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Transient Liquid Phase Metallic Bonding of an Inconel 718SPF Superalloy

The applicability of TLP metallic bonding for Inconel 718SPF superalloy by inserting Ni-P and Ni-Cr-P amorphous interlayers is evaluated

BY M. S. YEH AND T. H. CHUANG

ABSTRACT. The applicability of the transient liquid phase (TLP) metallic bonding method for joining fine-grained Inconel 718SPF® superalloy sheets by inserting a Ni-P or a Ni-Cr-P amorphous interlayer has been evaluated. The results show that a joint with uniform chemical composition could be obtained for the Inconel 718SPF superalloy with a Ni-P interlayer at 1100°C for 8 h. When a Ni-Cr-P interlayer was used under the same metallic bonding conditions, the concentrations of nickel, iron and niobium in the bond region and in the base metal had a difference of more than 2 wt-%. This means that longer bonding time was required to homogenize the chemical compositions of bonds with a Ni-Cr-P interlayer. The joints with a Ni-P interlayer showed higher bond strength than did those with a Ni-Cr-P interlayer. Furthermore, many grain boundary precipitates were found.

Introduction

Nickel-based superalloys possess excellent properties at elevated temperatures and have been widely used in the manufacture of gas turbine components. For the application of this alloy, an effective joining method is required. Traditionally, fusion welding is used for this purpose. However, the heat-affected zone (HAZ) formed in the fusion-welded Inconel 718 superalloy has been shown to be susceptible to hot cracking (Ref. 1). On the other hand, brazing also has been considered as a useful technique for joining nickel-based superalloys (Refs. 2, 3). The principal disadvantage of this method is that the service temperature of a brazed workpiece is limited to a temperature below the melting point of its filler metal, which is generally much lower than the usual application temperature of a superalloy. Diffusion welding is the third choice for joining nickel-based superalloys (Refs. 4, 5). However, the formation of brittle intermetallic phases at the interface of a diffusion-welded superalloy reduces its joint strength. Furthermore, the diffusion welding process requires high external pressure and a very smooth and clean contact surface, which is difficult to obtain in industrial applications.

Transient liquid phase (TLP) metallic bonding is a process developed by Duvall, *et al.* (Ref. 6), for joining nickel- and cobalt-based superalloys. An interlayer material is used as a bonding agent for the TLP process similar to the brazing process. In order to lower the liquidus temperature of the interlayer, melting temperature depressants such as phosphorus are added. A TLP process consists of four stages: namely, melting of the filler metal, homogenization of the liquid, isothermal solidification and homogenization of the bond region (Ref. 7). There are three basic reactions that occur at the interface between the interlayer and the base metal, *i.e.*, short circuit paths, irrigation effects and incipient volume diffusion (Ref. 8). Furthermore, Nakagawa, *et al.* (Ref. 9), found that for TLP metallic bonding of pure nickel with a Ni-Cr-P interlayer, the time required for complete dissolution is longer than that required when using a Ni-P interlayer. For the same TLP bonding system, Kokawa, *et al.* (Ref. 10), reported that the rate of isothermal solidification at 1200°C was greater when fine-grained nickel was employed.

The Inconel 718SPF superalloy is a precipitation-strengthened alloy and exhibits excellent mechanical strength and hot gas corrosion resistance. It has been used in the manufacture of complex-shaped parts for aircraft by the superplastic forming (SPF) technique (Ref. 11). This superalloy possessed a very fine equiaxed grain size of about 10 μm and reached the total elongation to 500% at a strain rate of $2 \times 10^{-4} s^{-1}$ at 982°C (Ref. 12). There are many grain boundary diffusion paths that promote the diffusion of elements from the interlayer into the base metal and might be beneficial for the TLP process. The atomic structure of the amorphous interlayer is a glassy state, possessing complete chemical homogeneity, which is considered another benefit of TLP metallic bonding. On the

KEY WORDS

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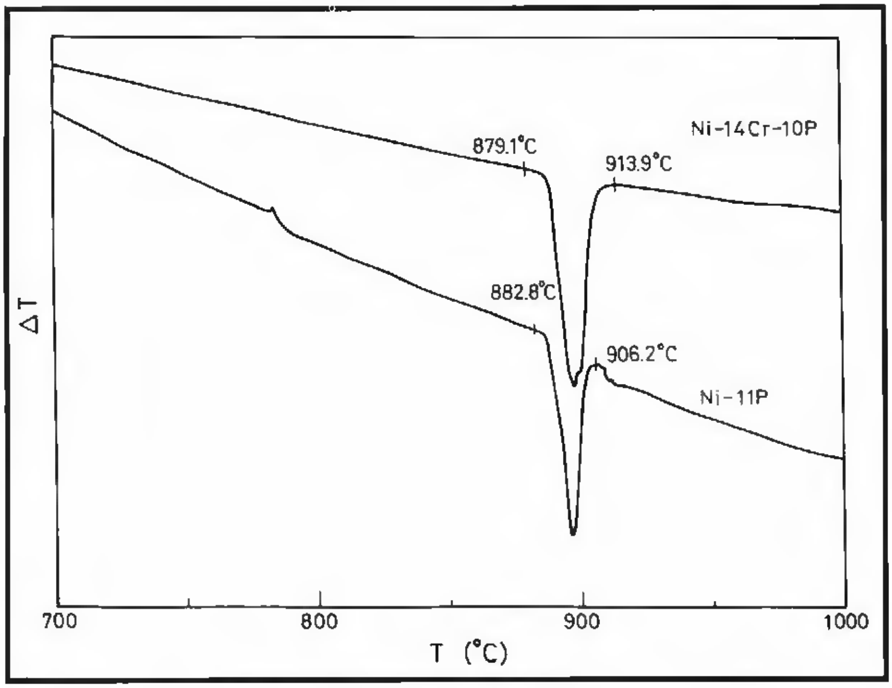

Fig. 1 — Thermograms of Ni-P interlayer and Ni-Cr-P interlayer.

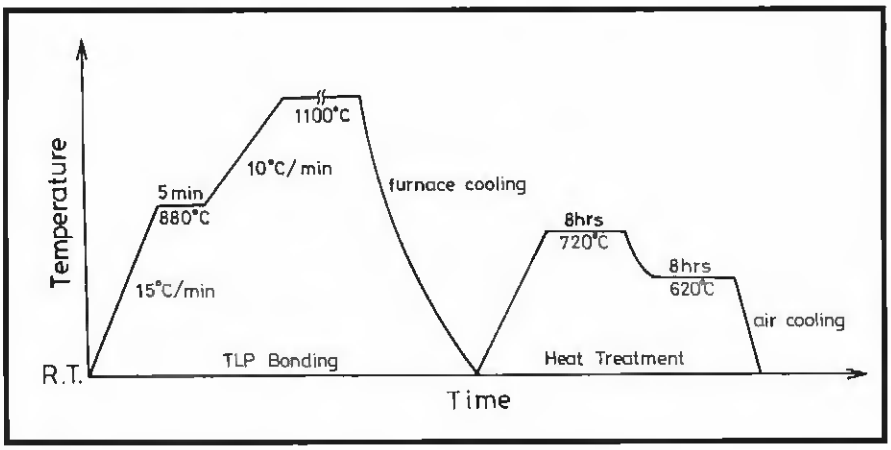

Fig. 2 — Temperature-time schedule for typical transient liquid phase (TLP) metallic bonding.

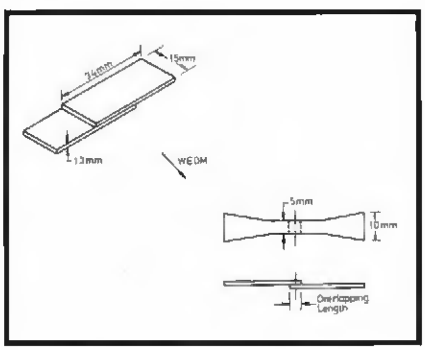

Fig. 3 — The dimensions for single lap shear test specimen.

other hand, a complex-shaped component can be joined easily by using these interlayers (Ref. 13). It was the goal of this study to evaluate the applicability of the TLP process for a very fine-grain material. For this purpose, the Inconel 718SPF superalloy was experimentally TLP-bonded by inserting interlayers of amorphous Ni-P. In addition, the bonding strengths and interfacial microstructures were analyzed in terms of dependence on the bonding time.

Experimental Procedure

The chemical composition of Inconel 718SPF superalloy sheet, manufactured by INCO Alloys International, Inc., Huntington, W.Va., which was used for this study, is given in Table 1. Strips of this alloy with dimensions of 34 x 15 x 1.3 mm were cut from the sheet material. The surfaces to be joined were prepared by grinding with 150-grit SiC paper, rinsing in distilled water, ultrasonic cleaning in 5 g/L NaOH solution, and finally, rinsing in acetone for 5 min. Two amorphous foils composed of Ni-11 P and Ni-14 Cr-10 P (wt-%), both with a thickness of 37 μm and produced by Metglas Products, an Allied Signal company were used as the interlayers for bonding. These interlayers possessed eutectic compositions and there existed an eutectic reaction of the nickel solid solution and the Ni_3P intermetallic phase at 880°C. The melting characteristics were determined using differential thermal analysis (DTA), which showed the solidus and liquidus for Ni-11P and for Ni-14Cr-10P — Fig. 1.

Two Inconel 718SPF strips sandwiched with an interlayer foil were arranged with an overlap of 3T (T = 1.3 mm, sheet thickness). Tests then were carried out at 1100°C ± 7° for various amounts of bonding time under a vacuum of 10^{-4} torr. After TLP metallic bonding, the specimens were heat treated according to the following procedure: 720°C for 8 h, furnace cooled to 620°C; 620°C for 8 h, air cooled. A schematic of the TLP process used in this study is shown in Fig. 2. The bonding interfaces following heat treatment were observed by means of optical microscopy (OM), and their compositions were analyzed using an energy dispersive X-ray spectroscope (EDX) in a scanning electron microscope (SEM).

These test specimens then were machined using a wire cut electric discharge machine. The dimensions of the tensile shear test specimens are shown in Fig. 3. Tests were carried out in air at room temperature at a crosshead speed of 0.5 mm/min. The shear strength (T) was calculated using the following equation:

$$\tau = P/AW$$

where P is the breaking load, A is the overlap length, and W is the sample width. The shear strength was determined as the average taken from three bonded specimens. The fracture surfaces also were observed by SEM.

Results and Discussion

The optical micrographs of the TLP joint interfaces for the Inconel 718SPF superalloy with a Ni-P interlayer in test specimens maintained at 1100°C ±7° for various bonding times are shown in Fig. 4. At the TLP bonding temperature, the interlayer melted and the liquid zone further widened by melting adjacent to the Inconel 718SPF superalloy. The phosphorus in the molten interlayer rapidly diffuses into the base metal when a fine-grained superalloy is employed. The precipitates of phosphorus were formed at the grain boundaries of the base metal. The width of the total affected zone widened to about 150 μm, which was greater than the initial interlayer thickness (37 μm). Isothermal solidification took place across the joint. The nickel solid solution nucleated at the liquid/solid interface and grew toward the joint center. Since the isothermal solidification stage is controlled by the diffusion of phosphorous in solid nickel, this process will be very slow. At the same time, the solubility of phosphorus was rejected to the residual liquid. If the samples cooled before the completion of isothermal solidification, intermetallic phases were formed in the center of the joint. Fig. 4a show that a large number of precipitate grains, the restriction of grain growth by grain boundary precipitates, should more or less limit the homogenization effect during the TLP process.

The microstructures of the TLP bond with the Ni-Cr-P interlayer at 1100°C ±7° for various bonding times are shown in Fig. 5. The mechanisms of the bonding process and the microstructures were similar to those of the TLP bond with the Ni-P interlayer. However, the concentrations of nickel, iron and niobium in the bond region and in the base metal had a difference of more than 2 wt-% under the same metallic bonding conditions (1100°C for 8 h) — Fig. 6 and Table 2. This means that a longer time was required to homogenize the compositions of bonds with the Ni-Cr-P interlayer. This result might have been caused by the chromium, which may have reduced the diffusion of the nickel and iron in the interlayer and increased the bonding time for the homogenization process.

The results of the shear strengths of the TLP bonds with Ni-P and Ni-Cr-P interlayers are shown in Fig. 7. It can be seen that the shear strength of the TLP bonds increased with the bonding time. Under the same conditions, the shear strength of the TLP bonds with the Ni-P interlayer possessed higher strength than did those with the Ni-Cr-P interlayer. All the bonds failed at the interface in tensile shear tests. Figure 8 shows the fracture surfaces of the TLP bonds with the Ni-P interlayer for 30 and 480 min. As indicated in Fig. 4A, a large number of brittle intermetal-

Table 1—The Chemical Composition of Inconel 718SPF Superalloy

C	Mn	Fe	Si	Cu	Ni	Cr	Al
0.03	0.08	17.9	0.11	0.09	53.85	18.26	0.53
Ti	Co	Mo	P	B	S	Nb + Ta	
1.06	0.15	3.01	0.011	0.002	0.001	4.92	

Table 2—Phase Compositions Observed in TLP Metallic Bonding with Ni-P and Ni-Cr-P Interlayers (wt-%)

	Position	Ni	Cr	Fe	Mo	Nb	Ti	P	Al
Ni-P	1	Bal.	16.7	15.5	3.6	3.6	0.6	0.6	0.4
Interlayer	2	Bal.	16.7	16.2	3.7	3.6	0.7	0.6	0.8
Fig. 6	3	Bal.	9.0	6.4	3.5	34.5	5.7	16.1	—
Ni-Cr-P	1	Bal.	19.3	16.1	3.3	2.6	0.6	0.2	0.7
Interlayer	2	Bal.	19.1	18.6	3.6	4.8	1.3	0.2	0.7
Fig. 8	3	Bal.	11.3	6.2	3.3	32.4	5.2	15.8	—

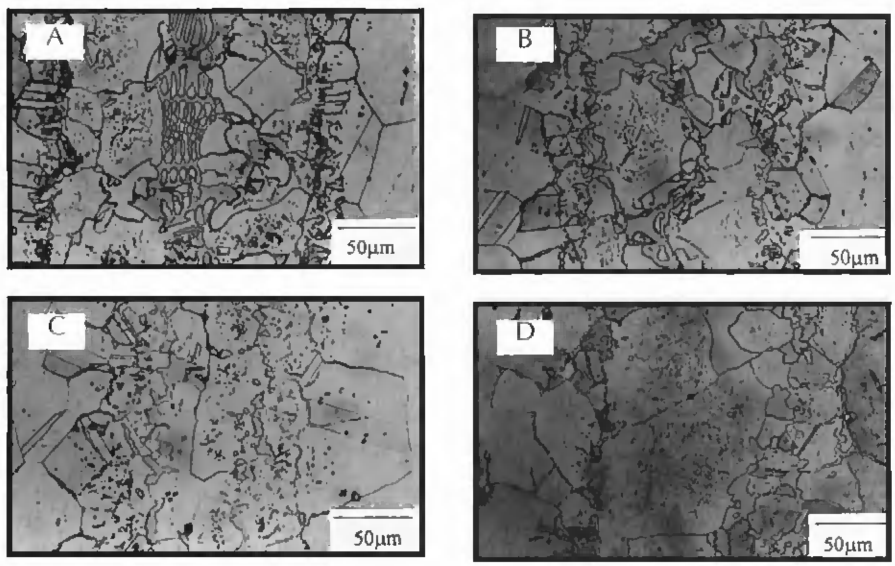

Fig. 4 — Microstructure of TLP bond produced with a Ni-P interlayer (vacuum of 10^{-4} torr, 1100°C). A — 30 min; B — 60 min; C — 240 min; and D — 480 min.

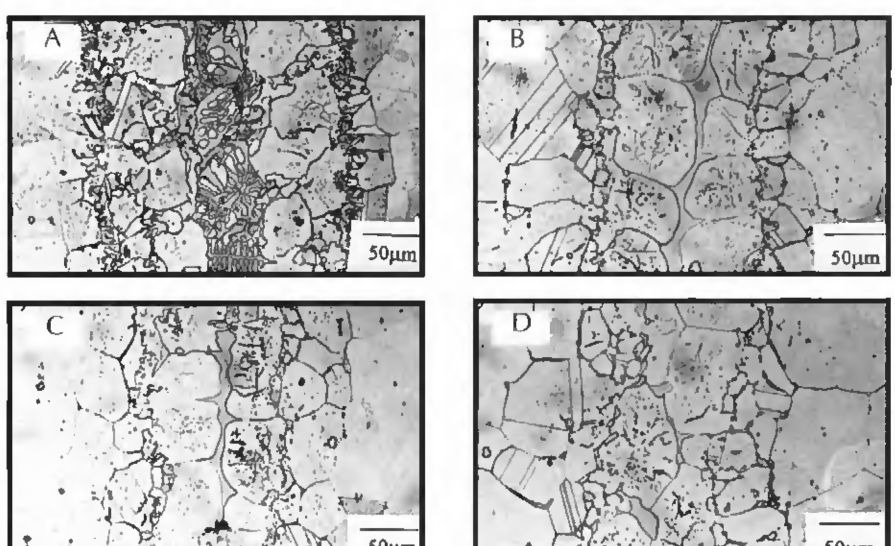

Fig. 5 — Microstructure of TLP metallic bond with Ni-Cr-P interlayer (vacuum of 10^{-4} torr, 1100°C). A — 30 min; B — 60 min; C — 240 min; D — 480 min.

Fig. 6 — Microstructure of joint produced with Ni-Cr-P interlayer at 1100°C for 480 min.

lic phases formed at the centerline of the specimen joint at 100°C for 30 min. These intermetallic phases decreased the strength of a bonded joint and caused the brittle fracture for the Ni-P bonds at 1100°C for 30 min — Fig. 8A. However, the intermetallic phases continue to decrease until the bonding time increased to 8 h. In this case, the bond strength of a joint with intermetallic-free phase was higher than that of a joint with brittle phases formed at the centerline of the specimen joints at 1100°C for 30 min. According to the Ni-P phase diagram, the intermetallic compounds were mixed with Ni_3P, Ni_5P_2 and $Ni_{12}P_5$. EPMA element mapping revealed that these phases consisted of nickel, chromium, phosphorus and niobium — Fig. 9. The appearance of niobium in these phases indicated dissolution of the solid base metal in the molten interlayer. Maintaining the specimens at TLP bonding temperature, the composition of the filler metal will change with time, because the phosphorus in the filler metal diffuses away from the joint and into the nickel matrix and grain boundaries of the superalloy. This caused the volume of the precipitate phases, which formed at the centerline of the specimen joints, to decrease and the volume of the nickel solid solution to increase — Figs. 4B, 4C. The precipitate phases almost disappeared at 1100°C when the bonding time increased to 8 h. Furthermore, many second phases then formed at the grain boundaries of the interlayer/base metal interface — Fig. 4D. The results of compositional analysis in the center of the bond region and in the base metal (label in Fig. 10) are presented in Table 2. No difference in the chemical composition in either region was observed. This means that the homogenization stage for the Inconel 718SPF superalloy bonded with the Ni-P interlayer can be completed under the 1100°C/8 h bonding condition. However, the second phases (Region 3) had higher concentrations of phosphorus and niobium than matrix. These phases formed as discrete globular particles, usually along the grain boundaries of the nickel solid solution. They provided the pinning effect to retard the grains of the interlayer/base metal interface to growth. For this reason, some small grains also were observed in this region. The migration of grain boundaries accompanying the grain growth can somewhat sweep off the inhomogeneity in the intermetallic phases. When the bonding time increased to 480 min, a bond with average strength of 191.2 MPa ±3.5 MPa can be obtained, and tear dimple fractographic features were observed — Fig. 8B. The fracture surfaces of the TLP bonds with the NiCr-P interlayer were similar in appearance to those of the bonds with the Ni-P interlayer (Fig. 11) for the similar reasons mentioned previously.

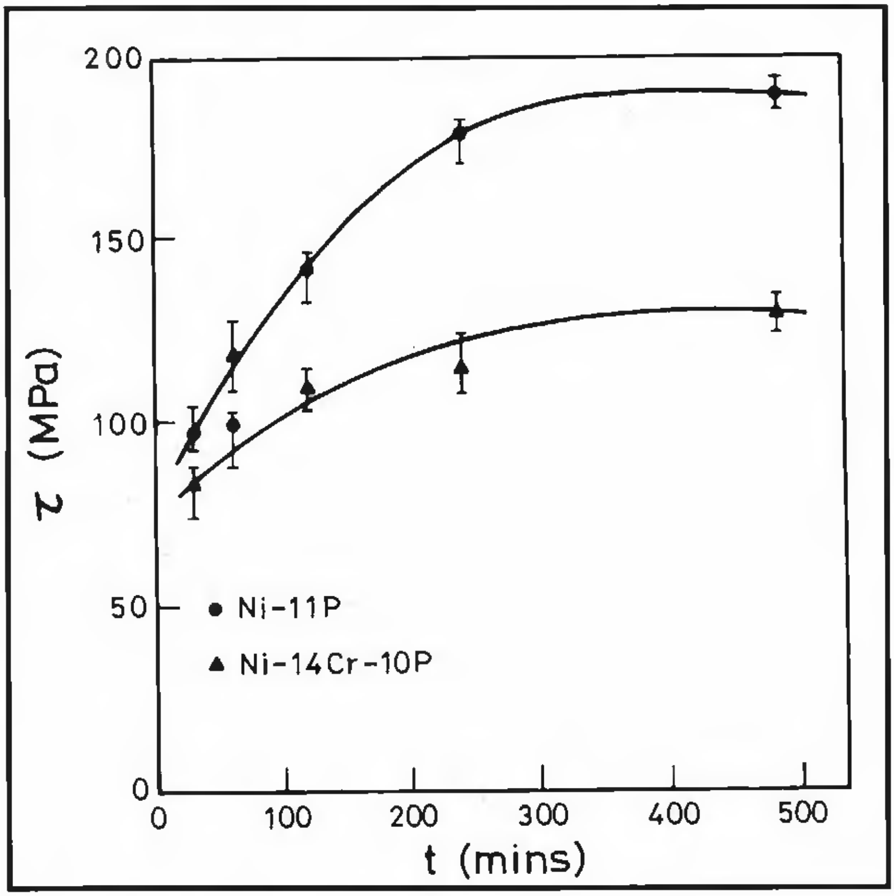

Fig. 7 — Shear strength of Inconel 718SPF superalloy TLP metallic bonds produced with Ni-P and Ni-Cr-P interlayers at 1100°C for various lengths of time.

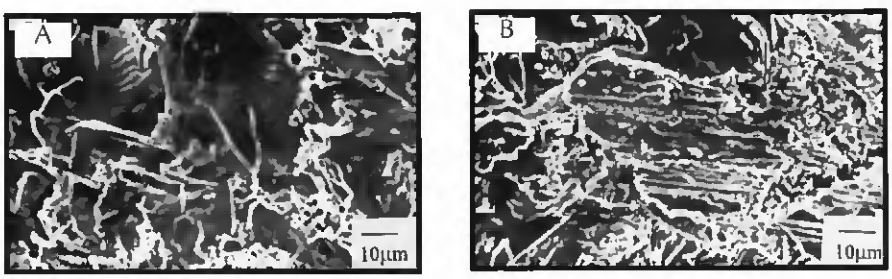

Fig. 8 — Fractographs of metallic bonds produced with Ni-P interlayer at 1100°C for various lengths of time (overlapping length 3T). A — 30 min; B — 480 min.

Conclusions

The following conclusions were obtained from the present study:

1. Transient liquid phase (TLP) metallic bonding of the Inconel 718SPF superalloy with the Ni-P interlayer at 1100°C for 8 h showed uniform chemical com-

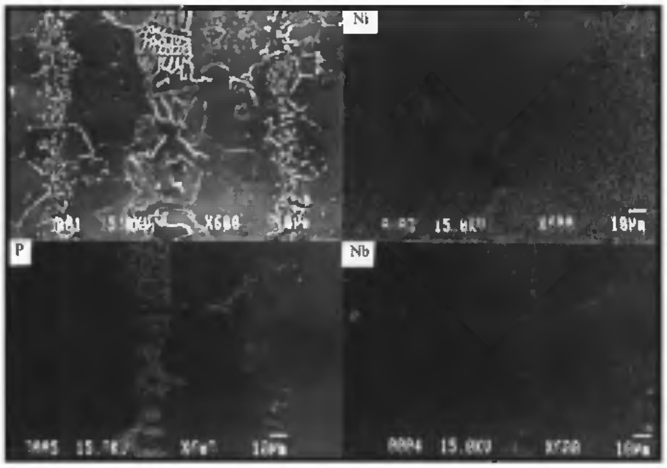

Fig. 9 — The EPMA element mapping of TLP metallic bond produced with Ni-P interlayer (vacuum of 10^{-4} torr, 1100°C, 30 min).

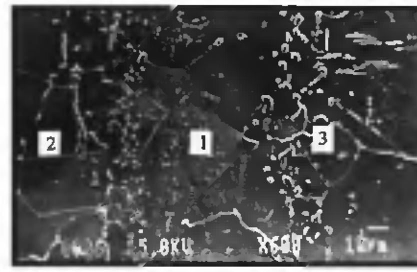

Fig. 10 — Microstructure of joint produced with Ni-P interlayer at 1100°C for 480 min.

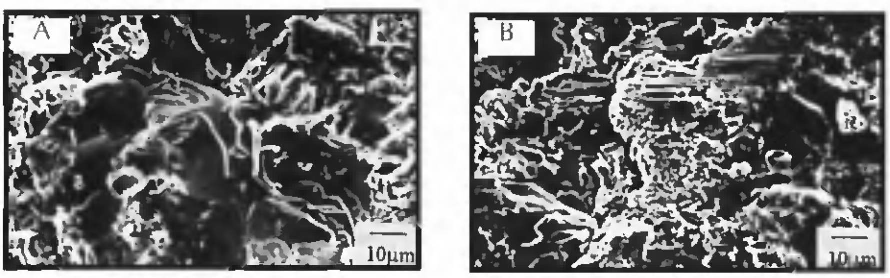

Fig. 11 — Fractographs of joints produced with Ni-Cr-P interlayer after bonding at 1100°C (overlapping length 3T). A — 30 min; B — 480 min.

position in the bond region and in the base metal. However, the Inconel 718SPF superalloy with the Ni-Cr-P interlayer had precipitate phases at the centerline of the joint.

2. The shear strength of the TLP bonds with the Ni-P interlayer indicated higher bond strengths than did that with the Ni-Cr-P interlayer under the same bonding conditions.

3. The second phases, which existed at the grain boundaries, retarded grain growth in the bonding region. Homogenization during the TLP metallic bonding process was, thus, limited.

References

1. Thompson, R. G., and Genculu, S. 1983. Microstructural evolution in the HAZ of Inconel 718 and correlation with the hot ductility test. *Welding Journal* 62(12): 337-s to 345-s.

2. Sakamoto, A., Fujiwara, C., Hattori, T., and Sakai, S. 1989. Optimizing processing variables in high-temperature brazing with nickel-based filler metals. *Welding Journal* 68 (3): 63–71.

3. Lugscheider, E., and Partz, K.-D. 1983. High temperature brazing of stainless steel with nickel-base filler metals BNi-2, BNi-5 and BNi-7. *Welding Journal* 62(6):160-s to 164-s.

4. Duvall, D. S., Owczarski, W. A., Paulonis, D. F., and King, W. H. 1972. Methods for diffusion welding the superalloy Udimet 700. *Welding Journal* 51(2): 41-s to 49-s.

5. Holko, K. H., and Moore, T. J. 1972. Enhanced diffusion welding of TD-NiCr sheet. *Welding Journal* 51(2): 81-s to 89-s.

6. Duvall, D. S., Owczarski, W. A., and Paulonis, D. F. 1974. TLP bonding: A new method for joining heat resistant alloys. *Welding Journal* 53(4): 203–214.

7. Feduska, W. 1958. The nature of high-temperature brazing alloy-base metal interface reactions. *Welding Journal* 37(2): 62-s to 73-s.

8. Tuah-Poku, I., Dollar, M., and Massalski, T. B. 1988. A study of the transient liquid phase bonding process applied to a Ag/Cu/Ag sandwich joint. *Metall. Trans. A*, 15(3): 675–686.

9. Nakagawa, H., Lee, C. H., and North, T. H. 1991. Modeling of metal dissolution behavior during transient liquid-phase bonding. *Metall. Trans. A*, 22(2): 543–555.

10. Kokawa, H., Lee, C. H., and North, T. H. 1991. Effect of grain boundaries on isothermal solidification during transient liquid phase brazing. *Metall. Trans. A*, 22(7): 1627–1631.

11. Mahoney, M. W., and Crooks, R. 1988. Superplastic forming of Inconel 718. *Superplasticity in Aerospace*. eds. H. C. Heikkenen and T. R. McNelley, TMS, pp. 331–344.

12. Smith, C. D., and Flower, H. L. 1995. Heat treatable superalloy developed for superplastic forming of high strength and hot gas corrosion resistant parts. *Industrial Heating*, 62 (4): 47–49

13. DeCristofard, N., and Henschel, C. 1978. Brazing Foil. *Welding Journal* 57(7): 33–38.