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Diffusion Bonding in Compact Heat Exchangers

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Abstract - *Heatric's diffusion bonding process is a solid-state joining technology that produces strong, compact, all-metal heat exchanger cores. Diffusion bonding allows for a large quantity of joints to be made in geometries that would normally be inaccessible for conventional welding techniques. Since Heatric's diffusion bonding process uses no interlayer or braze alloy, the resulting heat exchanger core has consistent chemistry throughout and, under carefully controlled conditions, a return to parent metal strength can be reached.*

This paper will provide an overview of the diffusion bonding process and its origins, and also its application to compact heat exchanger construction. The paper will then discuss recent work that has been done to compare mechanical properties of Heatric's diffusion bonded material with material that has been conventionally welded, as well as with material tested in the as-received condition.

I. INTRODUCTION

Heatric are a leading manufacturer of compact heat exchangers, whose product line includes Printed Circuit Heat Exchangers (PCHEs), Formed Plate Heat Exchangers (FPHEs), and Hybrid Heat Exchangers (H^2Xs) [1]. PCHEs consist of flat metal plates into which fluid flow channels are chemically etched, before being joined by Diffusion Bonding to make a heat exchanger block to which headers and nozzles may be welded. FPHEs consist of fins made by pressing metallic foils into corrugated patterns to form flow channels, separated by flat parting sheets, then diffusion bonded and fitted with connecting nozzles in the same way as PCHEs. H^2Xs are a hybrid of these two product forms, where fluid flow channels are produced using both chemical etching and fin forming, joined by diffusion bonding, and then fitted with headers and nozzles. Figures 1 through 3 show cross-sectional views for some examples of these product forms.

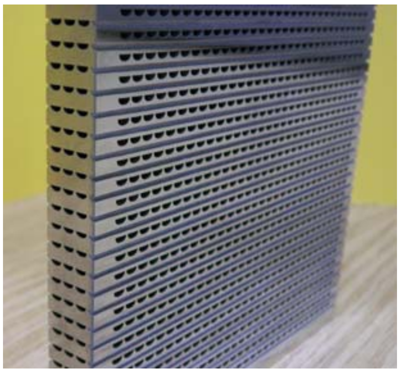

Fig. 1. PCHE section.

Fig. 2. FPHE section.

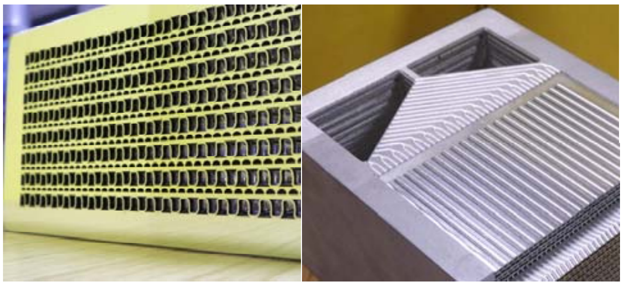

Fig. 3. H^2X sections: cross-layer, with corrugated fins and etched plates in alternating layers (left); in-layer, with corrugated fins and etched plates in the same layer (right).

All of these products are joined by Diffusion Bonding, also known as diffusion welding, which is an advanced form of forge welding. Forge welding is one of the oldest joining methods known, being the only method in common use prior to the nineteenth century, and traceable back to at least 1500 years B.C. [2]

Fig. 4. Forge welded steel piece [3].

Heatric's diffusion bonding process is a solid-state joining technology that produces strong, compact, all-metal heat exchanger cores. Heat and pressure are applied in a controlled atmosphere, to remove surface impurities and promote grain growth across the interface between components. The resulting matrix is a single-part block, with well-defined channels forming the flow and heat transfer passages.

This process allows a large quantity of joints to be made in geometries that would normally be inaccessible for conventional welding techniques. Heatric's diffusion bonding process uses no interlayer, flux, or braze alloy, thus the resulting heat exchanger core has consistent chemistry throughout, and a return to parent metal strength can be achieved.

Fig. 5. Micro showing grain pattern at a diffusion bonded joint (section taken through a PCHE).

Heatric recently carried out trials to evaluate room-temperature and elevated-temperature properties for dual certified 316/316L stainless steel, to compare the properties of diffusion bonded materials with those of conventionally welded and as-received materials. The results of these trials are presented below.

II. DESCRIPTION OF THE WORK

Heatric carried out the following trials under this test programme:

1. Room temperature tensile testing.
2. 100 hour creep and stress rupture testing, at a temperature of 600°C.
3. 1000 hour creep and stress rupture testing, at a temperature of 600°C.

A number of samples were produced for testing. For the results presented here, three separate stocks were selected for each test, from which at least three samples were prepared per stock code of material.

III. RESULTS FROM TRIALS

III.A. Room-temperature tensile tests

The room temperature tensile tests were carried-out to serve two purposes:

1. To compare tensile results when taken (a) perpendicular to the bond-line, (b) parallel to the bond line (see fig. 6)
2. To compare tensile results for diffusion-bonded material with (a) welded material, and (b) material as-received.

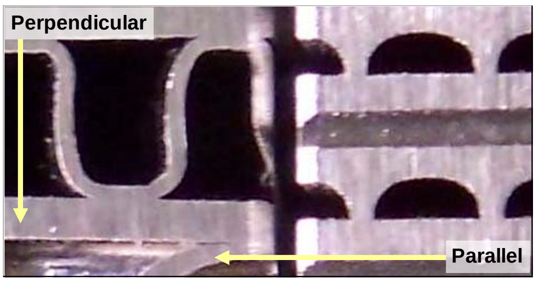

Fig. 6. Defining parallel and perpendicular directions with respect to bond line for FPHE (left), PCHE (right) (indicative only, tests carried out on solid sections)

The diffusion bonded material was SA240 SS316/316L seet. The results of the tests parallel and perpendicular to the bond line are shown in table I. 0.2% Proof Stress (0.2% PS) and Ultimate Tensile Strength (UTS).

TABLE I

Room-temperature tensile results for diffusion bonded SA240, taken parallel (par.) and perpendicular (perp.) to the bond line.

	0.2% PS (N/mm²)		UTS (N/mm²)	
	Par.	Perp.	Par.	Perp.
Stock 1 (mean values)	229.7	216.6	580.3	545.8
Stock 2 (mean values)	217.0	209.0	558.0	535.2
Stock 3 (mean values)	226.3	212.6	583.0	552.6
Group mean	224.3	212.3	573.8	544.5
ASME 240	205.0		515.0	
Group mean/ ASME SA240	1.09	1.04	1.11	1.06
Parallel / perpendicular	1.06		1.05	

For the second part of the tensile tests, as-received SA240 plate was tested, as was welded SA240 plate, for comparison with diffusion-bonded material tested perpendicular to the bond line. The results of the trials are shown tables II and III.

TABLE II

0.2% Proof Stress results from room-temperature tensiles tests for welded SA240 (stock codes W1, W2, W3), diffusion-bonded SA240 (stock codes B1, B2, B3), and as-received SA240 (stock coded A1, A2, A3).

	0.2% PS (N/mm²)		
	Bonded	As-received	Welded
Stock 1 (mean values)	216.6	248.4	411.6
Stock 2 (mean values)	209.0	242.4	394.4
Stock 3 (mean values)	212.6	245.8	435.4
Group mean	212.7	245.5	413.8
Max./min.	1.04	1.02	1.10
ASME SA240	205.0		
As-received/ ASME SA240	1.20		
As-received/ Bonded	1.15		
Bonded/ ASME SA240	1.04		

TABLE III

Ultimate Tensile Strength results from room-temperature tensiles tests for welded SA240 (stock codes W1, W2, W3), diffusion-bonded SA240 (stock codes B1, B2, B3), and as-received SA240 (stock coded A1, A2, A3).

	UTS (N/mm²)		
	Bonded	As-received	Welded
Stock 1 (mean values)	545.8	609.4	619.4
Stock 2 (mean values)	535.2	610.2	620.6
Stock 3 (mean values)	552.6	622.6	619.8
Group mean	544.5	614.1	619.9
Max./min.	1.03	1.02	1.00
ASME SA240	515.0		
As-received/ ASME SA240	1.19		
As-received/ Bonded	1.13		
Bonded/ ASME SA240	1.06		

III.B. 100 hour creep, stress rupture tests

For this series of tests, a sample from each stock code for the welded, bonded, and as-received material was creep tested for at least 100 hours at a temperature of 600°C, for an applied stress of 241.0 N/mm². None of the samples failed, and all were in the secondary phase when the tests were discontinued. Results indicating test duration and % Total Plastic Strain (% TPS) are presented below in table IV.

TABLE IV

Test Duration and % TPS results for 100 hour creep tests, at a temperature of 600°C and an applied stress of 241.0 N/mm², for welded SA240 (stock codes W1, W2, W3), diffusion-bonded SA240 (stock codes B1, B2, B3), and as-received SA240 (stock coded A1, A2, A3).

	% TPS, N/mm² (Test duration, hours)		
	Bonded	As-received	Welded
Stock 1 (mean values)	12.860 (112.6 hrs)	5.622 (113.3 hrs)	1.479 (111.4 hrs)
Stock 2 (mean values)	14.050 (112.2 hrs)	5.790 (113.8 hrs)	2.484 (133.7 hrs)
Stock 3 (mean values)	13.080 (111.7 hrs)	5.094 (115.8 hrs)	1.034 (111.6 hrs)
Group Mean	13.330 (112.2 hrs)	5.502 (114.3 hrs)	1.666 (118.9 hrs)

For each stock code that was creep tested, a further four samples from the same stock code were stress rupture tested. All of these tests were discontinued after 110% of the required test time of 100 hours, without any failures.

III.C. 1000 hour creep, stress rupture tests

A sample from each stock code for the welded, bonded, and as-received material was creep tested for at least 100 hours at a temperature of 600°C, but this time at an applied stress of 185.0 N/mm². None of the samples failed, and all were in the secondary phase when the tests were discontinued. Results indicating test duration and % Total Plastic Strain (% TPS) are presented below in table V.

TABLE V

Test Duration and % TPS results for 1000 hour creep tests, at a temperature of 600°C and an applied stress of 185.0 N/mm², for welded SA240 (stock codes W1, W2, W3), diffusion-bonded SA240 (stock codes B1, B2, B3), and as-received SA240 (stock coded A1, A2, A3).

	% TPS, N/mm² (Test duration, hours)		
	Bonded	As-received	Welded
Stock 1 (mean values)	7.717 (1117.4 hrs)	2.815 (1118.3 hrs)	0.502 (1102.9 hrs)
Stock 2 (mean values)	8.421 (1119.7 hrs)	2.996 (1119.5 hrs)	0.336 (1101.1 hrs)
Stock 3 (mean values)	7.453 (1119.4 hrs)	2.541 (1119.2 hrs)	0.277 (1119.0 hrs)
Group Mean	7.864 (1118.8 hrs)	2.784 (1119.0 hrs)	0.372 (1107.7 hrs)

Again, for each stock code that was creep tested, a further four samples from the same stock code were stress rupture tested. All of these tests were discontinued after 110% of the required test time of 1000 hours, without any failures.

IV. DISCUSSION

IV.A. Room-temperature tensile tests, parallel and perpendicular to bond-line.

The results of this series of tests indicate that the requirements for ASME SA240 are always exceeded, whether the tensile sample is taken parallel or perpendicular to the bond line. There is a small difference in properties observed depending on tensile direction (6% reduction in 0.2% PS, and a 5% reduction in UTS). This may be attributable to the production of the plate prior to bonding; the plates are rolled prior to etching, which elongates the grains in the direction of rolling. For the heat exchanger configurations discussed earlier, the rolled direction is parallel to the bond line. However, as mentioned, the properties exceed ASME requirements in both cases; also, manufacturing experience shows that when samples are subjected to a burst-test, the point of failure is typically remote from the bond line for a successfully bonded block.

IV.B. Room-temperature tensile tests, parallel and perpendicular to bond-line.

The tensile results are clearly much higher for the welded material than for the as-received or bonded plates. This is suggested to be due to the small size of the sample taken; given the location the sample was taken from (see fig. 7, for indicative purposes), the majority of the sample would have consisted of weld filler, rather than SS316/316L, meaning a different composition and thermal history can be expected.

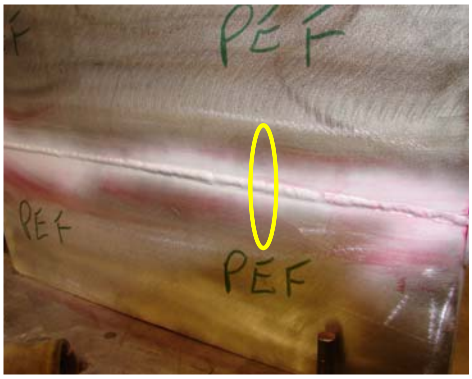

Fig. 7. Welded plates, showing indicative area from which tensiles specimen would have been prepared.

Both the as-received and the diffusion-bonded materials exceeded the requirements fo ASME SA240. However, the as-received material had higher values for 0.2%PS and UTS than the diffusion bonded material. This is suggested to be due to work-hardening of the original plate due to rolling, which is then reduced by the annealing and the grain growth that occurs during the diffusion bonding process.

Grain growth is necessary for diffusion bonding to take place, since the bond is formed across component boundaries as a consequence of this growth, and a change in material properties is to be expected as a consequence of this and of annealing. However, because the properties of the as-received material sufficiently exceeded ASME SA240 specifications, diffusion bonded materials remain compliant.

IV.C. High-temperature creep and stress rupture tests, 100 hour and 1000 hour

Reviewing the high temperature creep/rupture tests, all samples met code requirements. Comparing results, the welded material has a final % TPS that is lower than for the other materials. As for the room-temperature tensile tests, this is suggested to be due to differences in composition and thermal history.

The bonded material has a higher % TPS than the as-received material, which as before is suggested to be due to grain growth and a reduction in work-hardening due to annealing.

Thes results indicate that the bonded material satisfies code requirements, and is the most ductile of the materials tested. Compared to the welded material, which was the most brittle, and thus more prone to a brittle failure, bonded material remains ductile.

V. CONCLUSIONS

Heatric's diffusion bonding process produces high-integrity, all-metal heat exchangers, whose materials of construction in the finished form meet or exceed the material requirements of ASME SA240. Not only do the diffusion-bonded materials meet the room temperature requirements, they also meet high temperature creep and stress rupture requirements, whilst remaining more ductile than the more brittle welded joints.

Diffusion bonding is a process particularly suited to compact heat exchanger manufacture for demanding duties, for example high temperature environments, where a large quantity of joints need to be made that would otherwise be inaccessible for conventional welding. This can be achieved whilst maintaining a constant chemistry for the materials of construction, by the avoidoding the use of braze alloys, interlayers, filler materials, and flux.

Much like forge welding, which can be considered to be a precursor to diffusion bonding, separate metal components can be joined together to form a single finished component, with no discernable joints or boundaries.

These features, together with better thermal-hydraulic performance and high design flexibility, make Heatric's compact heat exchanger an attractive choice for the next generation of nuclear plants, and many other demanding duties.

REFERENCES

1. Website of Heatric Division of Meggitt (UK) Ltd., www.heatric.com
2. M.M. SCHWARTZ, "Metals Joining Manual," McGraw-Hill Inc., United States of America (1979).
3. Image reproduced from http://www.knivesandengraving.com/