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Effects of Superplastic Deformation on the Diffusion Welding of SuperDux 65 Stainless Steel

A two-stage diffusion process resulted in greatly improved weld strength

BY M. S. YEH, Y. H. TSENG AND T. H. CHUANG

ABSTRACT. The SuperDux 65[1] stainless steel diffusion welded in a nonsuperplastic state (880°C, 60 min) required greater pressure, compared to aluminum and titanium alloys, to create a contact area at the weld interface, which will increase the atomic diffusion paths. However, an unsatisfactory weld strength of 45.3 MPa was obtained under the applied pressure of 7 MPa. This alloy deformed easily at its superplastic temperature of 970°C, resulting in a tight contact surface. The higher welding temperature was also beneficial for atomic diffusion. Both effects were advantageous for diffusion welding, while the joined workpieces macroscopically deformed markedly. In this study, a two-stage diffusion welding method was proposed. The specimens were diffusion welded in a nonsuperplastic (or superplastic) state for a short time and then further diffusion welded at superplastic (or nonsuperplastic) temperatures for a longer heating period. It was found that the welding strength could be improved drastically using such a two-stage process. The contributions of superplastic deformation on the diffusion welding of this alloy during the two-stage process were clarified.

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1. SuperDux 65 stainless steel is manufactured by Nippon Yakin Kogyo Co. Ltd, Japan.

Introduction

Duplex stainless steels are Fe-Cr-Ni ternary alloys that possess a microstructure consisting of nearly equal amounts of ferrite and austenite. These stainless steels offer several advantages over the austenitic and ferritic stainless steels, namely, higher mechanical properties, good weldability, superior corrosion resistance and a lower price (Refs. 1–3). As a result, the duplex stainless steels have been widely used in the aerospace, chemical, power generation and oil and gas industries (Ref. 4). Good joining techniques are necessary for expanding the applications of duplex stainless steels. Fusion welding has been most commonly used. However, the heat-affected zone (HAZ) generated by fusion welding could reduce the mechanical properties and corrosion resistance of the joined workpieces (Refs. 1, 5). Diffusion welding is another choice. Because diffusion welding requires atomic diffusion at the weld interface for the transportation of elements, material with a finer grain size provides a larger number of grain-boundary diffusion paths and, therefore, would possess better diffusion weldability.

KEY WORDS

Diffusion Welding
SuperDux 65
Stainless Steel
Superplastic
Shear Strength

In addition, another necessary condition for satisfactory diffusion welding is intimate contact between the surfaces to be joined. Such intimate surface contact can be obtained in the conventional diffusion welding process by applying sufficient pressure, which causes microscopic plastic deformation at the contact surface between joined parts. It is well known that material with very fine grain size and a duplex structure will possess superplasticity at a certain strain rate (10-3~10-4 s-1) and higher temperature (>½T_m, where T_m is the melting point in degrees Kelvin). A superplastic material can be greatly deformed under very little applied stress. For this reason, intimate surface contact can be obtained easily during diffusion welding of a superplastic alloy. This implies a superplastic alloy can be diffusion welded under a lower applied normal pressure.

Using the advantageous effect of superplasticity on diffusion welding, a two-stage heating process was proposed. During such a process, the specimens were first diffusion welded at a nonsuperplastic (or superplastic) state for a short time and then further diffusion-welded at a superplastic (or nonsuperplastic) temperature for a longer heating period. The welding stage at superplastic temperatures (higher than 900°C) offered a beneficial effect of an intimate contact surface while the other stage at nonsuperplastic tempera-

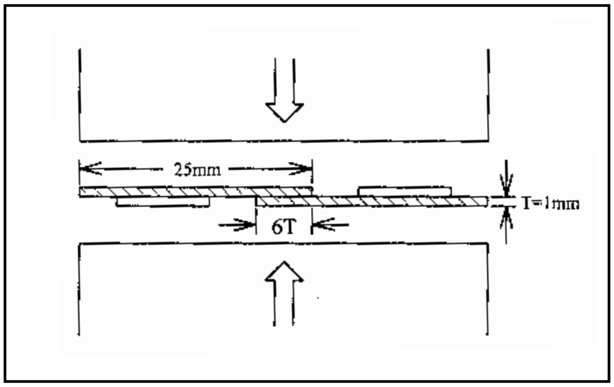


Fig. 1 — The dimensions of diffusion-welded specimens under applied pressure.

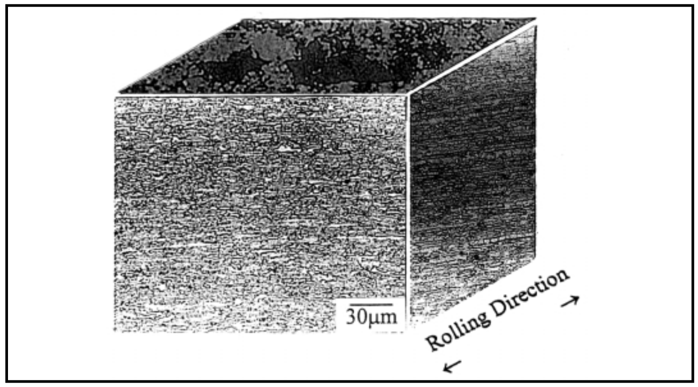


Fig. 2 — Microstructure of as-received SuperDux 65 stainless steel.

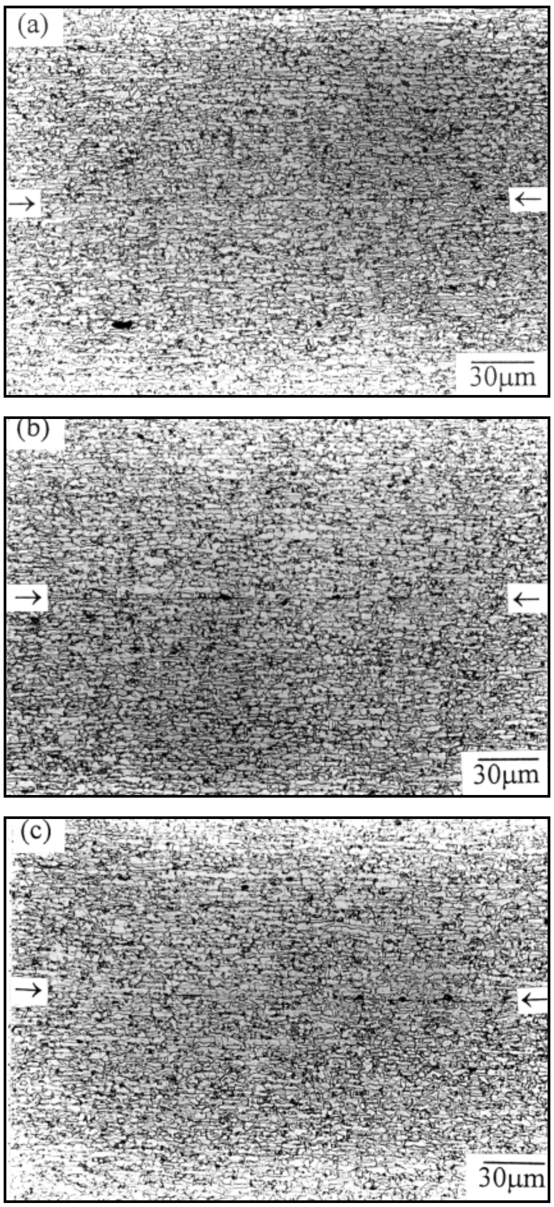


Fig. 3 — The welding interfaces of SuperDux 65 stainless steel subjected to various applied pressures at 880°C for 60 min. A — 7 MPa; B — 3.5 MPa; C — 2.1 MPa.

tures (lower than 900°C) was responsible mainly for atomic diffusion through the thermal effect. The lower temperatures in the nonsuperplastic heating stage offered the benefit of less energy consumption and material degradation.

If manufactured properly, duplex stainless steels can have a very fine grain microstructure, resulting in marked superplasticity (Ref. 6). Soylu, *et al*., developed two methods for refining the microstructure of 30Cr-8Ni steel. The first method involved alloying duplex stainless steels with copper. The second method utilized annealing of cold-rolled supersaturated ferritic stainless steel (Ref. 7). On the other hand, Smith, *et al*., found that the superplastic elongation of cold-rolled IN744 steel reached 1050% at a strain rate of 3.2 x 10–4s^{-1} at 960°C (Ref. 8). The diffusion weldability of superplastic duplex stainless steels had been evaluated by Ridley and coworkers (Ref. 9) using an isostatic pressure method with pressures of up to 2.8 MPa at a temperature between 927° and 1047°C for a long welding period (2–10 h). They found that a sound diffusion-welded joint could be obtained at a pressure of 2.1 MPa after 4 h at 1007°C or 2 h at 1047°C.

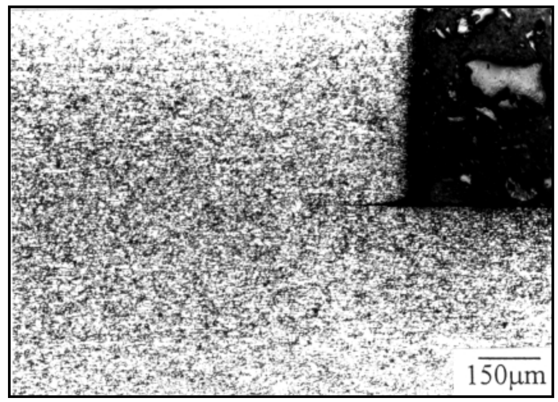


Fig. 4 — Appearance of unwelded crevice at the specimen edge after diffusion welding at 880°C for 60 min under 7 MPa.

The purpose of this study was to evaluate the diffusion weldability of SuperDux 65 stainless steel using a monodirectional hot press method. Also, the improvement of diffusion welding through various two-stage processes was investigated. The information obtained in this study should also be useful for the evaluation of the applicability of a concurrent superplastic forming/diffusion welding (SPF/DW) technique for this alloy. This technique has been considered as an advanced and economically beneficial manufacturing process in the aerospace industry. However, most of the successful SPF/DW workpieces were titanium alloys (Ref. 10). Information on application of this technique to duplex stainless steels was scarce.

Experimental Procedure

A SuperDux 65 stainless steel with a thickness of 1 mm and the chemical composition as shown in Table 1 was used in this study. Strips of this alloy with dimensions of 25 x 15 mm were cut from the as-received sheet material. The surfaces to be welded were prepared by grinding with 2000-grit SiC paper and polishing with 1-μm alumina powder, then cleaned by rinsing in distilled water, followed by ultrasonic cleaning in acetone for 5 min.

Two strips of specimens were arranged with an overlap of 6T (T = 1-mm sheet thickness), as shown in Fig. 1. Diffusion welding was carried out in a hot press under a vacuum of 4 x 10^{-4} Torr at various welding conditions. For A-type specimens, a single heating process at 880°C was used, which is below the superplastic deformation temperature of SuperDux 65 stainless steel (900°C). For comparison, various applied pressures (7.0, 3.5 and 2.1 MPa) were employed at the 880°C welding temperature. On the other hand, the B-type specimens were welded with a two-stage process: first, diffusion welded at a nonsuperplastic (or superplastic) state for 10 min, then further diffusion welded at a superplastic (or nonsuperplastic) temperature for a longer time. The welding conditions are shown in Table 2. After welding, the microstructure of the interface was observed using optical microscopy (OM) and scanning electron microscopy (SEM). In order to evaluate the welding efficiency, the average shear strength was determined from three welded specimens at room temperature with a crosshead speed of 1 mm/min. The shear strength (τ) was calculated by the equation

$$\tau = \frac{P}{AW}$$

where P is the breaking load, A is the overlap length and W is the sample width.

Table 1 — Nominal Chemical Compositions of SuperDux 65 Stainless Steel (wt-%)

	Fe	Cr	Ni	Mo	Cu	Si	Mn	N	C	Al	P	S	REM
Min.	Bal.	23.2	5.5	1.3	0.9	0.6	0.6	0.12	0.02	—	—	—	0.010
Max.	Bal.	23.8	5.9	1.5	1.1	0.7	0.7	0.14	0.03	0.05	0.035	0.002	0.025

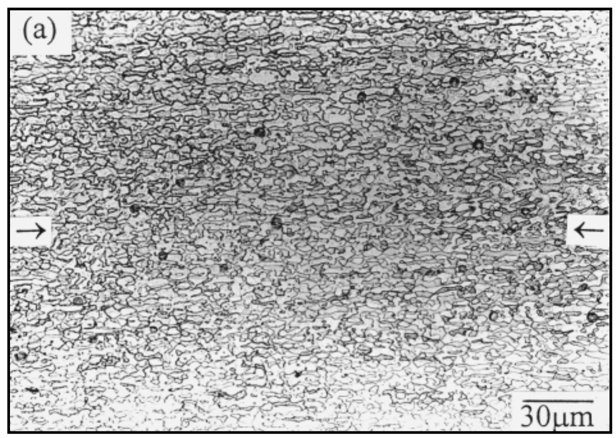
Table 2 — Welding Conditions and Shear Strength of SuperDux 65 Stainless Steel

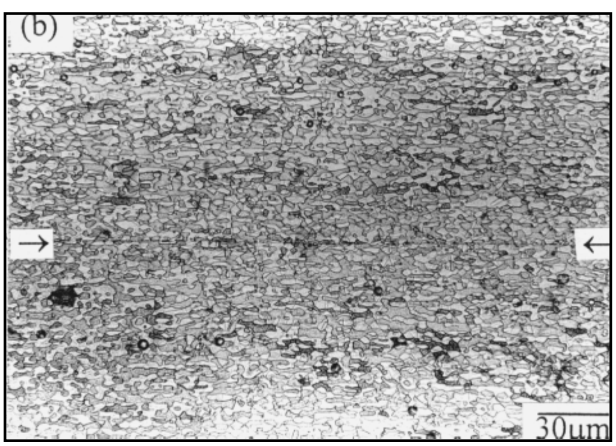
No. of Specimens	Diffusion Welding Conditions	Shear Strength (MPa)
A1	880°C/7.0 MPa/60 min	45.3
A2	880°C/3.5 MPa/60 min	35.7
A3	880°C/2.1 MPa/60 min	19.7
B1	880°C/7.0 MPa/10 min + 970°C/7.0 MPa/50 min	132.2
B2	970°C/3.5 MPa/10 min + 880°C/7.0 MPa/60 min	75.0
B3	970°C/3.5 MPa/10 min + 880°C/3.5 MPa/60 min	76.7

The mechanical properties of SuperDux 65 stainless steel at room temperature: σ_y = 539 MPa, σ_{UTS} = 774 MPa, Elongation = 27%.

Results and Discussion

The microstructure of as-received SuperDux 65 stainless steel in this study is shown in Fig. 2. This material possessed a rolling texture with a fine grain size of 6~7 μm. Figure 3 shows the interfacial microstructure of specimens after diffusion welding at 880°C for 60 min under various applied pressures from 2.1 to 7.0 MPa. The original contact surface representing the unwelded area was observed at all three applied pressures by optical microscopy, which revealed an unsatisfactory joint in this case. The shear strength (Table 2, A1–A3), which ranged only from 19.7 to 45.3 MPa, increased with increasing applied welding pressure. All of the specimens failed at the welding interface in tensile shear tests. Figure 4 is the morphology of the specimen edge, which obviously shows an unwelded crevice. The superplastic deformation behavior of SuperDux 65 stainless steel appeared at about 900°C, which is above the welding temperature (880°C). In this situation, diffusion welding for the SuperDux 65 stainless steel required greater normal pressure, which resulted in inti-





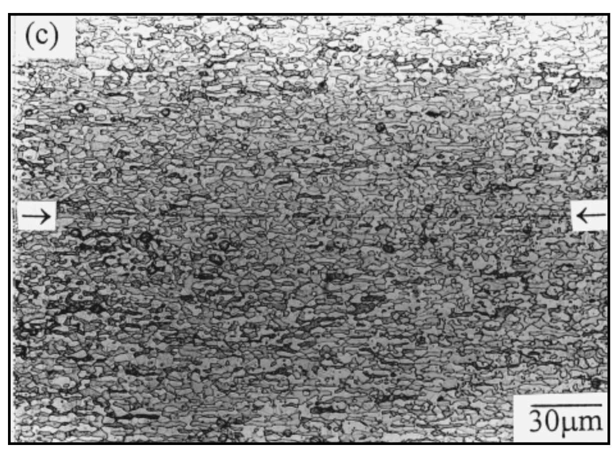


Fig. 5 — The welding interfaces of SuperDux 65 stainless steel conducted by using the two-stage welding method. A — 880°C/7 MPa/10 min + 970/7.0MPa/50 min; B — 970°C/3.5 MPa/10 min + 880°C/7 MPa/60 min; C — 970°C/3.5 MPa/10 min + 880°C/3.5 MPa/60 min.

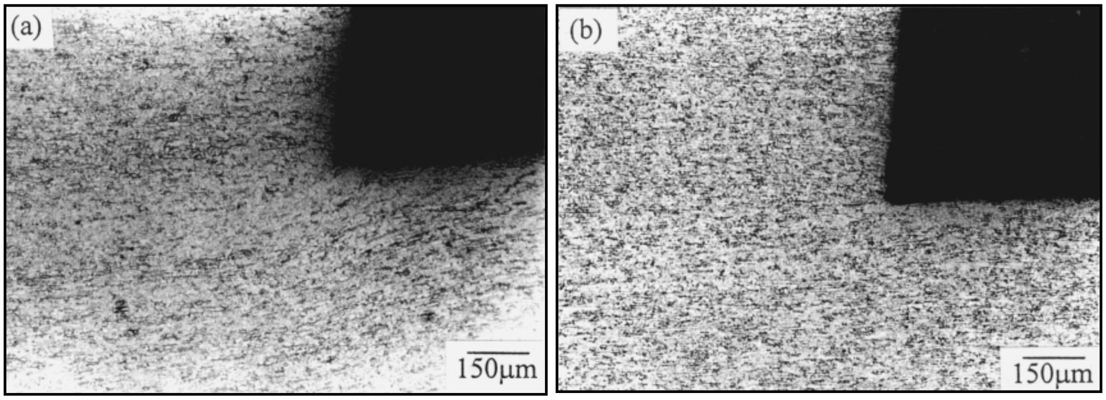


Fig. 6 — The microstructure at the specimen edge for SuperDux 65 stainless steel joined by the two-stage welding process. A — 880°C/7 MPa/10 min + 970°C/7 MPa/50 min; B — 970°C/3.5 MPa/10 min + 880°C/3.5M Pa/60 min.

mate contact, promoting atomic diffusion paths for a sound joint. For the diffusion welding in a nonsuperplastic state, increasing the applied load will cause more contact area to be plastically deformed, which results in higher welding strength.

The SuperDux 65 stainless steels were further diffusion welded with a two-stage process. The microstructures of the welding interface are shown in Fig. 5. Experimental results showed the two-stage welding process had a better effect than the conventional single-stage diffusion welding method (Table 2). The most obvious improvement was obtained in B1 specimens, which were welded in the following condition: 880 °C/7.0 MPa/ 10 min + 970°C/7.0 MPa/50 min. Original contact surface was still visible in the joined specimens as shown in Fig. 5A and the shear welding strength increased to 132.2 MPa. In comparison with the excellent joint in the B1 specimen, the B2 and B3 specimens revealed a discontinuous weld interface (Fig. 5B and C), which possessed shear welding strengths of 75.0 and 76.7 MPa, respectively. The microstructures of the specimen edge for SuperDux 65 stainless steel joined by the two-stage process are shown in Fig. 6. The unwelded edge crevices appearing in the specimens diffusion welded with a single-stage process in a nonsuperplastic state were absent when at least part of the welding was performed near superplastic conditions. This proves that the applied pressure during the superplastic diffusion-welding stage effectively increased the contact area and accelerated atomic diffusion. Furthermore, a near macroscopic deformation was observed in the welding condition used for specimen B1: 880°C/7.0 MPa/ 10 min + 970 °C/7.0MPa /50 min.

Although the welding strengths of the B2 and B3 specimens were lower than that of the B1 specimen, they were approximately twice as high as those of the A1 and A2 specimens. From Table 2, it can be seen that B2 and B3 specimens were joined with an additional stage in the superplastic range (970°C/3.5 MPa/10 min) during their diffusion welding processes in comparison with specimens A1 and A2. The effect of greater surface contact through superplastic deformation at the initial stage (even for a short time) on the strength of diffusion-welded SuperDux 65 stainless steel was thus demonstrated. That the weld strengths of B2 and B3 specimens were similar implied that the initial diffusion welding at a superplastic state (970 °C/3.5 MPa/10 min) had resulted in greater surface contact than when the first welding stage was nonsuperplastic. Thus, a higher applied load for the B2 specimen in comparison with the B1 specimen at the second stage played a minor role in the welding effect.

Conclusions

An obvious residue of the original weld interface and lack of welding at the specimen edge was observed for the conventional single-stage diffusion welding of SuperDux 65 stainless steel at 880°C for 60 min under applied pressures from 2.1 to 7.0 MPa. The weld strengths were very low, ranging from 19.7 to 45.3 MPa. On the other hand, in the SuperDux 65 stainless steel welded using a two-stage diffusion welding process, the original interface largely disappeared and the weld strength increased drastically. Diffusion welding under the condition of 880°C/7.0 MPa/10 min + 970°C/7.0 MPa/50 min resulted in a dramatically higher welding strength of 132.2 MPa, in which macroscopic deformation of such a specimen was noted. Using an initial superplastic diffusion-welding step (970°C, 3.5MPa) for only 10 min, when added to the single-stage process at a nonsuperplastic state, obviously improved the welding effect of this alloy, while resulting in a welding strength of approximately 76 MPa. In this case, sufficiently intimate surface contact had formed at the initial stage of diffusion welding in a superplastic state such that the further increase of the applied stress from 3.5 to 7.0 MPa at the second stage (880°C, 60 min) did not markedly increase the welding strength.

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