12/6-26-95 JS ①

UCRL-ID-119335

Concurrent Solid State Diffusion Bonding and Superplastic Forming of Aluminum Alloy 7475

Anne Sunwoo
Reynold Lum
Richard Vandervoort

January 1995

Lawrence
Livermore
National
Laboratory

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an acccount of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately own rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Concurrent Solid State Diffusion Bonding and Superplastic Forming

of Aluminum Alloy 7475

Anne Sunwoo, Reynold Lum, and Richard Vandervoort
Lawrence Livermore National Laboratory
7000 East Ave
Livermore, California 94550

Abstract

Earlier studies on diffusion bonding (DB) of Al alloys have focused mostly in extrinsically changing the bonding conditions through the use of interlayers, surface etching, or environment. The problem with focusing on the extrinsic conditions only is that the benefits of the DB process are not fully utilized and instead, it can create problems for the base alloy. The approach we have taken to study solid state diffusion bondability of Al alloy is to utilize the intrinsic behavior of superplastic material. Beginning with this preprocessed material, we used a unique method, to obtain diffusion bonding concurrently with superplastic forming to achieve ductile, oxide-free bonds at significantly lower pressures and temperature in an argon atmosphere.

Introduction

In diffusion bonding (DB), the surface condition of a base material is critical to successfully producing a sound bond. It is well known that aluminum (Al) forms a highly stable oxide film on the surface and that DB in either solid state or interlayer-enhanced condition has been difficult. Earlier studies on DB of Al alloys have focused mostly in extrinsically changing the bonding conditions through the use of interlayers, surface etching, or environment. Even in these conditions, the process has been limited to research interest and has not been production feasible.

The problem with focusing on the extrinsic conditions only is that the benefits of the DB process are not fully utilized and instead, it can create problems for the base material. The DB process, in general, is used to preserve the base material microstructure. The bonded parts have a microstructural continuity and, in turn, a structural integrity without concerns for distortion and residual stresses process. Thus, coupling of diffusion bonding with superplastic forming is considered a technology advancement since it will transform the manufacturing into a cost-effective, and material- and energy-efficient process. Despite the attractiveness of integrating the two processes, thus far, diffusion bonding and superplastic forming have been a sequential process. Because of the extensive time required at the DB temperature under the applied pressure, there is a potential for grain growth in these grain-size sensitive superplastic materials, which will adversely affect subsequent forming.

The approach we have taken to study solid state diffusion bondability of Al alloy is to utilize the intrinsic behavior of superplastic material. The primary deformation mechanism for superplasticity is grain boundary sliding with accommodation of either diffusion, slip, or both. For the conditions applied in this work, grain boundary sliding with a diffusional accommodation is favored. If superplasticity of a material is obtained by very fine internal grains sliding and rotating to allow neighboring grains to switch [1-3], then grains on the surface should be also sliding and rotating to allow the oxide film to be disrupted by new grains coming to the surface. A surface that contains these nonoxidized grains should be able to bond with a minimum of applied contact pressure. An additional benefit of fine-grained materials is the high density of grain boundaries on the bonding surface, combined with very low flow stress, which enhance grain boundary diffusion and ease the grain movement.

Using this concept of superplastic deformation enhanced solid state diffusion bonding, we were able to produce ductile, oxide-free bonds of superplastic Al alloy 7475 in an argon atmosphere, using less than 1 MPa bonding pressure [4]. The specimens were tensile pulled at 510°C and a strain rate of 2×10^{-4}/s, which simulates the superplastic forming (SPF) condition of 7475. The bonds were produced with no additional time at bonding temperature. The purpose of this work is to determine the optimum bonding pressure application during concurrent DB and SPF of Al alloy 7475.

Experimental procedure

The nominal composition (by wt-%) of aluminum alloy 7475 is 5.27Zn-2.01Mg-1.26Cu-0.17Cr-0.02Si-0.02Fe-bal. Al. The as-received sheet thickness was 1.5 mm and the average grain size in the long-transverse direction is about 10 µm. In the superplastic forming condition, this alloy exhibits greater than 1000% elongation, with average flow stress less than 1.4 MPa. At low strain, the strain rate sensitivity, m, is 0.8.

For the diffusion-bonding study, an apparatus (see Fig. 1) was designed and fabricated to simultaneously apply a tensile pull on the specimens and a lateral/bonding pressure on the bonding surface. To maintain a stable bonding location during the test, the specimens had to be pulled between two movable crossheads traveling at the same rate in the opposite directions. To accomplish this task, a small tabletop Instron test machine was placed inside a larger Tinius Olsen test machine, and the two machines were used in tandem.

The 12-mm-gage-length, dogbone-shaped specimens were machined parallel to the rolling direction. Surface preparation consisted of lapping both sides with 400 grit silicon carbide paper, and surface cleaning followed, which consisted of sequential rinsing with distilled water, *1M* nitric acid for 2 min, distilled water, and ethanol. The specimens were then dried with hot air from a heat gun. The surfaces were lapped parallel to the rolling direction. Subsequently, two specimens were mounted in the grips and placed inside a quartz tube. The tube ends were sealed with fiberfax, and the cavity was purged with argon for about 30 min. Two chromel-alumel thermocouples were used to monitor and compare the temperatures of the specimens and the furnace during the DB-SPF process. Because of the difficulty in putting thermocouples on Al using spot welding, a laser-brazing technique was used to place thermocouple at the center of the gage length of the specimens. Note that the cross-section of the joint showed no damage to the base alloy microstructure.

The specimens were heated by a radiant-heat, clam-shell furnace with a Eurotherm controller to the bonding temperature at a rate of about 100°C/min, and the specimens were held for an additional 5 min to ensure a steady-state temperature. Then, lateral pressure was applied to the bonding surface while the specimens were being pulled to about 100% strain at a constant crosshead speed of 0.3 mm/min, which is equivalent to a strain rate of $2 \times 10^{-4}\ s^{-1}$. To determine the importance of bonding pressure during forming, dual bonding pressure schedules were used. Some bonds were produced at an initial pressure of 0.3 MPa to 40% strain and then increased by either 0.3, 0.55, or 0.85 MPa to 100% strain. Others were produced at an initial pressure of 0.55 or 0.85 MPa to 40% strain and then decreased to 0.3 MPa to 100% strain. Bond quality was determined by room-temperature, 90° peel tests, in which the specimens were pulled at a constant crosshead speed of 0.3 mm/min. The bond interface and peeled surfaces were examined by means of optical metallography and scanning electron microscopy (SEM) fractography, respectively.

Results and Discussion

With a fast heating rate and a minimal time at equilibrating and bonding temperature, we were able to maintain the alloy's fine grain size throughout the specimen. Figure 2 shows the cross-section of a bonded specimen, displaying a microstructural continuity with indiscernible bond interface. However, there are a few voids already present in the alloy. Cavitation is a major inherent problem in superplastic Al alloy 7475. Although the effect of strain rate on bondability was not investigated, like other studies [5,6], we have observed that for a given temperature the cavity formation in 7475 was highly strain-rate sensitive [7].

The bonding pressure was the only DB parameter varied in order for the diffusion bonding to compliment superplastic forming. One of the important properties of a diffusion bond is its resistance to peeling [8-10]. Particularly at the superplastic forming temperature, the peel resistance strength should be greater than the yield strength of the base alloy at the SPF strain rate so that the critical flow stress in the bonded region during forming will be reached before the joint starts to peel. The effect of bonding pressure on the peel strength (PS) is summarized in Fig. 3a. As a comparison, the figure also included the effect of constant bonding pressure on the PS [4]. For all bonding pressure schedules, a similar trend is found. These results distinctly indicate that there is a narrow bonding pressure range where the superplastic deformation can be applied to enhance solid-state diffusion bonding. They also suggest that after the alloy reaches yielding, a continuous application of large bonding pressure is not necessary. The PS-values show the advantage of applying a greater bonding pressure during initial forming, where PS of 23N/mm was achieved with less than 1 MPa pressure. This value is better than that of the low initial pressure bonds. For the bonds produced with less than 0.6 MPa pressure, the peel strength is poor due to insufficient bonding pressure(3a). For the bonds produced with greater than 0.9 MPa, on the other hand, the peel strength is poor due to restricting the uniform material flow in the gage length and may also affecting grain-boundary sliding deformation at the bonding surface (3a).

It is difficult to make a direct comparison with other reported data, since the diffusion bonding conditions differ significantly. Nevertheless, for a given 7475 composition and thermomechanical processing, the fine-grained superplastic alloys containing high density of grain boundaries and low flow stress can positively influence its diffusion-bonding characteristics. Figure 3b compares current results with other reported peel strength values as a function of bonding pressures. The bonds produced under sufficient pressure, enough time at temperature, and enclosed environment exhibit high bond strength [8,10].

The peel surfaces of the bonded specimens were indicative of their strength. Most of the bonded region showed ductile-dimple failure, but the uniformity and depth of the dimples varied with the bonding conditions, as shown in Fig. 4. The peel surface of a bond exhibiting 19 N/mm peel strength revealed an ideal ductile-dimple fracture (4a), which Heinz and Sahm [8] referred to as a "honeycomb" fracture. Although the bonding pressure was increased to enhance the interfacial contact, the dimples lacked the depth, giving a planar surface appearance (4b). A region away from the direct tensile pull alignment showed some bonding around the grain boundaries (4c), but the oxidized surface of the grains is still present. The peel surface suggests that there was not sufficient grain movement to break-up the oxide film on the surface. Pilling and Riddle [9] referred this type of fracture as a Type II failure where mostly planar surface was observed with narrow zones of ductile tearing around the grain boundaries. This type of fracture was predominant in their bonds, exhibiting average strength of about 50 MN/m^2.

Conclusion

we used a unique method to study diffusion bonding concurrently with superplastic forming to achieve ductile, oxide-free bonds at significantly lower pressures and temperature in an argon atmosphere. This work clearly proves that superplastic deformation enhances solid state diffusion bonding of superplastic aluminum alloy.

Acknowledgment

The authors would like to thank the Kaiser Aluminum Center for Technology for providing the material for this study. This work was performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

1. M. F. Ashby and R. A. Verrall, "Diffusion-Accommodated Flow and Superplasticity", Acta Metall., 21 (1973), 149-163.
2. D. J. Sherwood and C. H. Hamilton, "Grain dimensional changes from the deformation of a superplastic 7475 Al alloy", J. Mater. Sci. Lett., 12 (1993), 1199-1203.
3. A. K. Ghosh and R. Raj, Mechanical Testing for Deformation Model Development, eds. R.W. Rohde and J.C. Swearengen (Philadelphia, PA: SMTM, 1982), 414-434.
4. A.J. Sunwoo and R.C. Lum, "Superplastic Deformation Enhanced Diffusion Bonding of Aluminum Alloy 7475", submitted to Scripta Metallur., 1994.
5. Amit Ghosh, private communication with authors, Lawrence Livermore National Laboratory, 1993.
6. G. D. Smith and H.L. Flower, Superalloy 718, 625, 706 and Various Derivatives, ed. E.A. Loria (Warrendale, PA: TMS, 1994) 355-364.
7. A.J. Sunwoo, unpublished results, 1994.
8. B. Heine and K. F. Sahm, "Mechanical Properties of Diffusion-Bonding Superplastic 7475 Semifinished Sheets", Aluminum, 70 (1994), 94-98.
9. J. Pilling and N. Ridley, "Solid state bonding of superplatic AA 7475", Mater. Sci. Technol., 3 (1987), 353-359.
10. J. Kennedy, Superplasticity and Superplastic Forming, ed. C.H. Hamilton and N.E. Paton (Warrendale, PA: TMS, 1988) 523-527.

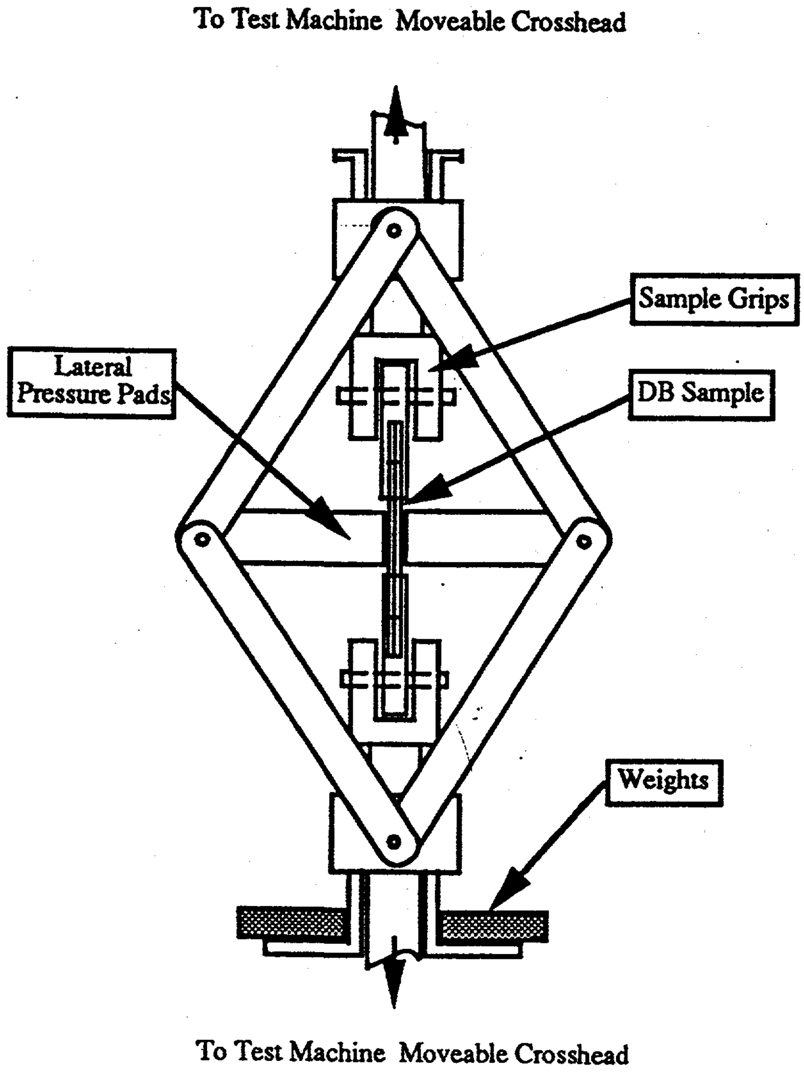

Figure 1 - A schematic drawing of an apparatus that allows simultaneous tensile pull on the specimens and a lateral/bonding pressure on the bonding surface.

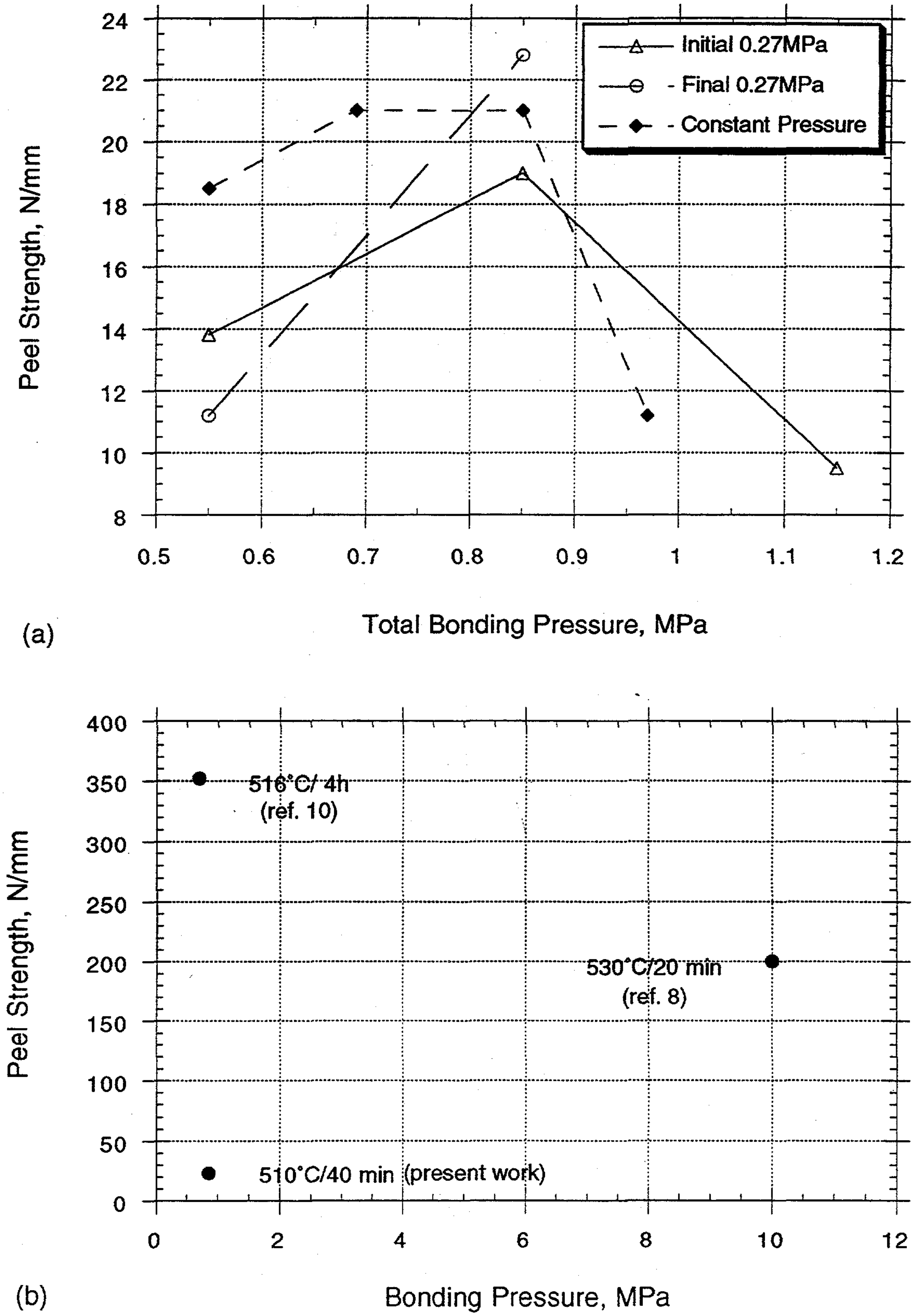

Figure 3 - Effect of bonding pressure on peel strengths of solid state diffusion bonds: (a) present results; (b) comparison of present results with refs. 8 and 10.

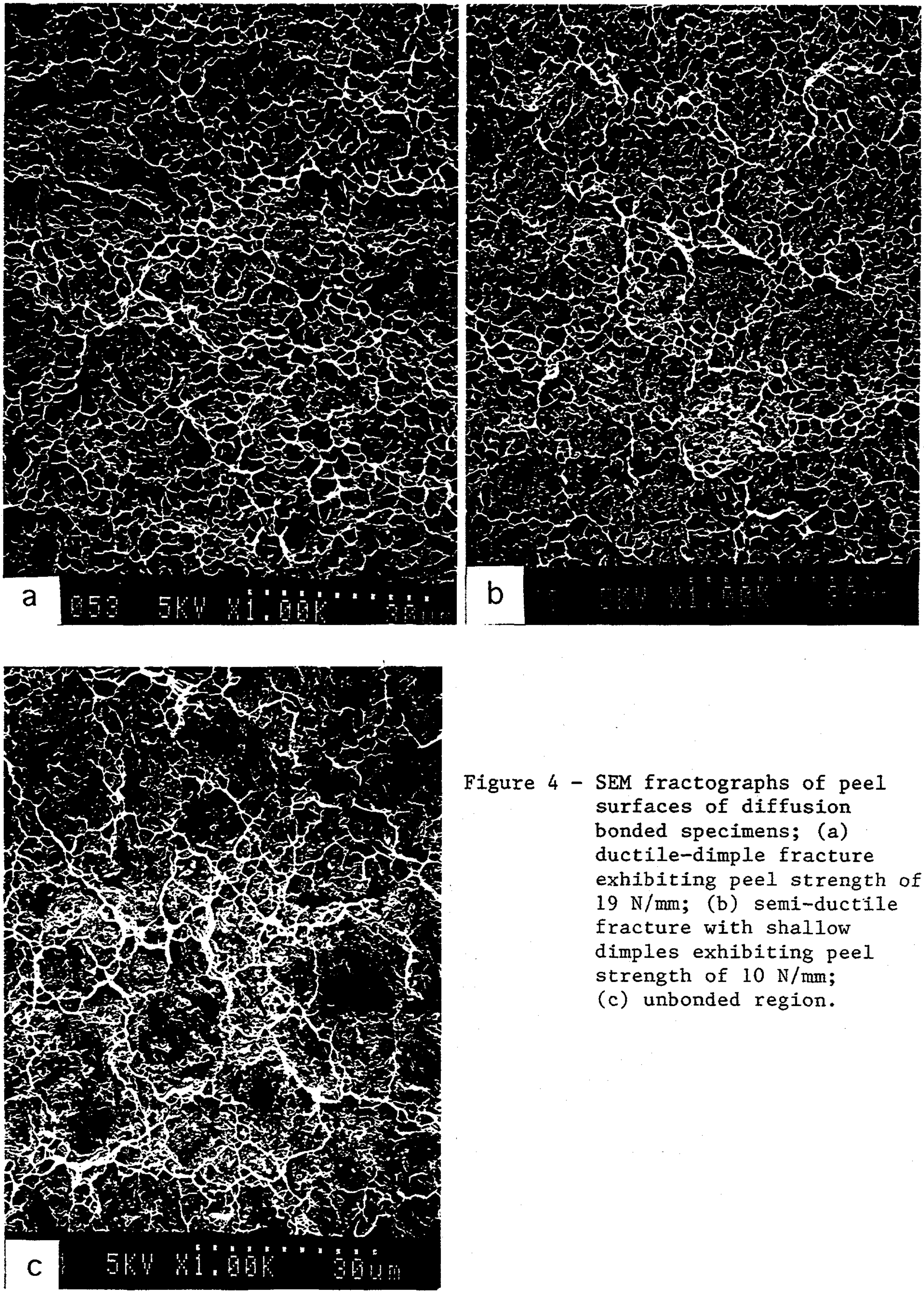

Figure 4 - SEM fractographs of peel surfaces of diffusion bonded specimens; (a) ductile-dimple fracture exhibiting peel strength of 19 N/mm; (b) semi-ductile fracture with shallow dimples exhibiting peel strength of 10 N/mm; (c) unbonded region.

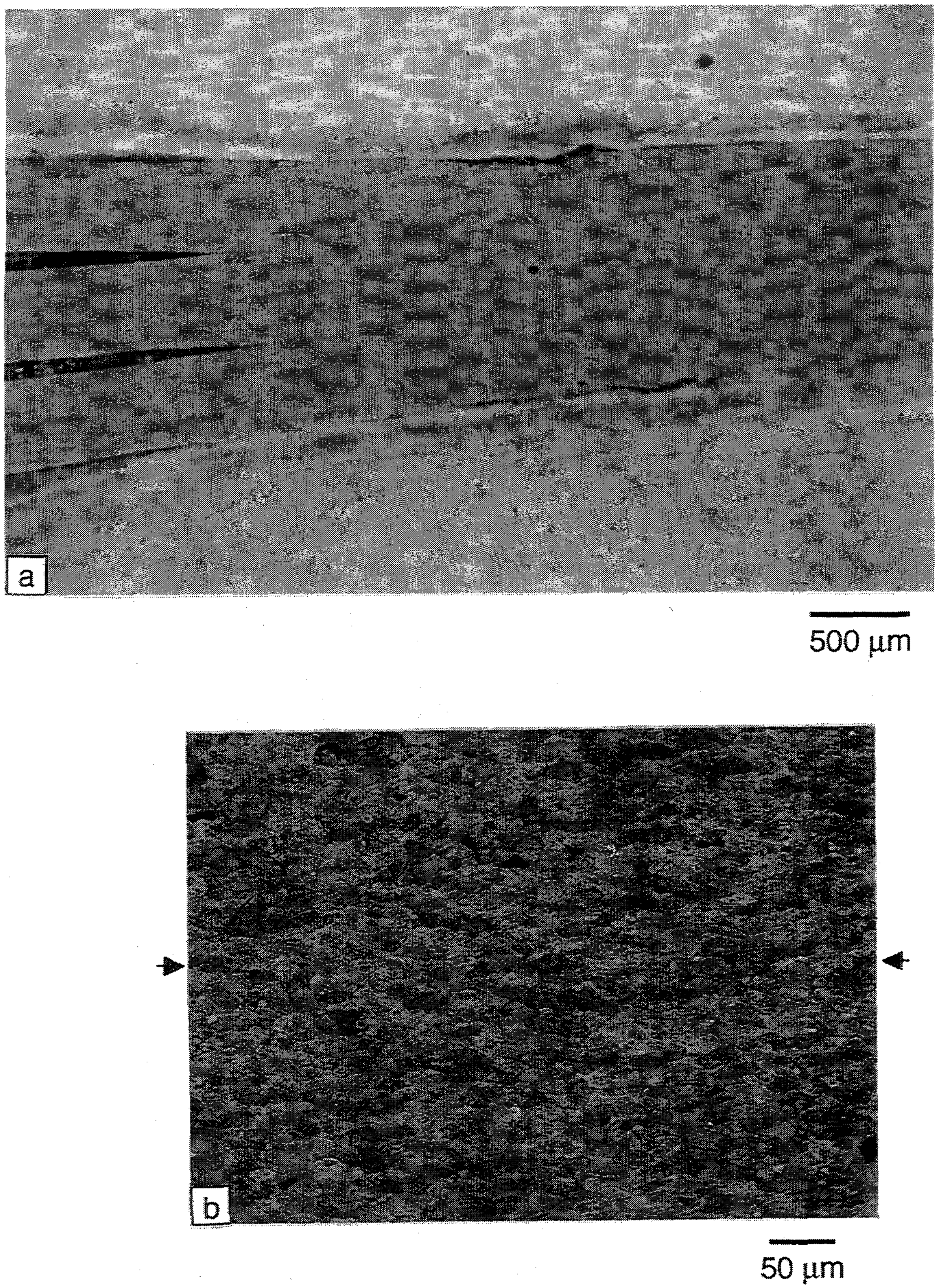

Figure 2 - Optical micrographs of a bonded specimen: (a) a low magnification view showing three specimens conversing to one bonded piece; (b) a high magnification view showing microstructural continuity with indiscernible bond interface. Micrograph also shows cavities in the base alloy (black voids).