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TECHNICAL ARTICLE—PEER-REVIEWED

Weld Failure Analysis of Air Radiator

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Abstract The air radiator had been in service for more than 30 years until a notch failure occurred. In this paper, a rare notch failure is completely investigated by means of macroscopic and microscopic observations, microstructural inspection, chemical analysis, and residual stress test. The results show that the notch failure mode of the air radiator is attributed to high-cycle fatigue fracture, due to the welded lapping surfaces near the notch on both sides of the corrugated plate trough not being put onto one plane during the welding process. Therefore, in order to prevent or reduce possible tensile stress, it is recommended that the welded lapping surfaces be put onto one plane before welding.

Keywords Failure analysis · Residual stress · Tensile stress · High-cycle fatigue fracture

Introduction

The failed air radiator is a 1st stage cooling accessory for aircraft temperature-controlled air supply, which is a heat exchanger with a thin-walled sandwich structure made of 1Cr18Ni9Ti stainless steel as shown in Fig. 1. Between the inner wall and the outer wall, there is a corrugated plate. The inner wall and the corrugated plate are seam welded through lapping. Thus, two air stream passages among the inner wall, outer wall, and corrugated plate are formed, and the cooling gas is imported via 320 small holes of 2.5 mm diameter located at the inner wall. Based on the layout of air radiator, the cooling gas and hot gas flow conversely through the two air stream passages, after which the hot gas turns into the turbo intercooler to be cooled. The air radiator works at room temperature. When the notch failure was detected with the naked eye, several compressor blades were observed to have been damaged.

Visual Observation

The failed air radiator is shown in Fig. 1, and a rectangular notch left in the inner wall is shown in Fig. 2. The two long sides of the notch are roughly parallel to the circumferential direction of the air radiator, which correspond to the indentation boundary of the seam weld formed in the course of the welding process, and four cracks are also found at the notch borders. Contrasting with the notch in the inner wall, the notch in the corrugated plate is a little bigger; as shown in Fig. 3, its shape is jagged and the position of one side is in accord with one long side of the notch of the inner wall. The indentation boundary along both sides of the corrugated plate is visibly cracked. The surfaces near both notches are intact, and no abnormal welded traces are left [1–3].

Viewed from the outer wall of the air radiator, there is a rectangular repair welding zone at the bottom of the cooling tongue (Fig. 4), of the size 55 mm × 580 mm. The inner wall corresponding to the back of rewelding zone is slightly humped. In order to find the cause of deformation, the air radiator is disassembled and another rewelding zone along the direction of the corrugated plate trough with a length of 254 mm is also found. It corresponds to the humped zone (Fig. 5), which show that the humped deformation is formed because of repair welding.

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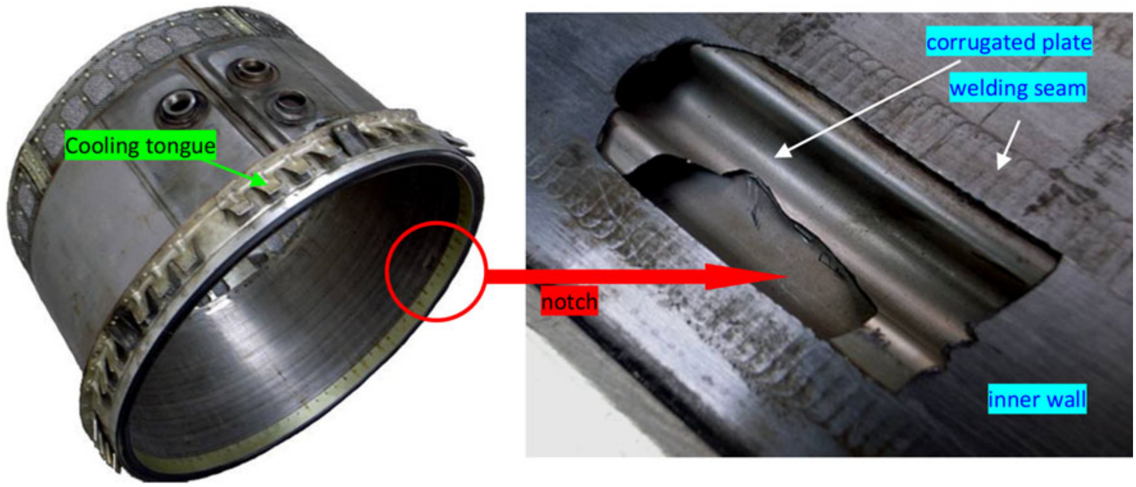

Fig. 1 The failed air radiator

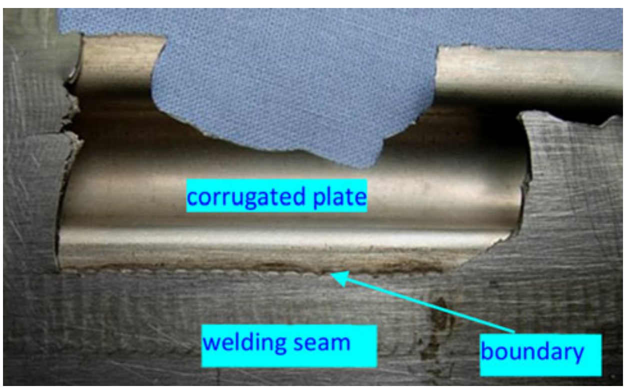

Fig. 2 The notch of the inner wall

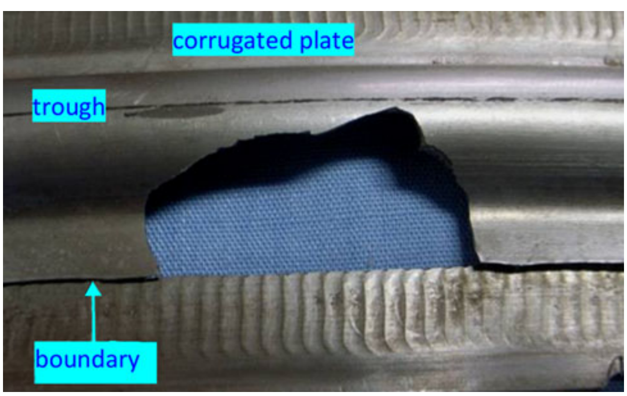

Fig. 3 The notch of the corrugated plate

Corresponding to the position of the notch, the welded lapping surfaces on both sides of the corrugated plate trough are not being put onto one plane as shown in Fig. 6. One side of the welded lapping surface obviously inclines, and there is an angle between the welded lapping surface and the inner wall. Other surfaces are in good conditions; no traces of corrosion and abnormal damage are found. No

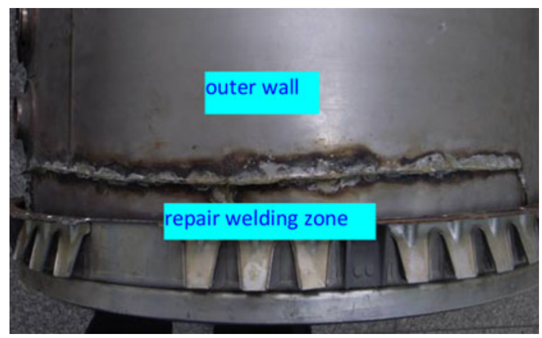

Fig. 4 The repair welding zone of the outer wall

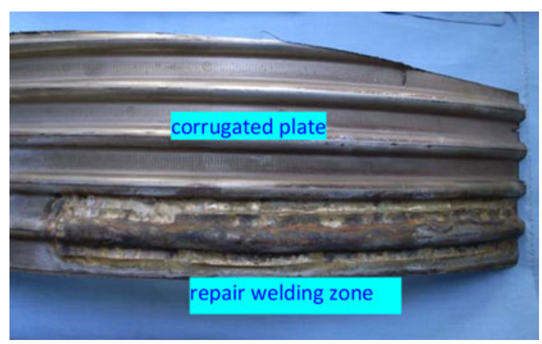

Fig. 5 The repair welding zone of the corrugated plate

cracks are detected in the inner wall using the eddy current method.

Fracture Analysis

Macroscopic Analysis

The fractures of the inner wall and the corrugated plate along the indentation boundary of seam weld have the

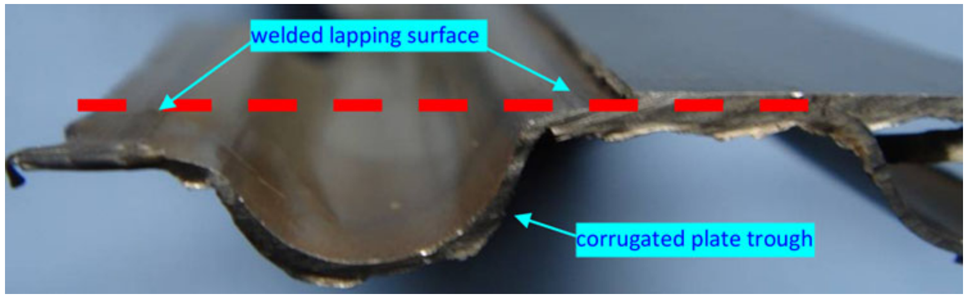

Fig. 6 The appearance of welded lapping surfaces of the corrugated plate

Fig. 7 The notch fractures of the inner wall and corrugated plate

Fig. 8 The other halves of the notch fractures

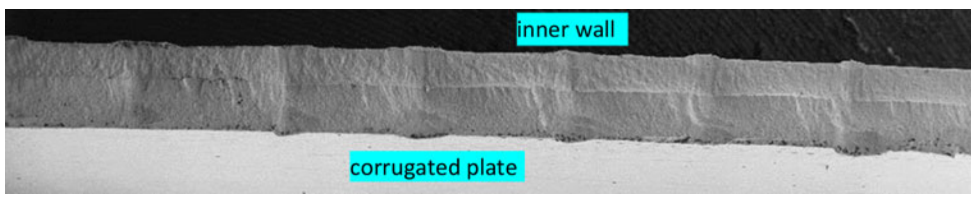

Fig. 9 The microcharacteristics of fractures along the seam weld indentation boundary

same macrocharacteristics as shown in Figs. 7 and 8. Both fractures are flat and perpendicular to the exterior surfaces, with dark black colors and non-metallic luster. No plastic deformations are found either. On both fractures, the jagged stripes corresponding to the positions of the welding corrugations are parallel to each other and uniformly spaced, with a spacing of about 1.5 mm.

The other two-side fractures of the inner wall also have the same macrocharacteristics, and they are made up of several fractures with different inclined angles; the max inclined angle is about 45°. Except the fracture along the indentation boundary of the seam weld, other fractures of the corrugated plate are perpendicular to the corrugated plate surface, and no plastic deformations are clearly found.

Microscopic Analysis

The fractures of the inner wall and the corrugated plate along the weld indentation boundary have obvious fatigue characteristics. Between each welding corrugation, there is a linear fatigue origin, and the fatigue crack starts at the welded interface between the inner wall and the corrugated plate as shown in Figs. 9 and 10. No cracks and defects are found in the fatigue origin zone as shown in Fig. 11. In the fatigue propagation zone, the radical lines and fatigue steps

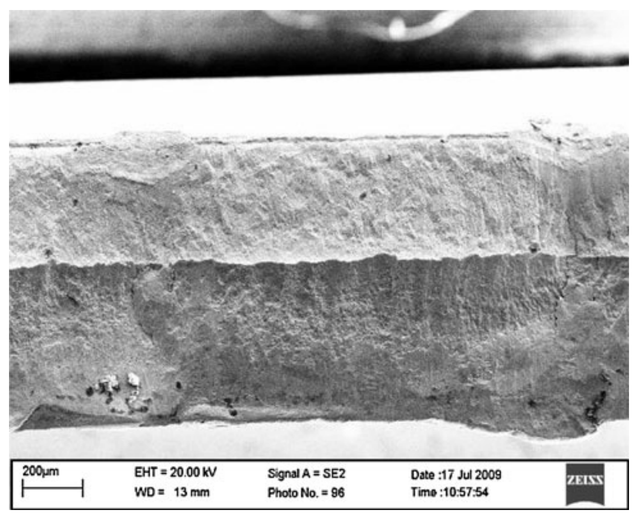

Fig. 10 The characteristics of fatigue origin

are particularly evident, and the fatigue striations are dense as shown in Figs. 12, 13, 14, and 15. In the later fatigue propagation zone, the fracture is badly damaged.

The other two-side fractures of the inner wall have been scraped to different degrees, and the dimple characteristics can be seen at the local non-scraped areas as shown in Fig. 16. The fracture near the corrugated plate trough has two

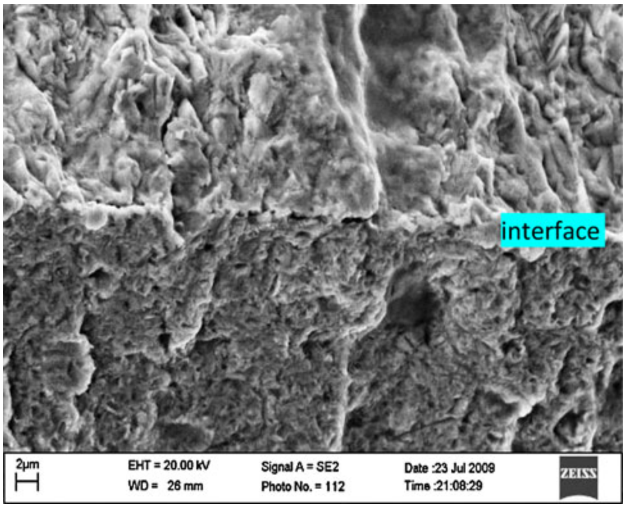

Fig. 11 The welded interface

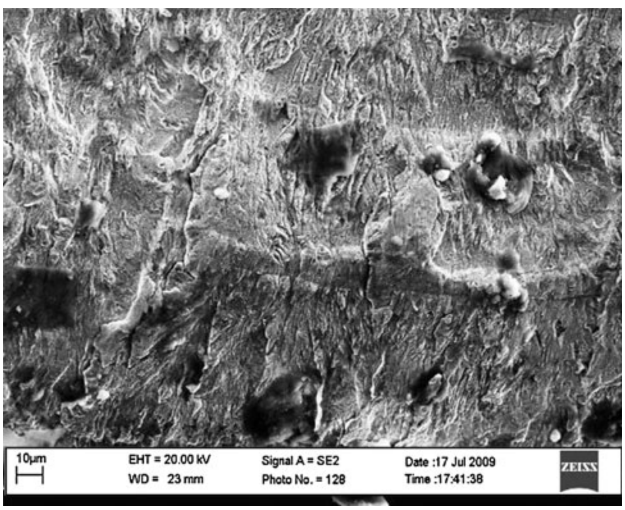

Fig. 12 The fatigue beaches of the inner wall

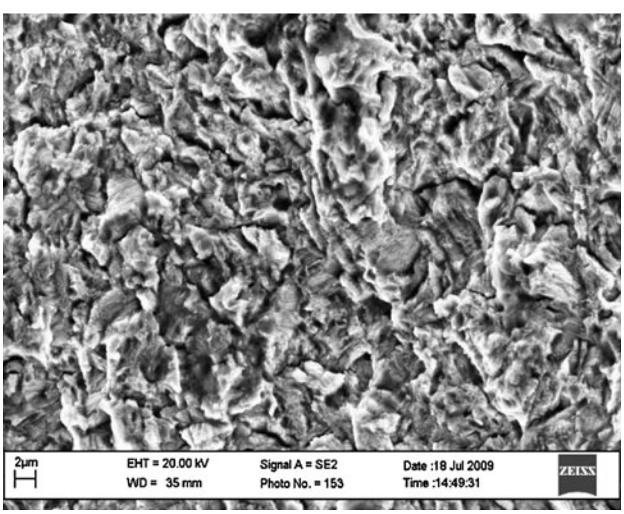

Fig. 13 The fatigue striations of the inner wall

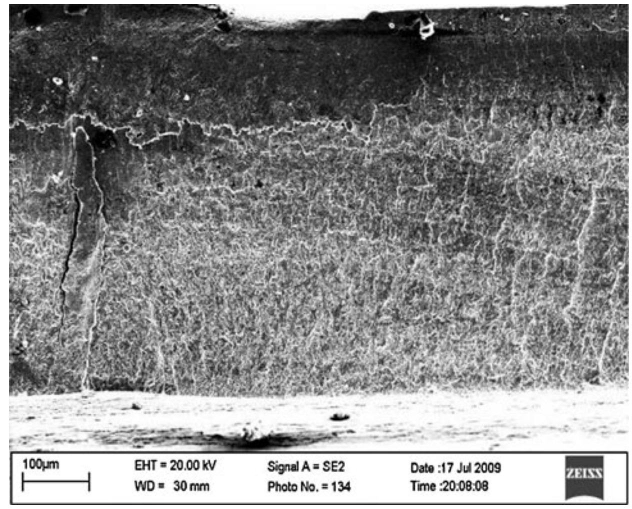

Fig. 14 The fatigue beaches of the corrugated plate

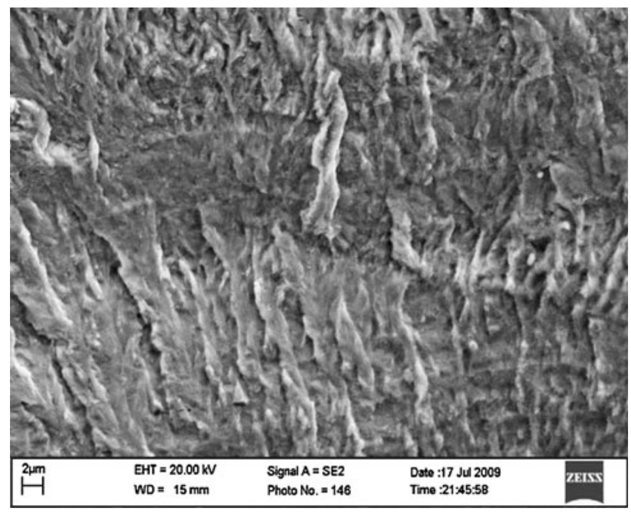

Fig. 15 The fatigue striations of the corrugated plate

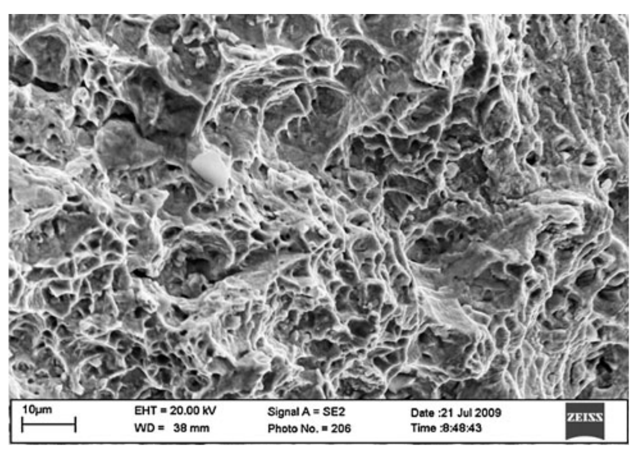

Fig. 16 The dimple characteristics of the other two-side fractures of the inner wall

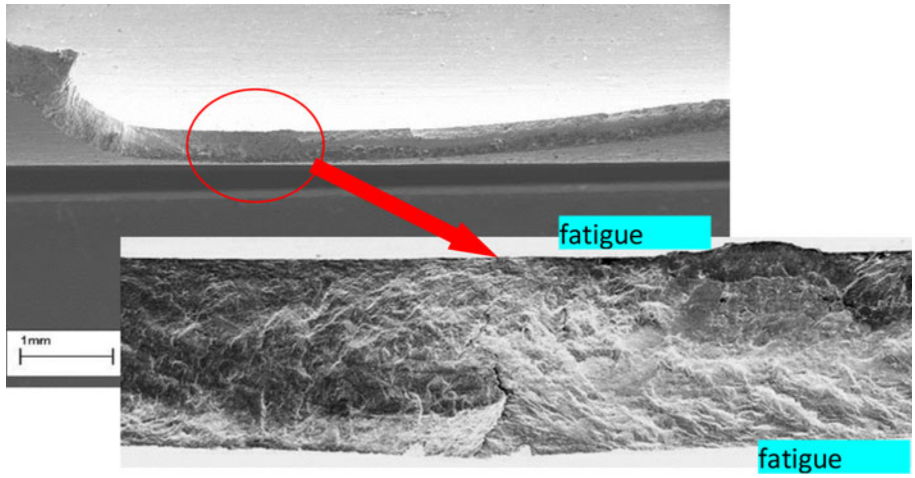

Fig. 17 The fatigue characters of fracture near the corrugated plate trough

Table 1 The width and height of the weld nugget

	Sample			
Weld nugget	Sample 1, mm	Sample 2, mm	Sample 3, mm	Technical requirements, mm
Nugget height	4.78	5.25	5.23	≥4.5
Nugget width	0.53	0.64	0.54	≥5.0

fatigue origins that are distributed at the two-side surfaces as shown in Fig. 17. The typical fatigue characteristics, such as radical lines and fatigue steps, can be seen clearly, but no corrosion, defects, and foreign object damage are found in the fatigue origin zone. The result indicates that its failure mode is due to bilateral bending fatigue. The remaining fractures are attributed to the fast fracture region, and local dimple characteristics can be seen.

Welding Seam Section Inspection

Three samples are cut from the notch, near and apart from the notch, and they are designated as sample 1, sample 2, and sample 3. The measured results are listed in Table 1. In the three places, the sizes of the weld nugget width and height are almost the same, and the welding metallurgical structure is normal, all of which meet the technical requirements as seen in Figs. 18 and 19. No porosities, shrinkage cavities, and welding spatters are found in the welding nugget zones. The fatigue origin is not in the heat-affected zone, so the weld process qualities are specifically excluded to cause the notch failure.

Chemical Composition Analysis

The chemical analysis of the damaged part is carried out, and the result is shown in Table 2. It shows that chemical compositions of the inner wall and the corrugated plate coincided with those of 1Cr18Ni9Ti steel [4].

Vickers Microhardness Measurement

The Vickers microhardness values are measured using a load of 300 g and a dwell time of 15 s as shown in Table 3. It can be seen that the obtained hardness distribution is characterized by homogeneous material properties in the three different zones. The hardness values of the fracture site and the zone apart from the heat-affected zone are basically equal, and both are lower than the hardness value of the weld nugget zone. It turns out that the fracture site is not affected during the welding process.

Residual Stress Test

Ten points at the welding seam boundary are chosen to measure the welded residual stress by the x-ray diffraction method using the parameters of $\Phi2$ facula and Fe (2 2 0) crystal face; they are distributed on both sides of the notch along the welding seam, with an interval of 20 mm every two adjoining points, and the results are shown in Fig. 20. It can be seen that the tensile stress exists at the welding boundary, and it is visibly different. Near the notch of the inner wall, the tensile stress nearly reaches up to 538 MPa, which greatly decreases the fatigue resistance of the inner wall and the corrugated plate.

Discussion

Failure Mode Analysis

In the fractures of the inner wall and the corrugated plate along indentation boundary of the seam weld, there are

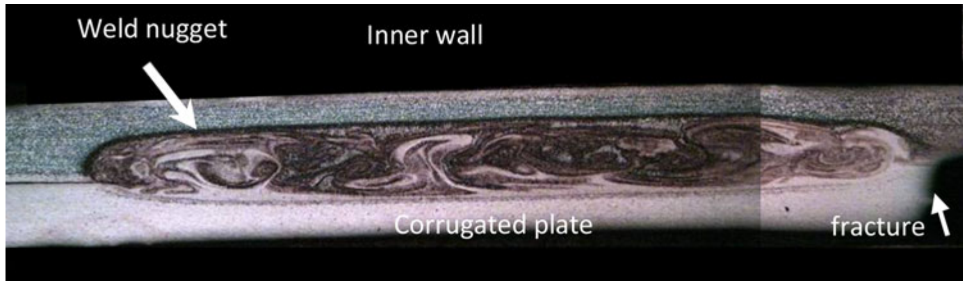

Fig. 18 The welding seam section

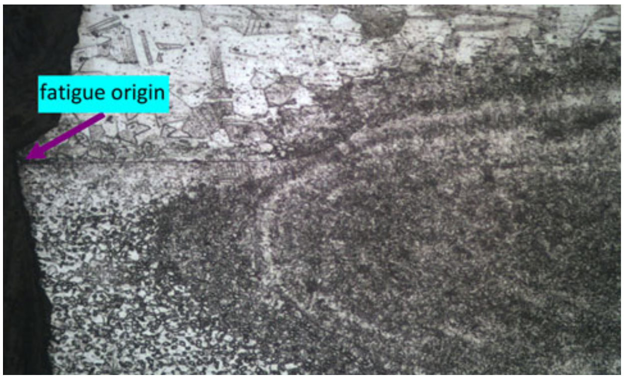

Fig. 19 The microstructure of the welding seam

Table 2 The chemical compositions of the inner wall and corrugated plate (wt.%)

	Element					
Content	Si	Cr	Ni	Ti	Mn	Fe
Inner wall	0.77	18.98	9.62	0.74	0.60	69.29
corrugated plate	0.78	18.51	8.26	0.71	1.02	70.72
1Cr18Ni9Ti	≤0.80	17–19	8–11	≤0.80	≤2.0	Base

Table 3 The measured Vickers microhardness values

	Position		
Value, HV_{03}	Fracture site	The zone apart from the fracture site	Weld nugget zone
Inner wall	237.8	239.6	262.9
Corrugated plate	215.4	217.2	239.4

multiple linear fatigue origins, and each fatigue origin starts at the welded interface between the inner wall and the corrugated plate. The fatigue cracks have propagated enough, the radical lines and fatigue steps are particularly evident, and the fatigue striations are dense. In summary, it is not difficult to draw conclusions that the failure mode of the notches is attributed to high-cycle fatigue fracture, and the stress is small when the fatigue cracks propagate [5–7].

Failure Cause Analysis

In the weld nugget zone, no porosities, shrinkage cavities, welded sputter, and inner cracks are found, and the nugget width and height both accord with its technical requirements. In the welded lapping surface, the welding characteristics are normal; no defects, corrosion, and welded damages can be seen. Moreover, the fracture site is not in the weld heat-affected zone. So, the result shows that the failure causes have no relation to the welding process.

The compressed air pressure from the aero-engine inlet is not steady under different working conditions. It is easy to create different impact stresses on the inner wall, the outer wall, and the corrugated plate, and then the alternating stress is offered to initiate fatigue crack. When the failure was found, the air radiator had been used for about 1500 h and repaired twice. The repair welding shows that the corrugated plate had once cracked, but no notches were formed. During the overhaul of the aircraft, the tightness test of the air radiator shows that its performance accords with the required standard. Combined with the fracture characteristics, it is easy to judge that the failure causes have no direct relations to the repair quality.

The fractures of the notches have fatigue characteristics, and all fatigue origins are initiated from the welded interface between the inner wall and the corrugated plate. Between the two welded lapping surfaces, there is a gap. Therefore, a stress concentration is formed and the tensile stress easily exists at the seam-welding boundary during the welding process. On the other hand, the welded lapping surfaces on both sides of the corrugated plate trough are not in one plane near the notches of the inner wall and the corrugated plate, while the one-side welded lapping surface is obviously inclined. All these validate that the tensile stress is present at the seam-welding boundary before the fatigue cracks are formed. Besides, the tensile stress is also confirmed to be present by means of the x-ray diffraction method. To sum up, the present tensile stress at the seam-welding boundary is the main reason for the notch failure, and it is formed because the welded lapping surfaces on both sides of the corrugated plate trough are not put onto one plane during the welding process. Besides this, no other unusual lines of evidence are found to elucidate the notch failure.

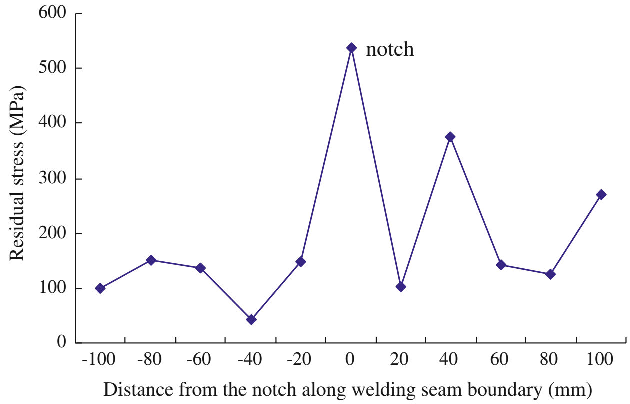

Fig. 20 The variation curve of residual stress at the welding seam boundary

According to the overhaul facility, the notch failure has never happened until this one occurred, and it is difficult to detect the welding bond zone. The failed air radiator has been used for a long time, but its welding process qualities meet the technical requirements. Although the tensile stress exists at the seam-welding boundary, the initiating time and propagative cycle of the fatigue cracks are long. So, the failure causes are not related to its normal lifetime.

Conclusions

(1) The failure mode of the notches is attributed to high-cycle fatigue fracture, and the fatigue cracks start at the welded interface between the inner wall and the corrugated plate.

(2) The tensile stress at the seam-welding boundary is the main reason for the notch failure, and it is formed because the welded lapping surfaces on both sides of the corrugated plate trough near the notches are not on one plane during the welding process.

(3) The notch failure of the air radiator is not related to its normal fatigue lifetime, and a suggestion is offered that the welded lapping surfaces should be put onto one plane before the welding process of the air radiator.

References

1. J.L. Otegui, P.G. Fazzini, Failure analysis of tube-tube sheet welds in cracked gas heat exchangers. Eng Fail Anal. **11**, 903–913 (2004)
2. L. Zheng, D. Petry, H. Rapp, T. Wierzbicki, Characterization of material and fracture of AA6061 butt weld. Thin Walled Struct. **47**, 431–441 (2009)
3. D. Zhang, *Mark Analysis in Mechanical Failure* (Defensive Industries Press, Beijing, 1996). in Chinese
4. Editorial Committee of China Aeronautical Materials Handbook, *China Aeronautical Materials Handbook*. Standards Press of China, Beijing, (2002)
5. X. Sun, E.V. Stephens, M.A. Khaleel, Effects of fusion zone size and failure mode on peak load and energy absorption of advanced high strength steel spot welds under lap shear loading conditions. Eng. Fail. Anal. **15**, 356–367 (2008)
6. S.-H. Lin, J. Pan, S.-R. Wu, T. Tyan, P. Wung, Failure loads of spot welds under combined opening and shear static loading conditions. Int. J. Sol. Struct. **39**, 19–39 (2002)
7. P. JohanSingh, B. Guha, D.R.G. Achar, Fatigue tests and estimation of crack initiation and propagation lives in AISI 304L butt-welds with reinforcement intact. Eng. Fail. Anal. **10**, 383–393 (2003)