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ABSTRACT. This case study deals with the existence of excessive porosity in the welds of an air compressor rotor duct. The duct does not meet the testing criteria because the diameters of the pores in the weld exceeded allowable specifications. As such, the duct failed inspection for excessive pore diameter and shrinkage due to welding. At this point, the part was beyond repair, and it was scrapped. The possible causes of failure were analyzed, and it was concluded that the source of the problem was the welding technique.

CASE STUDY

The objective of this case study is to determine the cause of excessive porosity in the welds of a titanium alloy compressor rotor duct. The air compressor rotor duct was obtained from an aerospace company in California that manufactures these ducts for General Electric aircraft engines. The engines and aircraft are listed in Table 1. When in use, the air compressor rotor duct rotates at 3700 rpm. The temperature of the air passing through it is 593°C (1100°F). A sketch of the air compressor duct is shown in Figure 1.

The porosity is a subsurface problem in this case. The duct does not meet testing criteria because the diameters of the pores in the welds exceeded allowable specifications [1]. A weld pore diameter greater than 0.43 mm (0.017 inches) is cause for part rejection. According to the radiographic inspection report, ten of the eleven welds were rejected for excessive porosity. A radiograph is shown in Figure 2. The part was rejected at this stage because rewelding at this point to correct the porosity would create excessive shrinkage. The detection of 0.43-mm (0.017-inch) diameter pores was an ongoing problem in these air compressor rotor duct parts.

BACKGROUND

Titanium Alloys

Titanium is a reactive metal. It has a strong affinity for oxygen and nitrogen at elevated temperatures. At temperatures above 649°C (1200°F), the corrosion resistance of titanium alloys decreases rapidly and the metal must be shielded from air to avoid contamination and embrittlement by oxygen and nitrogen. Titanium alloys must be welded in a shield of high-purity inert gas or in a vac-

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TABLE 1 Engines and Aircraft in Which the Ti-6Al-2Sn-4Zr-2Mo Air Compressor Rotor Duct Is Used

Military	Commercial
Engines	
F101	CFM56-2
F110	CFM56-5
F118	
F29	
Aircraft	
B-1B Rockwell International	Airbus A340
Grumman F-14 Tom Cat	Boeing Super 70
General Dynamics F-16	Boeing 737
General Dynamics F-110-GE-129	

uum. Accordingly, a common method for welding is electron beam welding (EBW), which is performed in a controlled vacuum atmosphere.

The Ti-6Al-2Sn-4Zr-2Mo (AMS No. 4975) alloy's composition is classified as a near-alpha alloy that is entirely dependent on solid solution strengthening. These alloys are commonly used where creep resistance is required. The mechanical properties of Ti-6Al-2Sn-4Zr-2Mo are shown in Table 2.

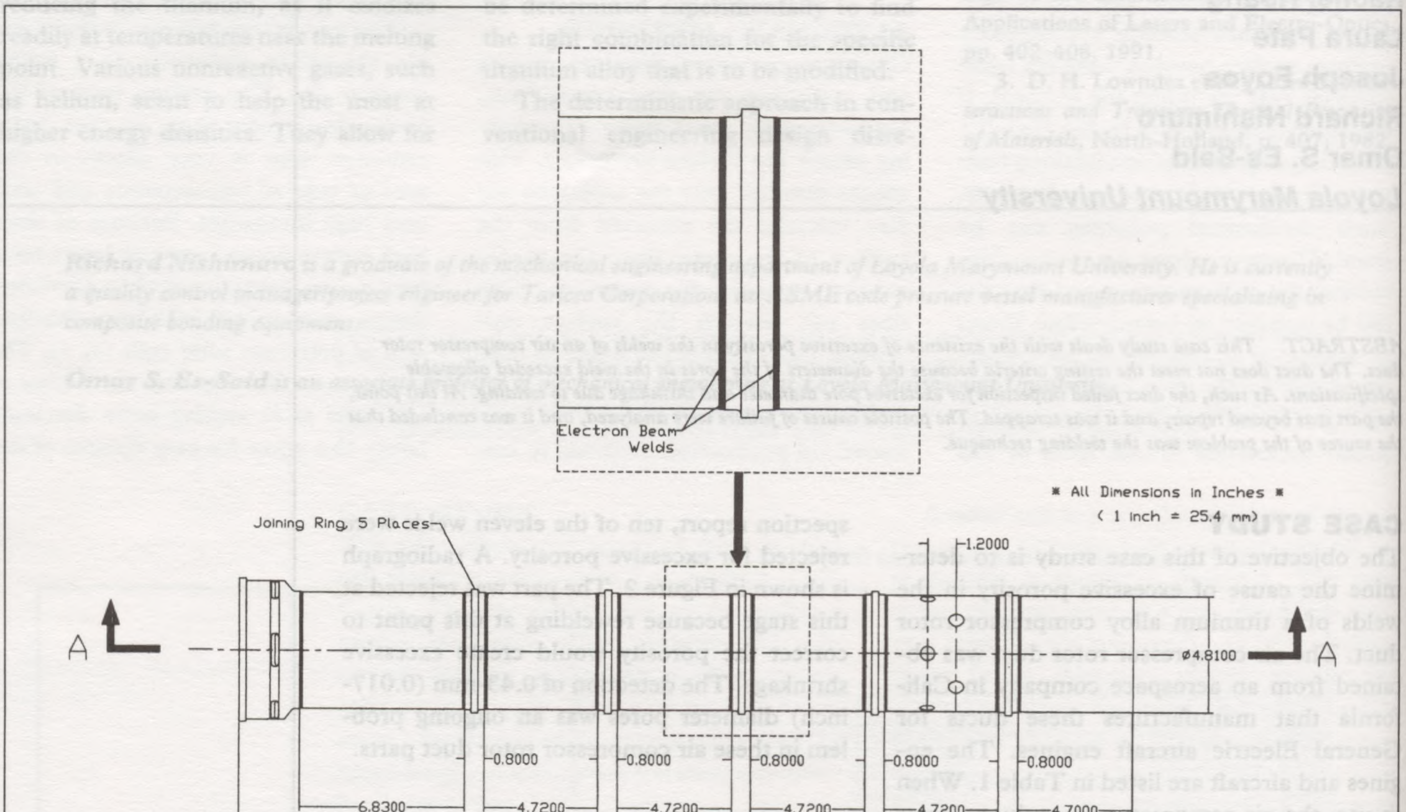
EBW of Titanium

EBW is a fusion welding process in which heat input to the workpiece is derived from energy released when a stream of electrons impinges on the surface. For the EBW process of the air compressor rotor ducts, the following specifications were used:

Chamber vacuum pressure	10^{-4} TORR (high vacuum)
Beam voltage	80 kV
Weld speed	12 ipm

EBW provides high rates of heat input for short periods of time to minimize the exposure of metals adjacent to welds to temperatures above recrystallization and grain growth [2]. This problem, heat-affected zone, is not of concern in this specific case study because the titanium alloy for the rotor

FIGURE 1 Sketch of Air Compressor Duct



ducts is annealed prior to welding. It is annealed at 593° to 621°C (1100–1150°F) for 1 hour to eliminate the effects of cold work and provide a combination of high ductility and good strength (Table 2).

Porosity

Porosity is a result of gas being entrapped in solidifying weld metal. This discontinuity is usually spheroidal. Porosity can occur either on the surface or subsurface. Subsurface porosity is detected by radiographic inspection. Most, if not all, porosity in titanium welds is apparently caused by gas bubbles formed during solidification of the weld metals [3].

Cleanliness and the welding procedure and technique are key issues in producing porosity-free welds in titanium and its alloys. Some of the common causes of porosity and the suggested remedies are shown in Table 3 [2–4].

ANALYSIS

The first probable cause of the porosity considered was cleanliness oversight. As shown in Table 3, dirty base metal, burrs on as-sheared edges, and die lubricant in filler metal and filler metal are probable causes. However, using the mechanical cleaning procedure guidelines provided by the aerospace company, the applicable possibilities of cleanliness oversights were eliminated. Aside from the mechanical cleaning procedures, the aerospace company also follows recommended chemical cleaning methods. The titanium alloy is cleaned with a solution of 3% hydrochloric and nitric acid prior to welding.

The second probable cause investigated was that of faulty equipment. This possibility was eliminated by determining that the aerospace company follows regular inspection schedules of equipment investigations and calibrations. The equipment successfully met required standards as far as the vacuum environment was concerned.

The possibility of hydrogen in solution in the metal was eliminated by tests conducted at the aerospace com-

FIGURE 2 Radiograph Showing the Presence of Pores

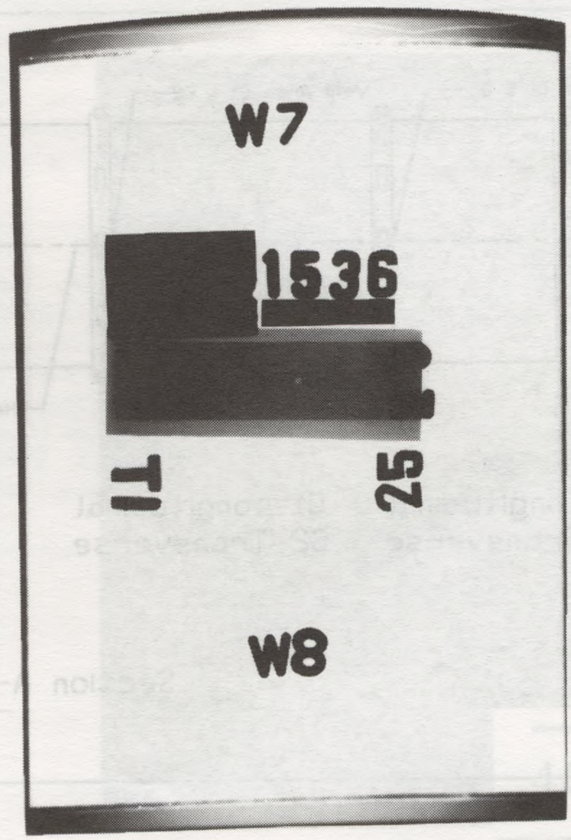


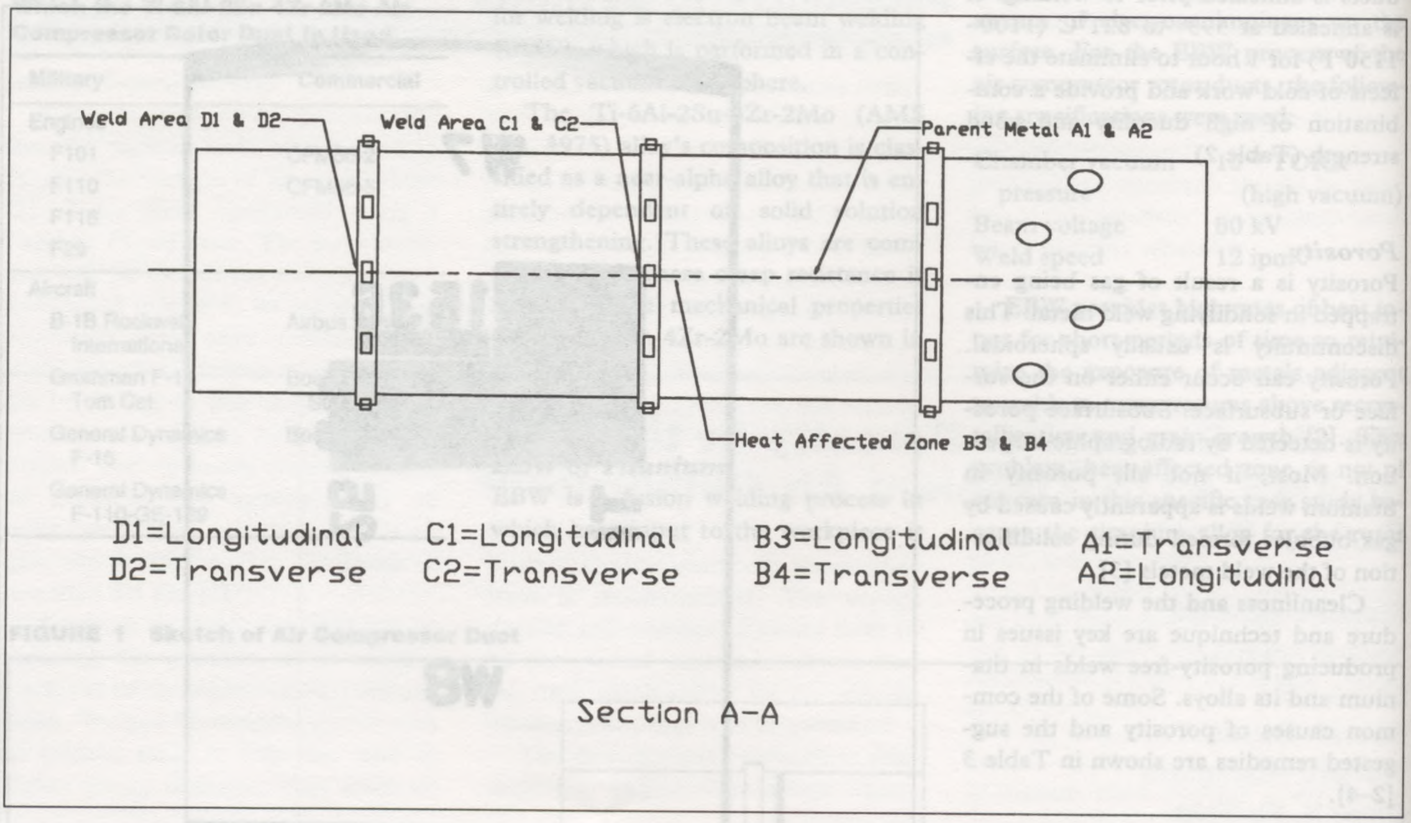
TABLE 2 The Mechanical Properties of Ti-6Al-4Zr-2Mo-2Sn Alloy

Condition	Tensile Strength in MPa (KSI)	Yield Strength in MPa (KSI)	Percent Elongation
Bar form, annealed	985.3 (143)	937 (136)	13

TABLE 3 Some Common Causes and Remedies of Porosity

Cause	Remedy
Excessive H_2, O_2, or N_2 in welding atmosphere	Weld in high (10^{-3}–10^{-6} TORR) or medium (10^{-3}–25 TORR) vacuum
Faulty equipment	Periodic inspections
Dirty base metal	Follow prescribed cleaning procedures for joint faces and adjacent surfaces: avoid using rubber gloves and alcohol together; use clean, lint-free clothes and gloves; avoid fingerprints
Burrs on as-sheared edges trapping contaminants	Remove metal along joint area by mechanical or chemical means a few hours prior to welding
Improper beam current, welding speed, or gun manipulation	Change welding conditions and techniques
Hydrogen in solution in the metal	Keep within specified limits <150 ppm—not a prime cause
Die lubricant worked into filler metal during drawing	Remove all traces of lubricant prior to welding
Filler metal cleanliness	Wipe with solvent-moistened, lint-free cloth

FIGURE 3 Location of the Optical Microstructures



pany laboratories. The titanium alloy was impregnated with hydrogen using a hydrogen bright anneal furnace. However, when the impregnated alloy was welded, there was no noticeable difference in the weld quality from that of the non-hydrogen-impregnated alloy.

Thus, with the elimination of the previously stated probable causes, the next area to concentrate on was the welding technique itself. After a literature search, an article dealing with a similar situation and problem was found [5]. In this study, titanium alloys were welded in the annealed condition and tested. The findings relevant to this study are:

1. Attempts to produce high-voltage (150-kV) welds at moderate weld speeds (40–60 ipm) resulted in welds that contained a variable degree of porosity.
2. Attempts to link the presence of this porosity with the form and duration of the cleaning of the butting surfaces were unsuccessful. Note that the aerospace company also has been unable to link the cleaning solutions/techniques to the porosity problems encountered in the air ducts.
3. *It was found that with the introduction of high-voltage (150-kV)/high-weld speed (120 ipm) technique, the porosity was no longer encountered.*

Figure 3 shows the rotor duct. Four areas have been identified: A1/A2 parent unaffected metal; B3/B4 heat affected zone; C1/C2 fusion zones; and D1/D2 fusion zones. The designations 1 and 2 refer to longitudinal and transverse views. In Figure 4, the microstructures of the parent unaffected metal (A1) and the heat-affected zone (B1), top right and left, indicate equiaxed fine grains, whereas those of the fusion zones (C1 and D1), bottom right and left, reveal elongated coarse grains.

RECOMMENDATION

The aerospace company should employ the high-voltage/high-weld speed techniques in the EBW process for the titanium air compressor rotor ducts. The beam voltage should be increased from 80 kV to around 150 kV, and the weld speed should be increased from 12 to 120 ipm. A high-vacuum system (10^{-3}–10^{-6} TORR) should be maintained to reduce the likelihood of contamination by atmospheric gases.

In this case defects introduced at some manufacturing stage degraded the design and the part was scrapped. The critical pore size approach used is safe but overly conservative. An analysis based on the more realistic conditions of probabilistic fracture mechanics should be used.

ACKNOWLEDGMENT

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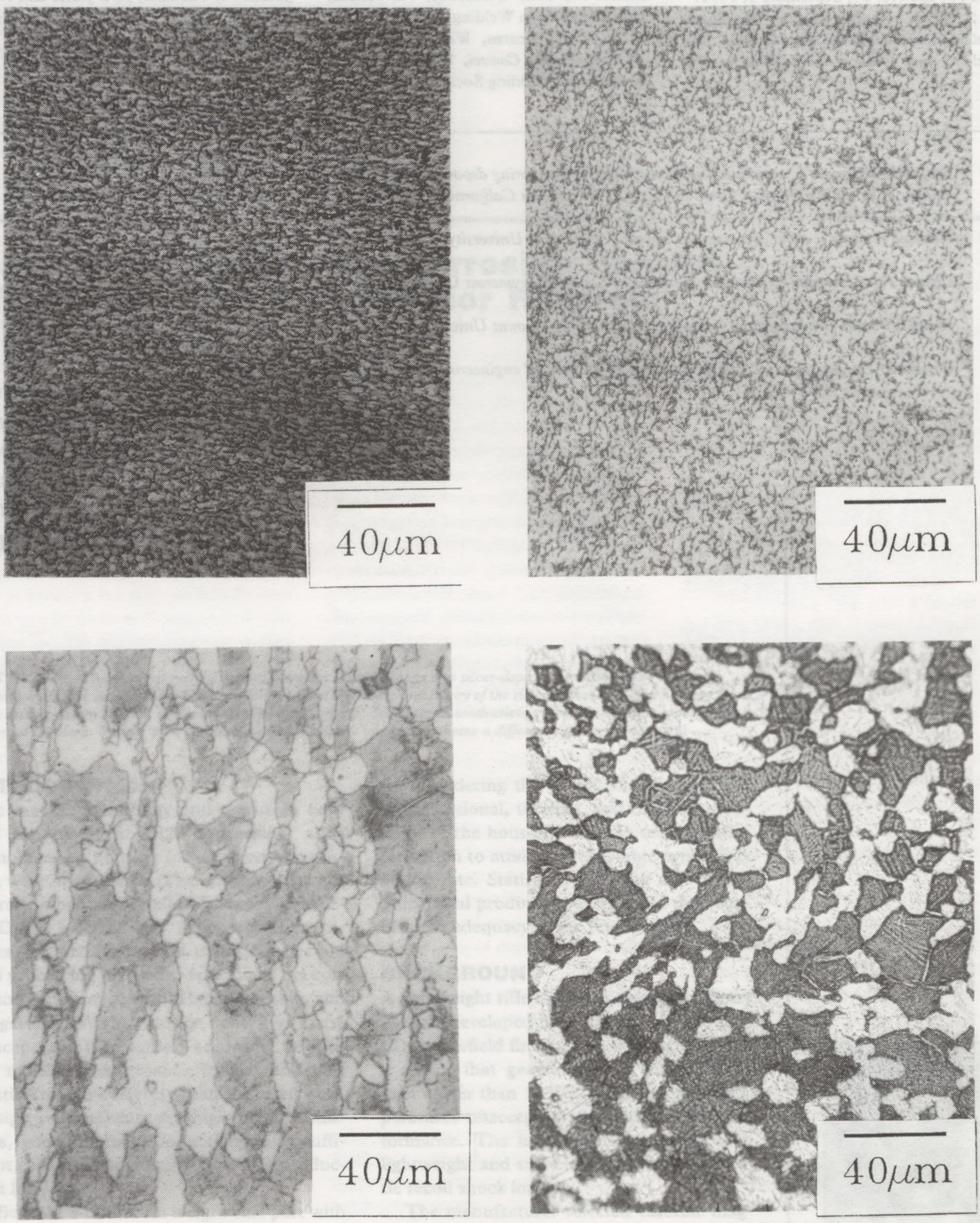
FIGURE 4 Optical Microstructures of the Parent Metal (top left), Heat-Affected Zone (top right), and Fusion Zones (bottom right and left), Longitudinal Views



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