	2.00	63.77	7.74	0.24	0.88	4.10	1.40	8.75	4.27	0.00
76.651	65.076	11.043	4.40	1.92	63.55	7.82	0.23	0.94	3.90	1.41	8.82	4.35	0.00
76.653	65.076	11.043	4.34	1.91	63.37	7.79	0.28	0.93	3.87	1.44	8.77	4.13	0.00
76.655	65.076	11.043	4.32	1.85	63.62	7.81	0.25	0.93	3.75	1.43	8.87	3.96	0.00
76.657	65.076	11.043	4.40	1.90	63.30	7.76	0.21	0.98	3.79	1.35	8.81	4.19	0.01
76.659	65.076	11.043	4.36	1.83	63.90	7.83	0.20	1.01	3.50	1.44	8.89	3.90	0.00
76.661	65.076	11.043	4.37	1.87	64.21	7.83	0.24	1.01	3.55	1.50	8.77	4.05	0.00
76.663	65.076	11.043	4.49	2.05	64.23	7.72	0.22	0.97	3.77	1.37	8.70	4.23	0.01
76.665	65.076	11.043	4.43	2.01	64.16	7.70	0.25	1.01	3.74	1.41	8.65	3.67	0.01
76.667	65.076	11.043	4.42	1.96	64.26	7.74	0.22	1.00	3.72	1.42	8.72	3.97	0.00
76.669	65.076	11.043	4.48	2.00	64.48	7.69	0.24	0.97	3.64	1.45	8.57	3.74	0.00
76.671	65.076	11.043	4.45	1.96	64.21	7.77	0.26	1.01	3.62	1.42	8.74	3.54	0.00
76.673	65.076	11.042	4.36	1.95	64.01	7.80	0.19	1.00	3.79	1.42	8.72	3.87	0.00
76.675	65.076	11.042	4.38	1.95	63.79	7.81	0.22	0.98	3.77	1.40	8.71	3.90	0.00
76.677	65.076	11.043	4.45	2.00	64.28	7.74	0.22	1.00	3.65	1.41	8.73	3.71	0.00
76.679	65.076	11.043	4.40	1.96	64.36	7.73	0.24	1.00	3.92	1.39	8.73	3.69	0.00
76.681	65.076	11.043	4.38	1.97	64.19	7.70	0.20	1.04	3.63	1.40	8.68	3.56	0.00
76.683	65.076	11.043	4.41	1.97	64.20	7.68	0.23	1.04	3.79	1.44	8.73	3.90	0.02
76.685	65.076	11.043	4.38	1.94	64.42	7.59	0.24	1.03	3.85	1.44	8.78	3.88	0.00

Table 48 – (continued).													
X (mm)	**Y (mm)**	**Z (mm)**	**Al**	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**
76.687	65.076	11.043	4.42	1.94	64.33	7.63	0.20	1.03	3.80	1.44	8.68	3.90	0.00
76.689	65.076	11.043	4.36	1.92	63.96	7.62	0.23	1.06	3.99	1.43	8.71	3.66	0.01
76.691	65.076	11.043	4.29	1.81	63.56	7.64	0.18	1.03	3.93	1.48	8.79	3.64	0.00
76.693	65.076	11.043	4.41	1.94	64.08	7.56	0.24	1.09	3.94	1.43	8.71	3.55	0.01
76.695	65.076	11.043	4.38	1.92	64.03	7.59	0.22	1.07	3.93	1.44	8.69	3.90	0.00
76.697	65.076	11.043	4.37	1.90	64.16	7.63	0.22	1.11	3.69	1.46	8.66	3.80	0.00
76.699	65.076	11.043	4.42	1.91	64.26	7.64	0.20	1.10	3.76	1.54	8.73	3.64	0.00
76.701	65.076	11.043	4.39	1.94	64.11	7.67	0.25	1.10	3.88	1.43	8.63	3.54	0.00
76.703	65.076	11.043	4.35	1.88	64.24	7.79	0.23	1.15	3.54	1.50	8.71	3.89	0.00
76.705	65.076	11.043	4.38	1.90	64.52	7.82	0.28	1.12	3.65	1.52	8.69	3.55	0.00
76.707	65.076	11.043	4.38	1.89	64.51	7.86	0.21	1.18	3.72	1.48	8.67	3.31	0.00
76.709	65.076	11.043	4.44	1.92	64.62	7.93	0.22	1.19	3.53	1.52	8.68	3.24	0.00
76.711	65.076	11.043	4.40	1.89	64.75	7.95	0.25	1.15	3.78	1.51	8.64	3.44	0.00
76.713	65.076	11.043	4.43	1.99	64.31	7.80	0.23	1.21	3.69	1.50	8.55	3.08	0.01
76.715	65.076	11.043	4.34	1.85	64.00	7.98	0.21	1.25	3.87	1.57	8.63	3.22	0.00
76.717	65.076	11.043	4.33	1.86	64.46	7.97	0.26	1.28	3.59	1.56	8.68	3.13	0.00
76.719	65.076	11.043	4.41	2.00	64.22	7.87	0.24	1.27	3.90	1.54	8.49	3.11	0.00
76.721	65.076	11.043	4.36	1.91	64.30	7.96	0.24	1.34	3.99	1.56	8.57	3.32	0.00
76.723	65.076	11.043	4.33	1.85	64.47	7.95	0.22	1.35	4.07	1.61	8.58	3.13	0.00
76.725	65.076	11.043	4.33	2.81	63.11	7.74	0.34	1.39	4.51	1.61	8.35	3.06	0.00
76.727	65.076	11.042	4.26	1.81	63.33	8.02	0.24	1.48	4.19	1.65	8.42	3.04	0.02
76.729	65.076	11.043	3.78	7.14	59.37	7.68	0.63	1.49	5.70	1.56	7.92	2.94	0.00
76.731	65.076	11.043	3.86	7.12	59.30	7.69	0.64	1.56	5.50	1.58	8.04	2.71	0.00
76.733	65.076	11.043	4.21	1.74	63.93	8.38	0.23	1.85	3.78	1.90	8.51	3.31	0.00
76.735	65.076	11.043	4.13	1.70	63.82	8.47	0.23	1.98	3.83	1.88	8.48	3.34	0.00
76.737	65.076	11.043	4.00	1.52	63.46	8.79	0.20	2.18	3.54	2.07	8.50	3.67	0.00
76.739	65.076	11.043	3.95	1.41	63.11	9.04	0.16	2.41	3.38	2.20	8.34	3.50	0.00
76.741	65.076	11.043	3.92	1.38	63.12	9.12	0.16	2.56	3.26	2.24	8.34	3.46	0.00
76.743	65.076	11.043	3.87	1.31	63.07	9.30	0.14	2.71	3.17	2.37	8.38	3.49	0.00
76.745	65.076	11.043	3.83	1.25	63.10	9.42	0.14	2.93	2.99	2.51	8.34	3.08	0.00
76.747	65.076	11.043	3.74	1.17	62.72	9.68	0.16	3.16	2.86	2.62	8.30	3.47	0.00
76.749	65.076	11.043	3.64	1.08	62.55	9.76	0.15	3.34	2.98	2.74	8.36	3.20	0.00
76.751	65.076	11.043	3.61	1.02	61.95	10.00	0.17	3.60	2.99	2.91	8.06	3.07	0.00
76.753	65.076	11.043	3.51	0.93	62.06	10.23	0.12	3.83	2.93	3.05	8.00	3.04	0.00
76.755	65.076	11.043	3.41	0.82	62.00	10.45	0.14	4.10	2.81	3.19	8.09	2.90	0.00
76.757	65.076	11.043	3.31	0.72	61.47	10.67	0.10	4.34	2.73	3.41	8.03	2.92	0.00
76.759	65.076	11.043	3.26	0.65	60.91	10.86	0.07	4.61	2.69	3.51	7.89	3.14	0.00
76.761	65.076	11.043	3.17	0.51	60.73	11.10	0.06	4.87	2.50	3.64	7.81	2.65	0.00
76.763	65.076	11.043	3.09	0.87	60.18	11.17	0.11	5.03	2.31	3.77	7.76	3.09	0.00
76.765	65.076	11.043	1.83	0.07	41.03	8.09	28.44	3.80	7.28	2.90	5.16	0.98	0.02
76.767	65.076	11.043	2.71	4.42	56.84	11.29	0.57	5.32	2.77	3.97	7.34	2.40	0.00
76.769	65.076	11.043	2.81	0.49	59.27	12.00	0.07	5.83	2.14	4.19	7.54	2.77	0.00
76.771	65.076	11.043	2.71	0.24	58.61	12.20	0.03	6.24	1.79	4.38	7.42	2.77	0.00
76.773	65.076	11.042	2.57	0.82	57.49	12.50	0.12	6.35	1.85	4.53	7.20	2.65	0.00
76.775	65.076	11.042	0.90	8.45	35.71	6.05	26.87	3.31	9.97	2.49	3.14	0.00	0.04
76.777	65.076	11.042	1.13	9.42	33.34	7.90	25.31	4.43	8.72	3.25	3.87	0.00	0.01
76.779	65.076	11.043	0.95	8.54	40.64	7.75	23.83	4.67	6.23	3.38	3.63	0.00	0.03
76.781	65.076	11.042	1.93	3.62	54.13	13.61	0.33	8.16	1.66	5.48	6.27	1.81	0.00
76.783	65.076	11.043	1.62	3.47	47.74	12.44	11.30	7.78	2.23	5.10	5.47	0.72	0.01
76.785	65.076	11.043	1.82	2.55	54.10	14.38	0.20	9.27	1.41	5.87	6.14	1.66	0.00
76.787	65.076	11.043	1.81	0.05	55.28	15.05	0.00	10.03	1.07	6.12	6.06	1.75	0.00
76.789	65.076	11.043	1.71	0.03	54.97	15.52	0.00	10.57	1.14	6.23	5.85	1.56	0.00
76.791	65.076	11.043	1.62	0.02	54.92	15.64	0.02	10.85	1.03	6.49	5.75	1.73	0.00
76.793	65.076	11.043	1.58	0.03	55.03	16.00	0.00	11.24	1.07	6.52	5.55	1.24	0.00
76.795	65.076	11.043	1.47	0.02	54.09	16.20	0.00	11.79	0.79	6.62	5.23	1.17	0.00
76.797	65.076	11.043	1.40	0.02	53.18	16.49	0.00	12.21	0.83	6.85	4.94	1.33	0.00
76.799	65.076	11.043	1.32	0.01	53.32	16.65	0.00	12.66	0.77	7.04	4.74	1.18	0.00
76.801	65.076	11.043	1.25	0.02	52.98	16.84	0.01	13.03	0.81	7.06	4.55	1.27	0.00
76.803	65.076	11.043	1.19	0.03	52.58	17.03	0.01	13.32	0.70	7.10	4.37	1.27	0.00
76.805	65.076	11.043	1.15	0.02	52.71	17.27	0.00	13.52	0.69	7.22	4.27	1.10	0.00

Table 48 – (continued).													
X (mm)	**Y (mm)**	**Z (mm)**	**Al**	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**
76.807	65.076	11.043	1.09	0.00	52.21	17.50	0.00	13.70	0.56	7.40	4.05	1.02	0.00
76.809	65.076	11.043	1.03	0.02	51.56	17.81	0.00	14.30	0.52	7.54	3.89	0.97	0.00
76.811	65.076	11.043	0.98	0.03	51.29	18.06	0.00	14.54	0.51	7.73	3.70	1.13	0.00
76.813	65.076	11.043	0.94	0.00	51.20	18.40	0.02	14.71	0.58	7.77	3.51	1.17	0.00

Table 49 - Quantitative EPMA data (taken at 15 keV and 80 nA with a focused spot beam) at four locations within the intermetallic phase (indicated in Figure 151(b)). (Percentage by weight).

	Al	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**	**Si**
Phase 1	0.20	0.0	66.81	1.34	27.54	0.12	1.32	0.19	2.31	0.03	0.62	0.26
Phase 2	0.22	0.0	66.64	1.15	27.83	0.08	1.11	0.21	2.23	0.00	0.64	0.28
Phase 3	3.83	0.0	74.46	9.70	0.82	0.49	1.00	0.95	4.39	0.35	3.61	0.18
Phase 4	0.65	0.0	70.43	6.80	9.74	0.26	0.66	0.81	4.42	0.02	2.07	0.15

In order to study the distribution of various elements within the Ni-Cr-Zr braze microstructure, EMPA maps were constructed. These maps are shown in **Figure 152** (for Al, C, Ni and Cr), **Figure 153** (for Zr, Hf and Si), **Figure 154** (for Ru, Ta, Ti and W) and **Figure 155** (for Fe and Mo).

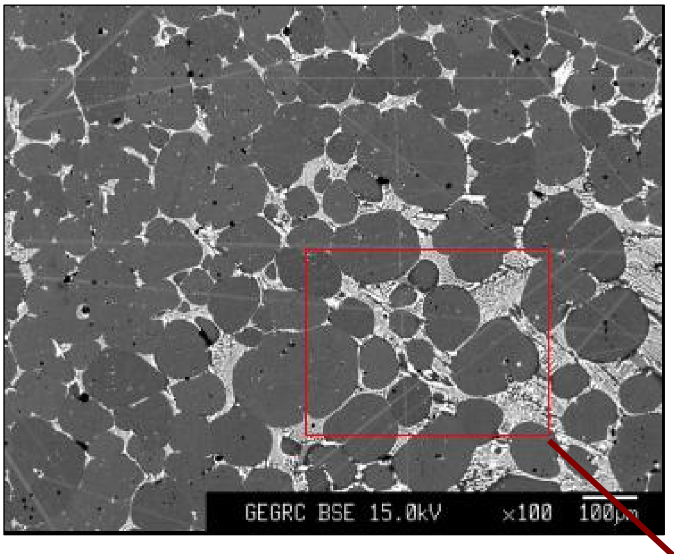


Figure 151(a) – Secondary electron image of the Ni-Cr-Zr alloy in the as-brazed condition.

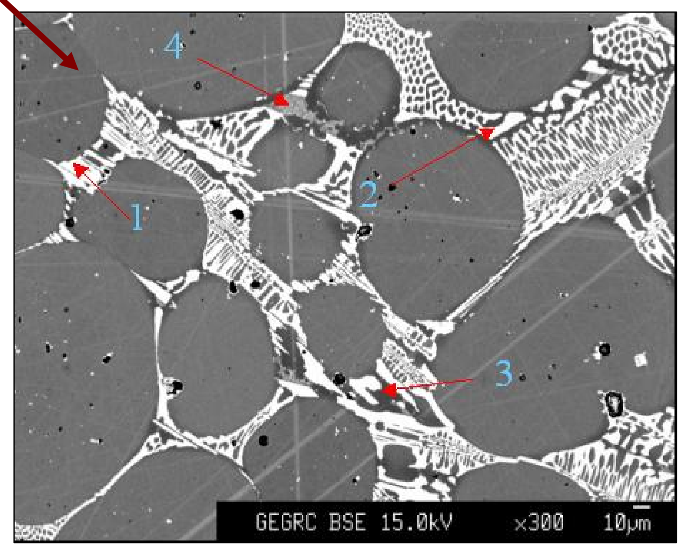


Figure 151(b) – Enlarged view of the secondary electron image of the Ni-Cr-Zr braze, shown in Figure 151(a), highlighting the location of four spot chemical analyses of the intermetallic compound within the braze.

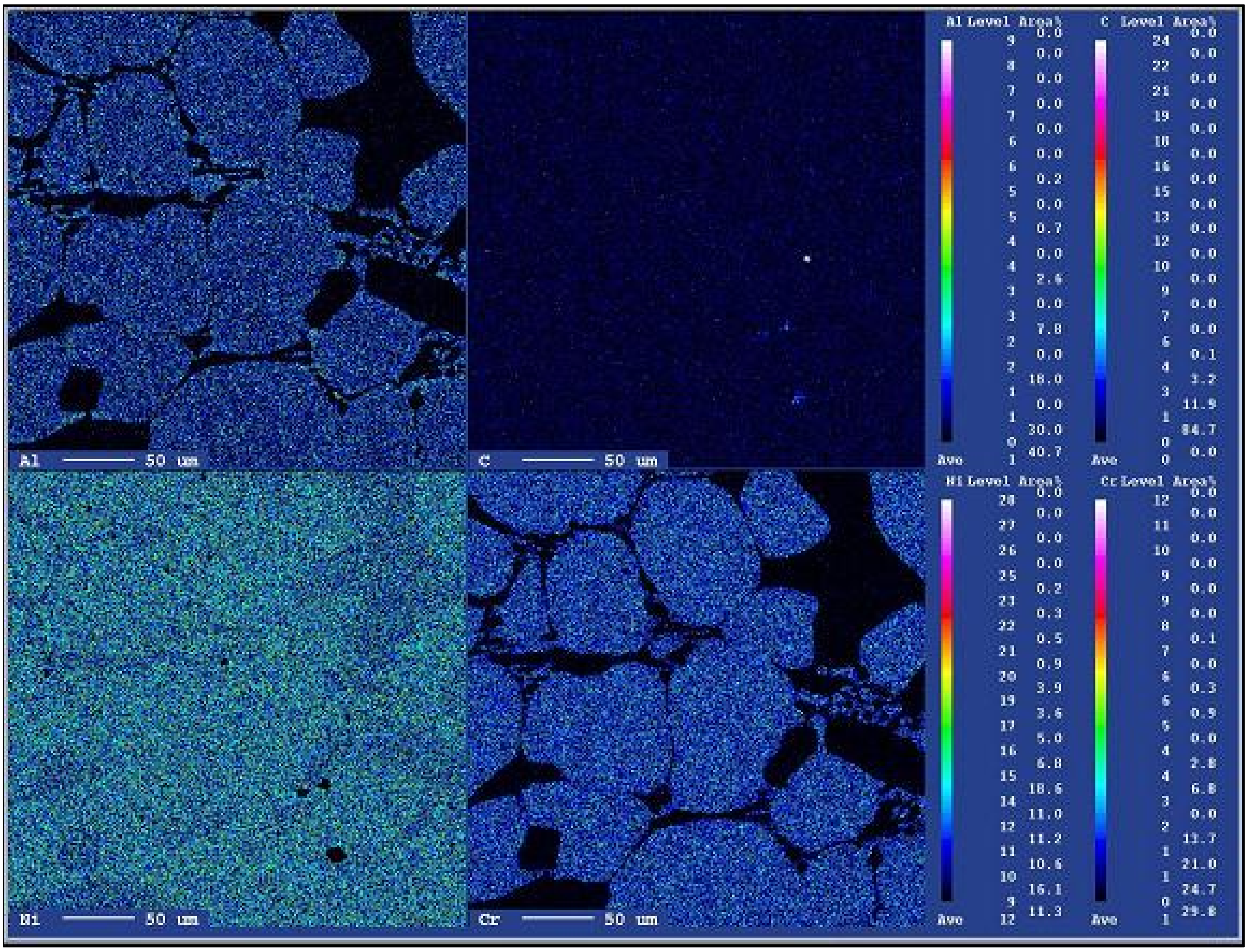


Figure 152 – EMPA maps displaying the distribution of Al, C, Ni and Cr within the MarM247/Ni-Cr-Zr braze microstructure (as-brazed condition).

The EMPA results shown in **Figure 152** indicate that in this braze Al and Cr also partitioned strongly to the MarM247 powder particles during brazing. Given that the braze alloy contains 7% Cr and that a diffusion cycle was not applied, the low Cr concentration measured in the braze alloy between the MarM247 particles was again surprising. Ni and C appeared to be fairly uniformly distributed between the braze alloy and the matrix, with a slightly higher Ni concentration measured in the MarM247 particles.

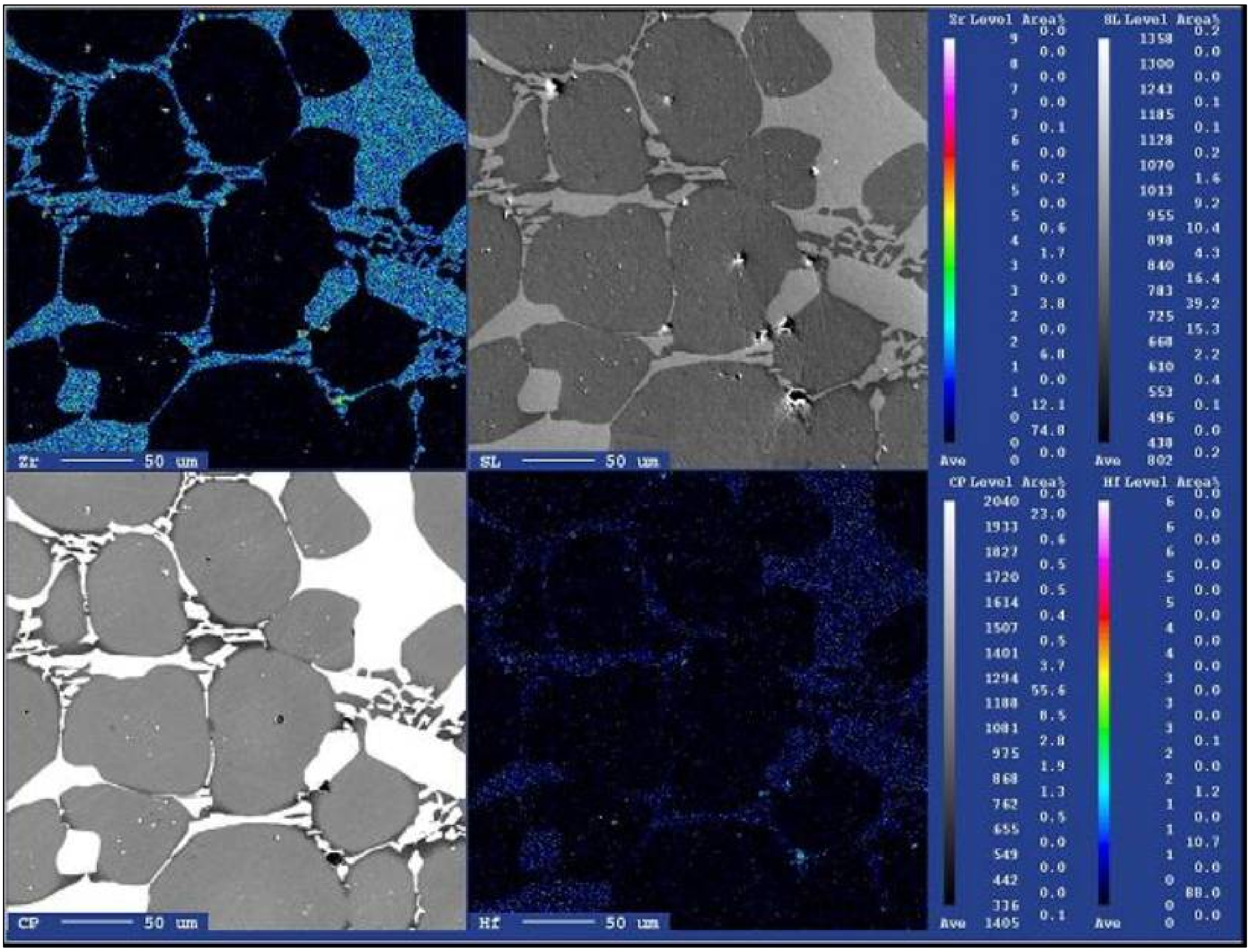


Figure 153 – EMPA maps displaying the distribution of Zr and Hf within the MarM247/Ni-Cr-Zr braze microstructure (as-brazed condition).

The results shown in **Figure 153** suggest that both Hf and Zr partitioned strongly to the braze alloy, which substantiates the results of the line and spot scans shown in **Tables 48 and 49**. The Zr EMPA map confirms that the intermetallic phase within the braze joint was Zr-rich, whereas Zr was almost completely absent from the MarM247 matrix particles (MarM247 has a nominal Zr content of 0.05 wt.%). Hf was not intentionally added to the braze alloy, and the binary eutectic Ni-Zr alloy analyzed in Chapter 3 (see **Table 9**) did not contain any Hf. The Hf detected in the Ni-Cr-Zr alloy may therefore be derived from the MarM247 powder particles (MarM247 has a nominal Hf content of 1.5 wt.%), or from the Cr powder used to make up the ternary alloy.

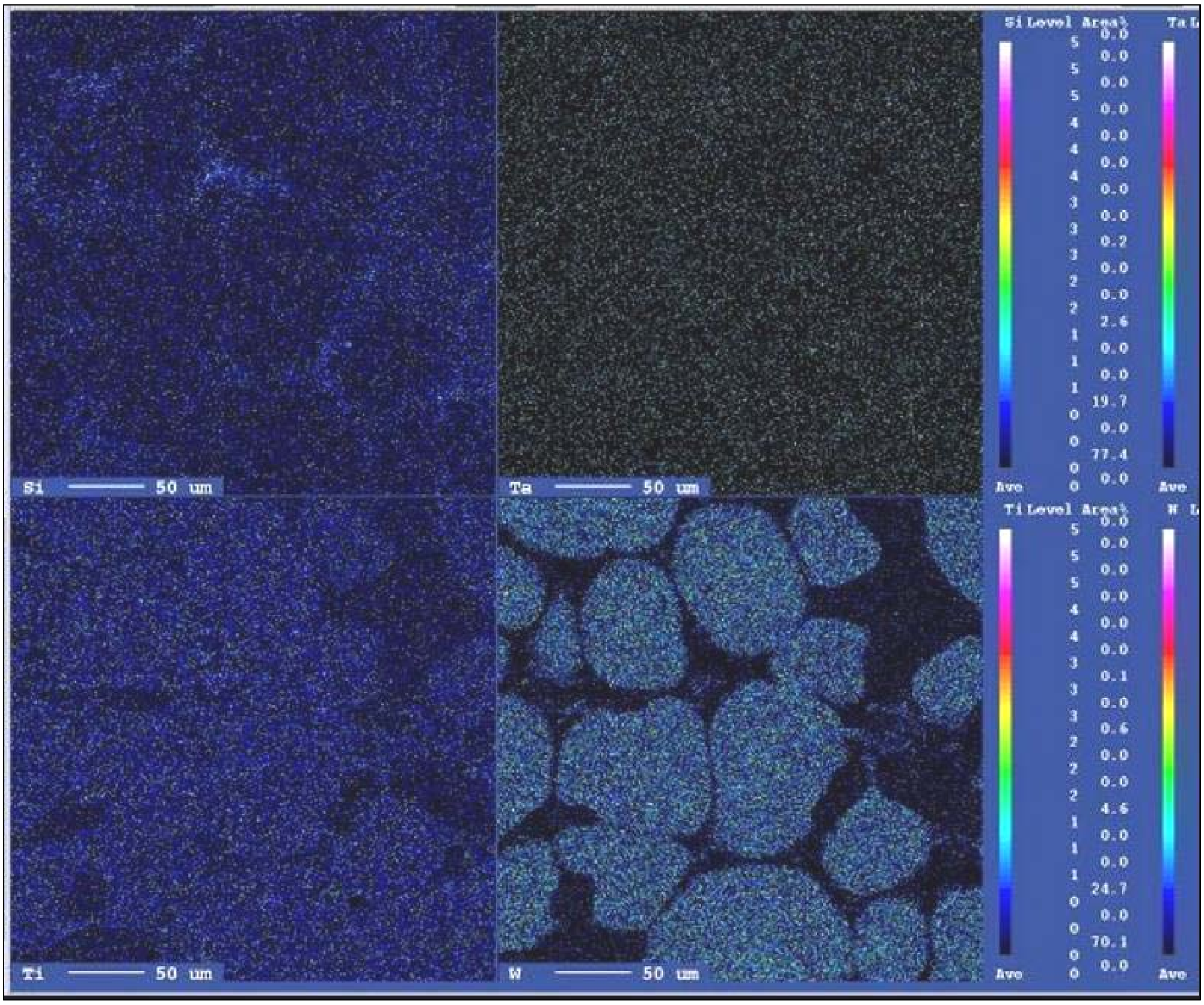


Figure 154 – EMPA maps displaying the distribution of Si, Ta, Ti and W within the MarM247/Ni-Cr-Zr braze microstructure (as-brazed condition).

As shown in **Figure 154**, Si, Ta and Ti were distributed fairly evenly between the braze alloy and the matrix. The Si apparently partitioned weakly to the intermetallic phase (suggesting limited solubility within the intermetallic compound), whereas Ti partitioned preferentially to the MarM247 powder particles. Tungsten, however, partitioned strongly to the MarM247 powder particles, suggesting low solubility within the intermetallic phase. The W appeared to be distributed evenly throughout the matrix particles, implying adequate solubility and little driving force for the precipitation of W-rich carbide particles or Laves phase.

The EMPA maps for Fe and Mo, shown in **Figure 155**, display weak partitioning to the matrix particles, but due to the low levels of these elements within the MarM247 particles and the braze alloy, this tendency was limited.

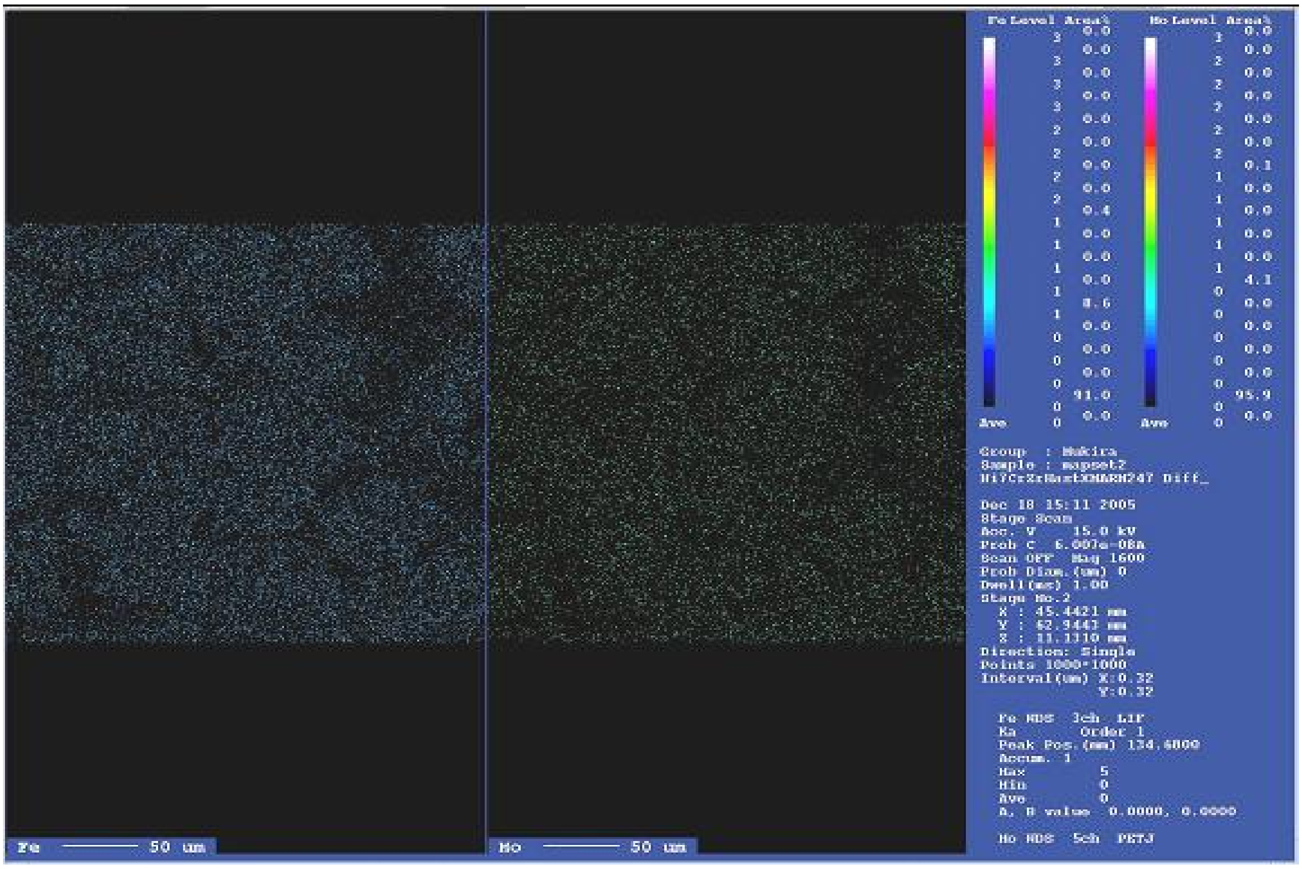
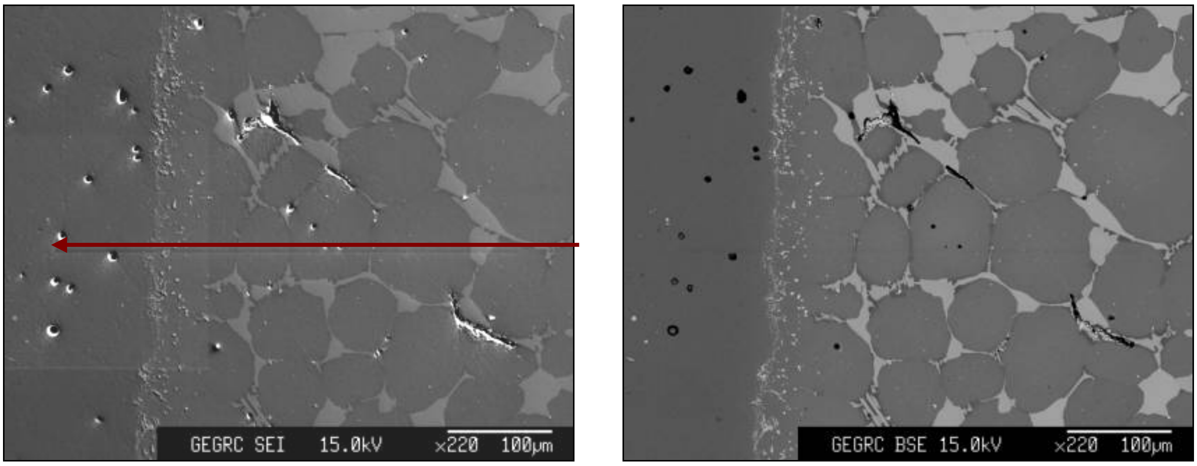


Figure 155 – EMPA maps displaying the distribution of Fe and Mo within the MarM247/Ni-Cr-Zr braze microstructure (as-brazed condition).

11.3.3 <u>The MarM247/Ni-Zr braze joint produced using Ni-7Cr-13Zr braze filler (after an extended diffusion cycle)</u>:

Secondary and backscatter electron images of the MarM247/Ni-Zr joint produced using the experimental Ni-7Cr-13Zr braze filler metal are shown in **Figure 156** after an extended diffusion cycle at 1230°C for 12 hours. The arrow indicates the location and direction of the 2 μm stepped EPMA line scan. The results of the EMPA scan are shown in **Table 50**.

The line scan results shown in **Table 50** revealed the presence of Zr-rich intermetallic phases containing between 20% and 29% Zr, and occasionally between 10% and 18% Zr. In order to perform a more detailed analysis of the intermetallic phase observed in the braze joint, four spot chemical analyses were performed within the intermetallic compound in the braze joint. Two backscatter electron images of the MarM247/Ni-Zr braze joint are shown in **Figure 157**, with the location of the spot analyses highlighted. The results of the microprobe phase analyses, shown in **Table 51**, suggest that the intermetallic phase within the braze alloy (phases 1, 2 and 3) contained between 27 and 28% Zr, as well as some Hf, Ta and Co. Phase 4, shown in **Table 51**, was most likely the Ni-rich γ phase, with some Cr, Co and W in solution. The binary Ni-Zr phase diagram, shown in **Figure 50**, indicates that the Ni_7Zr_2 intermetallic phase contains approximately 30 wt.% Zr, whereas the Ni_5Zr intermetallic compound contains approximately between 21 and 26 wt.% Zr. The results shown in **Table 51** are therefore inconclusive, suggesting that the intermetallic phase in the braze joint could be either Ni_5Zr or Ni_7Zr_2. As a result of this uncertainty, another line scan was performed. The results of this line scan are described in §11.3.4.



(a) (b)

Figure 156 – Secondary (a) and backscatter (b) electron images of the MarM247/Ni-7Cr-13Zr joint after an extended diffusion cycle (adjacent to the interface).

Table 50 – The results of the EMPA scan of the MarM247/Ni-7Cr-13Zr braze joint after an extended diffusion cycle. (All compositions given in wt.%).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
47.333	62.92	11.122	2.62	0.05	71.83	9.93	0.70	0.56	1.68	0.50	4.77	6.11	0.46
47.335	62.92	11.122	2.61	0.07	71.38	9.89	0.70	0.53	1.67	0.52	4.82	5.97	0.46
47.338	62.92	11.122	2.62	0.03	71.76	9.89	0.72	0.57	1.56	0.49	4.75	6.00	0.46
47.34	62.92	11.12	2.59	0.03	70.71	9.93	0.72	0.54	1.90	0.49	4.75	6.05	0.46
47.341	62.92	11.12	2.59	0.04	70.62	9.86	0.74	0.57	1.67	0.49	4.69	6.13	0.46
47.343	62.92	11.12	2.57	0.05	70.84	9.83	0.72	0.55	1.51	0.50	4.76	6.09	0.45
47.346	62.92	11.12	2.61	0.04	71.22	9.78	0.76	0.56	1.44	0.47	4.79	5.77	0.48
47.348	62.92	11.12	2.58	0.07	71.05	9.86	0.76	0.56	1.70	0.50	4.81	5.98	0.46
47.35	62.92	11.12	2.55	0.07	71.08	9.76	0.72	0.54	1.72	0.47	4.75	6.09	0.46
47.352	62.92	11.122	2.61	0.04	71.34	9.70	0.79	0.56	1.69	0.45	4.72	5.83	0.48
47.354	62.92	11.122	2.62	0.08	71.67	9.67	0.69	0.55	1.79	0.45	4.76	5.74	0.43
47.356	62.92	11.12	2.59	0.08	71.61	9.64	0.72	0.54	1.71	0.51	4.78	5.93	0.46
47.358	62.92	11.122	2.61	0.03	71.99	9.54	0.65	0.54	1.77	0.47	4.71	6.05	0.46
47.36	62.92	11.122	1.29	0.97	68.22	5.20	14.72	0.33	1.69	0.27	3.29	2.88	0.28
47.362	62.92	11.122	0.20	1.69	65.25	1.02	26.72	0.07	1.55	0.09	1.97	0.75	0.11
47.364	62.92	11.122	0.16	1.71	64.84	0.82	27.12	0.06	1.56	0.07	1.94	0.59	0.09
47.366	62.92	11.122	0.17	1.78	65.10	0.73	26.92	0.07	1.53	0.06	1.88	0.21	0.10
47.368	62.92	11.122	0.17	1.76	65.53	0.71	27.04	0.05	1.47	0.07	1.93	0.25	0.10
47.37	62.92	11.12	0.16	1.79	65.22	0.65	27.06	0.06	1.57	0.09	1.92	0.46	0.10
47.372	62.92	11.12	0.17	1.76	64.78	0.69	27.16	0.07	1.54	0.05	1.89	0.52	0.10
47.374	62.92	11.122	0.16	1.79	65.09	0.68	27.27	0.07	1.36	0.07	1.95	0.39	0.11
47.376	62.92	11.12	0.17	1.78	64.38	0.72	27.23	0.07	1.49	0.07	1.85	0.54	0.09
47.378	62.92	11.122	0.16	1.81	65.08	0.69	27.23	0.08	1.49	0.08	1.90	0.58	0.11
47.38	62.92	11.122	1.03	1.22	67.75	3.65	18.44	0.22	1.59	0.23	2.79	2.10	0.21
47.382	62.92	11.12	2.57	0.09	71.37	8.95	1.72	0.49	1.47	0.46	4.67	5.59	0.45
47.384	62.92	11.122	2.66	0.01	71.73	9.45	0.66	0.56	1.70	0.49	4.76	5.74	0.42
47.386	62.92	11.12	2.60	0.04	71.10	9.65	0.73	0.55	1.72	0.52	4.75	5.73	0.44
47.388	62.92	11.122	2.63	0.07	71.80	9.52	0.77	0.54	1.80	0.53	4.76	5.87	0.46
47.39	62.92	11.122	2.63	0.04	71.58	9.61	0.74	0.55	1.76	0.51	4.79	5.72	0.44
47.392	62.92	11.12	2.58	0.06	71.02	9.65	0.72	0.52	1.83	0.51	4.76	6.24	0.45
47.394	62.92	11.122	2.61	0.08	72.02	9.63	0.78	0.54	1.85	0.44	4.86	6.11	0.44
47.396	62.92	11.122	2.61	0.06	71.92	9.56	0.73	0.51	1.73	0.49	4.83	5.91	0.45
47.398	62.92	11.122	2.62	0.04	71.41	9.53	0.69	0.52	1.77	0.48	4.87	6.47	0.45
47.4	62.92	11.122	2.62	0.03	71.46	9.63	0.72	0.54	1.73	0.47	4.84	6.18	0.45
47.402	62.92	11.122	2.59	0.05	71.49	9.68	0.75	0.53	1.96	0.50	4.84	6.01	0.44
47.404	62.92	11.122	2.61	0.05	71.66	9.63	0.75	0.54	1.86	0.44	4.86	6.02	0.43
47.406	62.92	11.122	2.59	0.05	71.82	9.61	0.73	0.50	1.78	0.44	4.92	6.31	0.45

Table 50 – (continued).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
47.408	62.92	11.122	2.59	0.05	71.68	9.70	0.75	0.51	1.88	0.47	4.88	6.10	0.45
47.41	62.92	11.12	2.57	0.05	70.88	9.71	0.75	0.51	1.76	0.45	4.87	6.46	0.45
47.412	62.92	11.122	2.60	0.05	71.21	9.71	0.75	0.50	1.77	0.47	4.90	6.41	0.47
47.414	62.92	11.122	2.57	0.06	70.97	9.66	0.74	0.51	1.70	0.43	4.84	6.70	0.43
47.416	62.92	11.122	2.59	0.06	71.50	9.74	0.73	0.51	1.89	0.46	4.94	6.28	0.45
47.418	62.92	11.122	2.59	0.03	71.51	9.65	0.75	0.52	1.82	0.46	4.94	6.16	0.44
47.42	62.92	11.122	2.60	0.05	71.74	9.62	0.70	0.48	1.72	0.44	4.91	6.23	0.45
47.422	62.92	11.12	2.48	0.05	70.20	9.63	0.72	0.49	1.96	0.52	4.83	6.13	0.44
47.424	62.92	11.12	2.55	0.05	70.49	9.56	0.71	0.48	1.81	0.49	4.86	6.18	0.46
47.426	62.92	11.122	2.58	0.05	71.49	9.60	0.70	0.50	1.94	0.46	4.91	6.07	0.44
47.428	62.92	11.12	2.53	0.05	70.61	9.56	0.68	0.49	1.97	0.46	4.89	6.48	0.45
47.43	62.92	11.122	2.55	0.06	71.19	9.47	0.72	0.46	2.03	0.47	4.99	6.33	0.44
47.432	62.92	11.12	2.36	1.77	67.34	9.20	2.77	0.47	2.27	0.48	4.65	6.64	0.44
47.434	62.92	11.12	2.51	0.05	70.29	9.61	0.76	0.49	2.15	0.51	4.91	6.65	0.44
47.436	62.92	11.12	2.52	0.05	70.50	9.60	0.77	0.47	2.04	0.47	4.90	6.70	0.43
47.438	62.92	11.122	2.55	0.10	71.45	9.56	0.67	0.49	2.06	0.48	4.85	6.53	0.44
47.44	62.92	11.122	2.57	0.06	71.73	9.57	0.68	0.48	1.81	0.45	5.00	6.66	0.44
47.442	62.92	11.122	2.59	0.06	71.42	9.71	0.77	0.49	2.03	0.47	4.90	6.54	0.46
47.444	62.92	11.122	2.56	0.07	70.87	9.69	0.83	0.48	2.05	0.46	4.97	6.63	0.43
47.446	62.92	11.12	2.23	0.70	64.10	8.98	6.50	0.42	3.50	0.45	4.42	6.40	0.44
47.448	62.92	11.122	2.54	0.21	69.71	9.59	1.74	0.50	2.44	0.49	4.87	6.72	0.43
47.45	62.92	11.122	2.56	0.03	71.11	9.77	0.69	0.50	1.78	0.50	4.90	6.64	0.45
47.452	62.92	11.12	2.53	0.04	71.08	9.86	0.72	0.51	1.92	0.50	4.89	7.11	0.44
47.454	62.92	11.12	2.54	0.03	70.91	9.83	0.74	0.50	1.89	0.47	4.90	7.04	0.46
47.456	62.92	11.12	2.53	0.06	70.46	9.86	0.76	0.50	1.96	0.47	4.84	6.85	0.46
47.458	62.92	11.122	2.58	0.07	71.35	9.79	0.71	0.53	1.72	0.50	4.87	6.44	0.45
47.46	62.92	11.12	2.57	0.04	70.46	9.82	0.67	0.52	2.13	0.50	4.79	6.39	0.44
47.462	62.92	11.122	2.59	0.05	71.32	9.84	0.73	0.55	1.85	0.47	4.89	6.26	0.45
47.464	62.92	11.122	2.58	0.06	71.64	9.83	0.75	0.54	1.95	0.47	4.92	6.07	0.44
47.466	62.92	11.122	2.62	0.04	71.78	9.93	0.71	0.53	1.87	0.47	4.87	5.76	0.44
47.468	62.92	11.12	2.54	0.06	70.81	10.04	0.69	0.55	2.06	0.47	4.85	6.32	0.44
47.47	62.92	11.12	2.56	0.05	70.93	10.05	0.77	0.55	2.25	0.49	4.82	6.20	0.47
47.472	62.92	11.122	2.62	0.03	71.40	9.88	0.70	0.59	2.04	0.49	4.79	5.99	0.44
47.474	62.92	11.122	2.83	0.04	72.11	9.65	0.61	0.57	1.79	0.49	4.77	5.69	0.49
47.476	62.92	11.12	2.17	0.45	71.35	7.02	9.44	0.44	1.35	0.30	3.75	2.28	0.45
47.478	62.92	11.122	2.87	0.04	72.69	9.62	0.60	0.53	1.69	0.46	4.78	5.38	0.49
47.48	62.92	11.12	2.62	0.05	70.86	9.89	0.72	0.58	1.82	0.48	4.89	6.28	0.46
47.482	62.92	11.122	2.60	0.03	71.48	9.79	0.75	0.58	1.94	0.47	4.88	6.20	0.43
47.484	62.92	11.122	2.57	0.04	71.12	9.77	0.73	0.57	1.85	0.49	4.83	6.20	0.45
47.486	62.92	11.12	2.52	0.06	70.49	9.83	0.71	0.57	1.80	0.49	4.84	6.73	0.46
47.488	62.92	11.122	2.58	0.17	71.20	9.68	0.73	0.55	1.90	0.48	4.85	6.44	0.45
47.49	62.92	11.12	2.52	0.38	70.46	9.64	0.92	0.52	2.15	0.51	4.85	6.60	0.46
47.492	62.92	11.122	2.55	0.07	71.46	9.64	0.79	0.51	2.17	0.48	4.94	6.31	0.44
47.494	62.92	11.12	2.51	0.05	70.14	9.78	0.72	0.53	1.99	0.49	4.90	6.86	0.46
47.496	62.92	11.12	2.54	0.04	70.88	9.78	0.70	0.53	2.00	0.46	4.90	7.00	0.44
47.498	62.92	11.12	2.53	0.05	70.78	9.77	0.70	0.51	1.78	0.49	4.87	7.16	0.44
47.5	62.92	11.122	2.57	0.04	71.07	9.62	0.72	0.53	1.72	0.48	4.92	7.03	0.44
47.502	62.92	11.12	2.54	0.03	70.78	9.63	0.69	0.51	1.66	0.52	4.98	7.42	0.46
47.504	62.92	11.122	2.57	0.05	71.01	9.58	0.71	0.51	1.65	0.50	5.04	7.24	0.46
47.506	62.92	11.12	2.54	0.04	70.16	9.65	0.69	0.49	1.69	0.47	4.95	7.35	0.44
47.508	62.92	11.12	2.50	0.07	70.61	9.57	0.75	0.52	1.71	0.48	5.01	7.25	0.45
47.51	62.92	11.12	2.49	0.04	70.57	9.60	0.66	0.50	1.55	0.47	4.98	6.98	0.44
47.512	62.92	11.122	2.44	0.16	69.53	9.42	1.53	0.52	1.94	0.48	4.94	6.96	0.45
47.514	62.92	11.12	2.50	0.02	70.72	9.58	0.68	0.49	1.66	0.49	5.01	7.21	0.43
47.516	62.92	11.12	2.49	0.15	68.94	9.48	1.24	0.50	2.02	0.46	4.96	7.22	0.44
47.518	62.92	11.12	2.51	0.08	69.86	9.57	0.84	0.50	1.83	0.45	4.97	7.12	0.45
47.52	62.92	11.12	2.53	0.05	70.54	9.64	0.76	0.50	1.94	0.52	4.97	7.13	0.45
47.522	62.92	11.12	2.53	0.04	70.39	9.58	0.62	0.50	1.88	0.50	5.03	7.32	0.42
47.524	62.92	11.12	2.47	0.05	70.26	9.67	0.60	0.53	1.73	0.48	4.98	7.17	0.44
47.526	62.92	11.12	2.50	0.05	70.67	9.57	0.71	0.53	1.69	0.51	5.03	7.26	0.44

Table 50 – (continued).													
X (mm)	**Y (mm)**	**Z (mm)**	**Al**	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**
47.528	62.92	11.12	2.51	0.04	70.12	9.55	0.67	0.50	1.81	0.49	5.04	7.50	0.44
47.53	62.92	11.12	2.49	0.06	69.85	9.51	0.69	0.50	1.82	0.48	4.89	7.46	0.45
47.532	62.92	11.12	2.52	0.03	70.29	9.48	0.75	0.53	1.78	0.50	4.95	7.46	0.47
47.534	62.92	11.12	2.53	0.06	70.57	9.37	0.79	0.49	1.79	0.50	4.98	7.33	0.45
47.536	62.92	11.12	2.51	0.05	70.34	9.44	0.70	0.53	1.71	0.51	4.92	7.59	0.45
47.538	62.92	11.122	2.56	0.06	71.21	9.50	0.80	0.54	1.46	0.51	4.92	6.94	0.44
47.54	62.92	11.12	2.53	0.07	70.98	9.59	0.65	0.54	1.65	0.49	4.91	7.05	0.45
47.542	62.92	11.12	2.53	0.03	70.23	9.66	0.70	0.56	1.60	0.47	4.90	6.86	0.45
47.544	62.92	11.12	2.55	0.06	70.39	9.64	0.73	0.58	1.81	0.45	4.87	6.62	0.44
47.546	62.92	11.12	2.55	0.03	71.00	9.70	0.76	0.56	1.66	0.52	4.89	6.48	0.44
47.548	62.92	11.12	2.56	0.04	71.19	9.84	0.70	0.60	1.65	0.49	4.88	6.44	0.43
47.55	62.92	11.122	2.63	0.01	71.46	9.74	0.63	0.59	1.58	0.51	4.88	6.36	0.46
47.552	62.92	11.12	2.78	0.04	72.40	9.63	0.52	0.56	1.50	0.45	4.80	5.62	0.50
47.554	62.92	11.12	3.04	0.04	73.72	9.70	0.70	0.58	1.32	0.48	4.69	3.41	0.54
47.556	62.92	11.12	2.81	0.01	72.05	9.70	0.68	0.60	1.53	0.46	4.77	4.94	0.50
47.558	62.92	11.12	2.63	0.04	71.79	9.72	0.67	0.58	1.59	0.51	4.81	5.99	0.48
47.56	62.92	11.12	2.58	0.05	72.18	9.79	0.73	0.58	1.63	0.52	4.86	6.09	0.44
47.562	62.92	11.12	2.56	0.04	71.97	9.67	0.72	0.63	1.65	0.51	4.85	6.62	0.45
47.564	62.92	11.122	2.56	0.12	71.41	9.45	1.51	0.53	1.75	0.47	4.78	6.34	0.45
47.566	62.92	11.122	2.57	0.06	72.23	9.49	0.68	0.59	1.71	0.52	4.80	6.31	0.44
47.568	62.92	11.122	2.54	0.13	71.01	9.31	1.62	0.56	1.58	0.52	4.78	6.58	0.44
47.57	62.92	11.122	2.59	0.04	72.32	9.40	0.73	0.56	1.60	0.49	4.89	6.80	0.45
47.572	62.92	11.12	2.55	0.07	72.27	9.50	0.71	0.56	1.67	0.51	4.92	7.00	0.44
47.575	62.92	11.122	2.56	0.07	71.82	9.36	0.77	0.57	1.60	0.51	4.86	7.13	0.44
47.576	62.92	11.12	2.52	0.06	71.41	9.55	0.73	0.59	1.71	0.53	4.81	7.12	0.45
47.578	62.92	11.12	2.54	0.07	71.55	9.65	0.70	0.59	1.83	0.47	4.90	7.06	0.44
47.581	62.92	11.122	2.58	0.05	72.01	9.49	0.71	0.53	1.43	0.51	4.87	6.77	0.45
47.583	62.92	11.12	2.54	0.04	71.98	9.67	0.70	0.56	1.49	0.53	4.94	6.62	0.44
47.584	62.92	11.122	2.59	0.04	72.58	9.67	0.73	0.60	1.53	0.52	4.93	6.52	0.44
47.586	62.92	11.12	2.57	0.06	71.81	9.75	0.73	0.56	1.72	0.53	4.88	6.34	0.44
47.589	62.92	11.12	2.51	0.03	71.69	9.70	0.73	0.56	1.87	0.54	4.85	6.48	0.45
47.59	62.92	11.12	2.53	0.06	71.59	9.75	0.72	0.59	1.72	0.48	4.87	6.30	0.44
47.592	62.92	11.12	2.55	0.04	71.92	9.71	0.70	0.58	1.80	0.49	4.85	6.63	0.45
47.595	62.92	11.122	2.59	0.07	72.38	9.59	0.73	0.59	1.89	0.50	4.87	5.89	0.44
47.597	62.92	11.122	2.59	0.06	72.64	9.61	0.67	0.57	1.69	0.48	4.86	6.31	0.47
47.599	62.92	11.12	2.55	0.07	72.30	9.71	0.71	0.60	1.75	0.46	4.87	6.43	0.45
47.601	62.92	11.12	2.56	0.05	72.04	9.63	0.69	0.60	1.93	0.50	4.84	6.27	0.45
47.603	62.92	11.12	2.59	0.05	71.86	9.66	0.70	0.59	1.89	0.48	4.84	6.18	0.44
47.605	62.92	11.12	2.61	0.03	72.12	9.66	0.72	0.58	1.71	0.50	4.76	6.32	0.46
47.607	62.92	11.12	2.67	0.03	72.16	9.46	0.70	0.60	1.84	0.51	4.82	6.03	0.46
47.609	62.92	11.12	2.94	0.05	73.96	9.42	0.68	0.60	1.53	0.49	4.74	4.29	0.53
47.611	62.92	11.122	2.89	0.00	74.09	9.34	0.54	0.60	1.78	0.50	4.77	5.02	0.50
47.613	62.92	11.12	2.61	0.05	72.24	9.62	0.62	0.63	1.85	0.50	4.82	6.00	0.46
47.615	62.92	11.122	2.59	0.06	72.34	9.66	0.71	0.68	1.93	0.55	4.79	5.97	0.42
47.617	62.92	11.12	2.54	0.05	71.93	9.80	0.69	0.69	1.79	0.55	4.78	6.14	0.44
47.619	62.92	11.122	2.58	0.05	72.55	9.75	0.75	0.75	1.83	0.54	4.78	5.99	0.43
47.621	62.92	11.122	2.56	0.04	72.55	9.75	0.71	0.76	1.68	0.57	4.80	6.20	0.43
47.623	62.92	11.122	2.58	0.03	73.00	9.73	0.68	0.79	1.56	0.63	4.84	5.74	0.43
47.625	62.92	11.122	2.49	0.11	72.13	9.91	0.94	0.82	1.77	0.66	4.80	5.78	0.42
47.627	62.92	11.122	2.52	0.03	72.23	9.88	0.65	0.84	1.84	0.66	4.80	5.73	0.42
47.629	62.92	11.122	2.20	0.85	65.33	9.14	6.58	0.82	3.24	0.67	4.42	5.25	0.41
47.631	62.92	11.12	2.37	0.28	69.64	9.63	2.21	0.94	2.09	0.71	4.71	6.06	0.41
47.633	62.92	11.12	2.43	0.04	71.41	9.76	0.64	1.02	1.71	0.77	4.75	5.85	0.42
47.635	62.92	11.12	2.39	0.04	71.52	9.85	0.60	1.11	1.77	0.83	4.75	6.36	0.41
47.637	62.92	11.122	2.39	0.02	71.73	9.76	0.63	1.19	1.74	0.90	4.82	6.03	0.40
47.639	62.92	11.122	2.35	0.07	70.54	9.76	1.02	1.29	1.78	0.93	4.67	5.56	0.36
47.641	62.92	11.122	2.35	0.08	70.80	9.80	0.94	1.37	1.76	1.01	4.67	5.59	0.38
47.643	62.92	11.122	2.32	0.02	71.37	9.95	0.59	1.52	1.85	1.04	4.73	6.19	0.38
47.645	62.92	11.122	2.28	0.04	71.07	9.95	0.53	1.56	1.70	1.12	4.68	6.19	0.39
47.647	62.92	11.122	2.26	0.05	70.75	10.12	0.56	1.73	1.67	1.16	4.74	5.97	0.38

Table 50 – (continued).													
X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
47.649	62.92	11.122	2.23	0.03	70.37	10.16	0.57	1.85	1.45	1.25	4.68	6.13	0.34
47.651	62.92	11.122	2.17	0.03	69.91	10.27	0.53	1.95	1.83	1.36	4.65	5.98	0.35
47.653	62.92	11.122	2.13	0.03	69.66	10.41	0.45	2.15	1.59	1.46	4.61	6.15	0.36
47.655	62.92	11.122	2.06	0.14	68.70	10.41	1.81	2.30	1.67	1.52	4.51	5.73	0.33
47.657	62.92	11.122	2.05	0.02	69.91	10.83	0.43	2.62	1.28	1.77	4.55	5.95	0.31
47.659	62.92	11.122	2.01	0.00	69.86	11.13	0.43	2.82	1.36	1.84	4.59	5.33	0.32
47.661	62.92	11.122	2.00	0.03	69.28	11.27	0.43	3.01	1.30	1.97	4.53	5.38	0.29
47.663	62.92	11.122	1.93	0.00	68.83	11.41	0.37	3.17	1.35	2.09	4.45	5.33	0.29
47.665	62.92	11.122	1.90	0.00	68.45	11.53	0.33	3.36	1.40	2.18	4.37	5.02	0.28
47.667	62.92	11.122	1.83	0.01	68.75	11.70	0.28	3.56	1.26	2.34	4.33	4.99	0.27
47.669	62.92	11.122	1.79	0.02	68.58	11.74	0.28	3.84	1.40	2.47	4.40	4.86	0.25
47.671	62.92	11.122	1.75	0.00	68.48	11.92	0.19	4.11	1.48	2.63	4.32	4.56	0.24
47.673	62.92	11.12	1.52	0.43	63.72	11.60	5.46	4.07	1.67	2.64	3.99	4.04	0.25
47.675	62.92	11.12	0.96	1.88	47.72	9.21	23.85	3.62	2.96	2.34	3.00	2.84	0.33
47.677	62.92	11.122	1.06	1.74	51.00	9.87	20.56	4.08	2.20	2.61	3.15	3.14	0.40
47.679	62.92	11.122	0.99	1.66	50.60	10.18	20.07	4.48	2.03	2.90	3.13	3.29	0.40
47.681	62.92	11.122	1.36	0.00	65.94	12.92	0.34	5.85	1.35	3.62	4.01	4.10	0.18
47.683	62.92	11.12	1.30	0.02	64.65	13.10	0.33	6.15	1.27	3.84	3.94	4.03	0.17
47.685	62.92	11.122	1.26	0.00	64.76	13.35	0.10	6.63	1.24	4.04	3.96	3.94	0.15
47.687	62.92	11.122	1.21	0.03	63.69	13.63	0.24	6.82	1.16	4.17	3.84	3.67	0.15
47.689	62.92	11.122	1.09	0.40	60.40	13.37	3.19	6.98	1.46	4.18	3.66	3.20	0.19
47.691	62.92	11.12	1.06	0.22	60.67	13.85	2.05	7.32	0.90	4.43	3.65	3.41	0.18
47.693	62.92	11.122	0.87	1.37	53.20	12.39	10.50	6.73	1.83	4.07	3.15	2.67	0.34
47.695	62.92	11.122	0.80	1.73	51.11	12.36	12.66	7.03	1.83	4.20	3.02	2.58	0.36
47.697	62.92	11.12	0.90	0.43	58.27	14.44	3.23	8.38	0.92	4.93	3.42	3.03	0.24
47.699	62.92	11.12	0.87	0.07	59.55	15.03	0.80	9.04	0.71	5.33	3.38	2.67	0.12
47.701	62.92	11.12	0.85	0.01	59.91	15.41	0.10	9.44	0.52	5.46	3.38	2.48	0.10
47.703	62.92	11.122	0.81	0.00	59.78	15.53	0.17	9.80	0.65	5.50	3.33	2.19	0.10
47.705	62.92	11.12	0.78	0.00	59.52	15.85	0.01	9.94	0.68	5.67	3.25	1.87	0.08
47.707	62.92	11.12	0.74	0.00	59.02	15.93	0.02	10.30	0.58	5.86	3.14	1.90	0.09
47.709	62.92	11.122	0.72	0.00	58.68	16.07	0.00	10.84	0.73	5.95	3.08	1.72	0.06
47.711	62.92	11.122	0.67	0.00	57.97	16.20	0.02	11.17	0.65	6.06	3.00	1.59	0.07
47.713	62.92	11.12	0.63	0.00	57.60	16.39	0.01	11.34	0.74	6.17	2.93	1.53	0.06
47.715	62.92	11.122	0.60	0.01	57.29	16.53	0.00	11.80	0.67	6.41	2.81	1.37	0.05
47.717	62.92	11.12	0.56	0.00	56.56	16.79	0.01	12.11	0.72	6.40	2.73	1.70	0.06
47.719	62.92	11.122	0.55	0.00	56.47	16.90	0.00	12.41	0.77	6.58	2.61	1.55	0.04
47.721	62.92	11.122	0.52	0.00	55.53	16.94	0.00	12.80	0.62	6.69	2.53	1.50	0.04
47.723	62.92	11.122	0.49	0.00	55.37	16.98	0.01	12.98	0.44	6.70	2.48	1.36	0.04
47.725	62.92	11.122	0.47	0.00	55.51	16.98	0.00	13.17	0.57	6.86	2.41	1.35	0.03
47.727	62.92	11.122	0.45	0.01	54.70	17.13	0.02	13.44	0.45	6.95	2.35	1.28	0.02
47.729	62.92	11.12	0.42	0.01	54.12	17.23	0.02	13.57	0.30	6.97	2.23	1.30	0.02
47.731	62.92	11.122	0.44	0.00	54.30	17.22	0.01	13.75	0.41	6.95	2.13	1.23	0.02
47.733	62.92	11.12	0.40	0.00	53.15	17.62	0.01	14.16	0.34	7.17	2.09	1.27	0.02
47.735	62.92	11.118	0.36	0.00	52.29	17.92	0.03	14.33	0.36	7.35	1.99	1.04	0.01
47.737	62.92	11.116	0.34	0.00	51.72	18.34	0.01	14.48	0.47	7.41	1.91	1.17	0.02
47.739	62.92	11.118	0.33	0.00	51.83	18.50	0.01	14.83	0.41	7.58	1.84	1.20	0.01
47.741	62.92	11.116	0.32	0.00	51.16	18.69	0.03	15.02	0.57	7.54	1.78	0.94	0.01
47.743	62.92	11.12	0.32	0.01	51.89	18.44	0.01	15.38	0.30	7.65	1.82	0.83	0.01
47.745	62.92	11.12	0.30	0.00	51.65	18.87	0.00	15.46	0.32	7.83	1.71	0.86	0.00
47.747	62.92	11.12	0.29	0.00	50.87	18.79	0.00	15.81	0.22	7.82	1.64	0.87	0.01
47.749	62.92	11.12	0.27	0.00	50.58	18.82	0.01	16.00	0.31	7.85	1.63	0.73	0.00
47.751	62.92	11.122	0.26	0.00	50.84	18.81	0.00	16.13	0.44	7.90	1.59	0.95	0.01
47.753	62.92	11.12	0.24	0.00	50.47	19.01	0.00	16.25	0.38	7.94	1.55	0.34	0.01
47.755	62.92	11.122	0.24	0.00	50.36	19.07	0.00	16.48	0.57	8.06	1.57	0.64	0.00
47.757	62.92	11.122	0.23	0.00	50.17	18.92	0.00	16.59	0.48	8.21	1.48	0.51	0.01
47.759	62.92	11.122	0.22	0.00	49.50	18.92	0.00	16.69	0.42	8.12	1.46	0.54	0.01
47.761	62.92	11.122	0.21	0.00	49.52	19.18	0.00	16.90	0.62	8.19	1.44	0.58	0.00
47.763	62.92	11.122	0.21	0.00	49.53	19.26	0.00	16.80	0.62	8.21	1.44	0.73	0.00
47.765	62.92	11.122	0.20	0.00	49.41	19.31	0.00	17.08	0.53	8.27	1.40	0.47	0.01
47.767	62.92	11.12	0.19	0.00	48.90	19.61	0.02	17.10	0.69	8.28	1.39	0.66	0.00

Table 50 – (continued).													
X (mm)	**Y (mm)**	**Z (mm)**	**Al**	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**
47.769	62.92	11.122	0.19	0.00	49.01	19.67	0.02	17.18	0.61	8.27	1.36	0.75	0.00
47.771	62.92	11.122	0.18	0.00	48.63	19.96	0.01	17.28	0.48	8.37	1.36	0.78	0.00
47.773	62.92	11.122	0.19	0.00	48.29	19.94	0.03	17.50	0.57	8.48	1.36	0.67	0.00
47.775	62.92	11.12	0.18	0.01	48.03	20.10	0.00	17.38	0.47	8.54	1.36	0.70	0.00
47.777	62.92	11.122	0.18	0.01	48.33	20.13	0.00	17.40	0.52	8.53	1.32	0.80	0.00
47.779	62.92	11.122	0.17	0.00	47.98	20.33	0.00	17.56	0.57	8.52	1.29	0.94	0.00
47.781	62.92	11.122	0.17	0.00	47.70	20.49	0.02	17.63	0.45	8.49	1.31	0.85	0.00
47.783	62.92	11.122	0.17	0.01	47.60	20.26	0.02	17.58	0.45	8.53	1.27	0.69	0.00

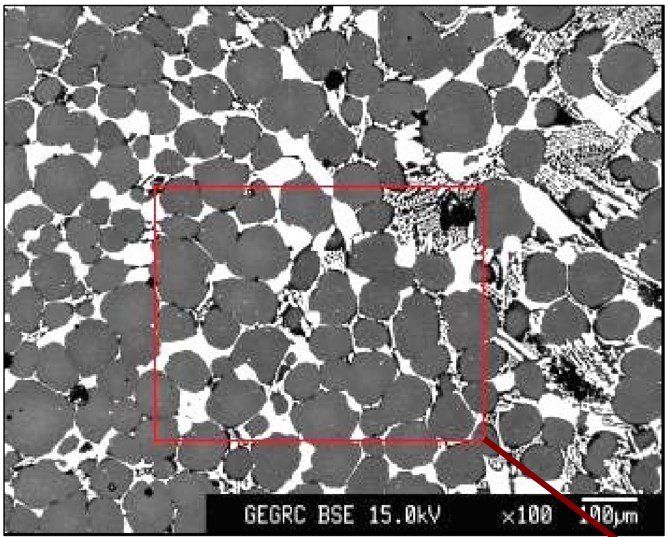


Figure 157(a) – Secondary electron image of the Ni-Cr-Zr alloy (after an extended brazing cycle).

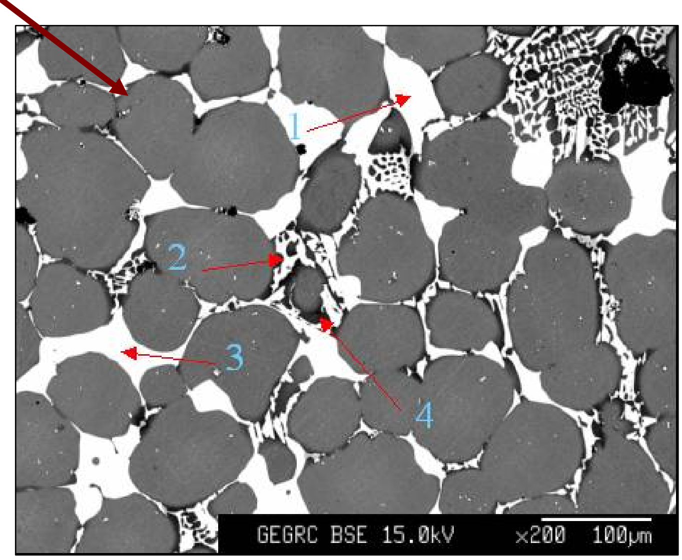


Figure 157(b) – Enlarged view of the secondary electron image of the Ni-Cr-Zr braze, shown in Figure 157(a), highlighting the location of four spot chemical analyses of the intermetallic compound within the braze.

Table 51 - Quantitative EPMA data (taken at 15 keV and 80 nA with a focused spot beam) at four locations within the intermetallic phase (indicated in Figure 157(b)). (Percentage by weight).

	Al	**Hf**	**Ni**	**Cr**	**Zr**	**Fe**	**Ta**	**Mo**	**Co**	**W**	**Ti**	**Si**
Phase 1	0.18	1.60	66.77	0.60	27.87	0.06	1.39	0.05	1.83	0.35	0.08	0.16
Phase 2	0.19	1.43	66.83	0.77	27.97	0.08	1.33	0.07	1.81	0.07	0.14	0.24
Phase 3	0.17	1.71	66.22	0.61	27.65	0.06	1.81	0.09	1.85	0.45	0.10	0.17
Phase 4	3.16	0.04	75.05	9.13	0.63	0.54	1.58	0.42	4.53	3.35	0.55	0.19

In order to study the distribution of various elements within the Ni-Cr-Hf braze microstructure, EMPA maps were constructed. These maps are shown in **Figure 158** (for Al, C, Ni and Cr), **Figure 159** (for Zr, Hf and Si), **Figure 160** (for Ru, Ta, Ti and W) and **Figure 161** (for Fe and Mo).

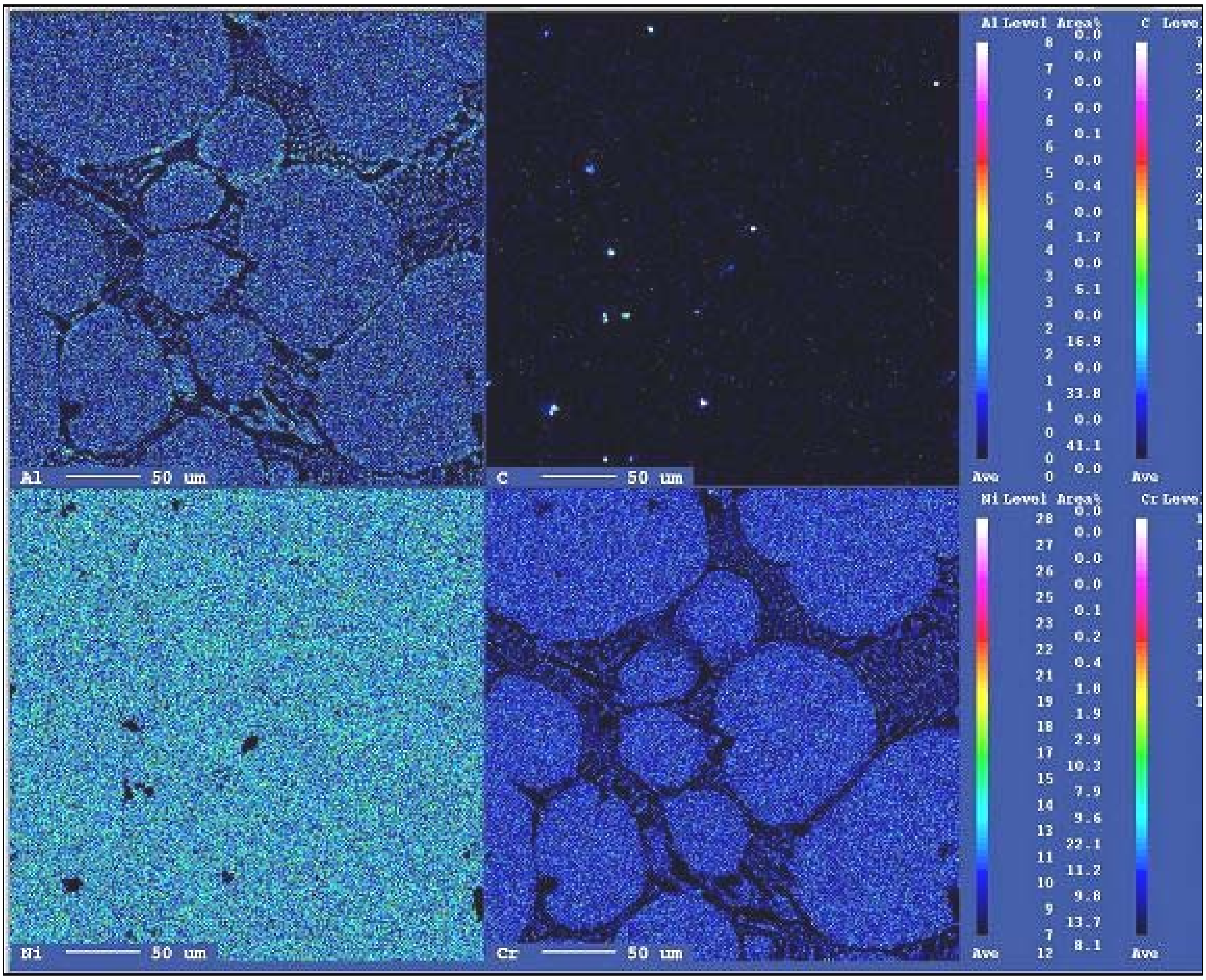


Figure 158 – EMPA maps displaying the distribution of Al, C, Ni and Cr within the MarM247/Ni-Cr-Zr braze microstructure (after an extended diffusion cycle).

The EMPA results shown in **Figure 158** indicate that Al and Cr partitioned strongly to the MarM247 powder particles and to one of the eutectic phases (most likely the Ni-rich γ phase) during the brazing and diffusion cycles. Both elements appeared to have limited solubility within the intermetallic phase in the eutectic component. The majority of the carbon within the structure was concentrated within small particles, probably carbides or pores saturated with C during the carbon coating process. Ni appeared to be fairly uniformly distributed between the braze alloy and the matrix.

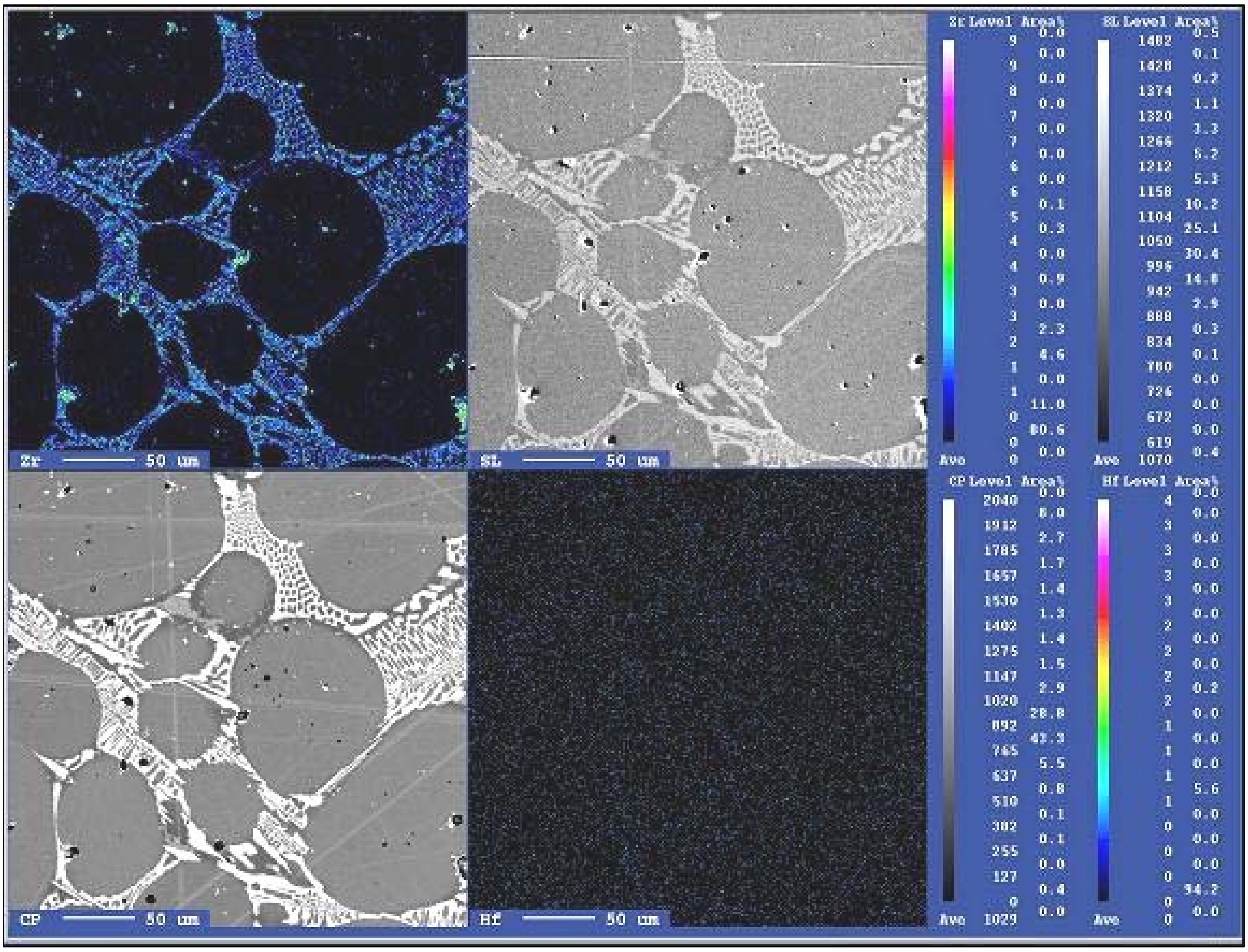


Figure 159 – EMPA maps displaying the distribution of Zr and Hf within the MarM247/Ni-Cr-Zr braze microstructure (after an extended diffusion cycle).

The results shown in **Figure 159** suggest that Zr partitioned strongly to the intermetallic phase within the braze alloy, which substantiates the results of the line and spot scans shown in **Tables 50 and 51**. The Zr EMPA map confirms that the intermetallic phase within the braze joint was Zr-rich, whereas Zr was almost completely absent from the MarM247 matrix particles. The Hf detected within the intermetallic compound in the Ni-Cr-Zr alloy after brazing (**Figure 153**) was not evident after the extended diffusion cycle, suggesting that the Hf diffused from the braze alloy into the MarM247 particles during heat treatment.

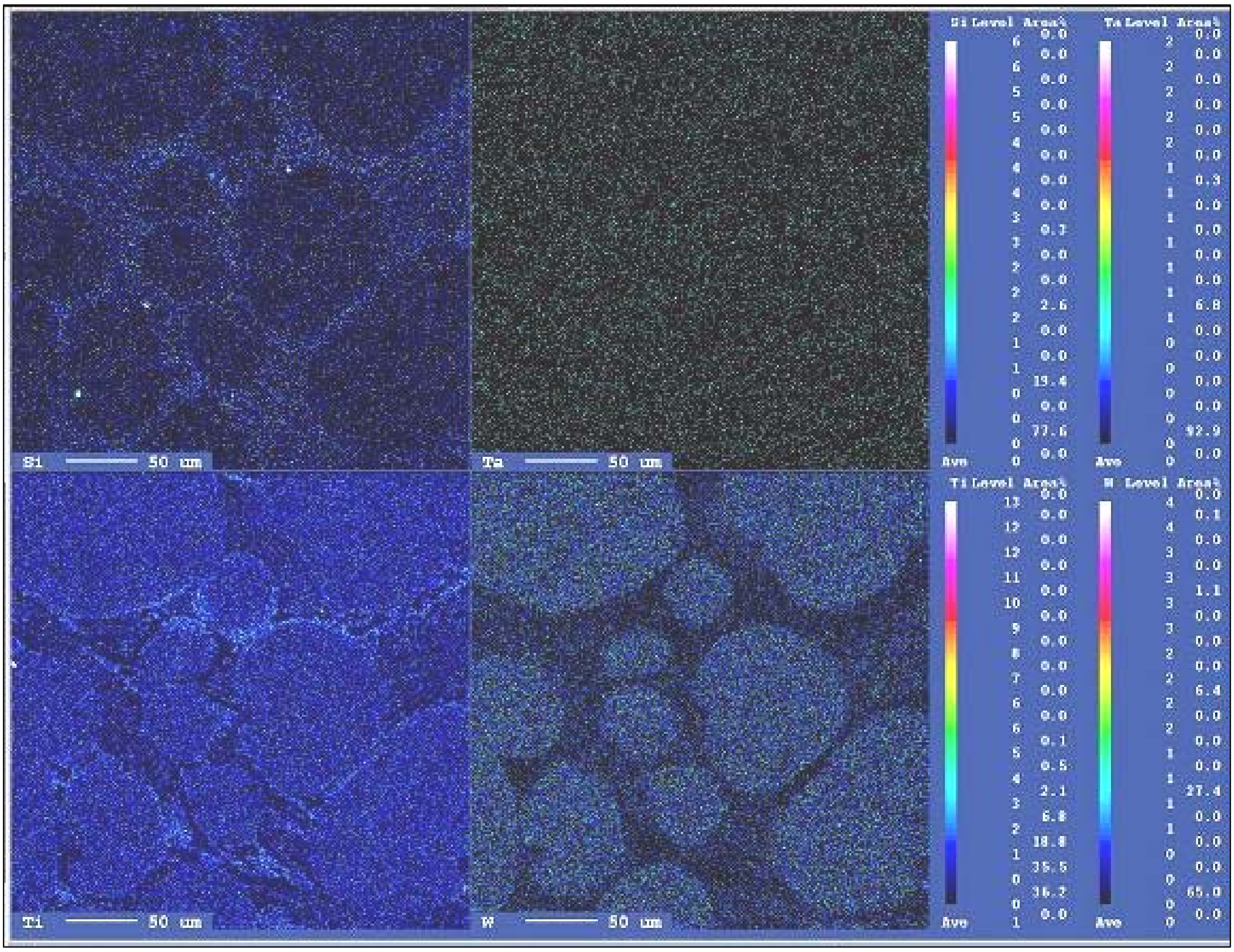


Figure 160 – EMPA maps displaying the distribution of Si, Ta, Ti and W within the MarM247/Ni-Cr-Zr braze microstructure (after an extended brazing cycle).

As shown in **Figure 160**, Si, Ta and Ti were distributed fairly evenly between the braze alloy and the matrix. Si apparently partitioned weakly to the intermetallic phase (suggesting limited solubility within the intermetallic compound), whereas Ti partitioned preferentially to the MarM247 powder particles. Tungsten, however, partitioned strongly to the MarM247 powder particles, suggesting low solubility within the intermetallic phase. The W appeared to be distributed evenly through the matrix phase.

The EMPA maps for Fe and Mo, shown in **Figure 161**, display weak partitioning to the matrix particles, but due to the low levels of these elements within the MarM247 particles and the braze alloy, this tendency was weak.

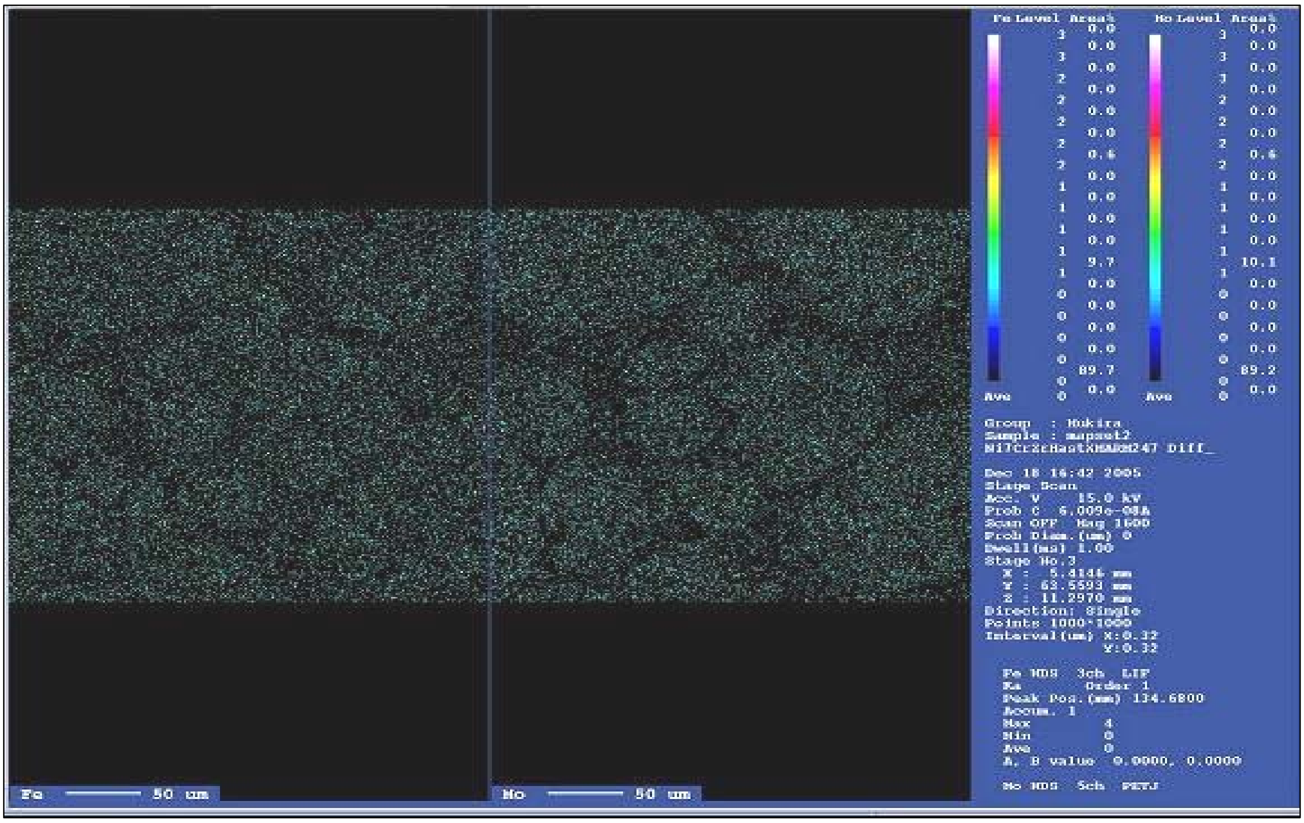
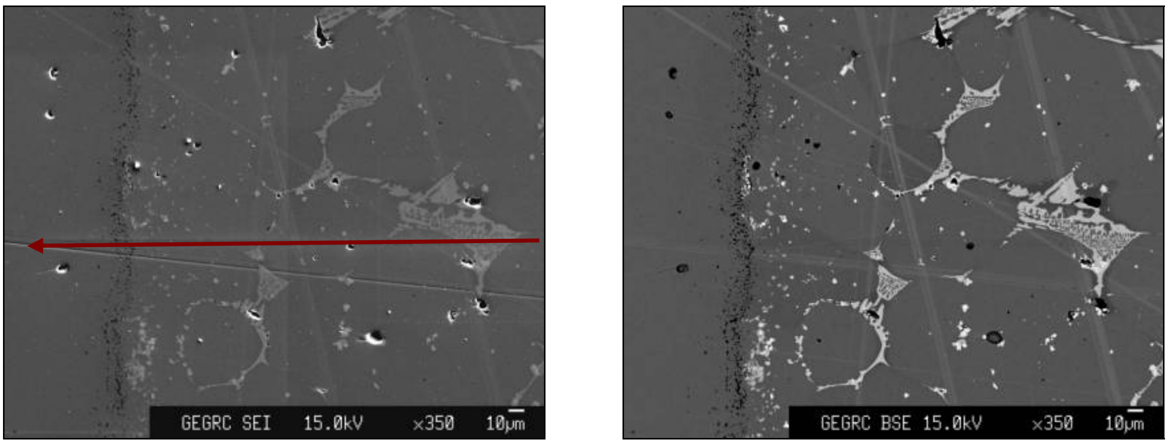


Figure 161 – EMPA maps displaying the distribution of Fe and Mo within the MarM247/Ni-Cr-Zr braze microstructure (as-brazed condition).

11.3.4 <u>Repeat: The MarM247/Ni-Zr braze joint produced using Ni-7Cr-13Zr braze filler (after an extended diffusion cycle)</u>:

Secondary and backscatter electron images of the MarM247/Ni-Zr joint produced using the experimental Ni-7Cr-13Zr braze filler metal are shown in **Figure 162** after an extended diffusion cycle. The arrow highlights the location and direction of the 2 μm stepped EPMA line scan. The results of the EMPA scan are shown in **Table 52**.



(a) (b)

Figure 162 – Secondary (a) and backscatter (b) electron images of the MarM247/Ni-7Cr-13Zr joint after an extended diffusion cycle (adjacent to the interface).

Table 52 – The results of the second EMPA scan of the MarM247/Ni-7Cr-13Zr braze joint after an extended diffusion cycle. (All compositions given in wt.%).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
7.431	70.131	11.255	2.18	0.00	69.20	13.26	0.58	0.51	1.58	1.51	5.67	2.11	1.86
7.433	70.131	11.255	2.19	0.01	69.33	13.29	0.60	0.53	1.53	1.48	5.59	2.12	1.87
7.435	70.131	11.255	2.23	0.00	69.32	13.10	0.59	0.56	1.55	1.50	5.54	2.34	1.91
7.437	70.131	11.255	2.09	0.00	68.91	11.79	3.46	0.46	1.58	1.33	5.20	1.85	1.88
7.439	70.131	11.255	1.05	0.01	66.61	5.95	17.02	0.27	1.42	0.71	3.54	0.68	1.27
7.441	70.131	11.255	1.30	0.00	67.61	6.59	14.95	0.28	1.44	0.74	3.78	0.91	1.38
7.443	70.131	11.255	1.30	0.00	67.38	7.03	14.15	0.31	1.26	0.86	3.91	0.84	1.42
7.445	70.131	11.255	0.95	0.00	66.98	5.24	18.23	0.25	1.37	0.63	3.36	0.63	1.17
7.447	70.131	11.255	1.06	0.00	67.79	5.53	17.26	0.24	1.45	0.69	3.50	0.76	1.25
7.449	70.131	11.255	1.07	0.00	67.26	5.56	17.39	0.26	1.65	0.70	3.41	0.84	1.22
7.451	70.131	11.255	1.07	0.00	66.95	5.92	16.81	0.27	1.52	0.74	3.55	0.58	1.27
7.453	70.131	11.255	1.57	0.00	68.01	8.08	11.77	0.36	1.40	0.93	4.20	1.12	1.53
7.455	70.131	11.255	1.58	0.00	67.85	8.12	11.70	0.34	1.53	0.94	4.14	0.85	1.52
7.457	70.131	11.255	1.30	0.00	67.89	6.92	14.22	0.30	1.46	0.83	3.88	0.83	1.38
7.459	70.131	11.255	1.05	0.00	67.72	5.64	17.06	0.25	1.49	0.67	3.49	0.39	1.22
7.461	70.131	11.255	1.00	0.01	67.36	4.94	18.11	0.23	1.41	0.65	3.38	0.76	1.14
7.463	70.131	11.255	1.41	0.00	67.60	7.11	13.29	0.31	1.24	0.86	3.96	0.88	1.44
7.465	70.131	11.255	1.52	0.02	67.97	8.18	10.93	0.38	1.42	0.98	4.24	1.08	1.55
7.467	70.131	11.255	0.69	0.00	66.72	3.79	21.20	0.19	1.57	0.55	2.95	0.85	1.00
7.469	70.131	11.255	1.55	0.00	68.11	7.74	11.47	0.36	1.32	0.99	4.20	1.37	1.54
7.471	70.131	11.255	2.32	0.01	69.87	12.24	1.20	0.51	1.33	1.44	5.42	1.98	1.95
7.473	70.131	11.255	2.27	0.01	69.81	12.58	0.57	0.53	1.47	1.49	5.46	2.13	1.91
7.475	70.131	11.255	2.22	0.01	69.35	12.89	0.60	0.54	1.43	1.47	5.45	2.43	1.88
7.477	70.131	11.255	2.21	0.01	69.15	13.04	0.62	0.54	1.50	1.52	5.60	2.27	1.84
7.479	70.131	11.255	2.20	0.00	69.56	13.12	0.59	0.53	1.26	1.51	5.64	2.14	1.84
7.481	70.131	11.255	2.22	0.00	69.29	13.12	0.58	0.52	1.45	1.50	5.59	2.23	1.85
7.483	70.131	11.255	2.21	0.03	70.13	13.20	0.59	0.51	1.28	1.49	5.67	2.23	1.85
7.485	70.131	11.255	2.24	0.01	70.30	13.18	0.57	0.53	1.30	1.48	5.71	2.00	1.86
7.487	70.131	11.255	2.23	0.00	69.98	13.26	0.59	0.54	1.16	1.48	5.69	2.05	1.85
7.489	70.131	11.255	2.23	0.00	69.46	13.29	0.58	0.56	1.25	1.54	5.75	1.93	1.80
7.491	70.131	11.255	2.22	0.00	69.70	13.22	0.59	0.51	1.34	1.49	5.71	2.17	1.85
7.493	70.131	11.255	2.22	0.00	69.99	13.13	0.57	0.51	1.25	1.49	5.71	2.16	1.84
7.495	70.131	11.255	2.23	0.00	69.97	13.07	0.58	0.57	1.51	1.55	5.76	2.30	1.84
7.497	70.131	11.255	2.23	0.00	69.84	12.93	0.52	0.53	1.24	1.53	5.77	2.17	1.85
7.499	70.131	11.255	2.21	0.00	69.72	12.84	0.56	0.56	1.25	1.51	5.76	2.15	1.84
7.501	70.131	11.255	2.23	0.00	69.60	12.89	0.57	0.53	1.06	1.53	5.70	2.29	1.85
7.503	70.131	11.255	2.23	0.00	70.00	12.86	0.55	0.53	1.35	1.48	5.74	2.15	1.82
7.505	70.131	11.255	2.23	0.02	70.03	12.83	0.57	0.54	1.49	1.50	5.73	2.10	1.83
7.507	70.131	11.255	2.24	0.00	70.11	12.65	0.60	0.51	1.29	1.49	5.68	2.02	1.83
7.509	70.131	11.255	2.23	0.00	70.00	12.72	0.59	0.51	1.41	1.53	5.71	2.13	1.85
7.511	70.131	11.255	2.25	0.00	70.08	12.79	0.61	0.53	1.39	1.49	5.71	2.11	1.88
7.513	70.131	11.255	2.26	0.00	69.53	12.77	0.57	0.52	1.27	1.51	5.55	2.33	1.87
7.515	70.131	11.255	2.30	0.00	69.88	12.09	1.47	0.50	1.24	1.36	5.43	1.87	1.98
7.517	70.131	11.255	0.90	0.00	39.93	5.86	37.02	0.25	5.56	0.75	2.73	0.61	1.44
7.519	70.131	11.255	1.92	0.03	66.82	10.97	7.59	0.46	1.47	1.30	4.89	1.43	1.77
7.521	70.131	11.255	2.25	0.02	69.54	13.11	0.60	0.55	1.43	1.51	5.60	2.19	1.93
7.523	70.131	11.255	2.24	0.01	69.97	13.17	0.58	0.54	1.35	1.56	5.62	1.82	1.86
7.525	70.131	11.255	2.25	0.02	69.52	13.23	0.64	0.53	1.17	1.53	5.63	2.10	1.84
7.527	70.131	11.255	2.23	0.00	69.58	13.17	0.52	0.51	1.39	1.51	5.68	2.04	1.82
7.529	70.131	11.255	2.23	0.00	69.93	13.23	0.59	0.55	1.38	1.50	5.75	1.81	1.83
7.531	70.131	11.255	2.24	0.00	69.92	13.18	0.59	0.51	1.41	1.50	5.77	2.08	1.84
7.533	70.131	11.255	2.21	0.00	69.64	13.11	0.60	0.54	1.38	1.49	5.77	1.96	1.84
7.535	70.131	11.255	2.25	0.02	69.46	13.15	0.58	0.51	1.48	1.54	5.87	1.84	1.84
7.537	70.131	11.255	2.29	0.00	69.13	13.09	0.54	0.51	1.74	1.51	5.76	1.65	1.84
7.539	70.131	11.255	2.17	0.04	65.92	12.74	0.50	0.49	1.55	1.27	5.49	1.71	1.71
7.541	70.131	11.255	2.11	0.01	66.78	12.76	0.56	0.51	1.73	1.35	5.55	1.85	1.75
7.543	70.131	11.255	2.16	0.00	68.70	13.06	0.94	0.51	1.67	1.50	5.68	1.98	1.84
7.545	70.131	11.255	2.21	0.00	69.66	13.27	0.54	0.51	1.48	1.50	5.87	2.02	1.85
7.547	70.131	11.255	2.21	0.00	69.70	13.47	0.58	0.52	1.49	1.51	5.90	2.13	1.86

Table 52 – (continued).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
7.549	70.131	11.255	2.22	0.01	69.54	13.37	0.59	0.51	1.41	1.53	5.86	1.99	1.87
7.551	70.131	11.255	2.22	0.00	69.15	13.41	0.58	0.52	1.56	1.54	5.84	1.88	1.86
7.553	70.131	11.252	2.19	0.00	68.86	13.56	0.56	0.51	1.48	1.58	5.84	1.85	1.84
7.555	70.131	11.255	2.21	0.00	69.48	13.45	0.56	0.53	1.52	1.58	5.88	2.18	1.82
7.557	70.131	11.255	2.20	0.00	69.67	13.55	0.54	0.50	1.54	1.51	5.89	2.14	1.85
7.559	70.131	11.255	2.21	0.00	69.37	13.57	0.56	0.51	1.36	1.54	5.96	2.19	1.85
7.561	70.131	11.255	2.21	0.02	69.59	13.56	0.55	0.52	1.48	1.56	5.90	2.22	1.87
7.563	70.131	11.255	2.22	0.00	69.11	13.62	0.53	0.50	1.38	1.57	5.86	2.03	1.83
7.565	70.131	11.255	2.23	0.00	69.26	13.54	0.55	0.52	1.58	1.54	5.89	1.87	1.87
7.567	70.131	11.255	2.22	0.00	69.61	13.72	0.53	0.49	1.69	1.54	5.93	1.79	1.83
7.569	70.131	11.255	2.20	0.00	69.50	13.50	0.55	0.53	1.61	1.57	5.93	2.09	1.83
7.571	70.131	11.255	2.23	0.02	69.38	13.59	0.54	0.53	1.57	1.54	5.92	1.98	1.81
7.573	70.131	11.255	2.22	0.00	69.32	13.51	0.56	0.51	1.62	1.53	5.87	2.16	1.82
7.575	70.131	11.255	2.23	0.00	69.45	13.44	0.51	0.50	1.50	1.50	5.88	1.93	1.86
7.577	70.131	11.255	2.24	0.00	69.61	13.50	0.56	0.52	1.50	1.56	5.82	1.86	1.83
7.579	70.131	11.255	2.21	0.02	69.94	13.50	0.56	0.54	1.46	1.51	5.87	2.33	1.84
7.581	70.131	11.255	2.22	0.00	70.09	13.40	0.57	0.55	1.70	1.46	5.76	2.06	1.82
7.583	70.131	11.255	2.22	0.00	69.80	13.44	0.52	0.51	1.60	1.51	5.72	1.96	1.86
7.585	70.131	11.255	2.22	0.00	70.03	13.28	0.56	0.55	1.37	1.52	5.69	2.12	1.84
7.587	70.131	11.255	2.21	0.00	69.73	13.42	0.55	0.54	1.50	1.54	5.74	2.53	1.83
7.589	70.131	11.255	2.22	0.00	69.89	13.29	0.57	0.54	1.07	1.57	5.61	2.43	1.83
7.591	70.131	11.255	2.24	0.00	69.93	13.34	0.55	0.55	1.37	1.49	5.63	2.07	1.88
7.593	70.131	11.255	2.23	0.00	70.27	13.34	0.56	0.57	1.45	1.58	5.65	1.92	1.84
7.595	70.131	11.255	2.22	0.00	70.06	13.32	0.55	0.57	1.34	1.52	5.56	2.19	1.85
7.597	70.131	11.255	2.09	0.01	69.85	12.24	3.08	0.52	1.32	1.44	5.21	1.85	1.85
7.599	70.131	11.255	2.19	0.00	70.21	12.83	1.71	0.53	1.45	1.40	5.35	1.87	1.90
7.601	70.131	11.255	2.25	0.00	70.33	13.39	0.59	0.59	1.50	1.51	5.50	1.75	1.89
7.603	70.131	11.255	2.25	0.00	70.38	13.41	0.58	0.57	1.46	1.47	5.59	1.83	1.85
7.605	70.131	11.255	2.23	0.00	70.32	13.60	0.57	0.57	1.40	1.49	5.51	2.25	1.84
7.607	70.131	11.255	2.25	0.00	70.42	13.39	0.59	0.58	1.53	1.51	5.63	1.74	1.86
7.609	70.131	11.255	2.22	0.01	70.14	13.42	0.52	0.59	1.29	1.51	5.55	2.06	1.85
7.611	70.131	11.255	2.23	0.00	70.12	13.31	0.55	0.58	1.44	1.52	5.61	2.17	1.82
7.613	70.131	11.255	2.21	0.01	70.17	13.37	0.57	0.60	1.39	1.50	5.47	2.05	1.85
7.615	70.131	11.255	2.22	0.00	69.97	13.17	0.57	0.64	1.67	1.54	5.54	2.20	1.84
7.617	70.131	11.255	2.22	0.01	70.34	13.20	0.52	0.65	1.35	1.55	5.59	2.26	1.81
7.619	70.131	11.255	2.19	0.00	69.74	13.22	0.57	0.67	1.52	1.59	5.57	2.03	1.80
7.621	70.131	11.255	2.21	0.00	69.90	13.16	0.55	0.70	1.44	1.60	5.57	2.23	1.79
7.623	70.131	11.255	2.20	0.00	69.75	13.22	0.50	0.77	1.46	1.62	5.63	2.51	1.78
7.625	70.131	11.255	2.18	0.00	69.29	13.43	0.52	0.87	1.48	1.71	5.68	2.40	1.76
7.627	70.131	11.255	2.17	0.00	69.55	13.41	0.55	0.94	1.17	1.72	5.75	2.05	1.71
7.629	70.131	11.255	2.13	0.01	69.17	13.54	0.51	1.08	1.12	1.73	5.70	2.48	1.69
7.631	70.131	11.255	2.12	0.00	68.82	13.62	0.46	1.17	1.29	1.83	5.80	2.58	1.63
7.633	70.131	11.255	2.07	0.00	68.36	13.83	0.44	1.29	1.10	1.96	5.81	2.53	1.61
7.635	70.131	11.255	2.05	0.00	68.08	13.95	0.39	1.44	1.08	2.05	5.81	2.13	1.54
7.637	70.131	11.255	2.04	0.00	67.86	14.10	0.40	1.62	1.04	2.09	5.89	2.42	1.53
7.639	70.131	11.255	2.00	0.00	67.59	14.10	0.32	1.76	1.24	2.20	5.87	2.16	1.48
7.641	70.131	11.252	1.96	0.00	67.14	14.24	0.33	1.88	1.14	2.28	5.85	2.35	1.46
7.643	70.131	11.255	1.97	0.00	67.27	14.15	0.33	2.05	1.07	2.40	5.85	2.30	1.43
7.645	70.131	11.255	1.93	0.01	66.73	14.35	0.28	2.16	1.09	2.44	5.82	2.20	1.38
7.647	70.131	11.255	1.91	0.00	66.30	14.41	0.24	2.40	1.08	2.60	5.84	2.25	1.33
7.649	70.131	11.255	1.87	0.00	66.22	14.63	0.24	2.64	1.00	2.75	5.93	2.05	1.27
7.652	70.131	11.255	1.85	0.00	66.12	14.72	0.23	2.77	0.93	2.81	5.85	1.91	1.20
7.654	70.131	11.255	1.82	0.00	65.55	14.77	0.21	3.04	1.08	2.87	5.83	2.17	1.18
7.655	70.131	11.255	1.45	0.00	55.42	12.92	10.59	2.88	2.90	2.67	4.89	1.57	1.63
7.657	70.131	11.255	1.26	0.01	51.72	12.41	13.76	2.97	2.88	2.69	4.65	1.59	1.65
7.66	70.131	11.255	1.68	0.01	64.13	15.24	0.13	3.86	1.14	3.30	5.73	1.77	1.01
7.661	70.131	11.255	1.62	0.00	62.95	14.98	1.42	4.00	1.19	3.40	5.63	2.11	1.06
7.663	70.131	11.255	1.39	0.00	56.23	13.64	8.52	3.82	1.99	3.18	4.92	1.54	1.73
7.666	70.131	11.255	1.55	0.00	62.67	15.42	0.66	4.53	1.09	3.62	5.57	2.06	0.94
7.668	70.131	11.255	1.55	0.00	62.77	15.90	0.07	4.92	1.00	3.83	5.59	1.90	0.81

Table 52 – (continued).

X (mm)	Y (mm)	Z (mm)	Al	Hf	Ni	Cr	Zr	Fe	Ta	Mo	Co	W	Ti
7.669	70.131	11.255	1.47	0.00	62.37	15.96	0.08	5.18	1.09	3.86	5.48	1.91	0.77
7.672	70.131	11.252	1.43	0.00	61.43	16.29	0.08	5.48	0.78	4.11	5.43	2.08	0.71
7.674	70.131	11.252	1.39	0.00	61.25	16.45	0.04	5.80	0.76	4.22	5.37	2.12	0.69
7.676	70.131	11.255	1.33	0.00	61.32	16.51	0.15	6.20	0.97	4.36	5.26	1.72	1.04
7.678	70.131	11.255	1.28	0.01	60.53	16.69	0.12	6.59	0.81	4.53	5.17	1.67	0.93
7.68	70.131	11.255	1.25	0.00	60.40	17.02	0.01	6.96	0.73	4.70	5.13	1.41	0.71
7.682	70.131	11.255	1.18	0.02	58.17	16.79	0.29	6.92	1.04	4.71	4.90	1.49	2.04
7.684	70.131	11.255	1.09	0.05	54.96	16.05	0.73	6.96	1.43	4.65	4.65	1.35	4.74
7.686	70.131	11.255	0.88	0.18	46.92	14.11	1.79	6.29	2.10	4.22	3.90	1.21	11.56
7.688	70.131	11.255	0.92	0.14	49.69	15.23	1.21	6.98	2.08	4.63	4.09	1.26	8.26
7.69	70.131	11.255	1.06	0.00	57.96	17.33	0.13	8.35	0.81	5.39	4.63	1.10	0.94
7.692	70.131	11.252	0.86	0.12	50.06	15.78	1.21	7.79	1.49	5.00	4.02	1.13	7.39
7.694	70.131	11.252	0.88	0.07	52.64	16.84	0.76	8.45	1.06	5.19	4.13	0.96	5.49
7.696	70.131	11.255	0.79	0.13	47.59	15.51	1.50	8.11	1.43	4.89	3.65	1.13	9.98
7.698	70.131	11.255	0.90	0.00	56.24	18.30	0.03	10.05	0.76	5.98	4.11	0.93	0.26
7.7	70.131	11.252	0.85	0.00	56.06	18.38	0.00	10.32	0.85	6.06	4.05	1.11	0.20
7.702	70.131	11.255	0.83	0.00	56.23	18.40	0.08	10.67	0.80	6.28	3.97	1.31	0.22
7.704	70.131	11.252	0.80	0.00	55.11	18.69	0.04	10.83	0.62	6.42	3.77	1.50	0.28
7.706	70.131	11.255	0.77	0.00	55.24	18.74	0.00	11.33	0.71	6.55	3.68	1.47	0.13
7.708	70.131	11.252	0.73	0.00	54.73	19.09	0.00	11.46	0.69	6.76	3.49	1.09	0.12
7.71	70.131	11.255	0.70	0.00	54.72	19.21	0.00	12.08	0.54	6.83	3.36	1.19	0.11
7.712	70.131	11.255	0.68	0.01	54.07	19.19	0.02	12.33	0.58	6.97	3.23	1.30	0.11
7.714	70.131	11.255	0.65	0.01	54.06	19.32	0.00	12.54	0.62	6.99	3.13	1.11	0.14
7.716	70.131	11.252	0.61	0.00	53.25	19.58	0.01	12.92	0.63	7.11	2.88	1.30	0.08
7.718	70.131	11.255	0.58	0.00	52.97	19.67	0.01	13.33	0.59	7.24	2.81	1.09	0.08
7.72	70.131	11.255	0.57	0.00	52.94	19.77	0.02	13.55	0.47	7.30	2.69	1.04	0.06
7.722	70.131	11.252	0.53	0.00	52.30	19.84	0.01	13.67	0.44	7.35	2.60	1.07	0.07
7.724	70.131	11.255	0.53	0.00	52.42	19.69	0.02	14.06	0.41	7.41	2.46	0.90	0.08
7.726	70.131	11.255	0.50	0.00	52.12	19.82	0.00	14.21	0.33	7.50	2.38	1.16	0.05
7.728	70.131	11.255	0.48	0.01	51.69	19.89	0.02	14.45	0.60	7.57	2.26	0.98	0.05
7.73	70.131	11.255	0.47	0.01	51.41	19.97	0.00	14.73	0.42	7.64	2.15	0.97	0.05
7.732	70.131	11.255	0.45	0.00	51.49	20.22	0.02	14.94	0.31	7.73	2.10	1.11	0.04
7.734	70.131	11.255	0.41	0.00	51.05	20.24	0.00	15.22	0.30	7.73	1.97	0.96	0.04
7.736	70.131	11.255	0.39	0.00	50.51	20.27	0.00	15.50	0.47	7.91	1.86	1.22	0.04
7.738	70.131	11.255	0.38	0.01	50.34	20.41	0.00	15.79	0.55	8.04	1.83	0.66	0.04
7.74	70.131	11.255	0.37	0.00	50.07	20.50	0.00	15.89	0.50	8.05	1.79	0.87	0.02

The line scan results shown in **Table 52** revealed the presence of Zr-rich intermetallic phases containing between 11% and 22% Zr, and occasionally containing approximately 37% Zr. The binary Ni-Zr phase diagram, shown in **Figure 50**, indicates that the Ni_7Zr_2 intermetallic phase contains approximately 30 wt.% Zr, whereas the Ni_5Zr intermetallic compound contains approximately between 21 and 26 wt.% Zr. The results shown in **Table 52** therefore suggest that the intermetallic phase in the braze joint was Ni_5Zr, rather than Ni_7Zr_2.

11.4) Conclusions

- The MarM247/Ni-7Cr-31Hf braze mixture in the as-brazed condition (prior to diffusion treatment) apparently contained a Hf-rich intermetallic phase with between 31 and 36% Hf. The binary Ni-Hf phase diagram predicts that the Ni_7Hf_2 phase contains approximately 46 wt.% Hf, whereas the Ni_5Hf phase contains approximately 38 wt.% Hf. The presence of significant amounts of Zr and Ta in solution in the intermetallic phase, however, complicates identification, shifting its composition away from the equilibrium composition predicted by the phase diagram. If it is assumed that the intermetallic compound contains between 7.4% and 9.6% Zr in solution, as well as 3% Ta, its composition may well approach that of the Ni_7Hf_2 intermetallic compound, rather than that of the Ni_5Hf phase.

- The ternary MarM247/Ni-7Cr-13Zr braze mixture in the as-brazed condition (i.e. no diffusion heat treatment) was shown to contain an intermetallic compound with a Zr content ranging between 27 and 29%. The binary Ni-Zr phase diagram indicates that the Ni_7Zr_2 intermetallic phase contains approximately 30 wt.% Zr, whereas the Ni_5Zr intermetallic compound contains approximately between 21 and 26 wt.% Zr. This suggests that the intermetallic phase in the braze joint could be either Ni_5Zr or Ni_7Zr_2.

- The MarM247/Ni-7Cr-13Zr braze mixture contained a Zr-rich intermetallic phase with a Zr content of approximately 37 wt.% after an extended braze cycle. This suggests that the intermetallic phase in the braze joint is Ni_5Zr, rather than Ni_7Zr_2.

CHAPTER 12 – EXPERIMENT 10

DEVELOPMENT OF COMPLEX Ni-Cr-Hf BRAZE ALLOYS

12.1) Introduction

During the course of Experiment 8 (described in Chapter 10), the microstructures of a number of ternary Ni-Cr-Hf alloys, containing 13% Cr and between 15% and 25% Hf, were examined. The compositions of the eutectic component within these alloys were found to deviate from the predicted eutectic point in the binary Ni-Hf system (located at 30.5% Hf). The composition of the eutectic constituent observed in the Ni-13Cr-15Hf braze alloy was 65.2Ni-9.0Cr-25.8Hf (wt.%), the eutectic within the Ni-13Cr-20Hf braze alloy had a composition of 64.3Ni-10.5Cr-25.2Hf, whereas the eutectic component observed in the Ni-13Cr-25Hf braze alloy consisted of 63.1Ni-15.1Cr-21.8Hf (wt.%). The Hf content of the eutectic component in these alloys therefore ranged from approximately 21% Hf to 26% Hf.

This experiment aimed at developing and characterizing the microstructures of novel "near-eutectic" braze alloys in the as-cast condition, with or without additional alloying elements (Co, W, C, Ti and/or Al). An attempt was also made to identify the intermetallic phases and eutectic components observed in each alloy.

12.2) Experimental procedure

Five novel "near-eutectic" alloys, with chemical compositions given in **Table 53**, were melted at 1500^{o}C, and allowed to cool to form an ingot. In addition to Ni, Cr and Hf, deliberate additions of Co (for high temperature strength and oxidation resistance), W and C (for high temperature strength and to promote the formation of carbides), as well as Ti and Al (to facilitate the formation of γ' precipitates) were made to some of these alloys. The resultant as-cast microstructure of each alloy was analyzed using microprobe spot analysis techniques (as described in §11.2).

Table 53 – Chemical compositions (wt.%) of the novel "near-eutectic" alloys examined during the course of this investigation.

PV Heat	Cr	Co	W	Ti	Al	C	Hf	Ni
9020	8.5	-	-	-	-	-	25	66.5
9023	7.4	-	4.7	1.4	2.3	0.03	25.5	58.7
9025	8.4	-	5.4	1.6	6.1	-	14.5	64.0
9024	8.3	5.6	5.3	-	4.3	-	14.2	62.4
9026	7.9	5.4	5.0	1.5	4.1	0.04	20.3	55.8

12.3) Results and discussion

12.3.1 Alloy PV9020 (Ni-8.5Cr-25Hf):

Figure 163 displays photomicrographs at increasing magnification of the as-cast structure of alloy PV9020, with a chemical composition of Ni-8.5Cr-25Hf (wt.%).

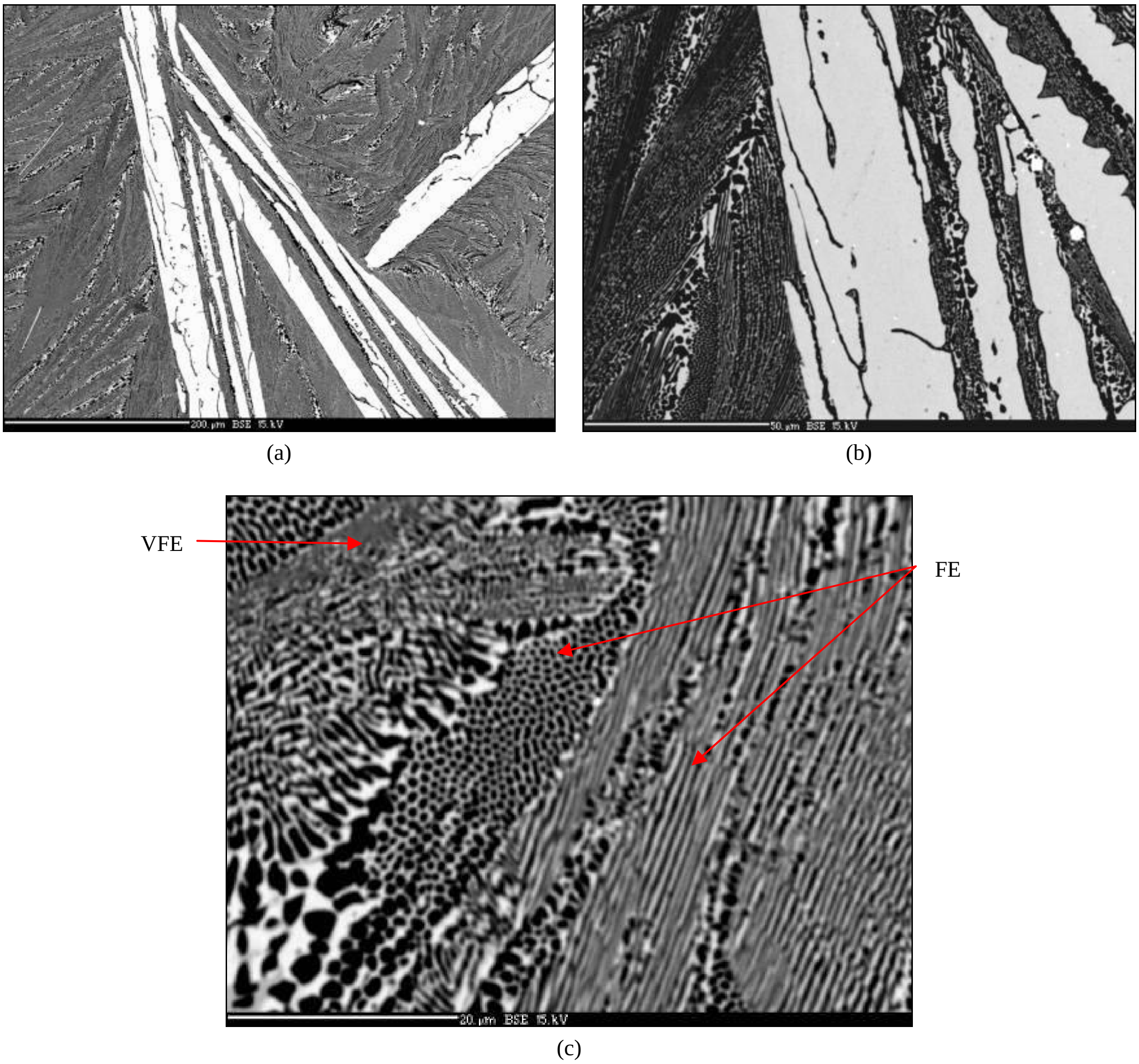


Figure 163 – Backscatter electron microprobe images of the Ni-8.5Cr-25Hf alloy in the as-cast condition (PV9020).

This alloy appears to be hypereutectic, with a needle-shaped primary Hf-rich intermetallic phase (light etching phase), consisting of 71.5Ni-1.5Cr-4.6Co-22.4Hf (at.%). This composition (given as atomic percentage) suggests that the intermetallic phase in **Figure 163** could be Ni_3Hf (a non-equilibrium phase) or Ni_7Hf_2 (more likely). The fine binary eutectic component evident in the micrographs was shown to consist of 76.3Ni-14.2Cr-9.4Hf (analyzed at the location labelled "VFE" in **Figure 163(c)**) and 76.5Ni-13.3Cr-10.1Hf (analyzed at the location labelled "FE" in **Figure 163(c)**). An attempt was made to analyze the individual phases within the eutectic component (see **Table 54**), but the results were inconsistent (probably due to the fine morphology of the eutectic component). It is assumed that the light phase within the eutectic component is the non-equilibrium Ni_3Hf or Ni_7Hf_2 intermetallic phase, and the dark component Ni-rich γ phase. This alloy had a solidus temperature of 1195°C and a liquidus temperature of 1281°C (ΔT = 86°C). This solidification temperature range makes the Ni-8.5Cr-25Hf alloy unsuitable for use in the repair of equiaxed Ni-base superalloys, such as In738 and MarM247. Single crystal Ni-base superalloys, however, can be processed at temperatures up to 1310°C, so this braze alloy may be suitable for use in repairing these materials.

Table 54 – EMPA results of the individual phases within the eutectic component observed in alloy PV9020 (wt.%).

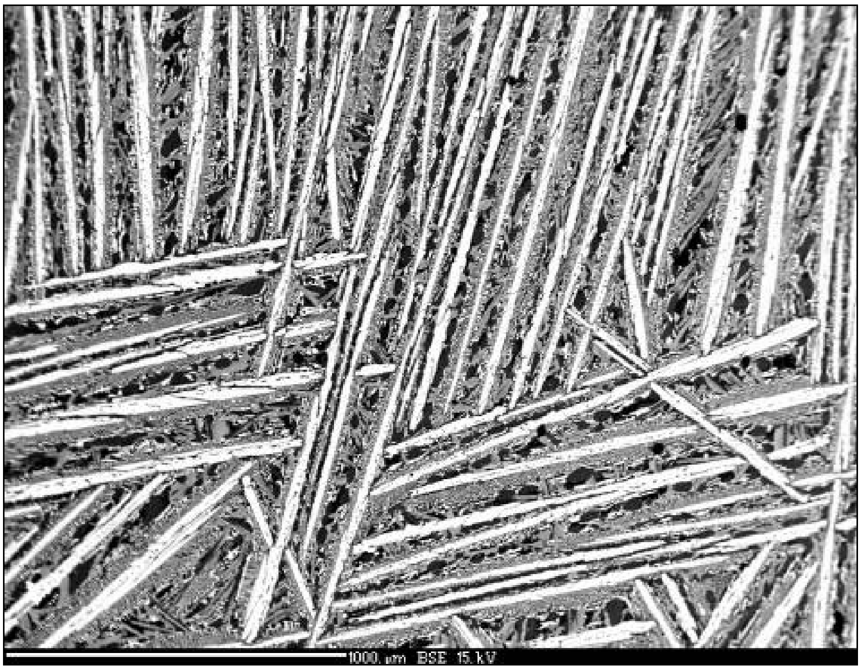
	Ni	Cr	Hf
Dark eutectic phase (Analysis 1)	84.0	11.8	4.1
Dark eutectic phase (Analysis 2)	78.9	6.5	14.5
Light eutectic phase (Analysis 1)	92.7	2.9	4.3
Light eutectic phase (Analysis 2)	70.4	11.2	18.4

12.3.2 Alloy PV9023 (Ni-7.4Cr-4.7W-1.4Ti-2.3Al-0.03C-25.5Hf):

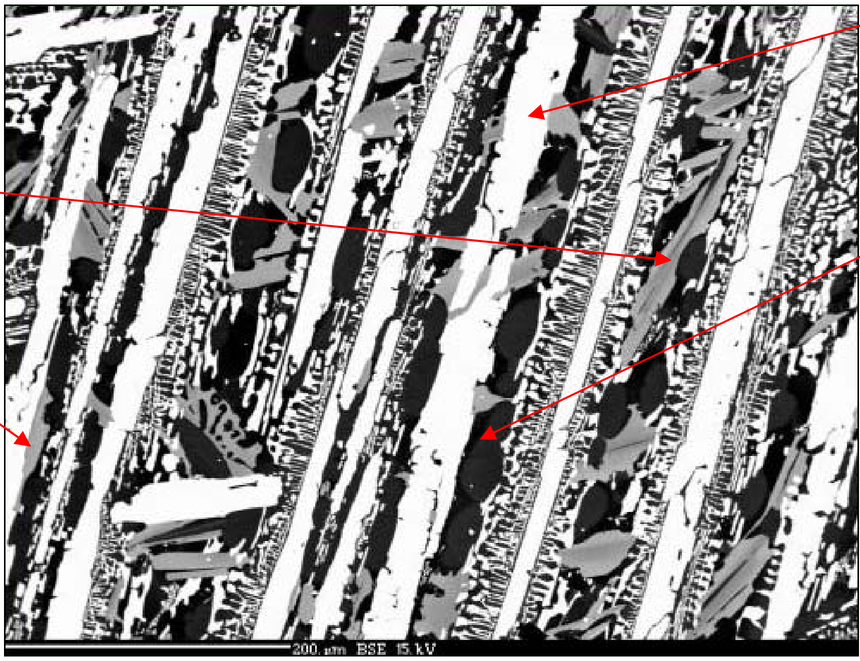
Figures 164(a) and (b) display photomicrographs at increasing magnification of the as-cast structure of alloy PV9023, with a chemical composition of Ni-7.4Cr-4.7W-1.4Ti-2.3Al-0.03C-25.5Hf (wt.%). The as-cast microstructure is considerably more complex than that of alloy PV9020, probably as a result of the deliberate addition of W, Al, Ti and C to this alloy. The white needle-shaped Hf-rich phase was shown to consist of 52.4Ni-1.1Cr-0.2W-0.4Ti-0.4Al-46.2Hf (at.%), suggesting a non-equilibrium NiHf or $Ni_{11}Hf_9$ intermetallic compound. The light to medium gray phase consisted of 61.0Ni-1.9Cr-2.1W-3.4Ti-3.2Al-28.9Hf (at.%) and 63.3Ni-2.8Cr-3.7W-3.8Ti-3.6Al-23.1Hf (at.%), suggesting a possible non-equilibrium Ni_3Hf or Ni_7Hf_2 intermetallic compound. The darkest phase contained 61.4Ni-21.2Cr-5.4W-2.0Ti-5.4Al-4.6Hf (at.%) and appears to be the Ni-rich γ phase with significant amounts of Cr, Al and W in solution. An attempt was made to analyze the individual phases within the eutectic component, yielding compositions of 61.7Ni-17.1Cr-11.3W-1.9Ti-3.8Al-4.2Hf for the dark eutectic phase (Ni-rich γ phase) and 52.6Ni-1.9Cr-0.4W-0.6Ti-0.8Al-44.4Hf for the light eutectic phase (possibly the non-equilibrium NiHf or $Ni_{11}Hf_9$ intermetallic compound). This alloy had a solidus temperature of 1140°C and a liquidus temperature of 1282°C (ΔT = 142°C). This solidification temperature range makes the Ni-7.4Cr-4.7W-1.4Ti-2.3Al-0.03C-25.5Hf alloy unsuitable for use in the repair of equiaxed Ni-base superalloy materials, such as In738 and MarM247, but this braze alloy may be suitable for use in repairing single crystal Ni-base superalloys.

12.3.3 Alloy PV9025 (Ni-8.4Cr-5.4W-1.6Ti-6.1Al-14.5Hf):

Figures 165(a) and (b) display photomicrographs of the as-cast structure of alloy PV9025, with a chemical composition of Ni-8.4Cr-5.4W-1.6Ti-6.1Al-14.5Hf (wt.%). This alloy appears to be hypo-eutectic, with primary Ni-rich γ dendrites consisting of Ni-7.1Cr-16.5Al-1.8W-2.6Ti-2.9Hf (at.%). The fine binary eutectic component between the dendrites was shown to consist of 61.2Ni-15.0Cr-13.3Al-0.6W-1.3Ti-8.6Hf (at.%). An attempt was made to analyze the individual phases within the eutectic component, yielding compositions of 56.4Ni-19.4Cr-17.6Al-0.7W-2.4Ti-3.5Hf for the dark eutectic phase (Ni-rich γ phase) and 64.4Ni-10.3Cr-6.8Al-1.1Ti-17.4Hf for the light eutectic phase (possibly the Ni_7Hf_2 intermetallic compound). **Figure 165(b)** also reveals the presence of a number of W-rich particles, probably (W,Cr) carbides or Laves phase. The solidus and liquidus temperatures of this alloy were 1049^{o}C and 1119^{o}C, respectively (ΔT = 70°C). Both the solidus and liquidus temperatures were therefore lower than those of the simple eutectic Ni-Hf braze alloy described in Chapter 3. This alloy shows great promise for the repair of equiaxed, directionally solidified and single crystal Ni-base superalloys.

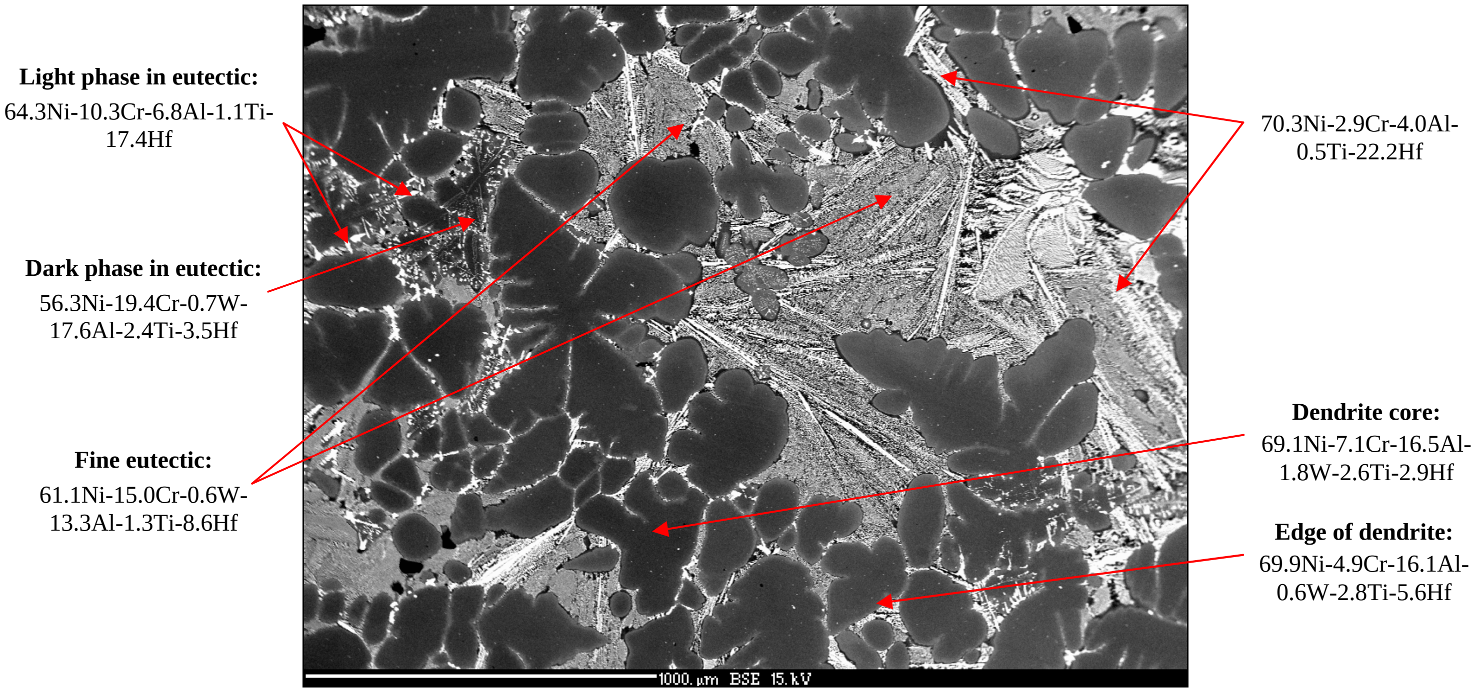


(a)

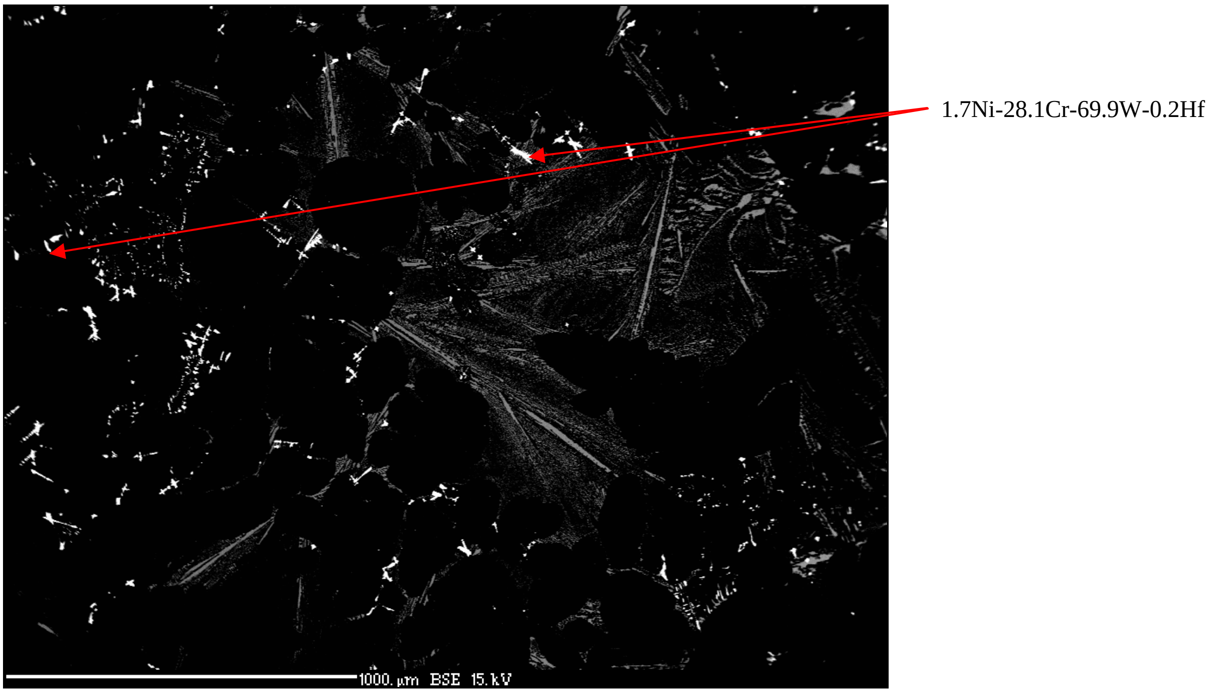


(b)

Figure 164 – Backscatter electron microprobe images of the Ni-7.4Cr-4.7W-1.4Ti-2.3Al-0.03C-25.5Hf alloy in the as-cast condition (PV9023). (All compositions given as atomic %).



(a)

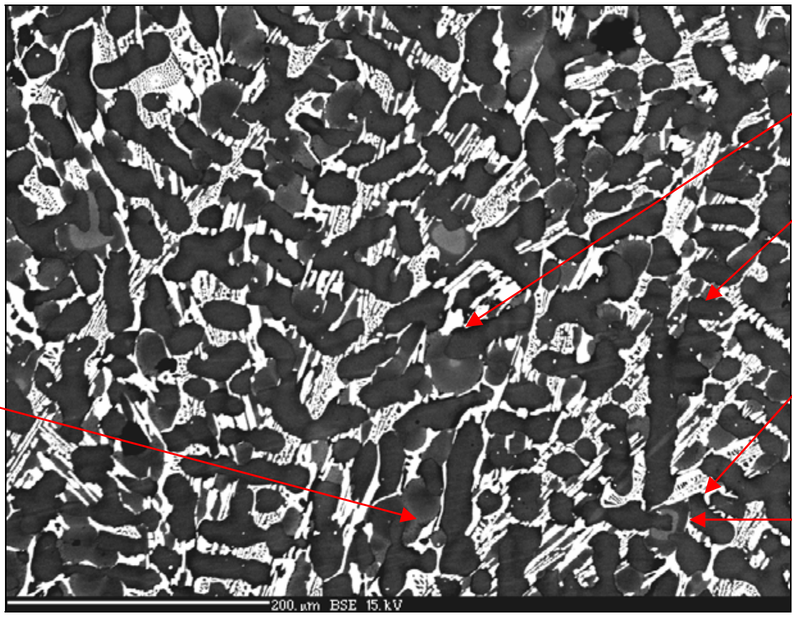


(b)

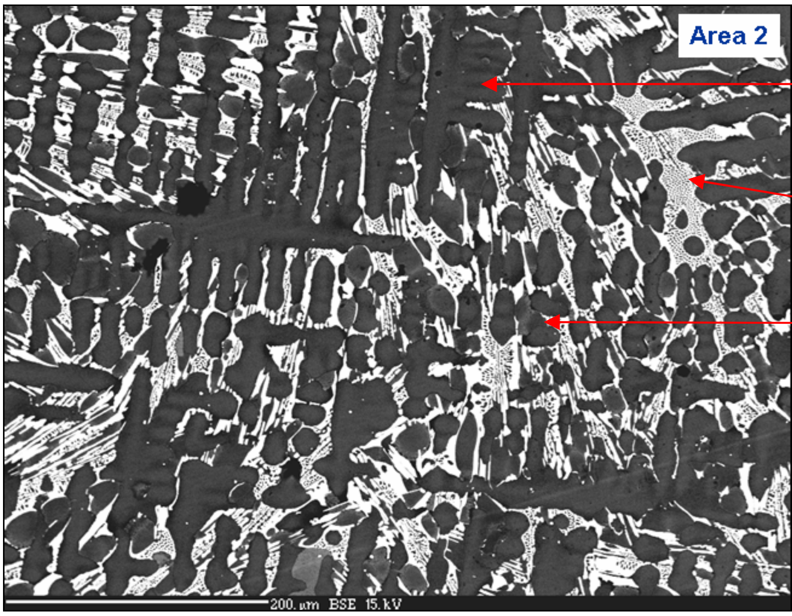
Figure 165 – Backscatter electron microprobe images of the Ni-8.4Cr-5.4W-1.6Ti-6.1Al-14.5Hf alloy in the as-cast condition (PV9025). (All compositions given as atomic %).

12.3.4 Alloy PV9024 (Ni-8.3Cr-5.6Co-5.3W-4.3Al-14.2Hf):

Figures 166(a) and (b) display photomicrographs of two different areas in the as-cast structure of alloy PV9024, with a chemical composition of Ni-8.3Cr-5.6Co-5.3W-4.3Al-14.2Hf (wt.%).



(a)



(b)

Figure 166 – Backscatter electron microprobe images of the Ni-8.3Cr-5.6Co-5.3W-4.3Al-14.2Hf alloy in the as-cast condition (PV9024). (All compositions given as atomic %).

This alloy also appears to be hypo-eutectic, with dark gray primary Ni-rich γ dendrites consisting of Ni-13.1Cr-7.3Co-10.7Al-3.1W-0.7Hf (at.%) in **Figure 166(a),** and Ni-17.5Cr-7.4Co-1.0W-11.5Al-0.7Hf (at.%) in **Figure 166(b)**. The fine binary eutectic component between the dendrites was shown to consist of 68.6Ni-6.9Cr-5.1Co-7.3Al-0.7W-11.4Hf

(**Figure 166(a)**), and 69.3Ni-8.3Cr-5.6Co-1.0W-5.6Al-10.0Hf (**Figure 166(b)**). Compositions of 70.6Ni-2.7Cr-4.4Co-2.4Al-19.9Hf (**Figure 166(a)**) and 74.5Ni-1.8Cr-4.5Co-1.4Al-21.8Hf (**Figure 166(b)**) were determined for the light eutectic phase (possibly the Ni_7Hf_2 intermetallic compound). The solidus and liquidus temperatures of this alloy were 1185^oC and 1334^oC, respectively (ΔT = 149°C). The liquidus temperature of this alloy was therefore too high to be of any practical use in the repair of the Ni-base superalloys utilized in production today, and the alloy is of no practical value in the short term.

12.3.5 Alloy PV9026 (Ni-7.9Cr-5.4Co-5W-1.5Ti-4.1Al-0.04C-20.3Hf):

Figure 167 displays a photomicrograph of the as-cast structure of alloy PV9026, with a chemical composition of Ni-7.9Cr-5.4Co-5W-1.5Ti-4.1Al-0.04C-20.3Hf (wt.%). This alloy appears to be hypo-eutectic, with dark gray primary Ni-rich γ dendrites consisting of Ni-9.8Cr-6.2Co-12.9Al-2.2W-2.7Ti-2.9Hf (at.%). The fine binary eutectic component between the dendrites was shown to consist of Ni-9.9Cr-6.4Co-7.8Al-1.5W-1.6Ti-10.2Hf (at.%). The coarse white phase was identified as the non-equilibrium Ni_3Hf or Ni_7Hf_2 intermetallic compound, consisting of 66.1Ni-2.4Cr-5.1Co-3.6Al-0.8Ti-22.0Hf (at.%). The composition of a number of white rosette-shaped particles (1.5Ni-11.4Cr-0.3Co-0.2Al-87.5W-0.1Ti-0.2Hf) suggests the presence of Laves phase or (W,Cr) carbides. Laves phase is not uncommon in some unstable Ni-base superalloys. Smaller dark particles observed in the microstructure were identified as Ni_3Al (γ') with a composition of 45.5Ni-6.2Cr-4.3Co-29.1Al-13.7Ti-1.2Hf. The solidus and liquidus temperatures of this alloy were 1034^oC and 1210^oC, respectively (ΔT = 176°C). Although the solidus and liquidus temperatures were lower than those of the simple eutectic Ni-Hf braze alloy described in Chapter 3, the potential of this alloy for the repair of equiaxed, directionally solidified and single crystal Ni-base superalloys may be limited by the presence of brittle Laves phase within the as-cast microstructure.

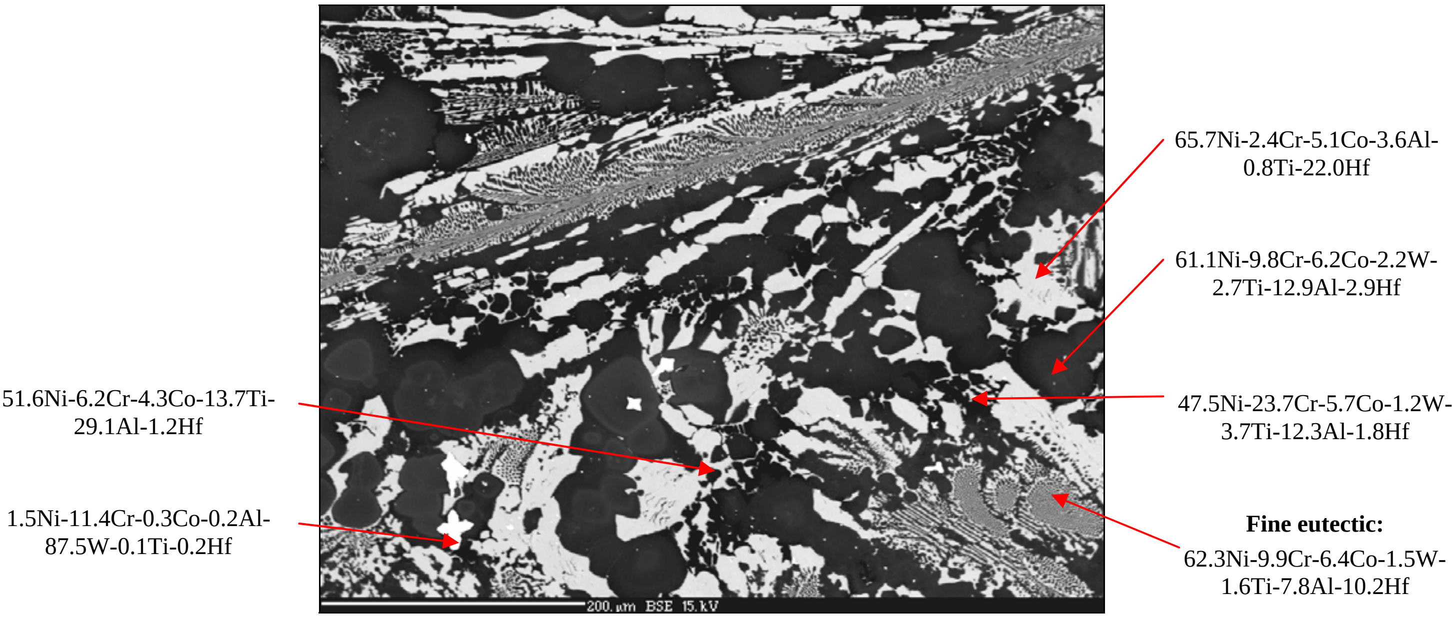


Figure 167 – Backscatter electron microprobe images of the Ni-7.9Cr-5.4Co-5W-1.5Ti-4.1Al-0.04C-20.3Hf alloy in the as-cast condition (PV9026). (All compositions given as atomic %).

12.4) Conclusions

- An alloy containing 66.5Ni-8.5Cr-25Hf (wt.%) appeared to be hypereutectic, with a needle-shaped primary Hf-rich intermetallic phase identified as non-equilibrium Ni_3Hf or Ni_7Hf_2, and a fine eutectic component consisting of Ni-rich γ and the Ni_3Hf or Ni_7Hf_2 intermetallic phase. This alloy had a solidus temperature of 1195°C and a liquidus temperature of 1281°C (ΔT = 86°C). This solidification temperature range makes the Ni-8.5Cr-25Hf alloy unsuitable for repairing equiaxed Ni-base superalloys, such as In738 and MarM247. Single crystal Ni-base superalloys, however, can be processed at temperatures up to 1310°C, so this braze alloy may be suitable for use in repairing these materials.

- An alloy with a chemical composition of Ni-7.4Cr-4.7W-1.4Ti-2.3Al-0.03C-25.5Hf (wt.%) displayed a complex microstructure consisting of a needle-shaped Hf-rich phase (identified as the non-equilibrium NiHf or $Ni_{11}Hf_9$ intermetallic compound), a non-equilibrium Ni_3Hf or Ni_7Hf_2 intermetallic compound, Ni-rich γ phase with a significant amount of Cr in solution, and a eutectic component consisting of Ni-rich γ and the non-equilibrium NiHf or $Ni_{11}Hf_9$ intermetallic compound. This alloy had a solidus temperature of 1140°C and a liquidus temperature of 1282°C (ΔT = 142°C). This solidification temperature range makes this material unsuitable for repairing equiaxed Ni-base superalloy materials, such as In738 and MarM247.

- Alloy PV9025, with a chemical composition of Ni-8.4Cr-5.4W-1.6Ti-6.1Al-14.5Hf (wt.%), appeared to be hypo-eutectic, with primary Ni-rich γ dendrites and a fine binary eutectic component consisting of Ni-rich γ phase and Ni_7Hf_2 intermetallic compound. A number of W-rich particles, probably (W,Cr) carbides or Laves phase, were also observed. The solidus and liquidus temperatures of this alloy were 1049°C and 1119°C, respectively (ΔT = 70°C). Both the solidus and liquidus temperatures were lower than those of the simple eutectic Ni-Hf braze alloy, and the alloy demonstrates great potential for the repair of equiaxed, directionally solidified and single crystal Ni-base superalloys.

- An alloy consisting of Ni-8.3Cr-5.6Co-5.3W-4.3Al-14.2Hf (wt.%) also appeared to be hypo-eutectic, with primary Ni-rich γ dendrites and a fine eutectic component consisting of Ni-rich γ and the Ni_7Hf_2 intermetallic compound. The solidus and liquidus temperatures of this alloy were 1185°C and 1334°C, respectively (ΔT = 149°C). The liquidus temperature of this alloy was therefore too high to be of any practical use in the repair of the Ni-base superalloys utilized in production today, and it is of no practical value as a braze alloy in the short term.

- The as-cast structure of alloy PV9026, with a chemical composition of Ni-7.9Cr-5.4Co-5W-1.5Ti-4.1Al-0.04C-20.3Hf (wt.%), appeared to be hypo-eutectic, with primary Ni-rich γ dendrites and a fine eutectic component between the dendrites. A coarse phase, (identified as the non-equilibrium Ni_3Hf or Ni_7Hf_2 intermetallic compound), a number of smaller rosette-shaped particles (identified as Laves phase), and small Ni_3Al particles were also observed. The solidus and liquidus temperatures of this alloy were 1034°C and 1210°C (ΔT = 176°C), respectively. Although the solidus and liquidus temperatures were lower than those of the simple eutectic Ni-Hf braze alloy, the potential of this alloy for the repair of equiaxed, directionally solidified and single crystal Ni-base superalloys may be limited by the presence of brittle Laves phase within the as-cast microstructure.