DOT/FAA/AR-05/29

Office of Aviation Research
Washington, D.C. 20591

Inspection Development for Nickel Billet—Engine Titanium Consortium Phase II

September 2005

Final Report

This document is available to the U.S. public
through the National Technical Information Service (NTIS),
Springfield, VA 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturers names appear herein solely because they are considered essential to the objective of this report. This document does not constitute FAA certification policy. Consult your local FAA aircraft certification office as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-05/29		

4. Title and Subtitle	5. Report Date
INSPECTION DEVELOPMENT FOR NICKEL BILLET—ENGINE TITANIUM CONSORTIUM PHASE II	September 2005
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Mike Keller[1], Thadd Patton[1], Andrei Degtyar[2], Jeff Umbach[2], Waled Hassan[3], Andy Kinney[3], Ron Roberts[4], Frank Margetan[4], and Lisa Brasche[4]	

9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
[1]General Electric Company Cincinnati, Ohio 45215	[3]Honeywell Engines, Systems, & Services Phoenix, AZ	
[2]Pratt & Whitney East Hartford, CT	[4]Iowa State University Ames, IA	11. Contract or Grant No. DTFA0398FIA029

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591	Final Report
	14. Sponsoring Agency Code ANE-110

15. Supplementary Notes

The FAA William J. Hughes Technical Center Technical Monitor was Cu Nguyen.

16. Abstract

The Engine Titanium Consortium (ETC) is comprised of Iowa State University; General Electric; Pratt & Whitney; and Honeywell Engines, Systems & Services, and its objective was to develop improved inspection methods for critical jet engine components. The ETC Phase I program focused on improved inspection of titanium (Ti) billet using zoned inspection approaches. In the current work reported here, the multizone inspection procedure and transducers used for Ti were applied to typical nickel billet, namely Inconel 718 and Waspaloy. The program goal was achieved for 5″ and 10″diameter billet.

17. Key Words	18. Distribution Statement
Nickel billet, Ultrasonic inspection	This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	119	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		ix
1.	INTRODUCTION	1-1
1.1	Purpose	1-1
1.2	Background	1-1
1.3	Program Objectives	1-2
2.	APPROACH	2-1
3.	DISCUSSION OF RESULTS	3-1
3.1	Initial Assessment	3-1
3.2	Baseline Assessment	3-1
3.2.1	Standards Fabrication	3-1
3.2.2	Defining Conventional Ni Inspection	3-2
3.2.3	Sensitivity Projections	3-4
3.2.4	Transducer Characterization	3-6
3.2.5	Standard Design and Fabrication	3-7
3.2.6	Evaluation Results on the Calibration Standards	3-9
3.2.7	IN718 Inspections	3-10
3.2.8	Waspaloy Inspections	3-14
3.2.9	Summary of Laboratory Evaluations	3-17
3.3	Laboratory Demonstration	3-17
3.4	Factory Pilot Lot Assessment	3-18
3.5	Factory Demonstration	3-20
3.6	Indication Characterization	3-21
3.7	Summary of 10″ Diameter Billet Assessment	3-23
3.8	Small-Diameter Billet Study	3-24
3.8.1	Inspection Setup and Results for Waspaloy	3-25
3.8.2	Inspection Setup and Results for Ti-6Al-4V	3-32
3.8.3	Comparison of the Three Inspection Methods	3-38
4.	SUMMARY	4-1
5.	REFERENCES	5-1

APPENDICES

A—Defect Characterization of Naturally Occurring Anomalies
B—Data Acquisition Procedure
C—Nickel Small-Diameter Billet Data
D—Titanium Small-Diameter Billet Data

LIST OF FIGURES

Figure		Page
3-1	V-Die and GFM Billet C-Scans	3-4
3-2	Waspaloy Billet C-Scans	3-6
3-3	Three Measurement Geometries for Acquiring Data for Transducer Characterization	3-7
3-4	Final Design of the Ni Billet Standards (IN718 Containing #1 and #2 FBHs and the Waspaloy Containing #2 and #3 FBHs)	3-8
3-5	Two 10″ Diameter Ni Billet Calibration Standards, IN718 and Waspaloy	3-9
3-6	C-Scan of Conventional Inspection Zones 1 and 2 of an IN718 Calibration Standard	3-11
3-7	C-Scans of Multizone Inspection Zones 1-6 of an IN718 Calibration Standard	3-12
3-8	Comparison of Multizone Inspection Capability to IN718 10″ Billet Program Goal and Laboratory Conventional Inspection Capability	3-13
3-9	C-Scan of Conventional Inspection Zones 1 and 2 of a Waspaloy Calibration Standard	3-15
3-10	C-Scan of Multizone Inspection Zones 1-6 of a Waspaloy Calibration Standard	3-16
3-11	Comparison of Multizone Inspection Capability to Waspaloy 10″ Billet Program Goal and Laboratory Conventional Immersion Inspection Capability	3-17
3-12	Schematic of Indication Removal From Billet With Associated Orientation Labels	3-23
3-13	The 5″ Diameter ETC Billet Reference Standards (Waspaloy and Ti-6Al-4V) Containing #1 and #2 FBHs	3-25
3-14	Single Transducer Inspection C-Scan of the 5″ Diameter Waspaloy Billet	3-26
3-15	Four Zones of Multizone Inspection C-Scans That Cover a Depth of 3″ Into the Billet	3-28
3-16	Layout of the 113 Elements on the Face of the 5-MHz Phased Array Transducer	3-30
3-17	The Mechanical Setup Used in the Scanning of the Billet Standard	3-30
3-18	Typical Results Collected During the Inspection for the #2 and #1 FBHs at a 1.5″ Depth	3-31

3-19 Sixty-Inch Cylindrically Focused Transducer 3-33

3-20 C-Scan of ST Inspection of the 5″ Diameter Ti Billet 3-34

3-21 C-Scans of the 5″ Diameter Ti Billet Reference Standard 3-35

3-22 Typical Results for the #2 and #1 FBHs at a 1.5″ Depth 3-37

3-23 Comparison of the SNR From the Three Techniques Used in Inspecting the 5″ Diameter Waspaloy Billet Reference Standard 3-38

3-24 Sensitivity vs Depth at SNR = 1.4 (3 dB) for the 5″ Diameter Waspaloy Billet Reference Standard 3-39

3-25 Comparison of the SNR From the Three Techniques Used in Inspecting the 5″ Diameter Ti Billet Reference Standard 3-40

3-26 Sensitivity vs Depth at SNR = 1.4 (3 dB) for the 5″ Diameter Ti Billet Reference Standard 3-41

LIST OF TABLES

Table		Page
3-1	Summary of OEM Processes for Conventional Ni Billet Inspection	3-3
3-2	Mean Noise Levels Normalized to Calibration Plus 30 dB for the Three Alloys	3-5
3-3	Calibration and Noise Statistics for #1 FBH Sensitivity on IN718 Standard	3-19
3-4	Multizone vs Conventional—Investment, Maintenance, Labor, and Operating Cost Comparisons	3-21
3-5	List of Indications and the Amplitudes Relative to #1 and #2 FBH Calibrations	3-22
3-6	The EDAC for Waspaloy Conventional and ST Inspections	3-25
3-7	Signal-to-Noise Ratio for Conventional and ST Inspections of 5″ Diameter Waspaloy Billet Reference Standard	3-27
3-8	Multizone Production Transducers	3-28
3-9	Signal-to-Noise Ratio for Multizone Inspection of 5″ Diameter Waspaloy Billet Reference Standard	3-29
3-10	Phased Array Inspection Parameters for the Waspaloy 5″ Diameter Billet Standard	3-31
3-11	Signal-to-Noise Ratio Results Collected During the Phased Array Inspection of the 5″ Diameter Waspaloy Reference Billet Standard	3-32
3-12	Electronic Distance-Amplitude Correction for Ti-6Al-4V Conventional and ST Inspections	3-33
3-13	Signal-to-Noise Ratio for Conventional and ST Inspections of 5″ Diameter Ti Billet Reference Standard	3-34
3-14	Signal-to-Noise Ratio for Multizone Inspection of a 5″ Diameter Ti Billet Reference Standard	3-35
3-15	Phased Array Inspection Parameters for the 5″ Diameter Ti Billet Standard	3-36
3-16	Signal-to-Noise Ratio Results Collected During the Phased Array Inspection of the 5″ Diameter Ti-6Al-4V Reference Billet Standard	3-37

LIST OF ACRONYMS

AMS	Aerospace Material Specification
ASTM	American Society for Testing and Materials
DAC	Distance-amplitude correction
dB	Decibel
EDAC	Electronic distance-amplitude correction
ETC	Engine Titanium Consortium
FAA	Federal Aviation Administration
FBH	Flat-bottom hole
FSH	Full-screen height
GE	General Electric
GE-QTC	General Electric Quality Technology Center
GFM	Gesellschaft fur Maschinenbau-und-fertigungstechnik
IN718	Inconel
ISU	Iowa State University
Ni	Nickel
OEM	Original equipment manufacturer
P&W	Pratt & Whitney
PoD	Probability of detection
SNR	Signal-to-noise ratio
ST	Single transducer
Ti	Titanium

EXECUTIVE SUMMARY

The Engine Titanium Consortium (ETC) Phase I production inspection efforts focused on titanium (Ti) billet using zoned inspection procedures. The Phase II program applied the multizone procedures and transducers originally developed for Ti to nickel (Ni) billet. The program included design of calibration standards, laboratory assessment and demonstration, and factory assessment and demonstration for 10″ diameter billet. A comparison of multizone and phased array inspection to conventional inspection was also completed for 5″ diameter billet.

- Billet converted with Gesellschaft fur Maschinenbau-und-fertigungstechnick (GFM) processing is more acoustically noisy than billet converted using V-Die processing. GFM material was selected for use in calibration standards since this provides a more conservative assessment.

- Transducer characterization procedures were developed for bicylindrically focused transducers, which are useful for ensuring that actual focal characteristics match the intended design values.

- The Waspaloy calibration standard was more ultrasonically noisy than the Inconel 718 (IN718) material (75% peak noise compared to 20%, respectively) when measured with the same calibration target.

- The multizone inspection procedure and transducers originally used for Ti successfully exceeded the program goal of #1 flat-bottom hole (FBH) for IN718 and #2.5 FBH for Waspaloy by substantial margins. The multizone system exceeded the IN718 goal by a minimum of 3.5 times and was a minimum of 31 times more sensitive than the current conventional inspection requirement. Multizone exceeded the Waspaloy goal by a minimum of 4 times and was a minimum of 14 times more sensitive than the current conventional inspection requirement.

- The use of conventional transducers in two-zone laboratory inspection nearly met the program goal for IN718. The laboratory conventional immersion inspection exceeded the program goal of #2.5 FBH sensitivity for Waspaloy in the near-surface zones. No data was gathered for the production conventional contact inspection of Waspaloy.

- The factory assessment showed that the surface finish used for conventional inspection was adequate for the increased sensitivity of the multizone test, although the multizone test is more sensitive to surface blemishes.

- The factory assessment showed comparable characteristics for inspection of Ni when compared to experience with inspection of Ti multizone procedures.

- A cost comparison revealed increased investment and operational cost for multizone compared to conventional. Increased operational costs associated with multizone inspections were documented for setup, scanning, and analysis.

- Suppliers expressed concerns regarding transducer manufacturability and limited availability of transducer vendors.

- The factory demo on 81,000 pounds of two and three times melted IN718 generated conclusive results that the multizone system can detect indications that are missed by the current conventional inspection. A total of 19 indications were detected by multizone, all of which were significantly smaller than conventional inspection requirements that are at a #2 FBH sensitivity and, therefore, below the threshold for detection.

- Conventional inspection of 5″ diameter billet nearly met the current #2 FBH sensitivity in the center zone of both Ti and Waspaloy standards. However, slight modification of the current conventional inspection to reflect the method used for evaluating the results from the single transducer inspection show that a significant improvement if the sensitivity could be achieved.

- Multizone and phased array inspections of 5″ diameter Waspaloy billet indicated that multizone achieved about a #0.5 FBH sensitivity throughout most of the billet depth while phased array achieved about a #0.75 FBH. The multizone inspection exceeded the conventional inspection sensitivity by about 20 times at the billet center.

- Multizone and phased array inspections of 5″ diameter Ti-6Al-4V billet indicated that both achieved about a #0.75 FBH sensitivity throughout the billet depth, which exceeded the conventional immersion sensitivity by about nine times.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this program was to develop higher-sensitivity inspection methods for nickel (Ni) billets that could be used to reduce the occurrence of melt-related defects in Ni forgings and, therefore, lower the engine failure risk. Two Ni alloys commonly used among the engine manufactures are Inconel 718 (IN718) and Waspaloy. Both represent a significant percentage of Ni disks in use by the industry. These alloys also present different challenges for ultrasonic inspection due to microstructure differences between the two and were selected for evaluation in this effort.

1.2 BACKGROUND.

Typical billet diameters of 8″, 10″, 12″, and 14″, which are currently inspected to a sensitivity of #2 flat-bottom hole (FBH) and larger are used for large engines that power commercial transports. A single, spherically focused, 5-MHz transducer is generally used to achieve the required sensitivity. Current inspection of Ni alloys is limited by material grain noise, with typical grain sizes of 11 to 90 μm (American Society for Testing and Materials (ASTM) 10 to 4) for IN718 and primarily 60 to 90 μm in Waspaloy. A program goal of four times improvement over the current conventional inspection method was established. The technical approach of this program was to reduce the impact of grain noise on the inspection capability by using multiple, bicylindrically focused multizone transducers. Alloy selection for jet engine applications is based on the operational requirements with factors such as stress, temperature, environmental conditions, and weight being considered. Ni alloys are selected for use at areas of high operational temperatures (800° to 1500°F), such as the compressor and turbine stages of the engine. Given the consequences of failure, there is a need for sensitive and effective inspection methods. A four times improvement in sensitivity would be achieved if the #2 FBH sensitivity of the current IN718 billet inspection were improved to a #1 FBH sensitivity. Waspaloy billets of 8″ to 14″ are currently inspected to a #5 FBH sensitivity, so a four times improvement would be achieved with a #2.5 FBH sensitivity inspection.

Considerable effort has gone into the development of focused zoned inspection. The method commonly referred to as multizone [1, 2, 3, 4, and 5] was initially developed by General Electric (GE) with subsequent improvement as part of the Engine Titanium Consortium (ETC) Phase I and Phase II programs. The ETC is a university/industry partnership comprised of Iowa State University (ISU); GE; Pratt & Whitney (P&W); and Honeywell Engines, Systems & Services. The ETC approach includes the measurement and utilization of materials properties information relevant to ultrasonic inspectability [6, 7, 8, 9, 10, and 11]. Properties including ultrasonic velocity, attenuation [12], and backscatter noise [, 13, 14, 15, 16, and 17] were correlated to microstructural and macrostructural conditions of representative alloy samples [18]. The Phase I program focused on improvements to inspection of titanium (Ti) billet [19].

Two approaches to zoned inspection of Ti billet were evaluated in the ETC Phase I program: multizone [20] and phased array [21]. In comparative studies performed as part of the contaminated billet study, both methods detected the same indications, although with variation in amplitude and signal-to-noise ratio (SNR). Given the success of the multizone method for

improved sensitivity inspection of Ti billet and the existence of several commercial inspections, the ETC Phase II program was aimed at extending this method to Ni billet.

Sound velocities for the Ni alloys (IN718 and Waspaloy) are only about 2% slower than the sound velocities of the Ti alloys used in ETC Phase I. It was postulated that the fixed-focus transducers used for multizone inspections in ETC Phase I would also be applicable to these Ni alloys in a straightforward manner. The ETC Phase II program generated fundamental property data [22] for IN718 and Waspaloy and applied the multizone inspection method to Ni billet. This report provides details of the latter.

1.3 PROGRAM OBJECTIVES.

- To apply technology developed in ETC Phase I for Ti billet inspection to improve Ni billet inspection.

- To perform factory inspection of approximately 100,000 pounds of Ni alloy billet, primarily IN718, to a #1 FBH sensitivity using a multizone inspection system with digital acquisition to provide necessary field experience that facilitates implementation decisions.

- To determine applicability of the multizone technique to Waspaloy.

- To provide the billet industry and original equipment manufacturers (OEM) with a demonstration of improved sensitivity inspection using FBH standards as the metric, with a goal of #1 FBH sensitivity in 10″ diameter IN718 billets and #2.5 FBH sensitivity in 10″ diameter Waspaloy billet.

- To provide necessary data to the Inspection Systems Capability team for estimation of probability of detection (PoD) for Ni billet, including cutup data generated in the pilot lot inspection.

2. APPROACH.

The approach used for this research program included the following:

- Initial Assessment: Activities included selection of representative alloys, design and manufacture of calibration standards, and identification of target sensitivity and SNR criteria.

- Baseline Assessment: Initial effort included definition of conventional Ni billet inspection, development of sensitivity curves for that conventional inspection, as well as for sensitivity curves for multizone using transducers originally designed for Ti billet.

- Laboratory Demonstration: Using calibration standards fabricated from 10″ diameter IN718 and Waspaloy billets, a laboratory demonstration was held with attendees from the billet and forging supplier community.

- Small Diameter Billet Assessment: A study specific to smaller diameter (5″) billet was carried out using both Ni and Ti calibration standards. The study compared conventional, multizone, and phased array inspection methods.

- Factory Demonstration: Upon completion of the laboratory demonstration, arrangements were made for a factory inspection of 50,000 pounds of triple-melt IN718, 25,000 pounds of double-melt IN718, and 25,000 pounds of Waspaloy. Because of industry production rates, the actual inspection was limited to IN718. The product evaluated in the factory was limited to 10″ diameter. Near the completion of the inspection pilot run, a factory demonstration was held with the billet supplier community.

3. DISCUSSION OF RESULTS.

3.1 INITIAL ASSESSMENT.

A kickoff meeting involving the ETC team members was held in June 1999 to reiterate the plans of the task and established a means of sharing information and data, including coordination of efforts with other tasks underway in the ETC Phase II program. This included coordination with reliability efforts. IN718 and Waspaloy were selected as the alloys to be studied in the program with target sensitivities of #1 and #2.5 FBHs, respectively. Requirements for signal-to-noise measurements were also established. The number and types of calibration standards were discussed, and design of the standards initiated. Production calibration standards for 10″ diameter IN718 and Waspaloy were agreed upon in the initial planning meeting and subsequently manufactured.

3.2 BASELINE ASSESSMENT.

An evaluation of the current capability of conventional inspections was performed as a baseline for both IN718 and Waspaloy using the production calibration standards rather than relying on nominal values stated in the respective specifications. Inspection development was performed with the calibration standards using existing production multizone transducers. These evaluations took place principally at the GE facilities with P&W personnel in attendance to facilitate hands-on involvement by the parties responsible for final implementation recommendations. Scans and associated measurements were used to determine the focal depth of each transducer, measure the axial beam profile and beam cross section, and compare these results to model predictions. SNRs were determined for the FBH targets and sensitivity curves were generated. Following evaluation of the existing production transducers, it was determined that redesigned transducers would not be necessary to meet the stated goals. The conventional inspection sensitivity was established based on production inspection criteria after a review of all three OEM's production inspection procedures.

3.2.1 Standards Fabrication.

The Fundamental Studies [22] effort of the ETC program was charged with studying and making recommendations to the Ni billet inspection development task regarding material sectioning for standards fabrication. Team members worked closely with the fundamental studies group in the initial stages of the program to select the material and establish the process for inspection development. Many of the decisions regarding alloy selection and billet diameters were agreed upon at the initial kickoff meeting and were based on industry needs. At that time it was decided that IN718 alloy was widely used by all three OEMs, Waspaloy is used by two of the three, and that 10″ diameter billet fit the requirements for larger engines. The inspection development effort focused on 10″ diameter IN718 and Waspaloy. A separate study for smaller diameter billet was also planned.

Experience indicates that acoustic properties and the resultant inspection sensitivities are often dependent on the way the material is processed. If these properties are significantly different, it is good practice to make a standard representing each process even though the alloy's chemical composition is the same. Because IN718 is ordered by the OEMs either using double

(VIM/VAR) or triple melt (VIM/ESR/VAR), or depending on the supplier, different conversion practices, further refinement of the material selection process was required. All Waspaloy used by the OEMs was double (VIM/VAR) melted so no material selection was necessary.

A survey of several IN718 inspection facilities reported only minor differences in acoustic noise between the double- and triple-melt product, and as a consequence, there was no further consideration in making a standard of each. The more significant difference would lie in the conversion process. Currently, there are two conversion practices commonly used to convert the cast 718 ingot into finished cylindrical billets, referred to as the Gesellschaft fur Maschinenbau-und-fertigungstechnik (GFM) and V-Die processes []. With direction from the fundamental studies effort, a 30-inch section of each type of IN718 was procured for study. An ultrasonic evaluation of these two 30-inch-long samples indicated the GFM-processed billet produced, on average, more acoustic noise than the V-Die material.

One standard of the noisiest (GFM converted) IN718 billet material was selected. It was reasoned that a standard made from the process that is presumably the more difficult to inspect would lead to a more conservative result. It was also postulated that if multizone evaluation takes place under the more difficult conditions, it is likely to work for the less noisy billet as well. For this reason, the GFM billet was chosen for fabrication of the standard. An order was placed for the GFM-produced billet according to the normal purchase specification for rotor-grade material. The grain size requirement for the billets was ASTM 5 or finer with less than 20% being ASTM 2 to be consistent with specifications for production material of 8″ diameter or greater.

A second survey of suppliers of Waspaloy material led to the selection of GFM-processed material because it is widely used for Waspaloy conversion. The final IN718 standard was 10″ diameter, triple-melt GFM-converted material. The final Waspaloy standard was also 10″ diameter, double-melt GFM-converted material. Detailed information on the evaluations leading to this decision is presented in a companion report of the ETC fundamental studies effort [].

3.2.2 Defining Conventional Ni Inspection.

To measure sensitivity improvement in the multizone inspection technique applied to Ni billet, the baseline conventional inspection sensitivities were needed to be defined. Each of the OEMs was asked to provide details on their conventional Ni billet inspection processes, which are summarized in table 3-1.

Comparison of the three processes used by the OEMs to inspect IN718 revealed a number of similarities, such as static calibration, zoned inspection permitted, 5-MHz transducers, normal incidence, and no strip charts or C-scans. However, some differences were noted in the FBH size used in the calibration standard that ranged from #2 to #3 FBH and reject levels that included 50% of #2 FBH or 100% of #3 FBH. Evaluation of the different techniques resulted in selecting process 1 as a representative baseline for IN718 and process 4 for Waspaloy billet inspection. In summary, the IN718 baseline conventional inspection was to a #3 FBH sensitivity and Waspaloy was to a #5 FBH sensitivity.

TABLE 3-1. SUMMARY OF OEM PROCESSES FOR CONVENTIONAL Ni BILLET INSPECTION

	IN718			Waspaloy	
Calibration Standard	Process 1	Process 2	Process 3	Process 4	Process 5
Alloy/Grade	VIM/VAR	VIM/ESR/VAR	VIM/ESR/VAR	N/A	Type 1/Type II VIM/VAR/ VIM/ESR
Is one std. used for all grades?	Yes	Yes	Yes 2x	N/A	Yes
Referenced to master standard?		No	No	No	No
Dynamic or Static	Static	Static	Static	Static	Static
FBH size	#3	#3	#2	#5	#8
FBH depths	0.25″-5″	Note 1	0.25″, 0.75″, 1.25″, 2.5″, 5.5″	0.25″-5″	Note 1
Inspection Transducers		Note 2			
For each zone if applicable			Zone 1/Zone 2		
Element size	0.75″		0.75″ dia / 0.75x1.0″	0.75″	
Focal length					
Frequency	5 MHz		5 MHz/5 MHz	5″	
Beam size (approximately)			0.112″		
3 dB depth of field			0.9″		
Calibration Procedure					
Zone inspect?	Allowed	Note 3	Yes	Allowed	Note 3
Zone 1 focus/DAC			Subsurface/yes		
Zone 2 focus/DAC			2″ subsurface/yes		
Zone 3 focus/DAC			N/A		
Reporting Requirements					
		80% FSH = 100%	80% FSH = 100%		80% FSH = 100%
Sensitivity Level (% of calibration)		#3 FBH	#2 FBH	N/A	#8 FBH
Alarm threshold/evaluation level	50% (Note 5)	50%	25%	50% (Note 5)	50%
Maximum-allowable noise level		50%	25%	N/A	50%
Reject level	100%	100%	50%	100%	100%
Inspection Parameters					
Angle of incidence	Normal	Normal	Normal	Normal	Normal
Pulse on position?		No	No	N/ A	No
Rotation speed	(>500 PRF)	Note 4	13″/sec. surface	(>500 PRF)	Note 4
Scan index	<1/2 EBW	<80% EBD	0.070″	<1/2 EBW	<80% EBW
Translational speed	N/A	Note 4	N/A	N/A	Note 4
Strip chart/C-scan	No	No	No	No	No

EBD-Effective beam diameter
EBW-Effective beam width
PRF-Pulse repetition frequency
N/A-Not available

Notes:

1. FBH depths as required for establishing distance-amplitude correction (DAC). Surface resolution shall be as agreed upon with an OEM-approved inspection procedure.
2. Transducers shall be capable of providing sufficient resolution and sensitivity to detect the applicable reference reflector.
3. When near-surface resolution and depth of penetration cannot be accomplished in a single scan, multiple scans shall be performed in a series of smaller metal travel tolerance using ASTM reference.
4. Scanning speed shall not exceed the maximum speed that provides for detection of all discontinuities in the part.
5. Value stated is not the required value but is a likely value that is used.

3.2.3 Sensitivity Projections.

Much of the research involved in the fundamental studies effort was conducted simultaneously and in cooperation with the production inspection development effort. With this in mind, the sections of material ordered for the fundamental studies measurements were specified to a length taking into account that the same material might be fabricated into standards. Once the material arrived, an initial evaluation was conducted at the GE laboratory facility using the multizone inspection procedure currently used for Ti. The instrumentation sensitivity level was calibrated using the GE Ti billet standard containing #2 FBHs. Each IN718 billet was then scanned with increased sensitivity so that the mean material noise was kept between 20% and 60% full-screen height (FSH) amplitude. This increased sensitivity over calibration was recorded in decibels (dB) for each of the six zones of the multizone inspection. Peak noise levels observed in the C-scans were kept below saturation. The results for the six zones are shown in figure 3-1. This includes both V-Die- and GFM-processed IN718 10″ diameter billet.

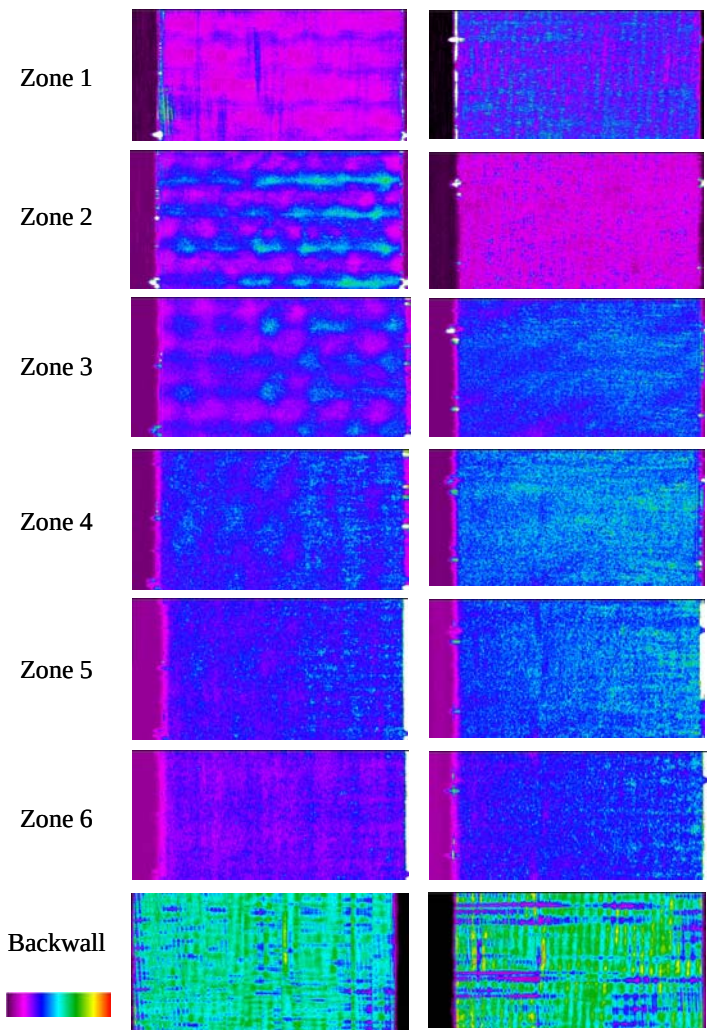


FIGURE 3-1. V-DIE AND GFM BILLET C-SCANS

Table 3-2 shows the normalized mean noise values, comparing the V-Die and GFM billets for IN718. These preliminary inspections at the arbitrary gain settings provided an initial look at the expected inspection capability for this material as well as identifying possible unacceptable inclusions or conditions that might render the material unacceptable for standard use.

TABLE 3-2. MEAN NOISE LEVELS NORMALIZED TO CALIBRATION PLUS 30 dB FOR THE THREE ALLOYS

Average Material Noise at Ti #2 + 30 dB			
	IN718		Waspaloy
Zone	D-Die	GFM	GFM
2	23	34	79
3	25	32	101
4	30	37	104
5	44	55	136
6	39	50	108

In estimating the potential inspection capability, the gain setting relative to the #2 Ti calibration level is compared to the peak noise level in the material under investigation. By comparing the acoustic impedance between Ti and IN718, a correction can be made for the energy transfer differential at the water-to-material interface. In the case of Ti versus IN718, the acoustic impedance is about 1.8 or 5.5 dB. Therefore, it will take about 5.5 dB additional gain to achieve the equivalent sound field in IN718 as for Ti. Using the area amplitude relationship between a #2 FBH and a #1 FBH, the sensitivity is about 4 times greater or 12 dB. Adding the 5.5 dB insertion loss to the 12 dB sensitivity, the resultant sensitivity to a #1 FBH is 17.5 dB. Since the prescans were conducted at plus 30 dB, this meant that the IN718 billet was inspected at a projected #1 FBH plus about 12 dB. Lowering the mean and peak noise values for each of the C-scan zones by 12 dB suggested that the goal of achieving #1 FBH sensitivity with a SNR of 3 dB or greater was highly probable. Having this much margin in sensitivity made it unlikely that new transducers would have to be designed, specifically for Ni. The more subtle differences in velocity and attenuation that will affect the transducer focus might well be ignored, allowing use of existing transducers originally designed for Ti.

The same analysis was conducted using the Waspaloy material. Figure 3-2 provides the C-scan results. Here again the prospects of achieving the goal of #2.5 FBH looked well within reach. Of course, one could not be certain of the final sensitivity until the FBHs were placed in the standard and the transducers calibrated on these targets. The noise values normalized to Ti #2 FBH level +30 dB for the Waspaloy billet are included in table 3-2.

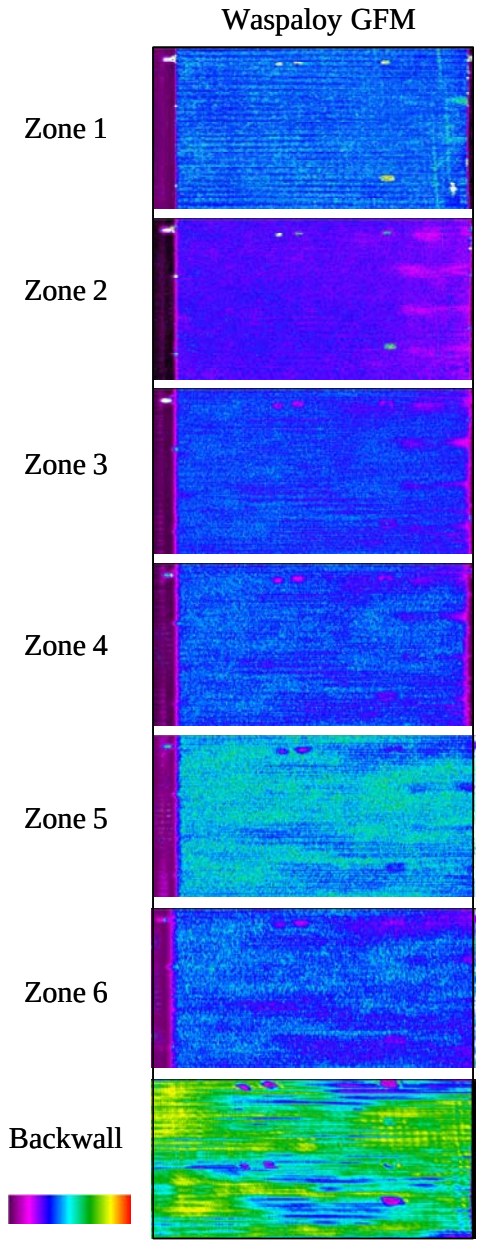


FIGURE 3-2. WASPALOY BILLET C-SCANS

3.2.4 Transducer Characterization.

Multizone transducers used for billet inspections are bicylindrically focused to compensate for the curved sound-entry surface of the billet. There are two distinct focal zones in water, but these coalesce to a single focal zone in the metal after transmission through the billet surface. The sharp focusing of the beam in the metal tends to improve SNRs for small internal defects. The focal characteristics claimed by transducer manufacturers are sometimes inaccurate. Thus, prior to certifying transducers for service, it is useful to determine how accurately actual focal characteristics match the intended design values. Such determinations are referred to as transducer characterization.

Investigators at ISU developed generic software to characterize multizone transducers using the IN718 10″ billet calibration standard. The software characterizes a transducer's projected beam pattern by measuring a quantity called the V(z) profile [23]. This software is beneficial in predicting the response and performance of transducers from known targets.

ISU developed three approaches for characterizing multizone transducers. The measurement geometry for each method is shown in figure 3-3. The three methods were then used to characterize a typical 5-MHz multizone transducer, namely one designed to focus 3.15″ deep (zone 4) in 10″ diameter Ti alloy billet. Details of the work are included in the companion ETC report for Ti billet [24]. It was recommended, on the combined basis of ease of use and overall accuracy, that the V(z) method be used by OEMs interested in performing their own transducer characterizations. The V(z) measurements consist of capturing digitized front-wall radio frequency (RF) echoes at normal incidence from a flat reflector in water. Data is gathered at 100-200 equally spaced water paths, which bracket the two principal focal zones. A user-friendly version of the V(z) probe characterization software was developed for use by the OEMs, and a companion user's manual was written. The results are also described in this report and several publications [23].

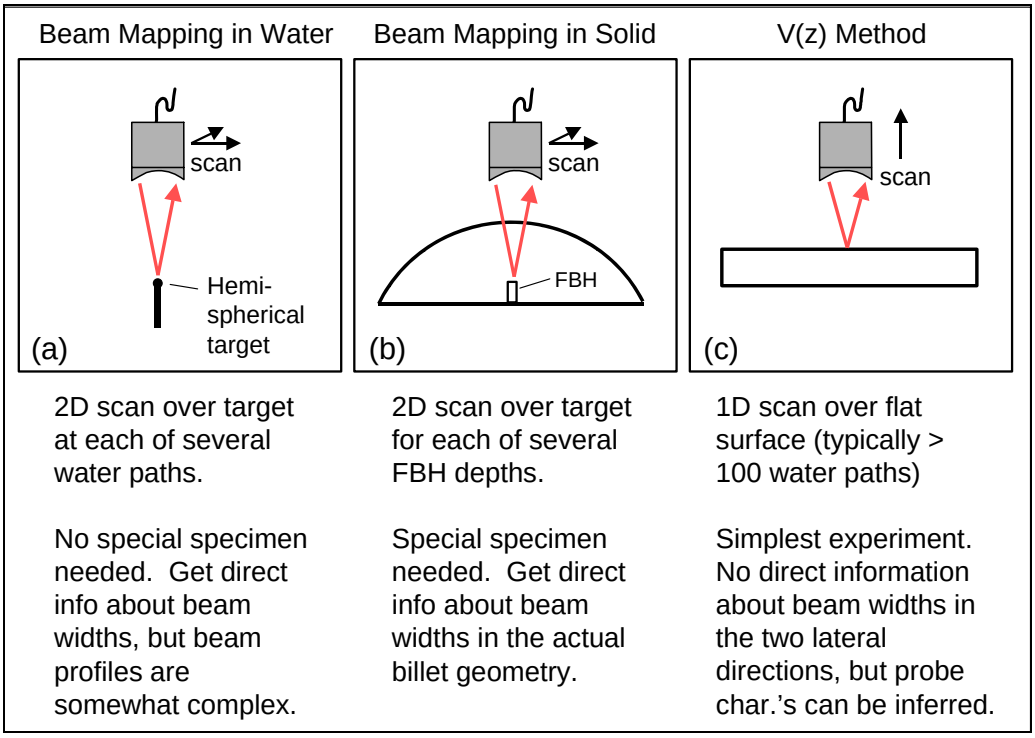


FIGURE 3-3. THREE MEASUREMENT GEOMETRIES FOR ACQUIRING DATA FOR TRANSDUCER CHARACTERIZATION

3.2.5 Standard Design and Fabrication.

Foremost to most ultrasonic inspection development is the design and fabrication of a standard containing a series of reflecting targets from which the sensitivity of the inspection is calibrated. The physical characteristics of the Ni standards were for the most part modeled after the design

provided in the SAE International Aerospace Material Specification (AMS) 2628 specification for Ti billet. These standard designs make provision for dynamic as well as the traditional static calibration. A dynamic-designed standard is one that will allow more complete testing of the whole inspection system and simulates actual inspection speed and motion. It also allows the creation of a C-scan image of the standard, useful in collecting noise statistics. The calibration standard design includes a solid section of material that provides an opportunity to evaluate attenuation characteristics and can aid in transducer normalization. A significant departure from the AMS design was the addition of an extra hole placed at a depth between the two extreme holes for each zone. This additional hole is useful in measuring beam profiles and determining scanning indexes for production inspection.

A second complete set of calibration holes were also planned for the standard. The goal was to achieve a #1 FBH sensitivity for IN718 to be compared with a #3 FBH sensitivity for conventional inspection. The team decided that instead of #3 FBHs being placed in the standard, #2 FBHs would be machined. There is significant evidence from the GE conventional inspection that #2 FBHs would be relatively easy to identify and that corrections could be made to inspection sensitivity at the #3 FBH level. Therefore, both #1 and #2 FBHs were placed in the standard to provide an opportunity to evaluate conventional inspection transducers as well. Figure 3-4 shows the final design of the standard.

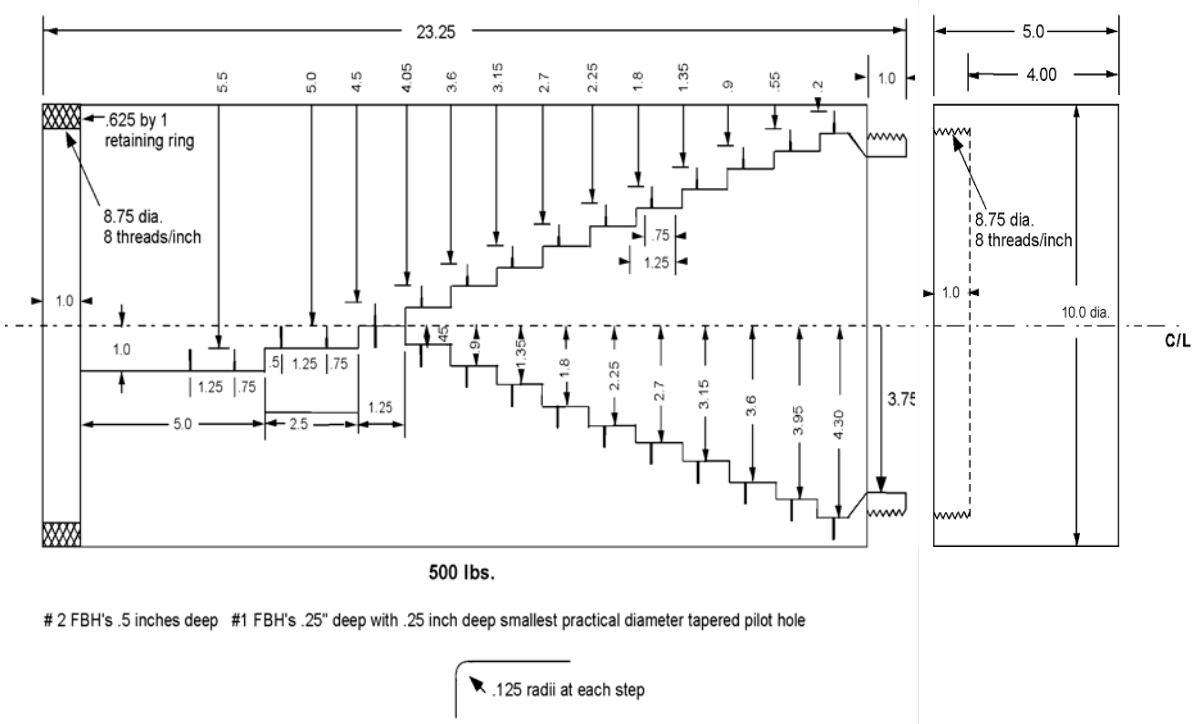


FIGURE 3-4. FINAL DESIGN OF THE Ni BILLET STANDARDS (IN718 CONTAINING #1 AND #2 FBHs AND THE WASPALOY CONTAINING #2 AND #3 FBHs)

Current hole drilling for the #1 FBHs in the IN718 standard is less than 1/2 inch deep. These small diameter holes required the drilling of a pilot hole 1/4 of an inch deep, then the #1 FBH

was drilled an additional 1/4 inch, making a total hole depth of 1/2 inch. This needs to be considered during calibration so as not to mistake the shoulder of the pilot hole for the FBH response.

The Waspaloy standard was designed in the same manner as the IN718 standard with the exception that both #2 and #3 FBHs were drilled. The Waspaloy inspection goal was a #2.5 FBH. Here, the #2 and #3 FBHs framed the target size. The target hole can be mathematically calculated from the responses of the actual targets based on the area amplitude relationship. Spacing between target holes was generous to permit evaluation of conventional transducer beams.

3.2.6 Evaluation Results on the Calibration Standards.

Once the calibration standards for IN718 and Waspaloy were machined, both of the 10″ diameter standards were evaluated at the GE Quality Technology Center (QTC) billet inspection facility. Figure 3-5 shows two 500-lb, 10″ diameter standards.

FIGURE 3-5. TWO 10″ DIAMETER Ni BILLET CALIBRATION STANDARDS, IN718 AND WASPALOY

Multizone inspections were conducted using the same 5-MHz transducers specified for production inspections of 10″ Ti billet material. Conventional inspections were conducted using similar transducers to those used by production billet suppliers.

3.2.7 IN718 Inspections.

A conventional inspection was conducted for IN718 in the GE-QTC laboratory tank using the test parameters identified below:

- Instrument: KB6000 (S/N 311269, pulser model 311526, receiver model 311316)

- Zone 1 transducer: Harisonic I7, 5 MHz, spherical focus, 0.75-inch element diameter, 6-inch focal length operated at a 6-inch water path

- Zone 2 transducer: KB Gamma, 5 MHz, 0.75- x 1.0-inch rectangular element, 7-inch cylindrical focus operated at a 5- and 2-inch water path

The two-zone inspection was conducted using DAC. The zone 1 transducer covered depths from 0.2″ to 2.25″. It has a 6″ focal length, and a 6″ water path was employed so the beam was focused very near the billet surface. The zone 2 transducer covered depths from 1.8″ to 5.5″. The laboratory inspection was conducted using a 5″ water path. A second inspection using a shorter (2″) experimental water path was also completed to evaluate the effect of moving the zone 2 focal point deeper into the billet. The standards were inspected by calibrating both transducers on the shallowest #2 FBH and adjusting the gain and DAC until all FBHs reached an amplitude of 80% FSH. To avoid reflections from the circumferentially machined surfaces, the nonproductive technique of gating each hole just short of these surfaces was used. This technique permitted clearer C-scans of all holes.

The simulated two-zone production inspection, using a #2 FBH calibration and a 5″ water path for the conventional two-zone transducers, produced the C-scans shown in figure 3-6. The zone 1 transducer C-scan indicates all the #2 and #1 FBHs can be identified. The zone 2 transducer C-scan easily identifies all the #2 FBHs, but the #1 FBHs are more below the threshold and cannot be distinguished from the background noises at depths greater than about 2.7″.

The multizone inspection was also conducted at GE-QTC in the laboratory tank using transducers manufactured to the same specification as production transducers. The same transducers specified for Ti billet inspections were used for inspecting the Ni standards. There are a total of six zones, each covering approximately 0.9″ of the billet. Details of the instrument and transducers are provided below:

- Instrument: P/N 94ASY020G, S/N 002
- Pulser preamp: P/N 91ASY028G, S/N 013
- Zone 1: NDT systems, P/N AE08402GE, S/N 124151, focus 0.4″ deep
- Zone 2: NDT systems, P/N AE08418GE, S/N 02554, focus 1.3″ deep
- Zone 3: NDT systems, P/N AE08420GE, S/N 035120, focus 2.2″ deep
- Zone 4: NDT systems, P/N AE08422GE, S/N 035127, focus 3.1″ deep
- Zone 5: NDT systems, P/N AE08424GE, S/N 035221, focus 4″ deep
- Zone 6: NDT systems, P/N AE08426GE, S/N 04544, focus 5″ deep

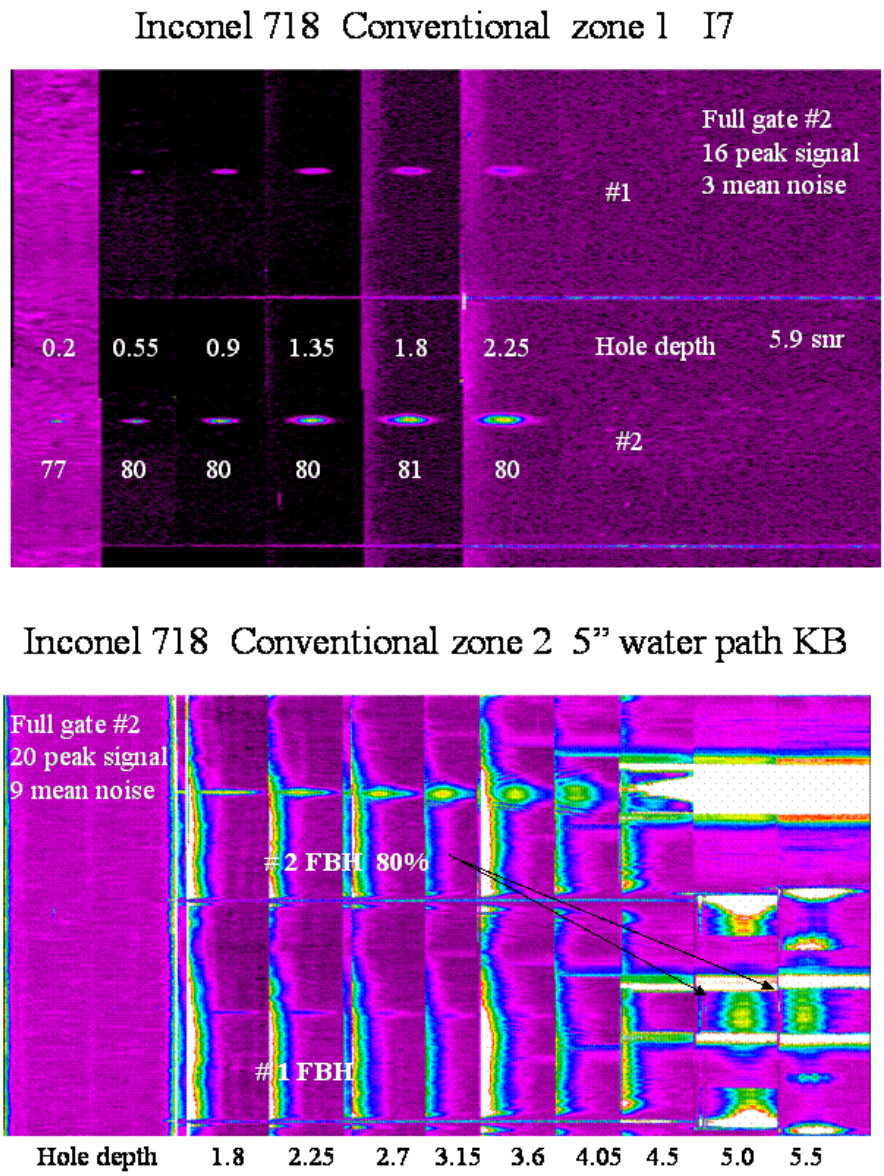


FIGURE 3-6. C-SCAN OF CONVENTIONAL INSPECTION ZONES 1 AND 2 OF AN IN718 CALIBRATION STANDARD

Prior to final sensitivity adjustment, the water path of the transducer for each zone was adjusted to produce the best balance in response from the near and far holes for each zone. Instrument sensitivity was then calibrated using #1 FBHs, with the individual gain levels adjusted to produce 80% FSH amplitude for the least reflective of the three FBHs in each zone. The C-scans for each zone are shown in figure 3-7. Note that all the #2 and #1 FBHs can be readily detected in all inspection zones.

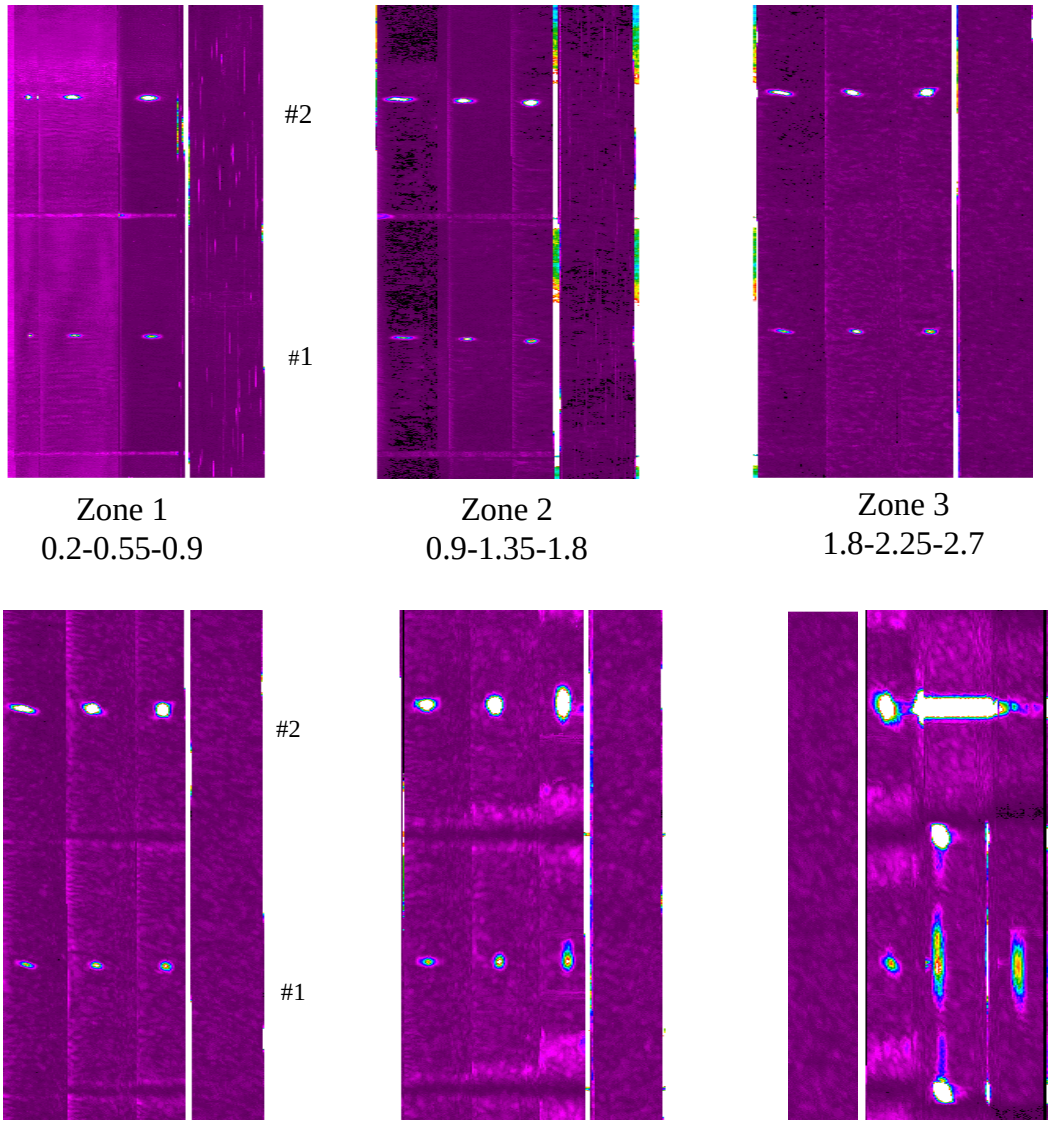


FIGURE 3-7. C-SCANS OF MULTIZONE INSPECTION ZONES 1-6 OF AN IN718 CALIBRATION STANDARD

- Comparison to Program Goal.

The program goal was to demonstrate that the multizone inspection, using the 5-MHz transducers developed for 10″ Ti billet, were capable of inspecting IN718 rotor-grade billet to a #1 FBH sensitivity from the surface to the center of the billet. If achieved, this would represent a nine times improvement over the production conventional inspection as defined in the program.

To determine whether the program goal has been attained, an SNR must be defined which permits detection of the FBH at an acceptable false call rate and provides a standard means of comparing conventional and multizone inspection procedures. The multizone Ti billet inspection specification used in production has identified an SNR of 2.5 as providing an acceptable level of detectability combined with a reasonable false call rate as established from field evaluations. However, because many conventional inspections use an SNR much less than 2, a 3 dB or 1.4125:1 was adopted for evaluation of inspection sensitivities. The multizone and laboratory conventional data were plotted against the program goal of #1 FBH in figure 3-8 in terms of FBH#. The FBH sensitivity plotted on the y axis is defined as:

$$Sensitivity\ in\ FBH\# \ = FBH\#_{cal}\ \sqrt{[(S_{npk})(1.4125)]/80}$$

Where $FBH\#_{cal}$ = Flat bottom hole number used for calibration

S_{npk} = Peak noise amplitude

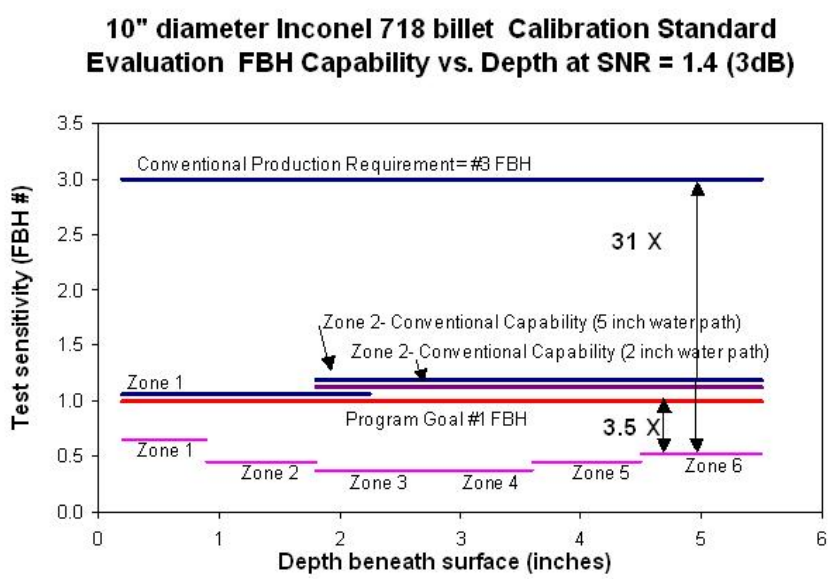


FIGURE 3-8. COMPARISON OF MULTIZONE INSPECTION CAPABILITY TO IN718 10″ BILLET PROGRAM GOAL AND LABORATORY CONVENTIONAL INSPECTION CAPABILITY

This sensitivity definition requires that the calibration target in the fully gated inspection zone be 3 dB higher than the peak noise and the calibration level be 80% FSH. These normalized FBH numbers are plotted for each zone in figure 3-8.

The multizone inspection sensitivity, after being normalized to an SNR of 3 dB, exceeded the program goal of #1 FBH at all depths in the billet. At the billet center, it is approximately 31 times more sensitive than the current conventional production inspection and about 3.5 times better than the program goal. These values were very

close to earlier predictions about the achievable sensitivity based on the initial material inspection of +30 dB. The laboratory conventional data (zone 2 at 5″ and 2″ water paths) are also plotted in figure 3-8. Although SNR is not normally measured on conventional inspections, the SNR was determined using the normalized sensitivity at SNR = 1.4125. The laboratory conventional inspection was approximately equal to the program goal for zone 1 and slightly less (FBH# 1.188 - 5″ water path) for zone 2.

3.2.8 Waspaloy Inspections.

Evaluation of the 10″ diameter Waspaloy calibration billet was completed using the same procedures as applied to the IN718 billet. The calibration billet was machined to the same configuration (see figure 3-4). The only difference was the size of the FBH calibration holes—the Waspaloy standard contained #2 and #3 FBHs at each of the inspection depths.

The conventional inspection used by suppliers on 10″ billet used contact transducers calibrated to a #5 FBH. This production inspection was used to set the program goal of four times improvement relative to a #5 FBH, which is equivalent to a #2.5 FBH as the goal. This inspection was not duplicated in the laboratory, and no data were obtained on the program. However, laboratory tests, using the same immersion transducers employed in the IN718 evaluation, were conducted to gather data on the Waspaloy calibration billet, providing a comparison with the immersion multizone inspection results.

This inspection was performed at the GE-QTC laboratory facility using test parameters similar to those applied to IN718. The zone 2 inspection was conducted using a 5″ water path. A second experimental inspection using a shorter (2″) water path was also completed to evaluate the effect of moving the zone 2 focal point deeper into the billet.

Both transducers were calibrated on the shallowest #3 FBH in the same manner as the IN718 test. The scan of each hole was gated just short of the inner-machined surfaces in order to produce clearer C-scans of all holes by eliminating the large reflection produced by each of the surfaces. The two-zone laboratory inspection calibrated to a #3 FBH, produced the C-scans shown in figure 3-9. The zone 1 transducer C-scan indicates all the #3 and #2 FBHs can be identified. The zone 2 transducer C-scan identifies the #3 FBH down to a depth of about 4″. The #2 FBHs are difficult to distinguish from the background at depths greater than about 3.6″. Note that the noise level is a more significant factor in Waspaloy than in IN718. The noise level shown at the extreme left side of the figure 3-9 C-scan (75% peak amplitude, 38% mean amplitude) was taken with the full gate in an area of the billet that did not contain FBHs and is indicative of the noise that would be encountered in a conventional immersion inspection of production billets.

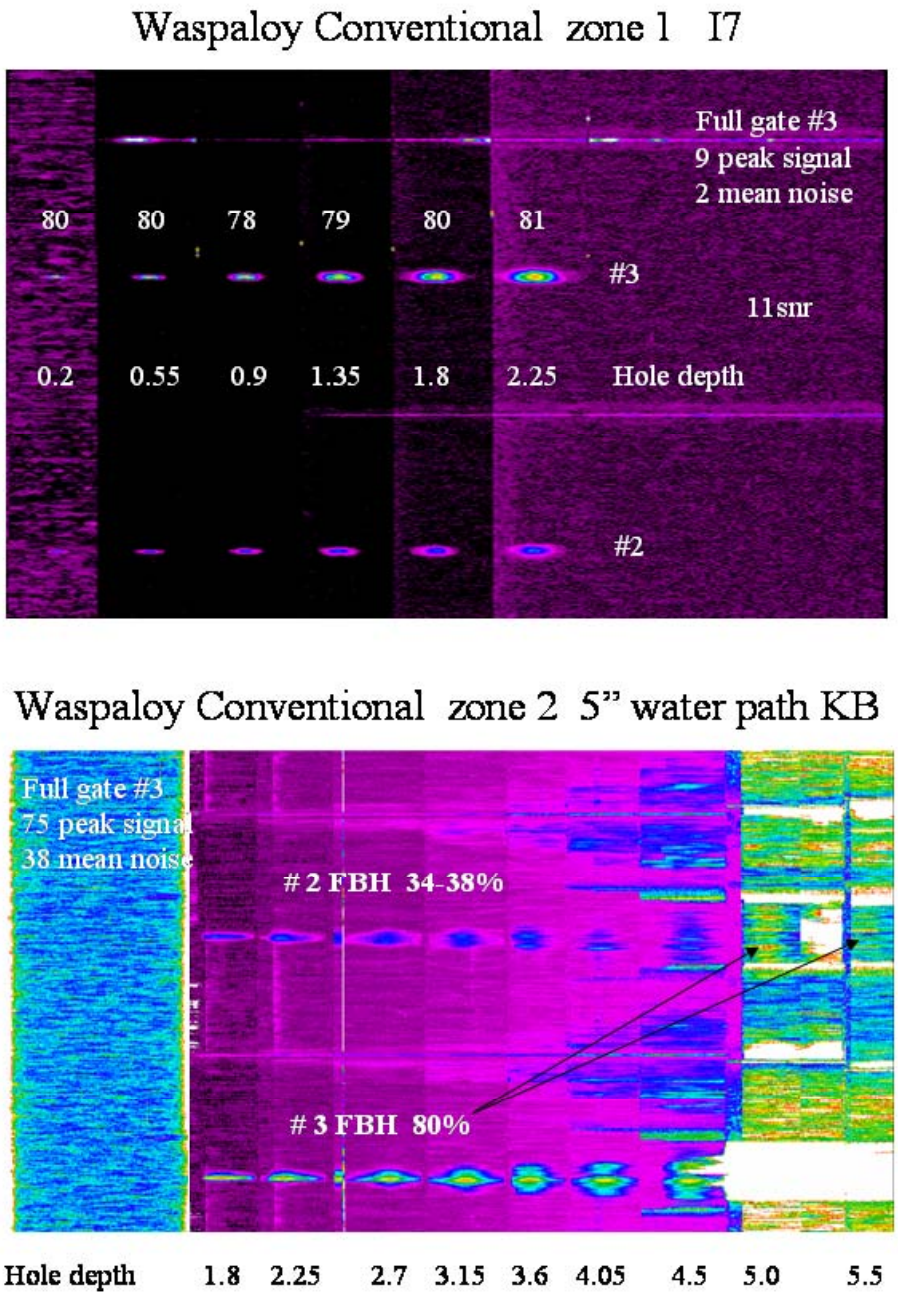


FIGURE 3-9. C-SCAN OF CONVENTIONAL INSPECTION ZONES 1 AND 2 OF A WASPALOY CALIBRATION STANDARD

The multizone inspection was also conducted at GE-QTC in the laboratory tank using transducers manufactured to the same specification as production transducers. A total of six zones were inspected using the same 5-MHz transducers developed for Ti billet inspections. The transducers were calibrated on the #2 FBH, with the individual gain levels adjusted to produce an 80% FSH at the least reflective of the three FBHs in each zone. The C-scans for each zone are shown in figure 3-10 and show that all the #2 FBHs were easily identified to the full depth of 5.5″.

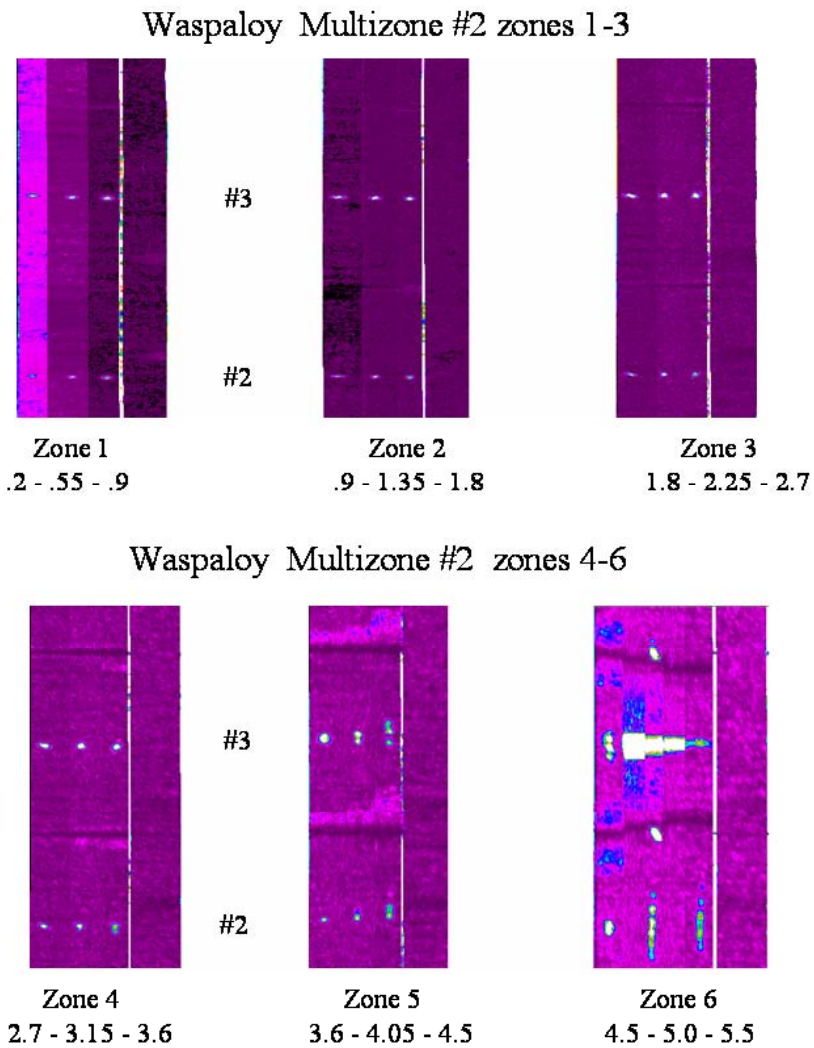


FIGURE 3-10. C-SCAN OF MULTIZONE INSPECTION ZONES 1-6 OF A WASPALOY CALIBRATION STANDARD

- Comparison to Program Goal.

  The same sensitivity calculations were performed on the Waspaloy data, resulting in the data presented in figure 3-11. The zone 1 laboratory conventional immersion inspection exceeded the program goal, while the zone 2 demonstrated a sensitivity of about #3.5 FBH. The multizone inspection exceeded the program goal of #2.5 FBH by about 4 to 20 times, depending on the zone. The average capability of multizone inspection was between #0.7 and #1.2 FBHs for all zones.

  The 5″ water path for zone 2 conventional laboratory immersion inspections of Waspaloy does not provide the optimum inspection that is possible with the conventional transducers. At a 2″ water path, the laboratory conventional zone 2 Waspaloy inspection improves to about a #2.8 FBH sensitivity. Contrary to the IN718 results, these data

indicate a beneficial effect of focusing the conventional immersion transducer deeper in the Waspaloy billet.

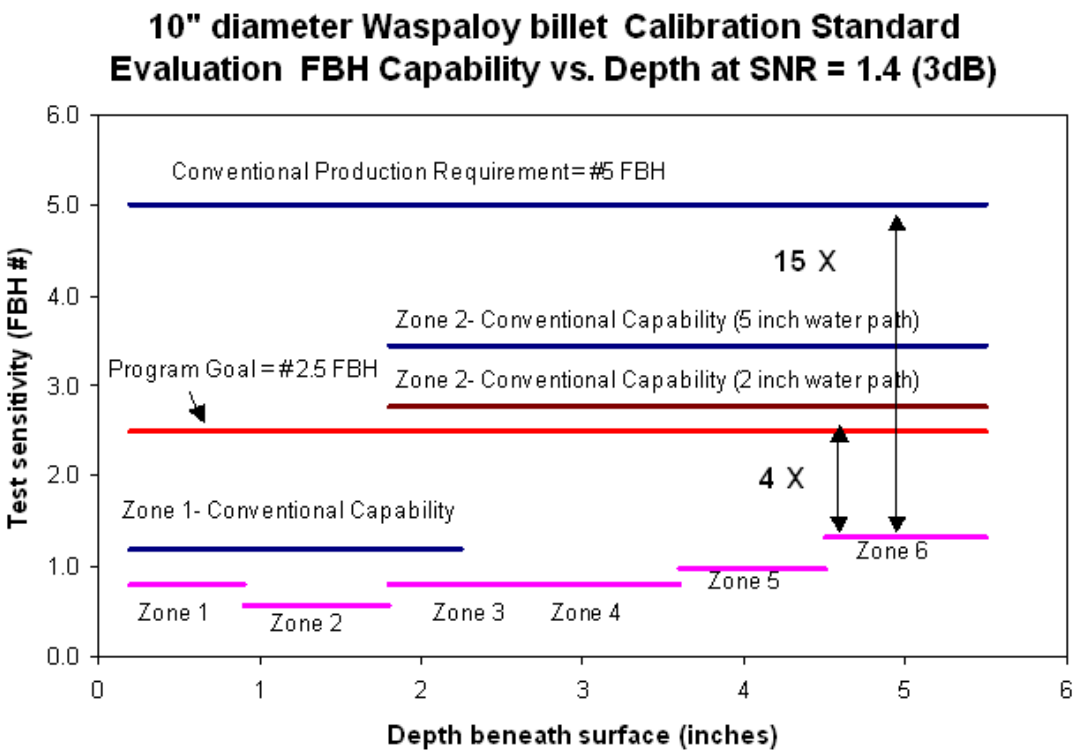


FIGURE 3-11. COMPARISON OF MULTIZONE INSPECTION CAPABILITY TO WASPALOY 10″ BILLET PROGRAM GOAL AND LABORATORY CONVENTIONAL IMMERSION INSPECTION CAPABILITY

3.2.9 Summary of Laboratory Evaluations.

The results from both the IN718 and Waspaloy 10″ billet conclusively demonstrate that the program goals can be achieved, and exceeded, using the same multizone transducers designed for Ti billet inspection in Phase I of the ETC program. Therefore, it was decided that no new transducers would be designed in this task. Results using the conventional transducers were also quite encouraging, given the improved sensitivity over current requirements.

3.3 LABORATORY DEMONSTRATION.

One of the steps to be completed prior to the pilot lot inspection or factory demonstration was a demonstration of the improved inspection capability for 10-inch diameter IN718 and Waspaloy in a laboratory setting using the calibration standards. Although the demonstration required only ETC members to participate, the team decided to invite all Ni billet suppliers, inspection houses, and aircraft engine manufacturers outside the ETC.

On October 30, 2001, the GE-QTC hosted a 1-day review of the Nickel Billet Inspection Development program that included the laboratory demonstration of the multizone inspection. Attendees included representatives from Alvac, Wyman-Gordon, Special Metals, Carpenter Technology, and West-Penn NDT as well as the Federal Aviation Administration (FAA) and ETC team members. The agenda included a presentation of the results of the standards evaluation for both conventional and multizone approaches followed by a laboratory demonstration of the multizone inspection for a couple of the deeper zones in the standards. The improved inspection sensitivity was accomplished by successful application of the ultrasonic multizone inspection process developed for Ti billet to Waspaloy and IN718. Minor adjustments to the transducer water paths to achieve zone balance were the only changes required to inspect the Ni billet compared to the established Ti inspection. The program goals of a four times improvement in sensitivity over conventional inspection for billets up to 10″ in diameter were not only met, but also substantially exceeded.

3.4 FACTORY PILOT LOT ASSESSMENT.

A request was forwarded to several production facilities to bid on the multizone inspection of several heats of production Ni billet. During the pilot program, a select number of indications found with multizone were purchased with preference given to those not rejected with conventional inspection. Ultrasonic and metallographic characterizations were performed on these indications for use in PoD studies and future inspection implementation decisions. The Ni billet inspection facility was contracted to inspect 75,000 pounds of 10″ diameter IN718 billet and 25,000 pounds of 10″ diameter Waspaloy billet using their existing multizone facilities. The 10″ diameter IN718 and Waspaloy standards were shipped to their facility to be used for inspection calibration.

A visit was made to the inspection supplier at the beginning of the factory evaluation. During the 2-day meeting, the primary objective was to demonstrate calibration on the IN718 10″ diameter billet standard and to collect data for the proposed sensitivity level. The same production transducers that were used for Ti multizone inspection were calibrated on the IN718 standard, and C-scans were acquired for each zone. Table 3-3 shows the calibration and noise statistics for each zone at #1 FBH equal to 80% calibration level.

Due to intermittent electronic noise present at the time of the evaluation, a C-scan was not made for zone 1. The noise was not a result of near-surface resolution; however, static measurements on zone 1 FBHs, indicated that the target calibration was achievable. The noise problem was corrected prior to the time of inspection. After the ETC members reviewed the data, it was agreed to increase the gain level for each zone by 6 dB over the calibration level. The only exception was zone 1 for which instrumentation limitations only allowed a 4 dB additional gain. The increase in sensitivity increased the average material noise to a higher level and reduced the rounding variability for the signal-to-noise calculation used in the evaluation software when noise levels are low.

The Waspaloy standard was not available at the time of this visit for calibration purposes. It was being machined to eliminate surface irregularities. The Waspaloy standard was machined and delivered to the facility after the visit.

TABLE 3-3. CALIBRATION AND NOISE STATISTICS FOR #1 FBH SENSITIVITY ON IN718 STANDARD

						Stats From Solid End of Standard			
Zone	Water Path (microsec.)	Water Path (inches)	Attenuation Setting	Target Depth	#1 FBH Amplitude	Min. Noise (%)	Max. Noise (%)	Mean Noise (%)	Std. Dev. (%)
1	130	3.79	4	0.2 0.55 0.9	83 95 89	System noise prevented getting numbers			
2	125	3.64	29	0.9 1.35 1.8	84 104 81	2	15	6	1
3	140	4.08	23	1.8 2.25 2.7	80 99 81	1	11	3	1
4	130	3.79	26	2.7 3.15 3.6	80 95 84	2	9	4	1
5	120	3.5	22	3.6 4.05 4.5	80 92 80	2	13	5	1
6	125	3.64	19	4.5 5 5.5	90 93 81	4	17	8	2

The IN718 inspection required calibration to a #1 FBH sensitivity and the Waspaloy to a #2 FBH sensitivity. Details of the inspection procedure and the metallographic data required for PoD analysis were reviewed with ETC team members responsible for reliability efforts of the program. Members of the PoD group had input the type of data that would be most useful for the PoD assessment. Additions to the normal six-zone inspection included two channels dedicated to the collection of conventional two-zone C-scan inspection and, if possible, back-wall attenuation C-scans. Although not originally planned, this request made it necessary to install additional instrumentation at the factory. This included two portable ultrasonic instruments and a voltage conditioner circuit to make the output of the portable machines compatible with the multizone instrumentation.

After the additional equipment was delivered to the factory, instructions were that multizone inspection and the modified C-scan conventional inspection would be performed following normal production material inspection procedures. These higher sensitivity inspections were not to be a substitute for the production inspections. The ETC planned to purchase six indications from IN718 and two from Waspaloy. Indications would be reported to the ETC and a decision to purchase the indication agreed upon. The ETC team hoped to have indications from both double- and triple-melt products. However, availability would be subject to the supplier's production orders.

3.5 FACTORY DEMONSTRATION.

Once the factory had conducted an initial inspection of some production material at the higher sensitivity, plans were made for hosting a demonstration for the industry. The factory demonstration took place on February 21, 2003. This 1-day event provided an opportunity for the FAA, ETC members, and Ni billet producers to see firsthand how the multizone inspection functioned in an industrial setting. Following a brief introduction by the factory quality and safety managers, ETC team members provided an overview of the entire ETC program covering all of the development efforts and a technical review of the Ni billet program. Finally, the factory host made a presentation dealing with the technical aspects and cost differences between conventional and multizone inspections. Some of the highlights from the factory presentation indicated that the multizone inspection for Ni was comparable to the multizone inspection of current production Ti product.

The company that performed the factory demonstration had approximately 2 years of experience in multizone inspection of Ti billet and over 20 years in the conventional inspection of all types of billet. This experience provided a reasonable baseline from which to compare the multizone inspection for Ni billet with conventional tests. All cost factors associated with the multizone inspection were tracked. In addition to the costs directly associated with calibration and billet scanning, other costs such as potential changes in surface finish requirements and postinspection evaluation of indications were accounted for. False calls were to be factored into the associated costs if some of the indications prove to be noise-related.

Costs associated with the improved sensitivity multizone inspection fall principally into two categories: (1) the initial investment costs of the equipment and the costs associated with the maintenance of that equipment and (2) costs that are associated with productivity of the process, which include material preparation, setup, scanning and evaluation time, and training. The factory was asked to keep records of the cost differentials associated with the multizone inspection of the Ni. In the case where it would be difficult to acquire the relative costs of the demonstration, they used historical data based on the Ti multizone inspection. An example of this would be for equipment and transducer replacement.

A difficult cost to predict was the loss of material due to increase in sensitivity or the evaluation of false calls. These values are very difficult to arrive at because there is no established reject level and generally requires sustained long-term inspection to get an adequate projection. If the reject level were set equivalent to a #1 FBH sensitivity, then none of the material inspected from the 80,000 pounds of IN718 would have been rejected. If, on the other hand, the reject criteria were for all signals greater than or equal to 2.5 SNR, then a good deal of material would have been rejected. Setting a reject level was not the purpose of this task. However, upon the characterization of the four indications and review by the PoD and engineering communities, these levels may come under review. It is sufficient to say that if the sensitivity level is increased from #2 or #3 FBHs to #1 FBH, the long-term effect will be that more material containing anomalies is going to be rejected.

Equipment investment costs for multizone inspection were the first to be compared to conventional inspection. The multizone inspection investment for the instrument, standards, and transducers would total approximately $360,000 and cover four different diameter billets verses

about $50,000 for a conventional two-zone inspection capability. The cost for multizone inspection transducers is about $60,000 to $80,000, which at this point, has limited suppliers. Facilities that use multizone to inspect Ti and process both Ti and Ni products might not have to incur these added transducer costs, since the same transducers are used for both materials. There is about a seven-fold increase in investment required to install an eight-channel multizone system over a conventional system. A survey of the equipment manufacturer who supports five multizone inspection facilities indicated that replacement cost across the industry have been running on average about $5,000 to $10,000 yearly for each of the Ti inspection facilities. This number is expected to be the same for Ni inspection. Out of a set of 20 transducers covering four billet diameters, it is likely that two transducers a year will need to be replaced at a cost of $10,000. Therefore, multizone maintenance costs are estimated to be about $18,000 per year. The cost cannot be compared to current maintenance costs, since data on conventional maintenance were unavailable.

Of initial importance was the determination of whether the surface finish used for conventional inspection was adequate for the increased sensitivity of the multizone inspection test. The factory reported that no additional surface preparation was required to inspect the 10″ billet that was used for this factory evaluation. However, the supplier that participated in the evaluation noted that the multizone test is more sensitive to surface blemishes than conventional inspection.

Table 3-4 is a comparison summary that was presented at the production site by the factory personnel that indicates their experience when comparing the conventional and multizone procedures with respect to labor and machine hours.

TABLE 3-4. MULTIZONE VS CONVENTIONAL—INVESTMENT, MAINTENANCE, LABOR, AND OPERATING COST COMPARISONS

	Multizone	Conventional
Investment	$360,000	$50,000
Maintenance	$17,000/yr	Not available
Setup	2-4 hrs	0.5 hr
Scanning	Multizone 36% longer than conventional	
Analysis	0.5-1 hr	0
Evaluation	0-2 hrs	0-1 hr

3.6 INDICATION CHARACTERIZATION.

Over the course of 1 year (August 2002-August 2003), the factory inspected 81,000 pounds of IN718, which included 33,000 pounds of double melt and 48,000 pounds of triple melt. During this time, no 10″ diameter Waspaloy billet was inspected because of the lack of orders placed for this material. Of the IN718 material inspected, there were a total of 19 indications that had an SNR of 2.5 or greater. Although none of the indication amplitudes equaled the #1 FBH calibration level, five had amplitudes exceeding the 50% evaluation threshold. Note that all 19 of the indications were undetected by the conventional billet inspection method that was calibrated to a lower sensitivity, and therefore, is not expected to be sensitive to anomalies with these small ultrasonic responses. Indications were detected based on the production multizone Ti

evaluation software that identifies signals in the C-scan image that have a local SNR $\geq$ 2.5 or exceed an amplitude threshold of 50%. The ETC was able to purchase five of these indications. Table 3-5 shows a summary of the indications identified, and the ones that were removed for metallographic evaluation.

TABLE 3-5. LIST OF INDICATIONS AND THE AMPLITUDES RELATIVE TO #1 AND #2 FBH CALIBRATIONS

Multizone Indication Summary								
IN718	Zone Detected	Depth (in.)	Amp. % FSH	SNR	Indication Length	Amp. to #1 FBH	Amp. to #2 FBH	Removal
Triple Melt	3	2.79	28	3.7	0.15	14	3.5	
Triple Melt	4	2.79	38	3.33	0.2	19.2	4.8	
Triple Melt	5	3.89	66	4.26	0.3	33.2	8.3	
Triple Melt	6	4.01	58	2.84	0.57	29.2	7.3	
Triple Melt	5	4.4	45	3.44	0.3	22.8	5.8	Cut out
Triple Melt	3	1.375	29	3.11	0.33	14.4	3.6	Cut out-not found
Triple Melt	5	4.375	67	4.91	0.19	33.6	8.4	Cut out
Double Melt	6	5.15	88	3.4	0.45	44	11	Cut out
Double Melt	3	1.7	41	11.3	0.18	20.4	5.1	Cut out
Double Melt	3	1.5	12	2.89	0.12	6	1.5	
Double Melt	2	0.61	9	2.51	0.28	4	1	
Double Melt	2	1.5	7	2.51	0.4	4	1	
Double Melt	3	1.8	8	2.84	0.07	4	1	
Double Melt	2	0.7	5	2.72	0.13	4	1	
Double Melt	2	1.8	5	2.72	0.07	4	1	
Double Melt	4	3.8	13	5.6	0.15	12	3	
Double Melt	5	3.9	7	2.7	0.07	8	2	
Double Melt	4	3.4	53	15.18	0.4	48	12	
Double Melt	4	3.9	16	3.55	0.14	16	4	

The procedure for removing the indications from the billet is shown in figure 3-12. Side 1 of the removed cube is facing the direction in which the indication was originally found. Four indications were sent to ISU for ultrasonic characterization. This is a procedure that examines the indications from all sides of a 1-inch cube at several of different frequencies and resolutions. Appendix A contains the detailed sonic and metallographic data and analysis for each of the four indications.

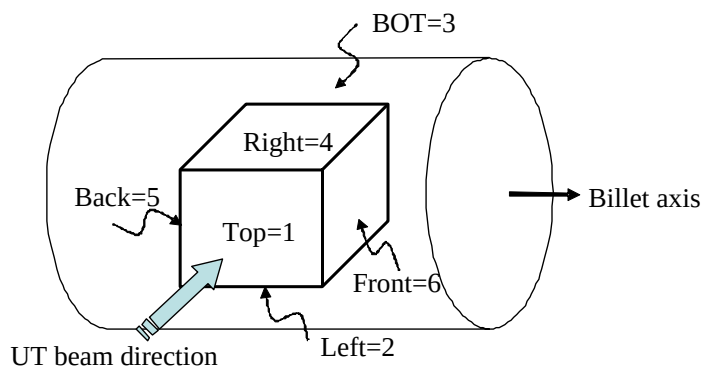


FIGURE 3-12. SCHEMATIC OF INDICATION REMOVAL FROM BILLET WITH ASSOCIATED ORIENTATION LABELS

Once an indication was identified and approved by the ETC for evaluation, a detailed ultrasonic and metallographic evaluation procedure was followed. Appendix B provides a copy of the ultrasonic procedure. This includes removing the cube that contains the indication and then ultrasonically characterizing the indication from six sides as well as computed tomography x-ray examination. The x-ray results were inconclusive because of the size constraints of the sample. Finally, the indication was sectioned using an existing detailed metallographic procedure so that the full extent of the size and shape is known. The indication also underwent a chemical microprobe at one step during the step-polishing routine.

3.7 SUMMARY OF 10″ DIAMETER BILLET ASSESSMENT.

- Billet converted with GFM processing is more acoustically noisy than billet converted using V-Die processing. GFM material was selected for use in calibration standards since this provides a more conservative assessment.

- Transducer characterization procedures were developed for bicylindrically focused transducers, which are useful for ensuring that actual focal characteristics match the intended design values.

- The Waspaloy calibration standard was more ultrasonically noisy than the IN718 material (75% peak noise compared to 20%, respectively) when measured with the same calibration target.

- The multizone inspection procedure and transducers originally used for Ti easily exceeded the program goal of #1 FBH for IN718 and #2.5 FBH for Waspaloy. The multizone system exceeded the IN718 goal by a minimum of 3.5 times and was a minimum of 31 times more sensitive than the current inspection requirement. Multizone exceeded the Waspaloy goal by a minimum of 4 times and was a minimum of 14 times more sensitive than the current inspection requirement.

- The use of conventional transducers in the two-zone laboratory inspection nearly met the program goal for IN718. The laboratory conventional immersion inspection exceeded the

program goal of #2.5 FBH sensitivity for Waspaloy in the near-surface zones. No data was gathered for the production conventional contact inspection of Waspaloy.

- The factory assessment showed that the surface finish used for conventional inspection was adequate for the increased sensitivity of the multizone inspection test, although the multizone test is more sensitive to surface blemishes.

- The factory assessment showed comparable characteristics for inspection of Ni when compared to experience with inspection of Ti multizone procedures.

- A cost comparison revealed increased investment and operational cost for multizone inspection compared to conventional inspection.

- Suppliers expressed concerns regarding transducer manufacturability and limited availability of transducer vendors.

- The factory demo on 81,000 pounds of two and three times melted IN718 generated conclusive results that the multizone system can detect indications that are missed by the current conventional inspection. A total of 19 indications were detected by multizone, all of which were significantly smaller than conventional inspection requirements that are at a #2 FBH sensitivity and, therefore, below the threshold for detection.

3.8 SMALL-DIAMETER BILLET STUDY.

In addition to the inspection of large (10″)-diameter billet, the ETC team also completed an evaluation of the inspection of small-diameter billet. The objective was to evaluate and compare the capability of the different ultrasonic inspection techniques, including conventional, single transducer (ST) multizone, and phased array inspection on 5″ diameter Ni and Ti alloys. The results for both materials are discussed below.

The 5″ diameter ETC billet reference standards (Waspaloy and Ti-6Al-4V) containing #1 and #2 FBHs were inspected using conventional, ST multizone, and phased array ultrasonic inspection techniques to evaluate the relative performance of these techniques for small-diameter billet. The geometry of the standard is illustrated in figure 3-13 along with the location of all the FBHs. All the inspection techniques were done in immersion. The collected data from the different inspection techniques were then analyzed, and a detailed comparison was conducted. This section summarizes the results of the small-diameter billet study.

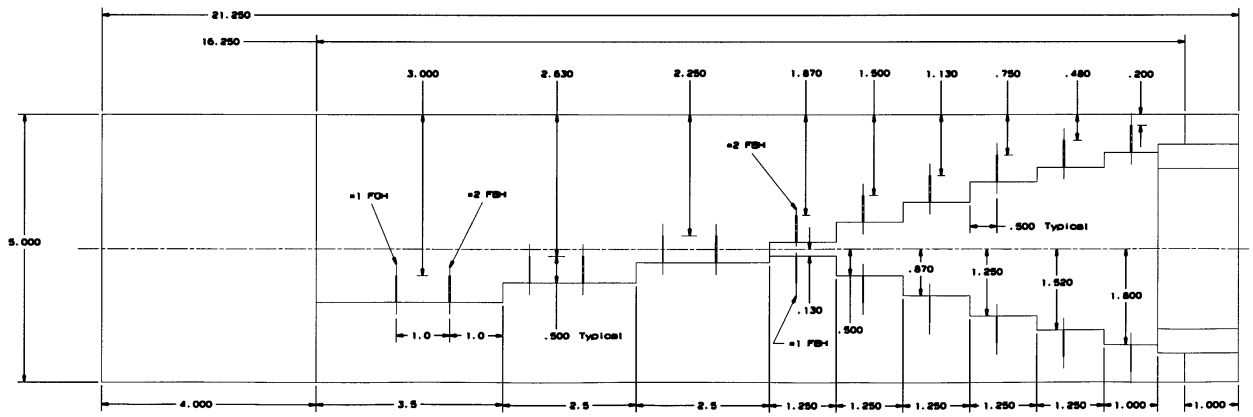


FIGURE 3-13. THE 5″ DIAMETER ETC BILLET REFERENCE STANDARDS (WASPALOY AND Ti-6Al-4V) CONTAINING #1 AND #2 FBHs

3.8.1 Inspection Setup and Results for Waspaloy.

The 5″ diameter Waspaloy reference small billet standard having #1 and #2 FBHs was scanned on a Sonix system. The inspection sensitivity was equivalent to a conventional production Waspaloy scan calibrated to 80% FSH using a #3 FBH. To achieve this sensitivity, 7 dB was removed after setting up a DAC curve using the #2 FBHs. The DAC used in these measurements is shown in table 3-6. The transducer used was S/N RB0802, with a 0.75″ diameter element and 6″ nominal focus (I8 type). This is typical of the 5-MHz spherically focused transducers that would be used to inspect 5″ diameter Waspaloy billet, which was determined by polling several billet inspection facilities. A 5″ water path was used. The conventional inspection and ST were done on a Sonix system with the following parameters:

- Pulser Voltage: 425 V — A/D gain: 10 V
- Gain: 43 dB + Electronic distance-amplitude correction (EDAC) — A/D offset: 2036
- Filter: HP 2-25 MHz, LP off — Impedance: Low
- Energy: 4 — Sample rate: 100 MHz

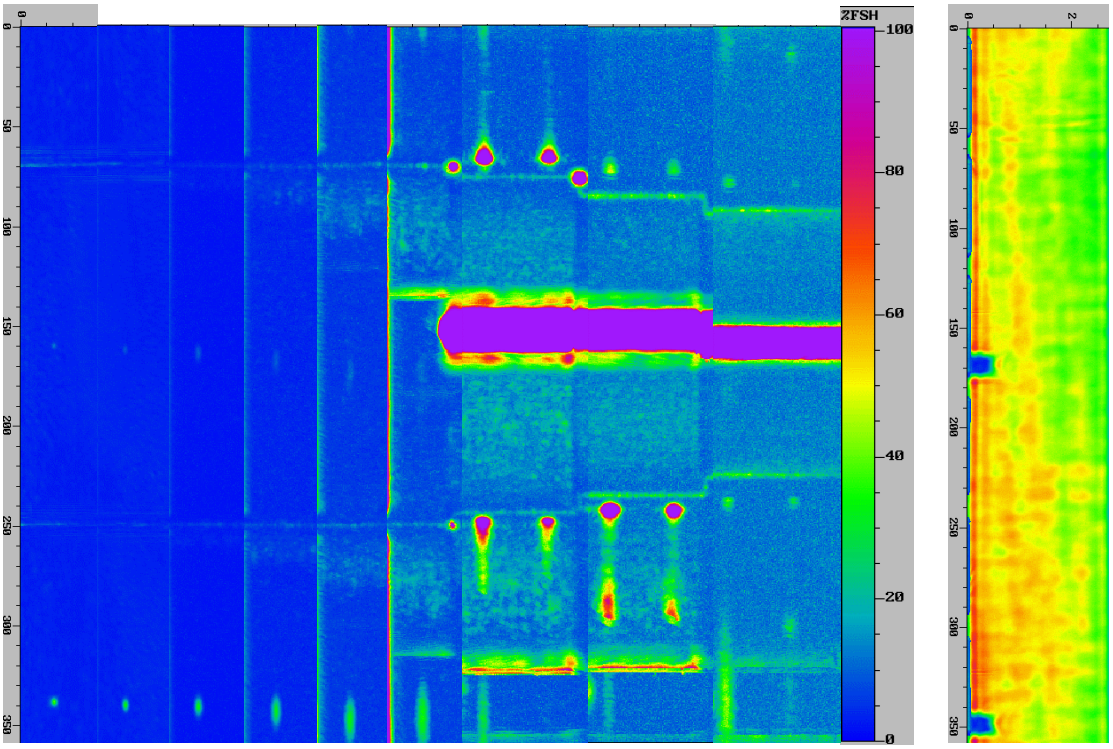
TABLE 3-6. THE EDAC FOR WASPALOY CONVENTIONAL AND ST INSPECTIONS

EDAC Point	Gain (dB) (Total = 43+)	Time (μsec)
1	0	2.09
2	1.27	4.39
3	4.88	6.66
4	9.12	9.85
5	13.34	12.96
6	16.00	16.11
7	17.87	19.20
8	20.22	22.48
9	22.57	25.63

Figure 3-14 shows the C-scan resulting from the conventional and ST inspections of the 5″ diameter Waspaloy billet reference standard along with a C-scan illustrating the back-wall echo from the standard. Table 3-7 summarizes the SNR results extracted from the C-scan for #2 and #1 FBHs, respectively. The SNR was calculated using the following equation:

$$SNR = \frac{PeakSignal\text{-}AverageNoise}{PeakNoise\text{-}AverageNoise} \tag{3-1}$$

which is an industry-acceptable definition of SNR. The peak signal was measured directly from the C-scan by drawing an appropriate rectangle around the indication, whereas the peak noise and average noise were determined by selecting an appropriate noise area close to the indication of interest for the case of ST inspection. As for the conventional inspection, the peak and average noise values were determined based on the whole volume of the billet inspected. The average noise was approximately 18% FSH with a #2 FBH calibration and at 36% FSH in deep zones. Note that the #2 FBH was essentially undetectable (i.e., SNR < 2.0) at depths greater than about 2.25″, while the #1 FBH was undetectable at depths of greater than about 1.87″.



Backwall

FIGURE 3-14. SINGLE TRANSDUCER INSPECTION C-SCAN OF THE 5″ DIAMETER WASPALOY BILLET

TABLE 3-7. SIGNAL-TO-NOISE RATIO FOR CONVENTIONAL AND ST INSPECTIONS OF 5″ DIAMETER WASPALOY BILLET REFERENCE STANDARD

FBH	FBH Depth (in.)	FBH Peak Amplitude (% screen)	Noise Peak Amplitude (% screen)	Mean Noise Amplitude (% screen)	ST SNR	ST SNR (dB)	Conventional SNR	Conventional SNR (dB)
#2 FBH Waspaloy	0.20	39.2	5.5	2.90	13.962	22.90	1.059	0.50
	0.48	33.7	5.5	3.40	14.429	23.18	1.059	0.50
	0.75	34.5	5.5	2.15	9.657	19.70	1.059	0.50
	1.13	32.9	9.4	3.86	5.232	14.37	1.059	0.50
	1.50	32.9	11.8	5.74	4.482	13.03	1.059	0.50
	1.87	36.1	15.7	7.98	3.642	11.23	1.059	0.50
	2.25	34.5	19.6	9.37	2.457	7.81	1.059	0.50
	2.63	27.5	21.2	10.80	1.606	4.11	1.059	0.50
	3.00	26.7	25.9	12.30	1.059	0.50	1.059	0.50
#1 FBH Waspaloy	0.20	26.7	11.8	6.50	3.8	11.62	1.740	4.81
	0.48	32.9	12.9	7.20	4.5	13.08	1.740	4.81
	0.75	25.9	11.0	7.40	5.1	14.22	1.740	4.81
	1.13	27.5	12.5	8.00	4.3	12.74	1.740	4.81
	1.50	35.3	18.8	10.60	3.0	9.58	1.740	4.81
	1.87	36.9	22.0	10.80	2.3	7.35	1.740	4.81
	2.25	32.9	23.5	10.80	1.7	4.81	1.740	4.81
	2.63	-	27.4	11.80	-	-	-	-
	3.00	-	27.4	12.80	-	-	-	-

Upon completion of the conventional and ST inspections, the Waspaloy standard was inspected using a multizone inspection procedure. For this study, the standard GE production multizone transducers were applied to the 5″ diameter Waspaloy and Ti reference standards. Four zones are used to examine the depth from 0.2″ to 3.0″ with each zone covering about 0.75″ of material. Table 3-8 summarizes the transducer specifications and gating requirements associated with each zone. For 5″ diameter billet, the transducers were positioned at approximately 3.5″ water path, and the instrument sensitivity adjusted to make the highest amplitude signal in each zone close to 80% FSH. This is somewhat different from the normal procedure in that the lowest amplitude target is raised to 80%. This prevented any calibration targets from being saturated during scanning. C-scans (as shown in figure 3-15) were then made of each calibration target at a 0.020″ index and a shortened gate that excluded the back wall at each step. The target amplitude, maximum, and mean noise values were taken from the image statistics in each zone and used to determine the SNR values summarized in table 3-9 using equation 3-1. Due to the increased gain level required for #1 FBH calibration, the zone 1 transducer was not able to clearly resolve the 0.2″ deep target and caused the lower than normal signal-to-noise value. This particular zone will require some added development in near-surface resolution to bring this value in closer agreement with other zones.

TABLE 3-8. MULTIZONE PRODUCTION TRANSDUCERS

Zone	Coverage (in.)	Gate (μsec)	Pulse/rev	Element Diameter (in.)	Designed Focus (in.)
1	0.2-0.75	0.2-1.15	1024	0.75	0.4
2	0.75-1.5	0.35-1.9	1024	1.0	1.2
3	1.5-2.25	1.1-2.65	512	1.375	2.1
4	2.25-3.0	1.85-3.5	512	1.75	3.0

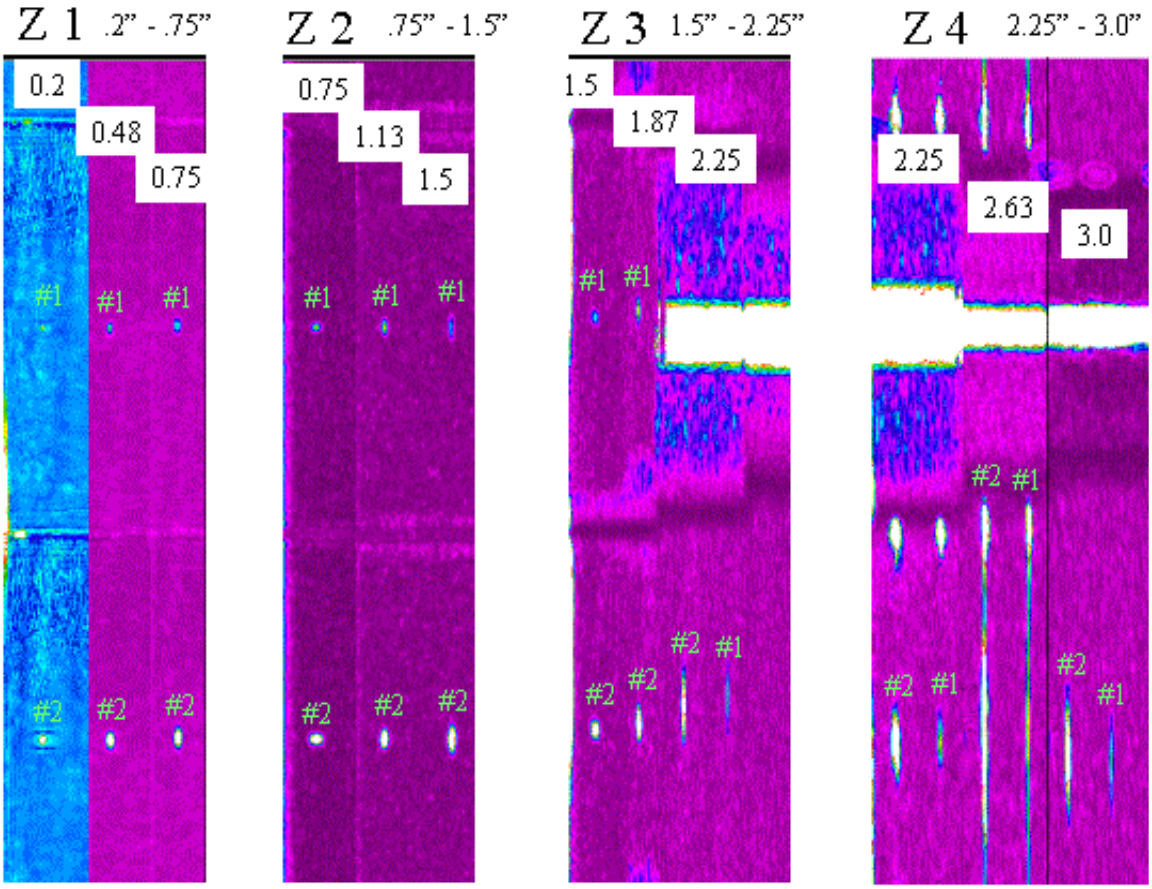


FIGURE 3-15. FOUR ZONES OF MULTIZONE INSPECTION C-SCANS THAT COVER A DEPTH OF 3″ INTO THE BILLET

TABLE 3-9. SIGNAL-TO-NOISE RATIO FOR MULTIZONE INSPECTION OF 5″ DIAMETER WASPALOY BILLET REFERENCE STANDARD

FBH	FBH Depth (in.)	Attenuation (dB)	FBH Peak Amplitude (% FSH)	Noise Peak Amplitude (% FSH)	Mean Noise Amplitude (% FSH)	Multizone Inspection SNR	Multizone Inspection SNR (dB)
#2 FBH Waspaloy	0.20	35.50	225.5	45.0	37.00	23.56	27.44
	0.48	35.50	220.0	12.0	8.00	53.00	34.48
	0.75	32.50	151.8	12.0	9.00	47.60	33.55
	0.75	36.50	211.4	12.0	3.00	23.15	27.29
	1.13	38.50	261.3	9.0	4.00	51.45	34.23
	1.50	36.00	187.9	10.0	4.00	30.65	29.73
	1.50	27.00	125.1	14.0	6.00	14.88	23.45
	1.87	29.50	185.9	15.0	6.00	19.99	26.01
	2.25	28.50	227.7	15.0	7.00	27.59	28.81
	2.63	27.00	240.3	18.0	8.00	23.23	27.32
	3.00	25.00	205.5	22	7.00	13.24	22.44
#1 FBH Waspaloy	0.20	26.50	80.0	44.0	38.00	7.00	16.90
	0.48	24.50	62.0	11.0	8.00	18.00	25.11
	0.75	22.50	48.0	12.0	8.00	10.00	20.00
	0.75	27.50	75.0	9.0	4.00	14.20	23.05
	1.13	28.00	78.0	12.0	5.00	10.43	20.36
	1.50	24.50	50.0	9.0	4.00	9.20	19.28
	1.50	18.50	47.0	12.0	6.00	6.83	16.69
	1.87	21.50	74.0	14.0	6.00	8.50	18.59
	2.25	16.00	54.0	26.0	13.00	7.00	16.90
	2.25	18.50	73.0	30.0	8.00	2.95	9.41
	2.63	17.00	76	19	8.00	6.18	15.82
	3.00	15.00	65	16	8.00	7.13	17.06

The 5″ diameter Waspaloy billet reference standard that has #2 and #1 FBHs at the depths shown in figure 3-13 was also scanned using Honeywell's 5-MHz annular sectorial phased array transducer [25]. Figure 3-16 shows the layout of the 113 elements on the face of the 5-MHz phased array transducer that was designed for the inspection of 5″ to 8″ diameter billets. The 113 elements were connected such that symmetrical elements are fired at the same time. This way, fewer channels are needed to drive the probe. The inspection was performed in an immersion tank that was designed for the inspection of Ti billets with a rotational axis and an index axis. After each rotation of the billet, a mechanical step is made on the index axis. Figure 3-17 shows a schematic of the mechanical setup used in the scanning of the billet standard using the 5-MHz phased array transducer.

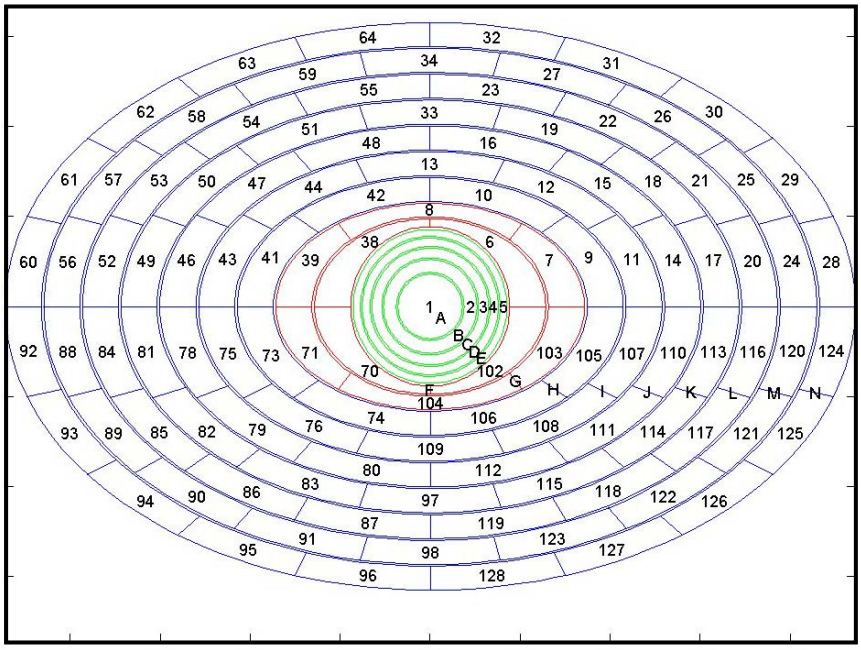


FIGURE 3-16. LAYOUT OF THE 113 ELEMENTS ON THE FACE OF THE 5-MHz PHASED ARRAY TRANSDUCER

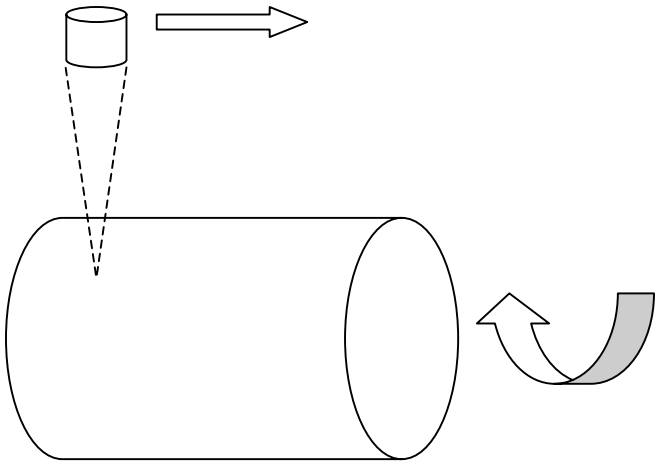


FIGURE 3-17. THE MECHANICAL SETUP USED IN THE SCANNING OF THE BILLET STANDARD

The standard focusing technique was used in this study. In this technique, the focus point in emission is the same as the focus point in reception. For each hole, the focusing is made (theoretically) at the exact depth of the defect. The gain is adjusted so that the echo from the defect appears on the screen with reasonable amplitude. A short scan is performed around each hole. All the A-scan data were saved so that the entire inspected volume could be reconstructed after the data acquisition. The water path was held at 4″ throughout the inspection. Table 3-10 shows some inspection parameters used for each of the FBHs in the billet standard.

TABLE 3-10. PHASED ARRAY INSPECTION PARAMETERS FOR THE WASPALOY 5″ DIAMETER BILLET STANDARD

FBH Depth (in.)	ER-Focus (in.)	Beam Size (mils)	Gain (dB)
3	3	100	15
2.63	2.63	100	15
2.25	2.25	100	10
1.87	1.87	100	10
1.5	1.5	100	13
1.13	1.13	100	13
0.75	0.75	100	13
0.48	0.48	100	15
0.2	0.2	100	20

Frequency = 5 MHz
Water Path = 4 inches

Figure 3-18 shows typical results collected during the inspection for the #2 and #1 FBHs at a 1.5″ depth. The figure shows the top (C), side (B), and the end (D) scans along with two A-scans showing the indications for the #2 and #1 FBHs. Appendix C shows similar scans for the rest of the holes at all remaining depths in the Waspaloy standard.

C

D

B

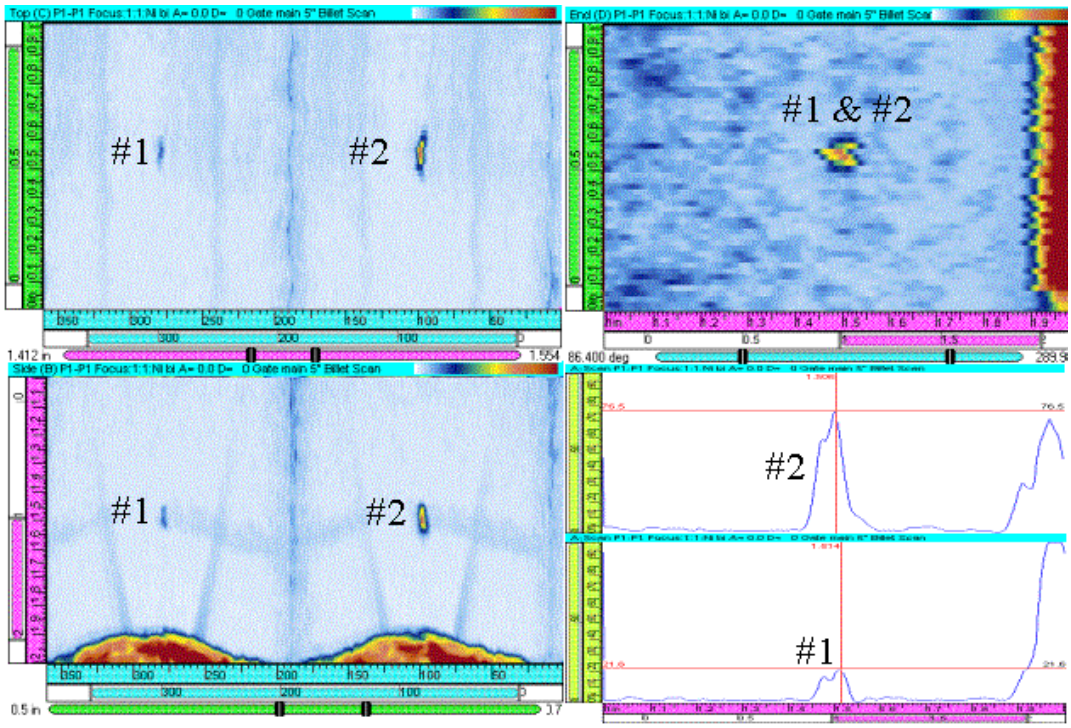


FIGURE 3-18. TYPICAL RESULTS COLLECTED DURING THE INSPECTION FOR THE #2 AND #1 FBHs AT A 1.5″ DEPTH

The SNR was calculated according to equation 3-1. The noise was measured using the contour tool in Tomoview, the proprietary software delivered with the R/D Tech phased array system hardware. A contour is drawn on a desired region over the C-scan. The tool measures the mean noise and the maximum noise in the region. Table 3-11 shows the SNR results collected during the inspection. A comparison of the SNR data shown in tables 3-7, 3-9, and 3-11 suggest the phased array sensitivity is greater than the conventional and ST inspections sensitivity but lower than the multizone sensitivity in the near-surface zone. At larger depths, the sensitivity of the phased array and multizone inspections is the same.

TABLE 3-11. SIGNAL-TO-NOISE RATIO RESULTS COLLECTED DURING THE PHASED ARRAY INSPECTION OF THE 5″ DIAMETER WASPALOY REFERENCE BILLET STANDARD

FBH	Depth (in.)	Peak Signal (% FSH)	Peak Noise (% FSH)	Average Noise (% FSH)	SNR	SNR (dB)
#2 FBH Waspaloy	0.2	50.2	18	13.5	8.16	18.23
	0.48	59.6	12.9	7.6	9.81	19.83
	0.75	84.3	9	4.8	18.93	25.54
	1.13	89.4	11.95	5.3	12.65	22.04
	1.5	76.5	9.4	4.7	15.28	23.68
	1.87	85.1	7.8	4	21.34	26.58
	2.25	64.3	8.6	2.9	10.77	20.65
	2.63	62.7	11	3.9	8.28	18.36
	3	89	9.8	4	14.66	23.32
#1 FBH Waspaloy	0.2	14.1	11.4	5.5	1.46	3.27
	0.48	16.1	12.9	7.6	1.60	4.10
	0.75	25.1	9	4.8	4.83	13.68
	1.13	21.6	11.95	5.3	2.45	7.79
	1.5	21.6	9.4	4.7	3.60	11.12
	1.87	23.1	7.8	4	5.03	14.02
	2.25	19.6	8.6	2.9	2.93	9.34
	2.63	20.4	11	3.9	2.32	7.32
	3	22	9.8	4	3.10	9.84

3.8.2 Inspection Setup and Results for Ti-6Al-4V.

The same techniques, namely, conventional, ST element, multizone, and phased array inspections, were used to inspect the 5″ diameter Ti-6Al-4V billet reference standard. The general procedure was the same as the one used for the Waspaloy standard with some minor differences, as described below.

The first step was completion of a conventional and ST inspections of the Ti billet standard. The transducer used in this case (figure 3-19) was S/N 98G097 from Timet Witton in Birmingham,

England. This is a typical 5-MHz, cylindrically focused transducer with which Timet would inspect the 5″ diameter Ti billet. The line focus was a nominal 6″ in water and a 4″ water path was used. The inspection sensitivity was equivalent to a conventional production Ti scan calibrated to 80% FSH using a #3 FBH. To achieve this sensitivity, 7 dB was removed after setting up a DAC curve using the #2 FBHs (see table 3-12). The conventional and ST inspections of the 5″ diameter Ti-6Al-4V billet reference standard was done on a Sonix system with the following parameters:

- Pulser Voltage: 400 V
- Gain: 43 dB + EDAC
- Filter: HP 2-25 MHz, LP off
- Energy: 4

A/D gain: 10 V
A/D offset: 2036
Impedance: Low
Sample rate: 100 MHz

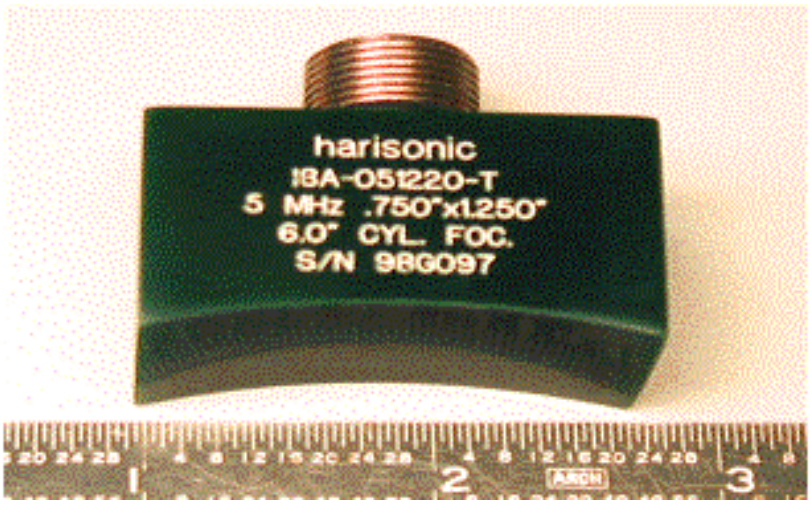
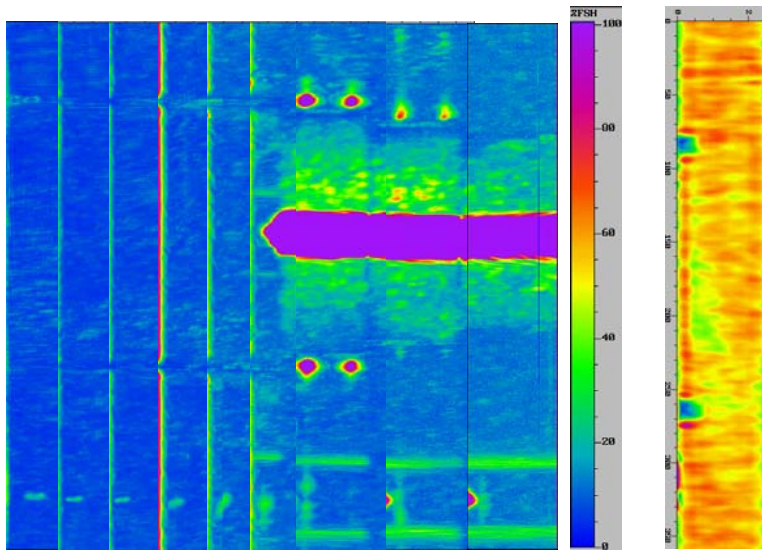


FIGURE 3-19. SIXTY-INCH CYLINDRICALLY FOCUSED TRANSDUCER
(Courtesy of Timet Witton)

TABLE 3-12. ELECTRONIC DISTANCE-AMPLITUDE CORRECTION FOR Ti-6Al-4V CONVENTIONAL AND ST INSPECTIONS

EDAC Point	Gain (dB) (Total = 43+)	Time (μsec)
1	4.40	1.76
2	3.61	4.23
3	3.30	6.36
4	6.59	9.44
5	7.22	12.58
6	9.57	15.69
7	10.36	18.83
8	12.24	21.94
9	13.81	24.96

Figure 3-20 shows the C-scan resulting from the ST inspection of the 5″ diameter Ti-6Al-4V billet reference standard along with a C-scan illustrating the back-wall echo from the standard. Table 3-13 summarizes the SNR results extracted from the C-scan for #2 FBH. Note that the #2 FBHs were essentially detected with SNR <2.0 at depths greater than 2.25″. All of the #1 FBHs were undetectable in this case. The SNR was calculated using equation 3-1.



Backwall

FIGURE 3-20. C-SCAN OF ST INSPECTION OF THE 5″ DIAMETER Ti BILLET

TABLE 3-13. SIGNAL-TO-NOISE RATIO FOR CONVENTIONAL AND ST INSPECTIONS OF 5″ DIAMETER Ti BILLET REFERENCE STANDARD

FBH Size	FBH Depth (in.)	FBH Peak Amplitude (% screen)	Noise Peak Amplitude (% screen)	Mean Noise Amplitude (% screen)	ST SNR	ST SNR (dB)	Conventional SNR	Conventional SNR (dB)
#2 FBH Ti-6Al-4V	0.20	26.7	11.8	6.50	3.81	11.62	1.14	1.11
	0.48	32.9	14.9	7.30	3.37	10.55	1.14	1.11
	0.75	25.9	14.1	7.40	2.76	8.82	1.14	1.11
	1.13	27.5	15.7	8.50	2.64	8.43	1.14	1.11
	1.50	35.3	22.0	10.90	2.20	6.84	1.14	1.11
	1.87	36.9	23.5	12.80	2.25	7.05	1.14	1.11
	2.25	32.9	20.4	10.60	2.28	7.14	1.14	1.11
	2.63	32.9	25.9	11.80	1.50	3.50	1.14	1.11
	3.00	26.7	25.1	13.40	1.14	1.11	1.14	1.11

After completing the conventional inspection, a multizone inspection was performed utilizing the procedure used for the 5″ diameter Waspaloy billet standard. The C-scans resulting from this inspection are shown in figure 3-21, and the SNR calculated from these C-scans are listed in table 3-14. Note that all the #2 and #1 FBHs were detected with a SNR >2.0 at all depths down to the centerline of the billet standard.

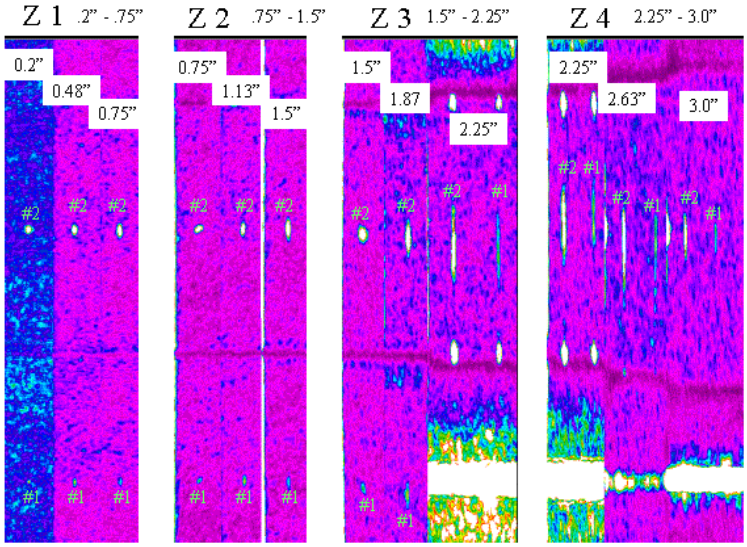


FIGURE 3-21. C-SCANS OF THE 5″ DIAMETER Ti BILLET REFERENCE STANDARD
(A total of four zones were used to cover a depth of 3″ into the billet.)

TABLE 3-14. SIGNAL-TO-NOISE RATIO FOR MULTIZONE INSPECTION OF A 5″ DIAMETER Ti BILLET REFERENCE STANDARD

FBH	FBH Depth (in.)	Attenuation (dB)	FBH Peak Amplitude (% FSH)	Noise Peak Amplitude (% FSH)	Mean Noise Amplitude (% FSH)	Multizone SNR	Multizone SNR (dB)
#2 FBH Multizone Ti	0.20	40.0	274.7	43.0	28.00	16.44	24.32
	0.48	39.0	223.9	32.0	17.00	13.79	22.79
	0.75	36.5	167.5	30.0	16.00	10.82	20.68
	0.75	40.0	132.1	31.0	14.00	6.95	16.83
	1.13	41.0	185.0	29.0	14.00	11.40	21.14
	1.50	40.0	166.8	29.0	13.00	9.61	19.65
	1.50	32.5	196.1	30.0	14.00	11.38	21.12
	1.87	34.5	225.5	39.0	18.00	9.88	19.89
	2.25	33.0	158.9	40.0	18.00	6.40	16.13
	2.25	29.5	160.6	33.0	17.00	8.98	19.06
	2.63	31.0	197.3	43.0	20.00	7.71	17.74
	3.00	27.5	126.8	32.0	18.00	7.77	17.81
#1 FBH Multizone Ti	0.20	29.5	82.0	53.0	29.00	2.21	6.9
	0.48	29.5	75.0	35.0	16.00	3.11	9.8
	0.75	26.0	50.0	26.0	14.00	3.00	9.5
	0.75	33.0	59.0	26.0	12.00	3.36	10.5
	1.13	33.5	78.0	31.0	14.00	3.76	11.5
	1.50	29.0	47.0	26.0	13.00	2.62	8.4
	1.50	22.5	62.0	29.0	14.00	3.20	10.1
	1.87	25.5	80.0	29.0	17.00	5.25	14.4
	2.25	25.5	67.0	32.0	17.00	3.33	10.5
	2.25	23.0	76.0	33.0	17.00	3.69	11.3
	2.63	22.0	70.0	39.0	21.00	2.72	8.7
	3.00	21.0	60	36	19.00	2.41	7.6

The final inspection performed on the 5″ diameter Ti standard was a phased array inspection. The procedure used for the 5″ diameter Waspaloy billet standard was applied to the 5″ diameter Ti billet standard.

Table 3-15 shows some inspection parameters used for each one of the FBHs in the Ti billet standard. Figure 3-22 shows typical results collected during the inspection for the #2 and #1 FBHs at a 1.5″ depth. The figure shows the top (C), side (B), and the end (D) scans along with two A-scans showing the indications for the #2 and #1 FBHs. Appendix D shows similar scans for the rest of the holes at all remaining depths in the Ti standard. Again, the SNR was calculated according to equation 3-1. The noise was measured using the contour tool in Tomoview. A contour is drawn on a desired region over the C-scan. The tool measures the mean and maximum noises in the region. Table 3-16 shows the SNR results collected during the inspection.

TABLE 3-15. PHASED ARRAY INSPECTION PARAMETERS FOR THE 5″ DIAMETER Ti BILLET STANDARD

FBH Depth (in.)	ER-Focus (in.)	Beam Size (mils)	Gain (dB)
3	3	100	10
2.63	2.63	100	12
2.25	2.25	100	13
1.87	1.87	100	15
1.5	1.5	100	12
1.13	1.13	100	6
0.75	0.75	100	15
0.48	0.48	100	10
0.2	0.2	100	15

Frequency = 5 MHz
Water Path = 4 inches

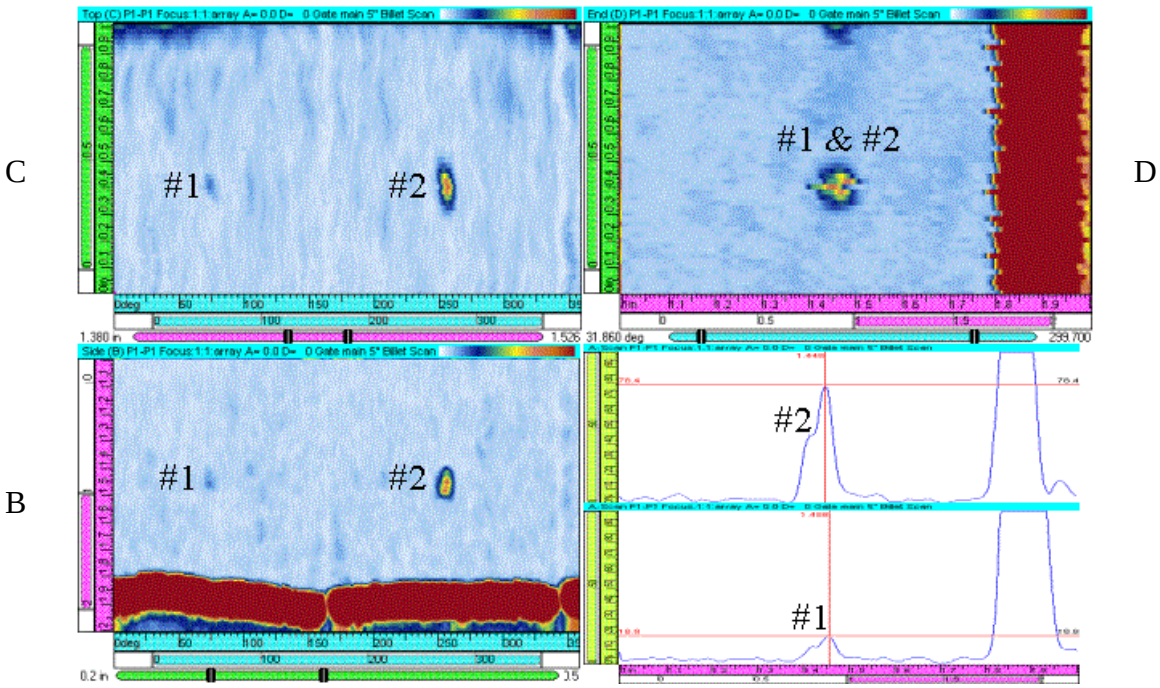


FIGURE 3-22. TYPICAL RESULTS FOR THE #2 AND #1 FBHs AT A 1.5″ DEPTH

TABLE 3-16. SIGNAL-TO-NOISE RATIO RESULTS COLLECTED DURING THE PHASED ARRAY INSPECTION OF THE 5″ DIAMETER Ti-6Al-4V REFERENCE BILLET STANDARD

FBH	Depth	Peak Signal (% FSH)	Peak Noise (% FSH)	Avg Noise (% FSH)	SNR	SNR (dB)
#2 FBH, Phased Array Ti-6Al-4V	0.2	71	22.4	11.2	5.34	14.55
	0.48	79.6	10.2	5.7	16.42	24.31
	0.75	74.1	8.6	4.8	18.24	25.22
	1.13	98.8	11.4	5.7	16.33	24.26
	1.5	78.4	13.7	6.9	10.51	20.44
	1.87	78	14.9	8.6	11.02	20.84
	2.25	76.1	18.8	8.3	6.46	16.20
	2.63	75.3	21.16	10	5.85	15.34
	3	57.6	14.5	8.8	8.56	18.65
#1 FBH, Phased Array Ti-6Al-4V	0.2	-			-	-
	0.48	22.4	10.2	5.7	3.71	11.39
	0.75	20.8	8.6	4.8	4.21	12.49
	1.13	32.2	11.4	5.7	4.65	13.35
	1.5	18.8	13.7	6.9	1.75	4.86
	1.87	23.5	14.9	8.6	2.37	7.48
	2.25	29	18.8	8.3	1.97	5.90
	2.63	28.2	21.16	10	1.63	4.25
	3	20.8	14.5	8.8	2.11	6.47

3.8.3 Comparison of the Three Inspection Methods.

The results collected from inspecting the 5″ diameter Waspaloy and Ti standards were compared to each other based on the SNR and the relative sensitivity of the technique. Figure 3-23(a) shows the results of comparing the SNR from each one of the three techniques used in the inspection of the 5″ diameter Waspaloy standard for the #1 FBH at the various depths, whereas figure 3-23(b) shows a similar comparison for the #2 FBHs at similar depths. The sensitivity curves were constructed based on this data and are illustrated in figure 3-24. Figures 3-23 and 3-24 show that the performance of the multizone and phased array inspections are almost on the same level and are slightly better than the conventional inspection.

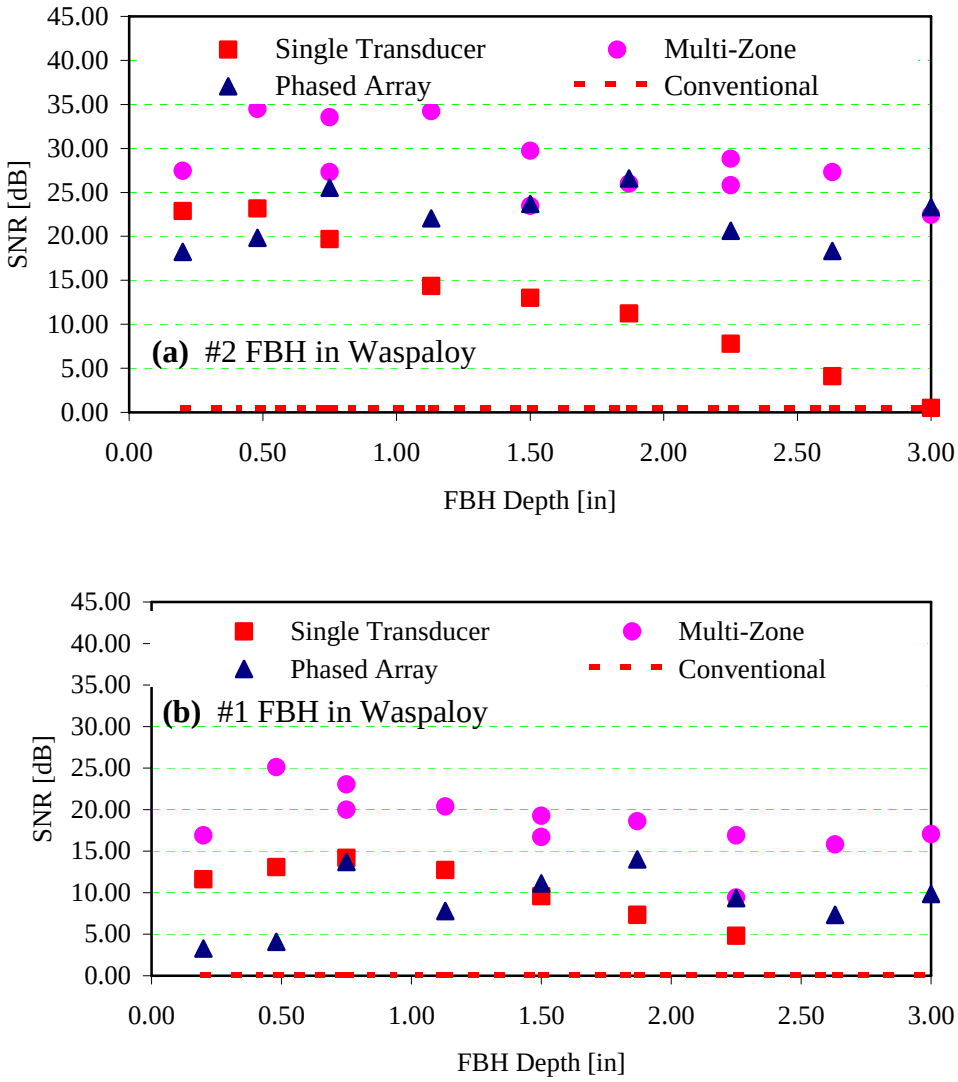


FIGURE 3-23. COMPARISON OF THE SNR FROM THE THREE TECHNIQUES USED IN INSPECTING THE 5″ DIAMETER WASPALOY BILLET REFERENCE STANDARD

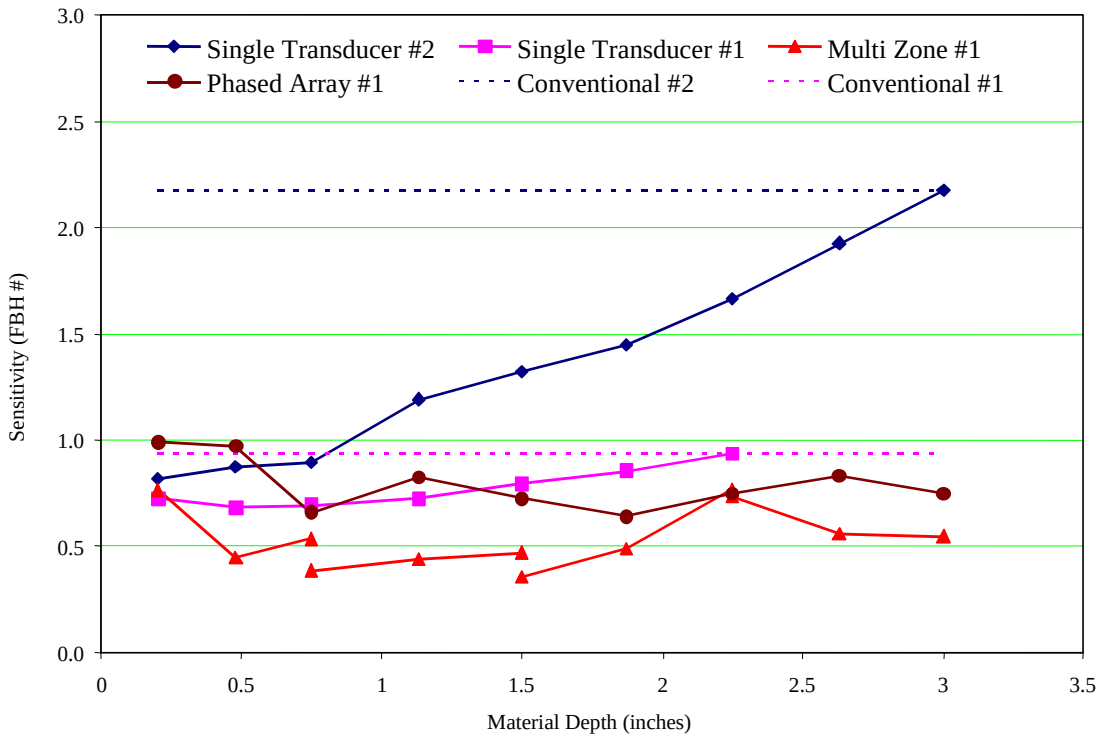


FIGURE 3-24. SENSITIVITY VS DEPTH AT SNR = 1.4 (3 dB) FOR THE 5″ DIAMETER WASPALOY BILLET REFERENCE STANDARD

Figure 3-25(a) shows the comparison for the SNR from each of the three techniques used in the inspection of the 5″ diameter Ti standard for the #1 FBH at various depths, whereas figure 3-25(b) shows a similar comparison for the #2 FBHs at similar depths. The sensitivity curves for this case were also constructed based on SNR data and are illustrated in figure 3-26. As with the Waspaloy data in figure 3-24, the ST inspection sensitivity in figure 3-26 is shown as a series of values, one for each of the FBH depths. As with the Waspaloy evaluation, the sensitivity of a production conventional inspection would again be represented by a single value equivalent to the sensitivity at the center of the billet. In this case, the production sensitivity in figure 3-26 is drawn as a straight line across all depths at a value of about #2.2 FBH. This single sensitivity again results from the fact that the conventional beam travels throughout the entire billet depth when evaluating FBH at all depths. This means the noise levels (mean and peak) for FBH at all depths would be identical and equal to the noise values obtained when scanning the deepest (3″ deep) FBH in this study. Figures 3-25 and 3-26 show that the performance of the multizone and phased array inspections are almost on the same level (sensitivity < #1 FBH), and both are much better (about six times more sensitive at the billet center) than the conventional inspection sensitivity that ranges between #1.5 FBH and #2 FBH.

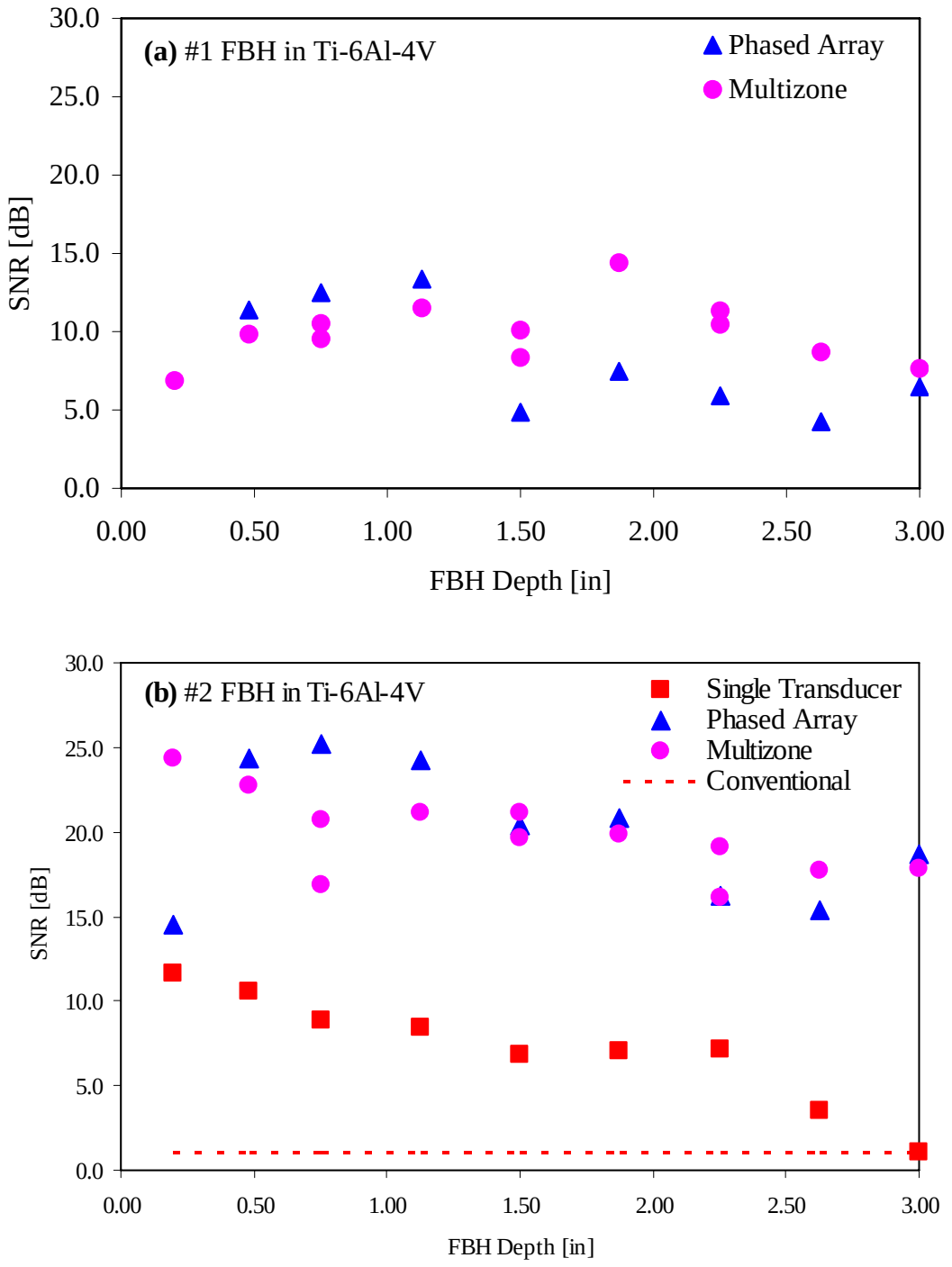


FIGURE 3-25. COMPARISON OF THE SNR FROM THE THREE TECHNIQUES USED IN INSPECTING THE 5″ DIAMETER Ti BILLET REFERENCE STANDARD

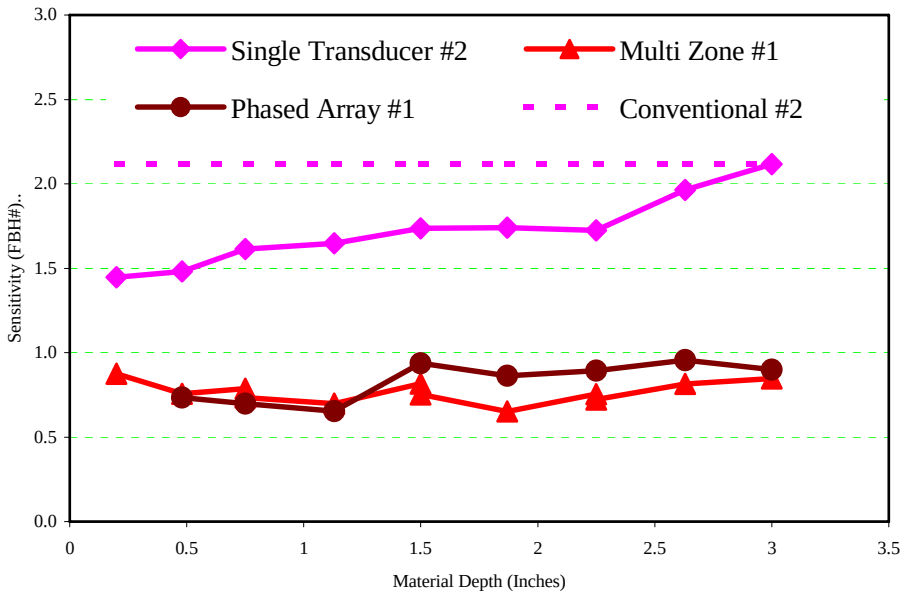


FIGURE 3-26. SENSITIVITY VS DEPTH AT SNR = 1.4 (3 dB) FOR THE 5″ DIAMETER Ti BILLET REFERENCE STANDARD

In this effort, 5″ diameter Waspaloy and Ti-6Al-4V billet reference standards have been inspected using four different inspection techniques, namely, conventional, ST, multizone, and phased array. For both materials, note that the multizone and phased array inspections performed, in general, significantly better than the conventional and ST inspections. The results obtained in this study seem to indicate that, in general, the multizone and phased array inspections performed at the same level with the multizone inspection performing slightly better than the phased array inspection for the Waspaloy standard. Some degraded performance of the phased array inspection was also noticed in the near-surface zone, which can be attributed to the improper shape of the spherically focused center element of the probe that resulted from the manufacturing process.

Note that a production setup was used for the multizone inspection for this inspection, which is not the case for phased array inspection. The phased array inspection is an experimental laboratory evaluation, which still requires some optimization. Currently, this is done empirically, and no systematic way exists to check the optimization. Therefore, the phased array data should be viewed as one set of data that was collected based on the current best knowledge of how to perform the inspection. Future work is needed to optimize this technique and make sure that the best inspection scenario is selected. Also note that for the multizone inspection, the amplitude of the #2 FBH indications was calculated by scaling the amplitude of the #1 FBH by the ratio of the attenuation set for the #1 and #2 FBHs during the calibration process. This was done because during collection of C-scans for the multizone inspection, the focus was on the #1 FBHs, which resulted in all the #2 FBH indications being saturated.

4. SUMMARY.

The following is a summary of this study:

- Billet converted with GFM processing is more acoustically noisy than billet converted using V-Die processing. GFM material was selected for use in calibration standards since this provides a more conservative assessment.

- Transducer characterization procedures were developed for bicylindrically focused transducers, which are useful for ensuring that actual focal characteristics match the intended design values.

- The Waspaloy calibration standard was more ultrasonically noisy than the IN718 material (75% peak noise compared to 20%, respectively) when measured with the same calibration target.

- The multizone inspection procedure and transducers originally used for Ti successfully exceeded the program goal of #1 FBH for IN718 and #2.5 FBH for Waspaloy by substantial margins. The multizone system exceeded the IN718 goal by a minimum of 3.5 times and was a minimum of 31 times more sensitive than the current conventional inspection requirement. Multizone exceeded the Waspaloy goal by a minimum of 4 times and was a minimum of 14 times more sensitive than the current conventional inspection requirement.

- The use of conventional transducers in the two-zone laboratory inspection nearly met the program goal for IN718. The laboratory conventional immersion inspection exceeded the program goal of #2.5 FBH sensitivity for Waspaloy in the near-surface zones. No data was gathered for the production conventional contact inspection of Waspaloy.

- The factory assessment showed that the surface finish used for conventional inspection was adequate for the increased sensitivity of the multizone test, although the multizone test is more sensitive to surface blemishes.

- The factory assessment showed comparable characteristics for inspection of Ni when compared to experience with inspection of Ti multizone procedures.

- A cost comparison revealed increased investment and operational cost for multizone compared to conventional. The initial cost layout was $310,000 higher for the multizone equipment and additional yearly costs were documented. Increased operational costs associated with multizone inspections were documented for setup, scanning, and analysis. The cost of increased material due to more material being rejected could not be clearly ascertained.

- Suppliers expressed concerns regarding transducer manufacturability and limited availability of transducer vendors.

- The factory demo on 81,000 pounds of two and three times melted IN718 generated conclusive results that the multizone system can detect indications that are missed by the current conventional inspection. A total of 19 indications were detected by multizone, all of which were significantly smaller than conventional inspection requirements, which are at a #2 FBH sensitivity and, therefore, below the threshold for detection.

- Conventional inspection of 5″ diameter billet nearly met the current #2 FBH sensitivity in the center zone of both Ti and Waspaloy standards. However, slight modification of the current conventional inspection to reflect the method used for evaluating the results from the ST inspection showed that a significant improvement in the sensitivity could be achieved.

- Multizone and phased array inspection of 5″ diameter Waspaloy billet indicated that multizone achieved about a #0.5 FBH sensitivity throughout most of the billet depth while phased array achieved about a #0.75 FBH. The multizone inspection exceeded the conventional inspection sensitivity by about 20 times at the billet center.

- Multizone and phased array inspection of 5″ diameter Ti-6Al-4V billet indicated that both achieved about a #0.75 FBH sensitivity throughout the billet depth, which exceeded the conventional immersion sensitivity by about nine times.

5. REFERENCES.

1. Howard, P., Copley, D., and Gilmore, R., "Transducer Design for High Sensitivity Ultrasonic Inspection of Titanium," in *Review of Progress in QNDE*, Vol. 16A, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1997, pp. 893-900.

2. Yalda, I., Panetta, P.D., Margetan, F.J., and Thompson, R.B., "Characterization of Ultrasonic Focused Transducers Using Axial Scans and C-Scans," in *Review of Progress in QNDE*, Vol. 16A, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1997, pp. 927-934.

3. Howard, P., Copley, D., Young, J., Nieters, E., and Gilmore, R., "An Improved Methodology for the Inspection of Titanium Alloys," *Proceedings of the 1996 IEEE Ultrasonics Symposium*, Vol. 1, M. Levy, S. Schneider, and B. McAvoy, eds., IEEE Press, 1996, pp. 727-730.

4. Howard, P. and Gilmore, R.S., "Ultrasonic Noise and the Volume of the Ultrasonic Pulse," in *Review of Progress in QNDE*, Vol. 15B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1996, pp. 1495-1502.

5. Howard, P., Copley, D., Nieters, E., Young, J., Keller, M., and Gilmore, R., "Ultrasonic Inspection of Cylindrical Titanium Billet," presented at ASNT Fall Conference, October 1994.

6. Gray, T.A., "Application of Measurement Models to Specification of Ultrasonic Inspections," in *Review of Progress in QNDE*, Vol. 16B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1997, pp. 2061-2068.

7. Thompson, R.B., "Use of UT Models in Titanium Inspection Development," in *Review of Progress in QNDE*, Vol. 16B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1997, pp. 1537-1545.

8. Thompson, R.B., "A Generalized Model of the Effects of Microstructure on Ultrasonic Backscattering and Flaw Detection," in *Review of Progress in QNDE*, Vol. 15B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1996, pp. 1471-1477.

9. Yalda, I., Margetan, F.J., Han, K.Y., and Thompson, R.B., "Survey of Ultrasonic Grain Noise Characteristics in Jet Engine Titanium," in *Review of Progress in QNDE*, Vol. 15B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1996, pp. 1487-1494.

10. Han, K.Y. and Thompson, R.B., "Relationship Between the Two-Point Correlation of Elastic Constants and Backscattered Ultrasonic Noise in Two-Phase Titanium Alloys," in *Review of Progress in QNDE*, Vol. 14A, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1995, pp. 67-74.

11. Margetan, F.J., Han, K.Y., Yalda, I., Goettsch, S., and Thompson, R.B., "The Practical Application of Grain Noise Models in Titanium Billets and Forgings," in *Review of Progress in QNDE*, Vol. 14B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1995, pp. 2129-2136.

12. Panetta, P.D., Margetan, F.J., Yalda, I., and Thompson, R.B., "Ultrasonic Attenuation Measurements in Jet-Engine Titanium Alloys," in *Review of Progress in QNDE*, Vol. 15B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1996, pp. 1525-1532.

13. Margetan, F.J., Panetta, P.D., and Thompson, R.B., "Ultrasonic Signal Attenuation in Engine Titanium Alloys," in *Review of Progress in QNDE*, Vol. 17B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1998, pp. 1469-1476.

14. Panetta, P.D., Thompson, R.B., and Margetan, F.J., "Use of Electron Backscatter Diffraction in Understanding Texture and the Mechanisms of Backscattered Noise Generation in Titanium Alloys," in *Review of Progress in QNDE*, Vol. 17A, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1998, pp. 89-96.

15. Thompson, R.B., Margetan, F.J., Yalda, I., Chiou, C.-P., and Panetta, P.D., "Coupling Microstructure Outputs of Process Models to Ultrasonic Inspectability Predictions," in *Review of Progress in QNDE*, Vol. 17B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1998, pp. 1847-1853.

16. Thompson, R.B., Panetta, P.D., and Margetan, F.J., "Relationship of the Ultrasonic Backscattering Coefficient of Titanium Alloys to Microstructure," in *Materials and Processes Affordability: Keys to the Future*, H.S. Kliger, B.J. Rasmussen, L.A. Pilato, and T.B. Tolle, eds., SAMPE, Covina, CA, 1998, pp. 1448-1457.

17. Margetan, F.J., Yalda, I., and Thompson, R.B., "Predicting Gated-Peak Grain Noise Distributions for Ultrasonic Inspections of Metals," in *Review of Progress in QNDE*, Vol. 15B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1996, pp. 1509-1516.

18. Panetta, P.D., Margetan, F.J., Yalda, I., and Thompson, R.B., "Observation and Interpretation of Microstructurally Induced Fluctuations of Back-Surface Signals and Ultrasonic Attenuation in Titanium Alloys," in *Review of Progress in QNDE*, Vol. 16B, D.O. Thompson and D.E. Chimenti, eds., Plenum Press, New York, 1997, pp. 1547-1554.

19. Margetan, F.J., Gigliotti, M., Brasche, L., and Leach, W., "Fundamental Studies: Inspection Properties for Engine Titanium Alloys," FAA Report DOT/FAA/AR-02/114, December 2002.

20. Brasche, L., Chiou, T., Thompson, R.B., Smith, K., Meeker, B., Margetan, F., Panetta, P., Chenail, R., Galli, F., Umbach, J., Raulerson, D., Degtyar, A., Bartos, J., Copley, D.,

McElligott, B., Howard, P., and Bashyam, M., "Contaminated Billet Study," FAA report DOT/FAA/AR-05/16, September 2005.

21. Umbach, J.A. and Roberts, R.A., "Ultrasonic Phased Array Transducers-Model and Experiment," presented at ASNT Fall Conference, October 1997.

22. Margetan, F., Nieters, E., Haldipur, P., Brasche, L., Chiou, T., Keller, M., Degtyar, A., Umbach, J., Hassan, W., Patton, T., and Smith, K., "Fundamental Studies of Nickel Billet Materials—Engine Titanium Consortium II," FAA report, DOT/FAA/AR-05/17, June 2005.

23. Roberts, R.A., "Phased Array Beam Modeling Using a Discretely Orthogonal Gaussian Aperture Basis," in *Review of Progress in QNDE*, Vol. 23, D.O. Thompson and D.E. Chimenti, eds., American Institute of Physics, Melville, NY, 2004.

24. Keller, M., Patton, T., Degtyar, A., Umbach, J., Hassan, W., Kinney, A., Roberts, R., Margetan, F., and Brasche, L., "Inspection Development for Titanium Billet—Engine Titanium Consortium Phase II," FAA report, DOT/FAA/AR-05/30, September 2005.

25. Hassan, W., "Evaluation of Multizone Inspection Variability at the Supply Base for 8-Inch-Diameter Ti-6Al-4V: A Round-Robin Study," in *Review of Progress in QNDE*, Vol. 22B, D.O. Thompson and D.E. Chimenti, eds., American Institute of Physics, Melville, NY, 2003, pp. 1870-1877.

APPENDIX A—DEFECT CHARACTERIZATION OF NATURALLY OCCURRING ANOMALIES

Four indications were ultrasonically and metallographically characterized. Samples were ultrasonically characterized at ISU and metallographically characterized by the OEM members of ETC. The results of the characterization are provided in appendix A. Details of the ultrasonic characterization procedure are provided in appendix B. A summary of the anomaly characterization is provided in table A-1.

TABLE A-1. ANOMALY CHARACTERIZATION DATA SUMMARY.

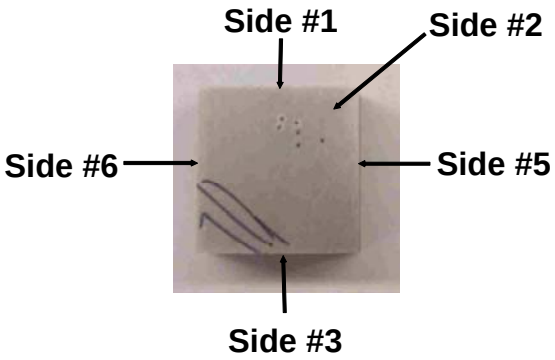
Indication Number	Material Description	Ultrasonic Response (% Full) Screen Height	Anomaly Type
1	IN718 VIM/ESR/VAR	22.5	Crack
2	IN718 VIM/ESR/VAR	33.6	Melt-related slag inclusion high in oxygen
3	IN718 VIM/VAR	44.0	Entrapped slag
4	IN719 VIM/VAR	20.5	Entrapped slag

Ni Billet Indication #1 – General Information

• Alloy	Inconel 718
• Melt method	triple melt VIM/ESR/VAR
• Billet diameter	10 inch
• Size of calibration reflector (1/64ths of inch)	#1
• Calibration amplitude (% screen height)	80%
• Indication amplitude before evaluation (% screen height)	22.5%
• Indication amplitude after evaluation (% screen height)	22.5%
• Distance Amplitude Correction (DAC)	No
• Indication Depth	4.4 inches
• Indication Length	0.75 inches
• Transducer information:	
– Frequency	5 MHz
– Transducer Element	2.0 inches circular
– Focal length	7.7 & 19.8 inches
– Lens curvature	bi-cylindrical
– Beam diameter	0.245” axial
– Test mode	longitudinal
– Water Path	3.0 inches

Ni Billet Indication # 1 – composite micrograph

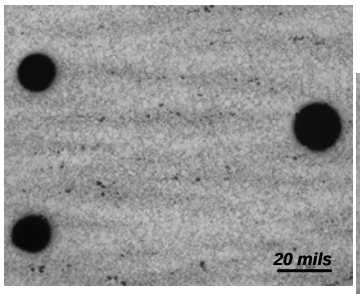
- Based on multizone UT data, the indication was believed to be 50 mils deep from side #2. After metallographic examination, the indication appears to have been around a depth of 30 mils. When the indication was revealed at 30 mils, the decision was made not to use the microprobe to obtain the composition of the indication since it was thought that indication was at a depth of 50 mils. There was no indication revealed at depths of 52 mils and 57 mils. Therefore, no microprobe results were obtained on this indication.
- *Maximum Indication Size:*
  - 12.5 mil axial length (Distance along crack length)
  - 1.2 mil radial length (Distance across crack length)
  - 6 mils in depth (Length determined from assuming indication present half way between step polishes in which indication was revealed and not revealed)



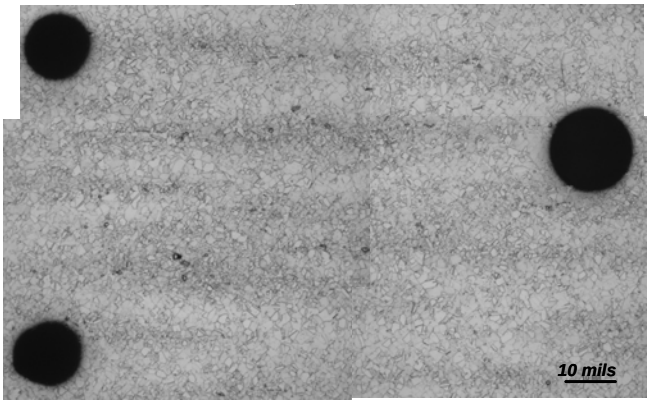
NOTE: Polished surface is Side #2 & indication was in between three EDM plunged holes

Ni Billet Indication # 1 – composite micrograph

Depth = 10 mils



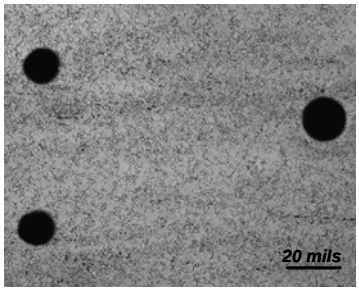
25X



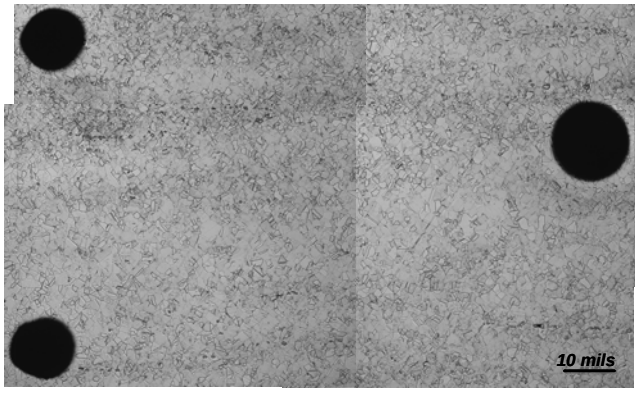
50X

Ni Billet Indication # 1 – composite micrograph

Depth = 20 mils



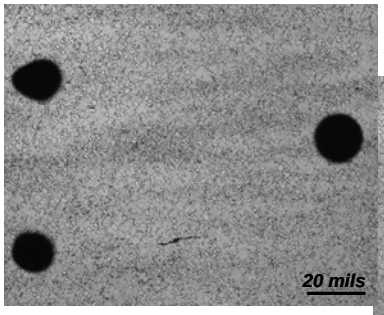
25X



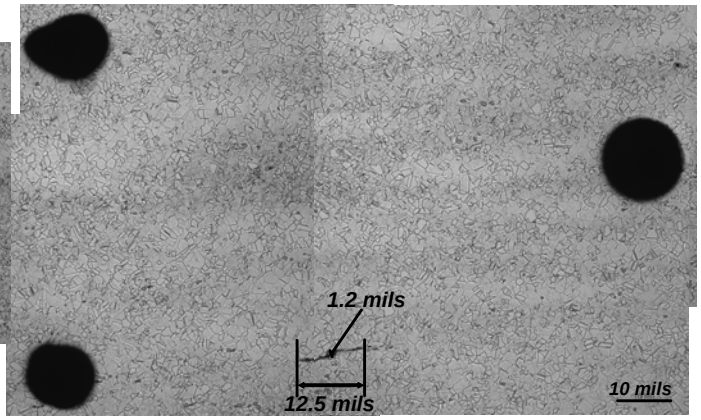
50X

Ni Billet Indication # 1 – composite micrograph

Depth = 30 mils



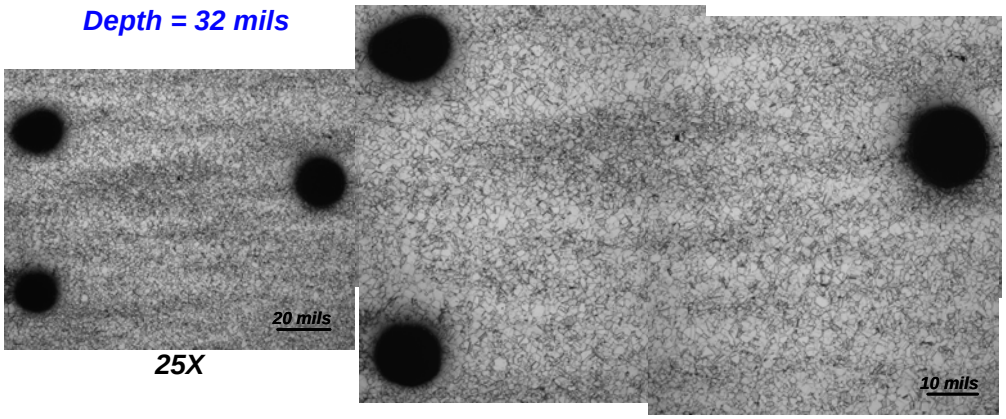
25X



50X

Ni Billet Indication # 1 – composite micrograph

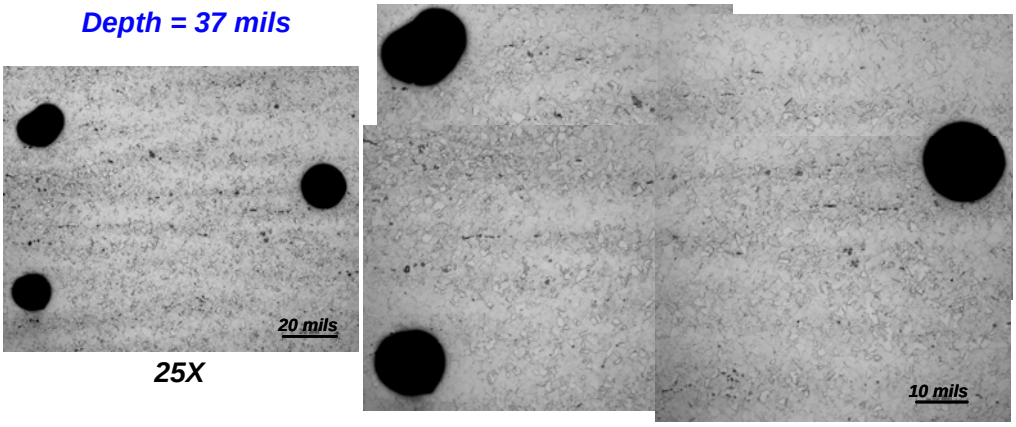
Depth = 32 mils



25X ***50X***

Ni Billet Indication # 1 – composite micrograph

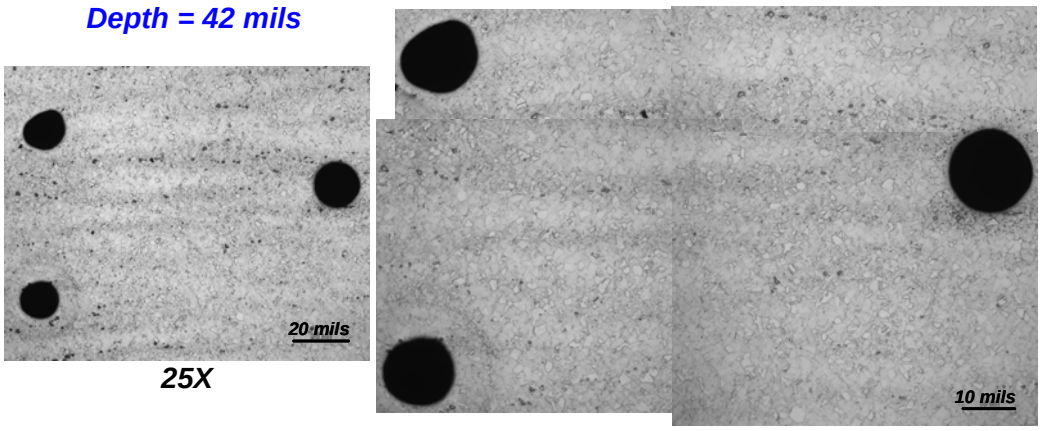
Depth = 37 mils



25X ***50X***

Ni Billet Indication # 1 – composite micrograph

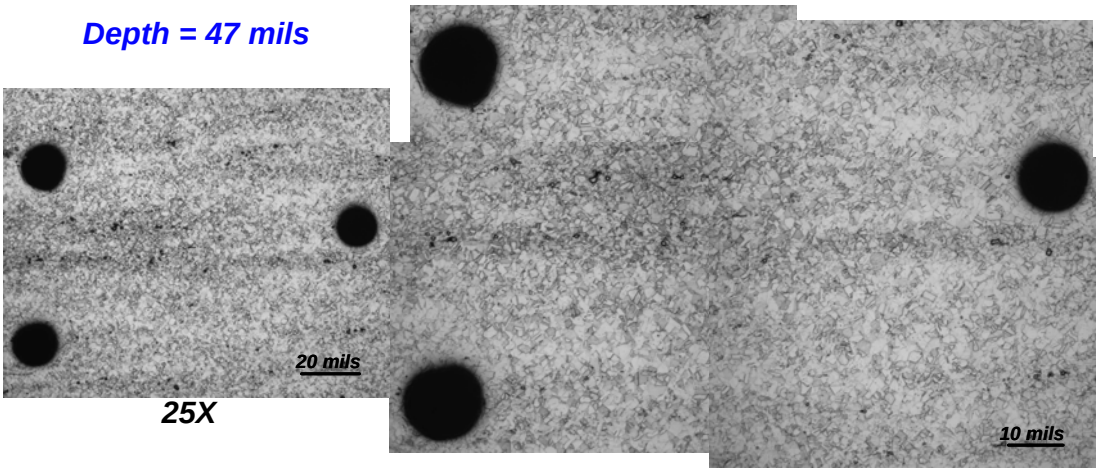
Depth = 42 mils



25X ***50X***

Ni Billet Indication # 1 – composite micrograph

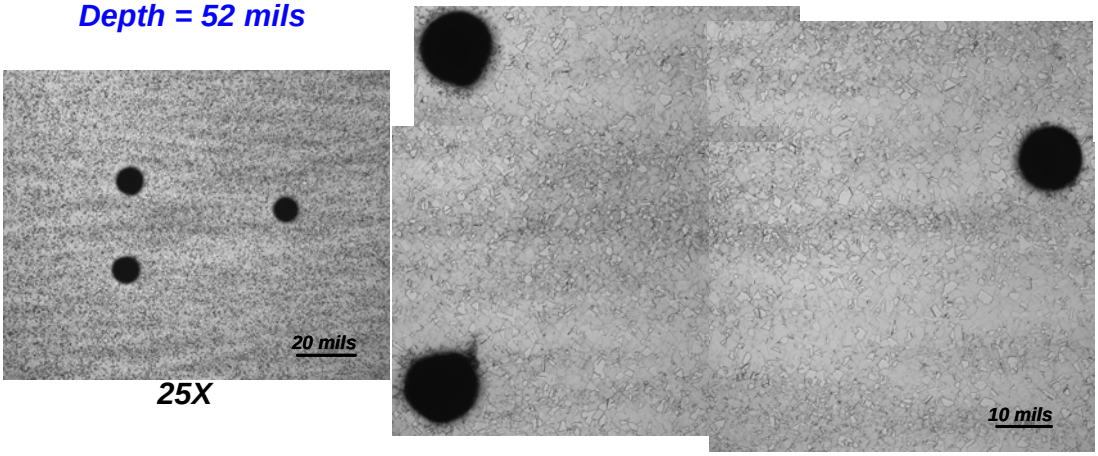
Depth = 47 mils



25X ***50X***

Ni Billet Indication # 1 – composite micrograph

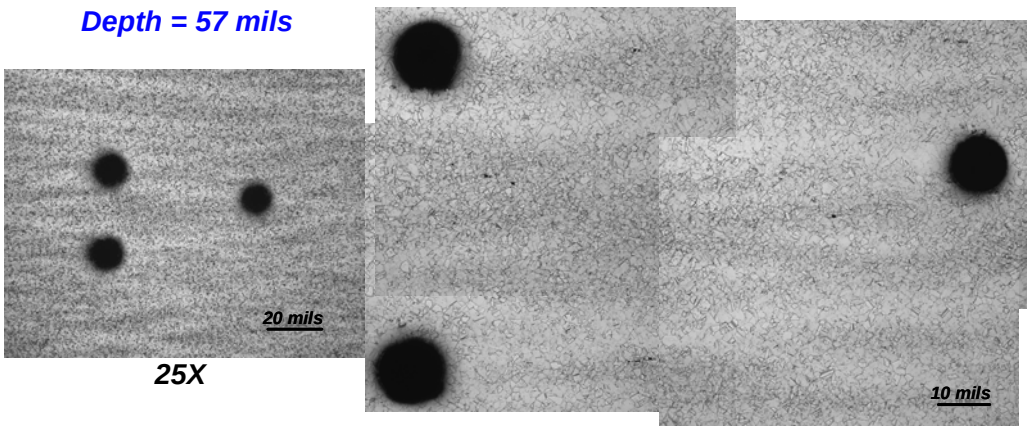
Depth = 52 mils



25X ***50X***

Ni Billet Indication # 1 – composite micrograph

Depth = 57 mils



25X ***50X***

Ni Billet Indication # 1 – Ultrasonic Measurements

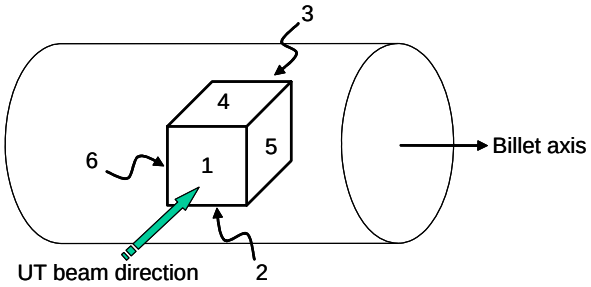
Billet Information

- Found in 10" triple melt Inconel 718 billet

Cube Information

- Dimension: sides 1&3 - 25.70mm, sides 2&4 - 25.23mm and sides 5 &6 - 25.37mm
- UT scans were performed at ISU using a Utex WinSpect system.
- UT data include single a-scans at peak positions, c-scan images, and volumetric a-scans at c-scan scan grids using 5 and 50 MHz transducers.
- Additional a-scans were obtained from fused quartz block as reference waveforms.
- Indication signals can only be identified on sides 1 and 3.

Billet/Cube Orientation

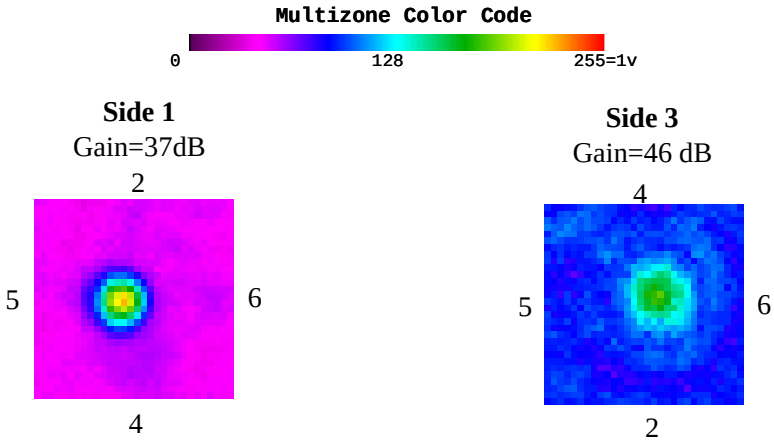


Scan Parameters

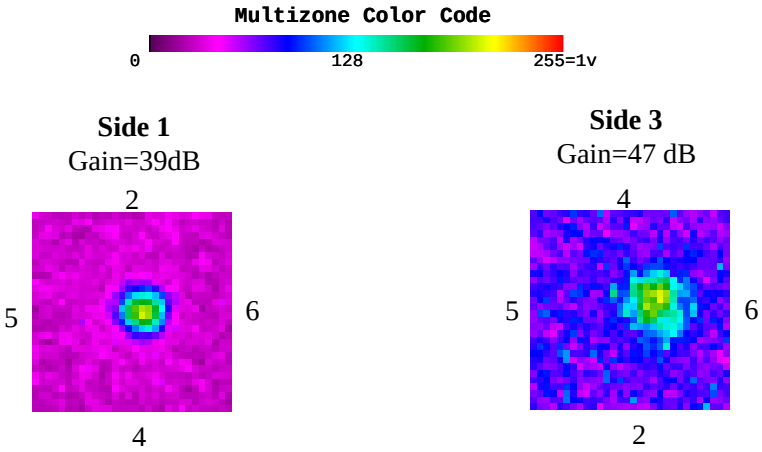
250 MHz sampling rate and 61 x 61 pixels (scan positions) at 5 mils spatial increment applied to all scans.
PH scans used 4 time averages and 0.5ms time gates.
P6 scans used 16 time averages and 1.37 and 0.78 ms time gates for sides 1 and 3, respectively.

Ni Billet Indication # 1 – Ultrasonic Measurements

P6 (5MHz) C-scan Images



PH (50MHz) C-scan Images

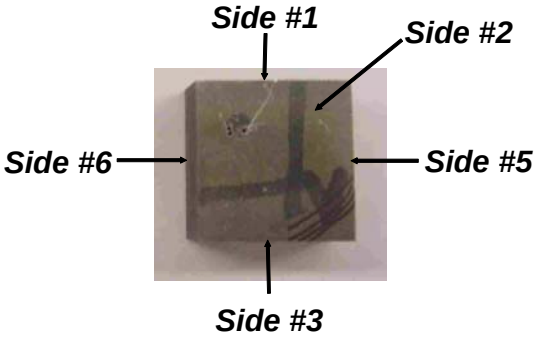


Ni Billet Indication #2 – General Information

• Alloy	Inconel 718
• Melt method	Triple melt VIM/ESR/VAR
• Billet diameter	10 inch
• Size of calibration reflector (1/64ths of inch)	#1
• Calibration amplitude (% screen height)	80%
• Indication amplitude before evaluation (% screen height)	33.6%
• Indication amplitude after evaluation (% screen height)	33.6%
• Distance Amplitude Correction (DAC)	No
• Indication Depth	4.375 inches
• Indication Length	0.75 inches
• Transducer information:	
• Frequency	5 MHz
• Transducer Element	2.0 inches circular
– Focal length	7.7 & 19.8 inches
– Lens curvature	bi-cylindrical
– Beam diameter	0.245” axial
– Test mode	longitudinal
– Water Path	3.0 inches

Ni Billet Indication # 2 – composite micrograph

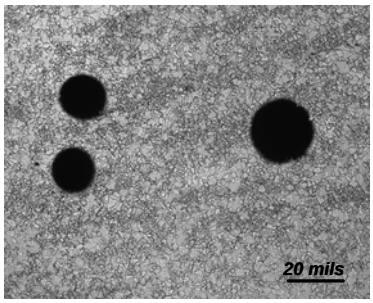
- Based on multizone UT data, the indication was believed to be 50 mils deep from side #2. After metallographic examination, the indication was revealed at a depth of 50 mils. When the indication was revealed at 50 mils, the decision was made to use the microprobe to obtain the composition of the indication. There was no diffusion zone around the indication. Indication was believed to be melt related (slag) defect based on chemical analysis.
- Maximum Indication Size:
  - 26.7 mil axial length
  - 0.4 mil radial length
  - 9.5 mils in depth (Length determined from assuming indication present half way between step polishes in which indication was revealed and not revealed)



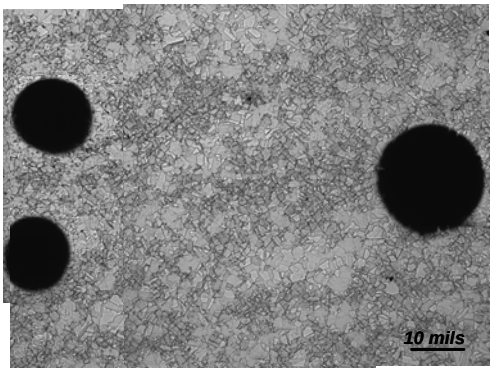
NOTE: Polished surface is Side #2 & indication was in between three EDM plunged holes

Ni Billet Indication # 2 – composite micrograph

Depth = 10 mils



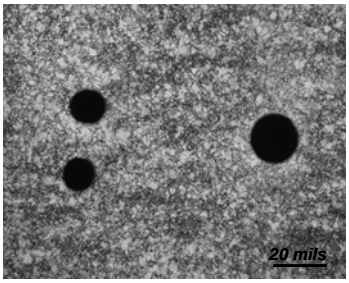
25X



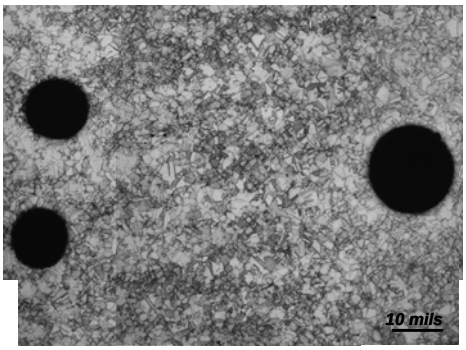
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 20 mils



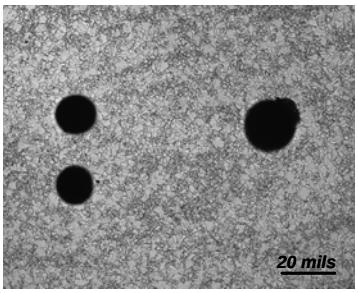
25X



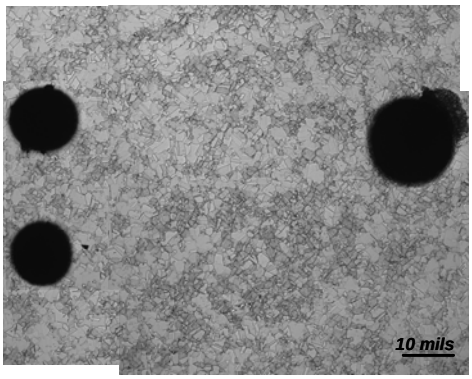
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 30 mils



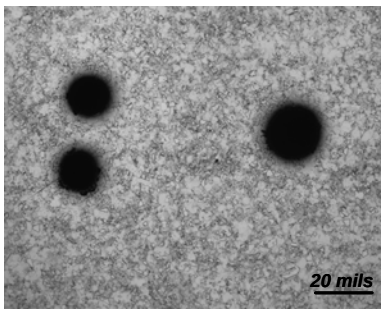
25X



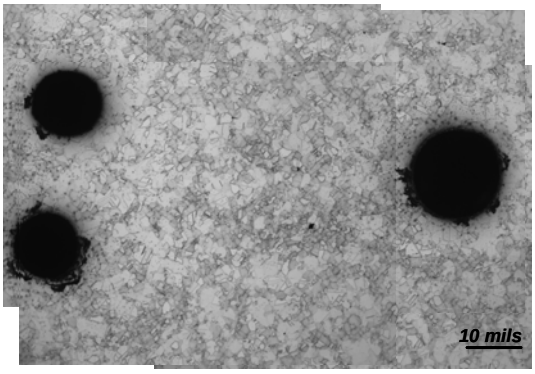
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 35 mils



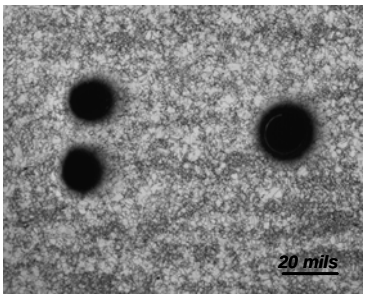
25X



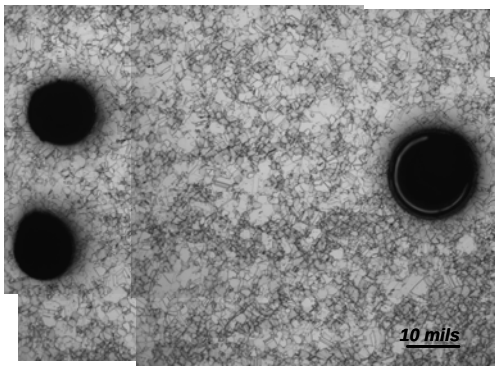
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 40 mils



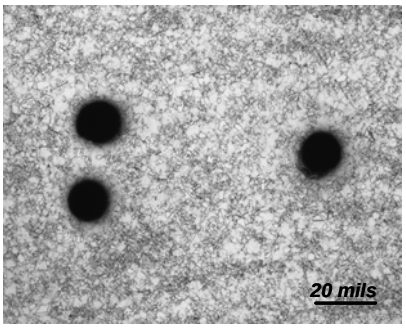
25X



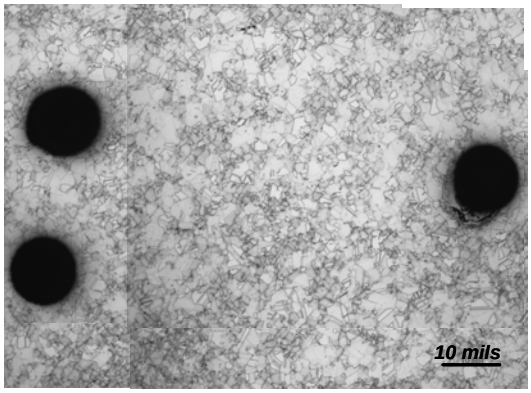
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 45 mils



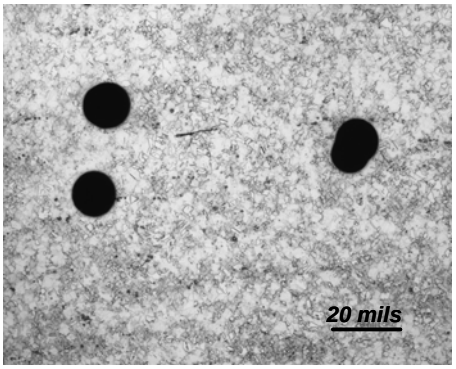
25X



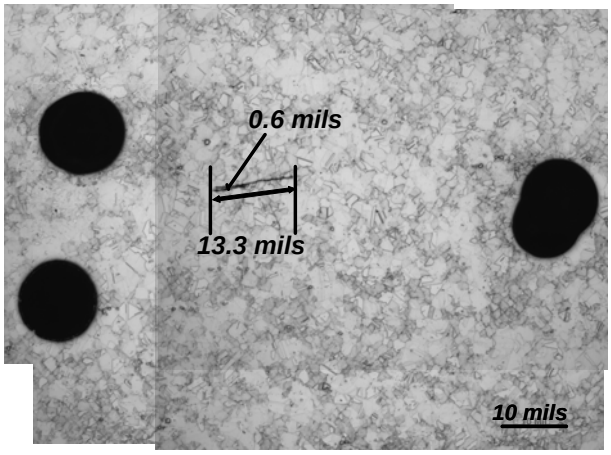
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 50 mils

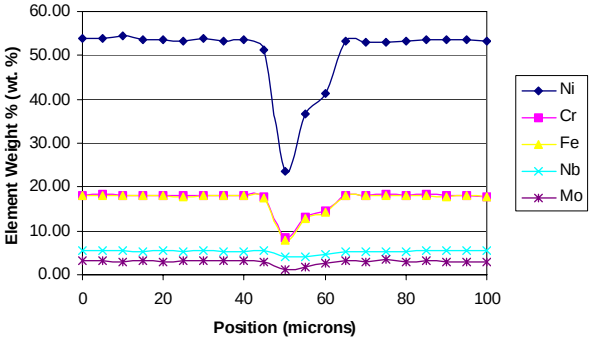


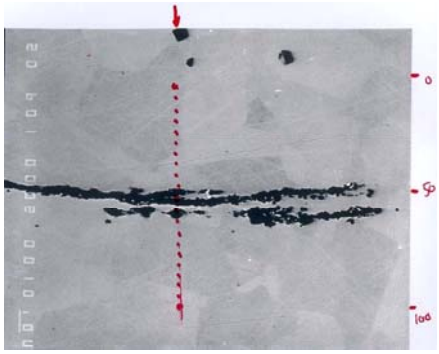
25X

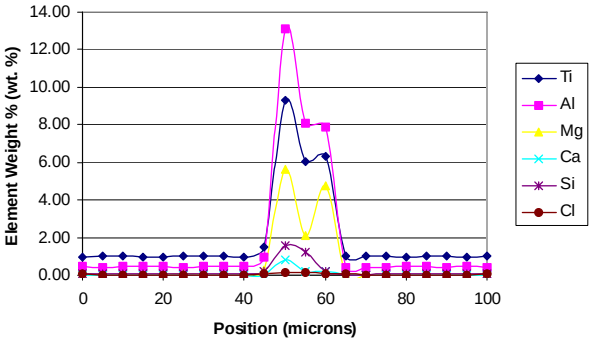


50X

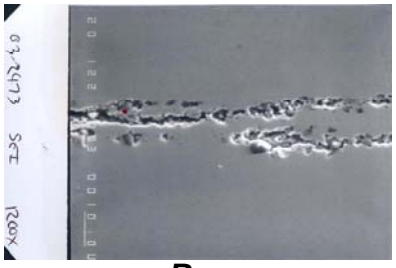
Ni Billet Indication # 2 – SEM analysis – 50 mil slice



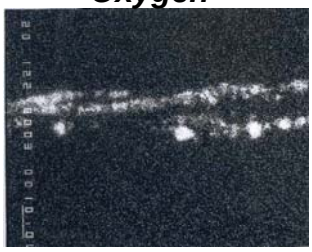




Ni Billet Indication # 2 – SEM analysis – 50 mil slice



Oxygen



Titanium

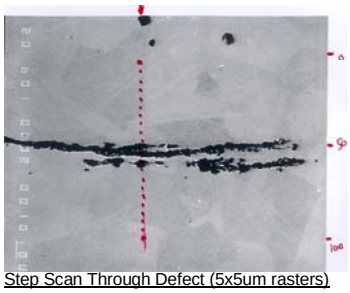
Boron

Carbon

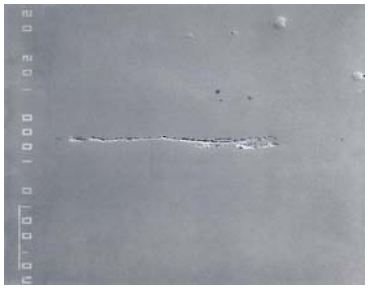
Nitrogen & Titanium

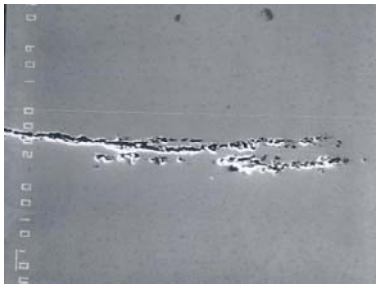
- ***Oxygen is present in abundance in indication.***
- ***Not clear if Nitrogen is present in indication***
- ***Could be just Titanium or Titanium and Nitrogen***

Ni Billet Indication # 2 – SEM analysis – 50 mil slice



Step Scan Through Defect (5x5um rasters)

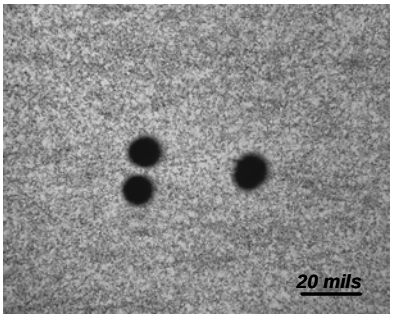




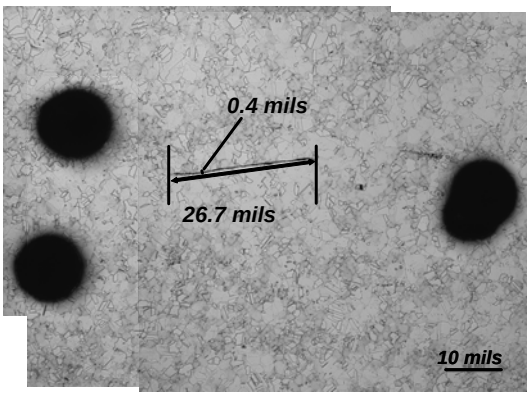
Pt#	um	Ni	Cr	Fe	Ti	Mo	Nb	Al	Mn	V	W	Zr	S	Mg	Ca	Na	Si	Cl
1	0	53.75	18.16	18.00	0.93	3.32	5.51	0.46	0.03	0.03	0.00	0.08	0.08	0.00	0.01	0.11	0.07	0.03
2	5	53.96	18.22	17.98	1.01	3.34	5.50	0.44	0.11	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.08	0.02
3	10	54.35	18.09	18.10	0.99	2.89	5.45	0.46	0.05	0.02	0.00	0.00	0.09	0.01	0.00	0.03	0.05	0.03
4	15	53.46	18.14	18.07	0.96	3.07	5.21	0.46	0.10	0.00	0.05	0.03	0.10	0.02	0.00	0.00	0.05	0.00
5	20	53.54	18.13	17.92	0.95	2.99	5.44	0.46	0.07	0.03	0.03	0.00	0.14	0.00	0.00	0.07	0.05	0.01
6	25	53.33	18.05	17.85	0.99	3.15	5.38	0.43	0.07	0.01	0.00	0.09	0.03	0.05	0.01	0.08	0.05	0.00
7	30	53.77	18.18	18.02	0.99	3.33	5.46	0.49	0.07	0.01	0.00	0.03	0.04	0.00	0.00	0.15	0.04	0.03
8	35	53.25	18.10	17.99	0.99	3.14	5.37	0.46	0.06	0.03	0.00	0.00	0.02	0.00	0.01	0.00	0.08	0.00
9	40	53.61	18.01	18.00	0.97	3.23	5.33	0.46	0.08	0.01	0.00	0.03	0.07	0.00	0.00	0.08	0.05	0.01
10	45	51.33	17.74	17.42	1.47	2.96	5.44	0.97	0.08	0.03	0.00	0.00	0.05	0.27	0.02	0.10	0.24	0.06
11	50	23.48	8.39	7.81	9.33	1.19	3.98	13.10	0.04	0.04	0.00	0.11	0.23	5.62	0.85	0.25	1.53	0.16
12	55	36.62	13.02	12.75	6.06	1.86	4.00	8.06	0.05	0.00	0.00	0.00	0.12	2.14	0.22	0.08	1.21	0.13
13	60	41.34	14.49	14.41	6.29	2.56	4.60	7.91	0.10	0.05	0.00	0.00	0.07	4.78	0.19	0.15	0.22	0.04
14	65	53.39	18.17	18.07	1.02	3.20	5.25	0.44	0.08	0.04	0.00	0.29	0.04	0.00	0.01	0.07	0.03	0.04
15	70	53.06	18.07	17.92	0.99	3.01	5.31	0.43	0.05	0.02	0.00	0.00	0.03	0.00	0.01	0.01	0.02	0.02
16	75	53.01	18.29	17.99	1.00	3.41	5.21	0.44	0.09	0.01	0.00	0.13	0.03	0.00	0.00	0.10	0.07	0.01
17	80	53.43	18.13	17.99	0.98	3.00	5.26	0.49	0.06	0.00	0.00	0.00	0.11	0.00	0.01	0.00	0.09	0.03
18	85	53.64	18.42	18.06	0.99	3.12	5.41	0.44	0.04	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.06	0.02
19	90	53.58	18.07	17.86	1.00	3.05	5.49	0.44	0.04	0.03	0.02	0.00	0.03	0.00	0.00	0.22	0.07	0.02
20	95	53.66	18.06	17.95	0.98	2.84	5.41	0.46	0.06	0.01	0.00	0.00	0.13	0.00	0.00	0.03	0.05	0.00
21	100	53.31	17.91	17.89	1.00	2.82	5.43	0.44	0.10	0.00	0.00	0.00	0.10	0.00	0.00	0.17	0.06	0.08

Ni Billet Indication # 2 – composite micrograph

Depth = 52 mils



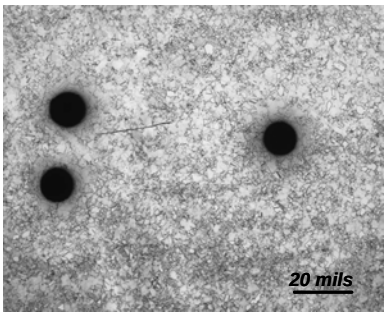
25X



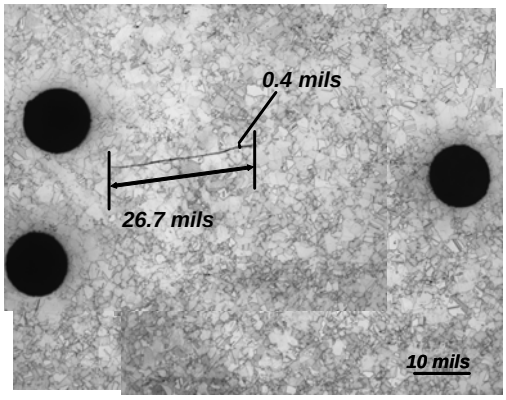
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 54 mils



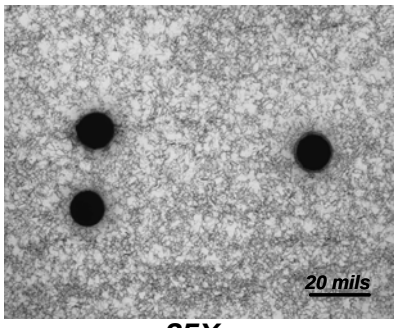
25X



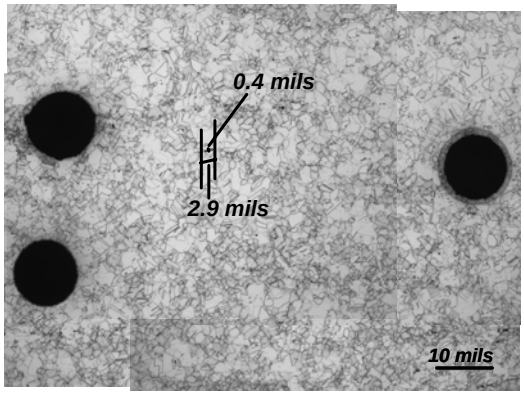
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 56 mils



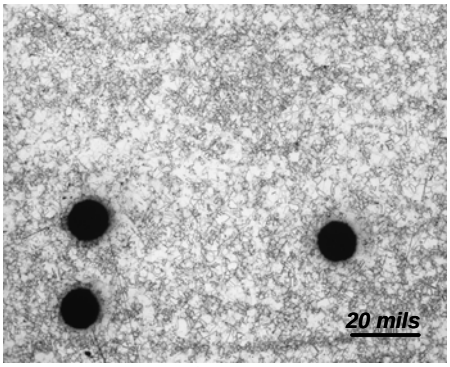
25X



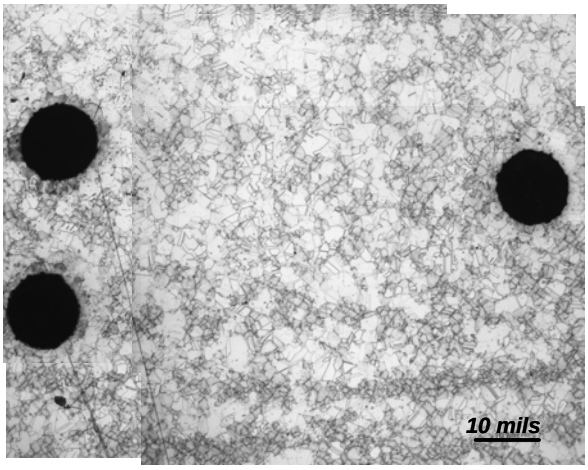
50X

Ni Billet Indication # 2 – composite micrograph

Depth = 58 mils



25X



50X

Ni Billet Indication # 2 – Ultrasonic Measurements

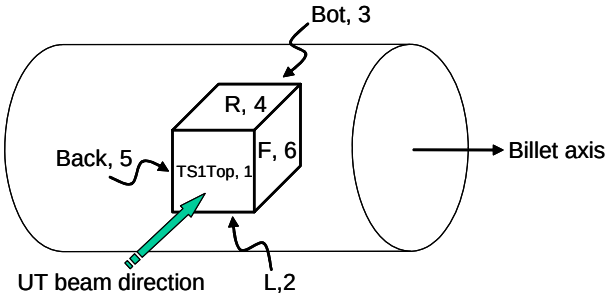
Billet Information

- Found in 10" triple melt Inconel 718 billet

Cube Information

- Dimension: sides 1&3-26.39mm, sides 2&4-26.83mm and sides5 &6-25.97mm.
- UT scans were performed at ISU using a Utex WinSpect system.
- UT data include single A-scans at peak positions, C-scan images, and volumetric A-scans at C-scan scan grids using 5 and 50 MHz transducers.
- Additional A-scans were obtained from fused quartz block as reference waveforms.
- Indication signals can only be identified on sides 1 and 3.

Billet/Cube Orientation

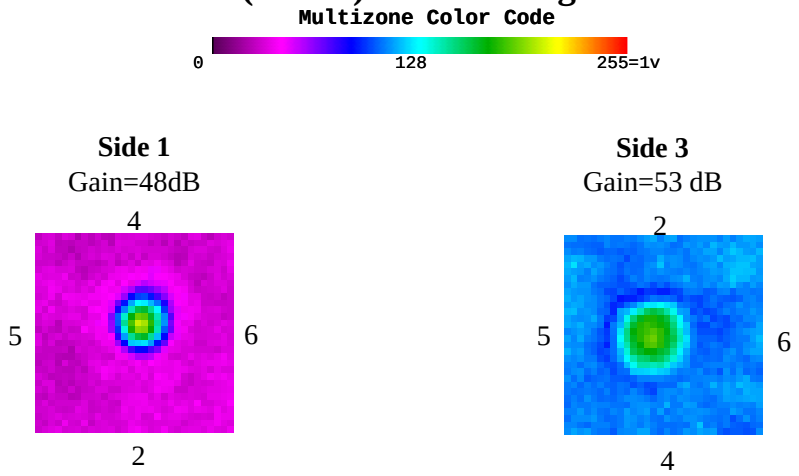


Scan Parameters

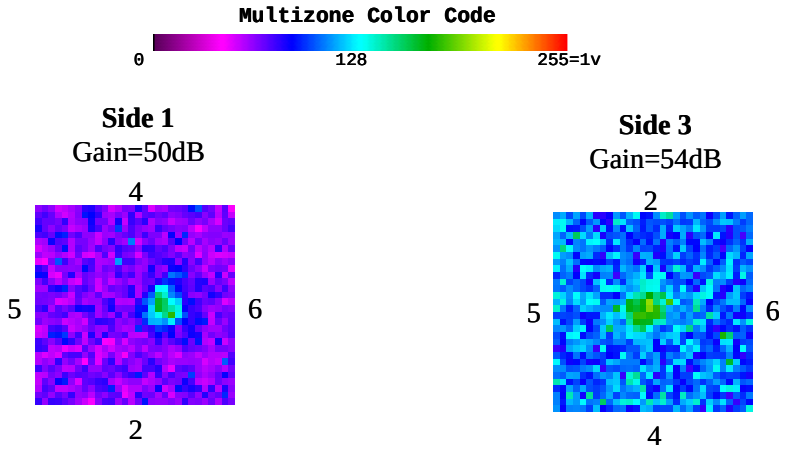
250 MHz sampling rate, 16 time averages and 61x61 pixels (scan positions) at 5 mils spatial increment applied to all scans.
PH scans used 0.69 ms time gates.
P6 scans used 0.49 and 1 ms time gates for sides 1 and 3, respectively.

Ni Billet Indication # 2 – Ultrasonic Measurements

P6 (5MHz) C-scan Images



PH (50MHz) C-scan Images

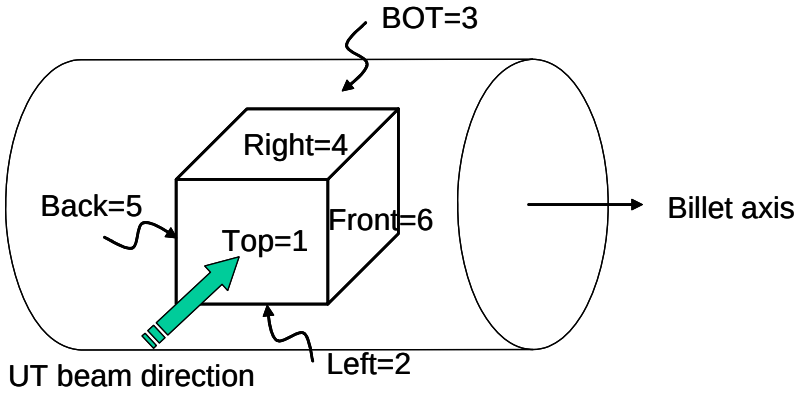


Ni Billet Indication #3 – General Information

- **Billet:** double melt 718, 10” diameter
- **MZ Calibration:** #1 flat-bottom hole at 80% of full screen height
- **MZ Indication Amplitude:** 44% of full screen height (zone 2)
- **MZ Depth:** 5.2”
- **MZ Length:** 0.45”
- **MZ Transducer Information:**
  - Frequency 5 MHz
  - Transducer Element 1.25 inches circular
  - Focal length 6.0 & 8.6 inches
  - Lens curvature bi-cylindrical
  - Beam diameter 0.245” axial
  - Test mode longitudinal
  - Water Path 3.0 inches

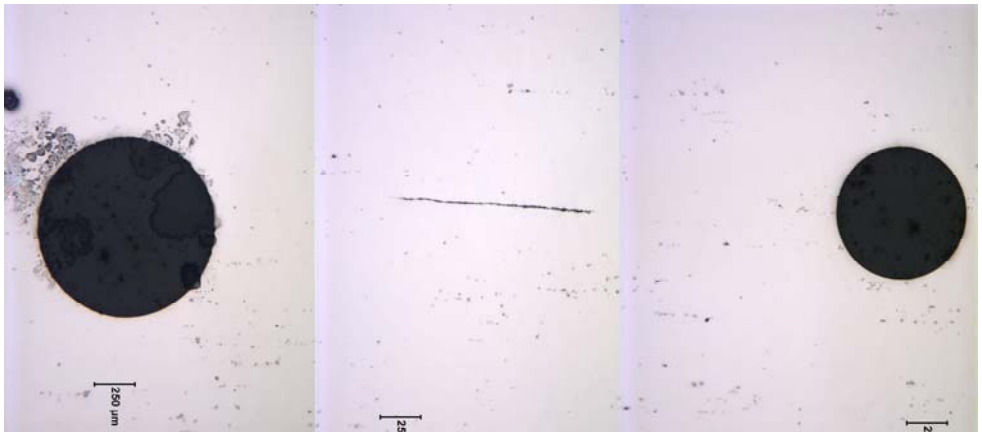
- **Conv Calibration:** #2 flat-bottom hole
- **Conv Indication Amplitude:** 15%
- **Conv Depth:** 4.8”
- **Conv Length:** 0.125”

Ni Billet Indication # 3 – sample sectioning convention



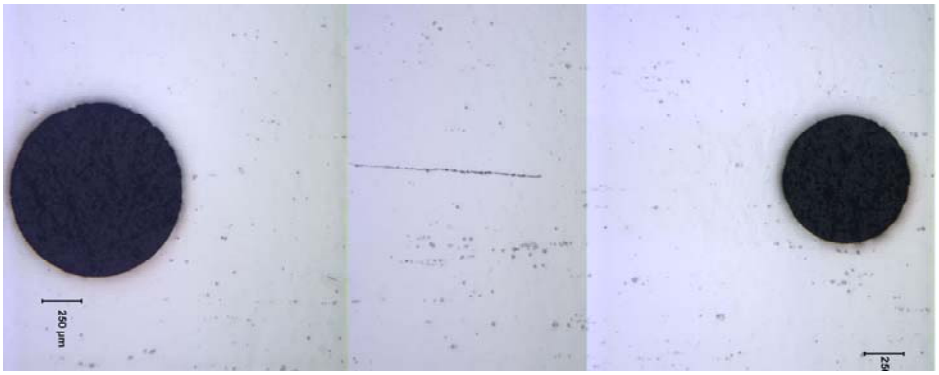
Ni Billet Indication # 3 – composite micrograph

Polish 1



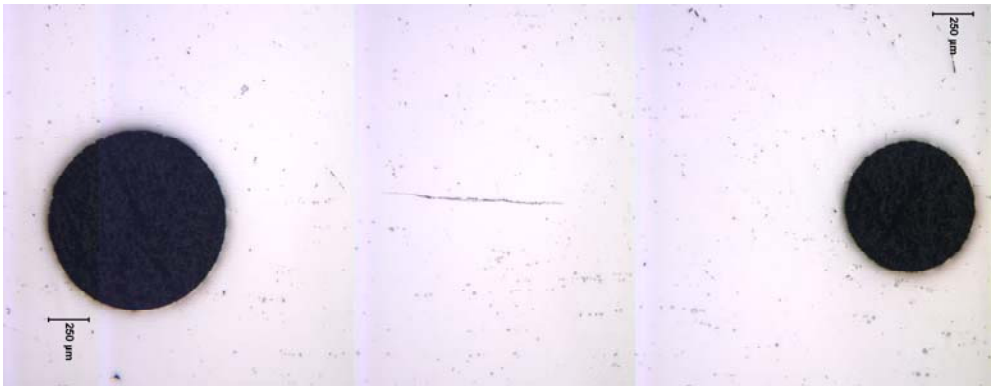
Ni Billet Indication # 3 – composite micrograph

Polish 2



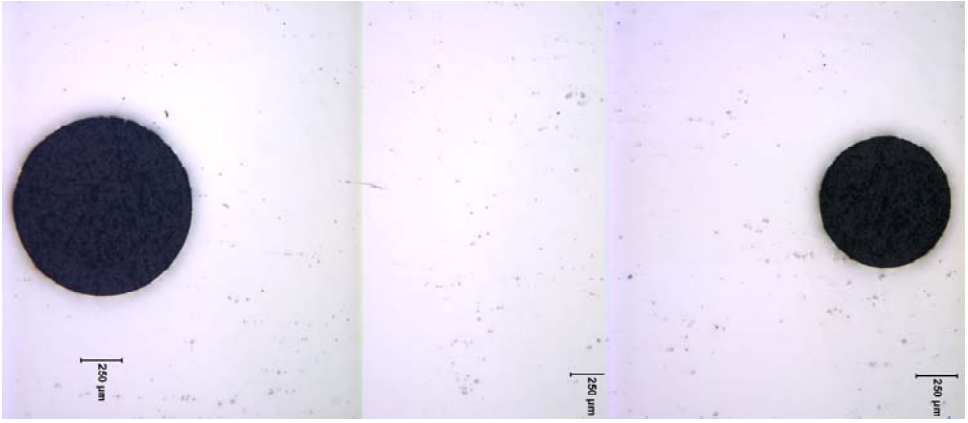
Ni Billet Indication # 3 – composite micrograph

Polish 3



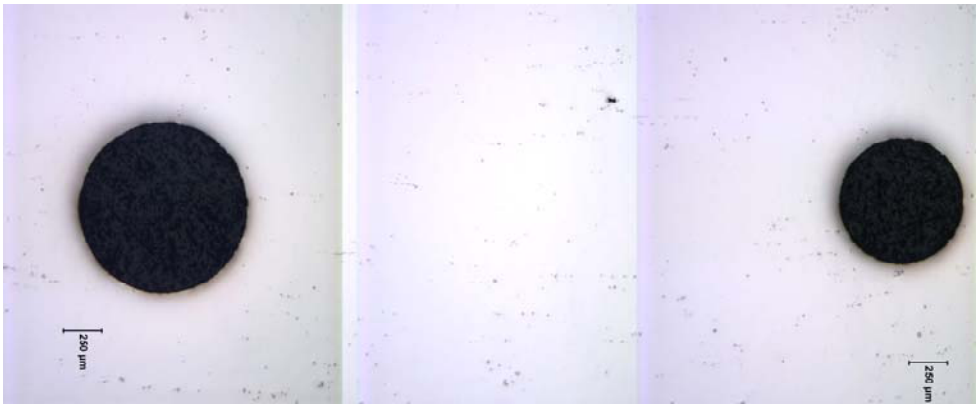
Ni Billet Indication # 3 – composite micrograph

Polish 4



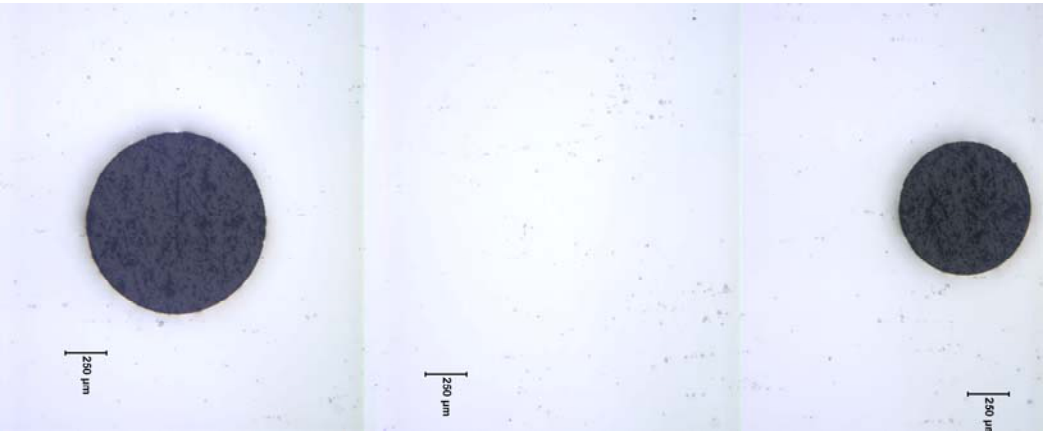
Ni Billet Indication # 3 – composite micrograph

Polish 5

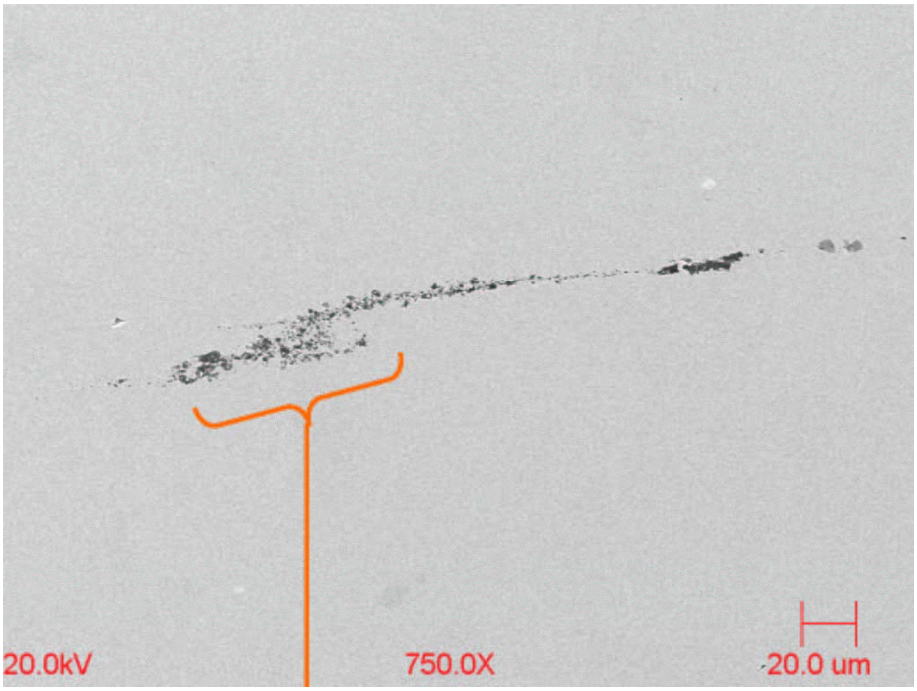


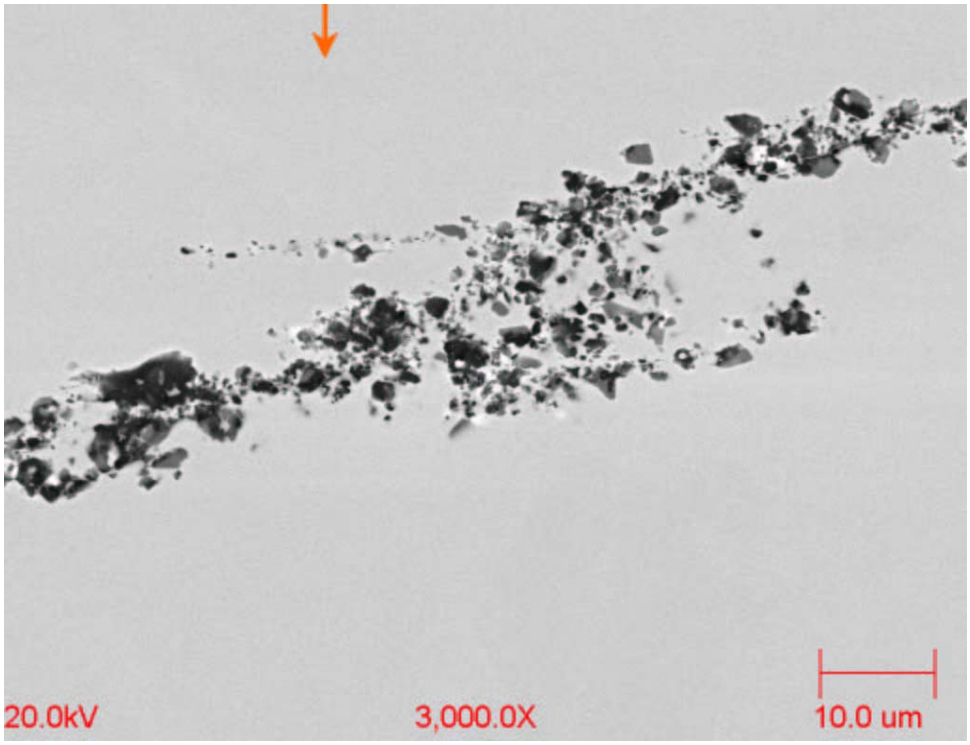
Ni Billet Indication # 3 – composite micrograph

Polish 6



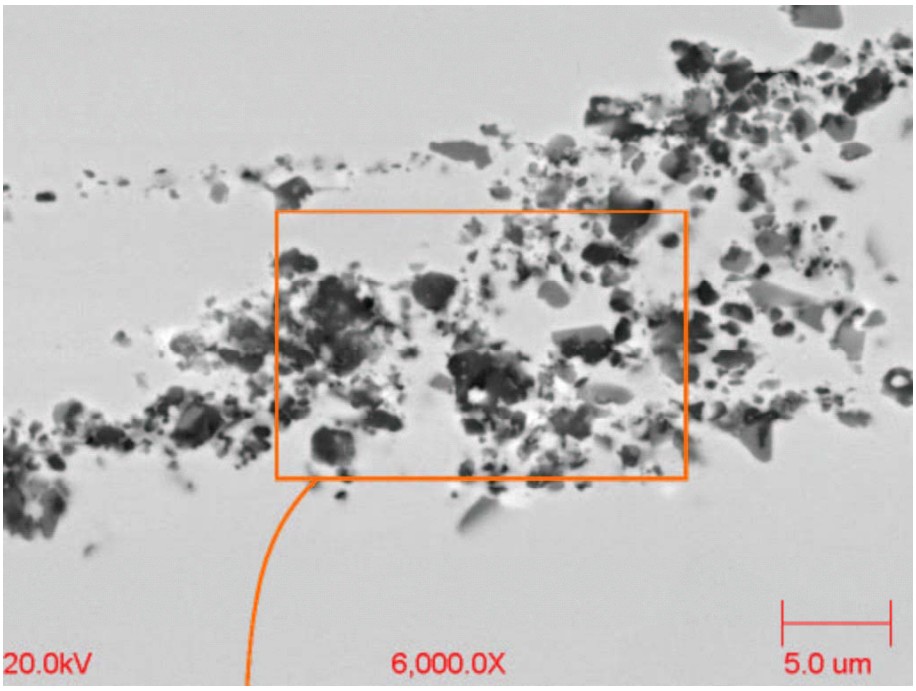
Ni Billet Indication # 3 – SEM analysis
Flaw approximately 0.015” as it appeared after removal of 0.052” of material

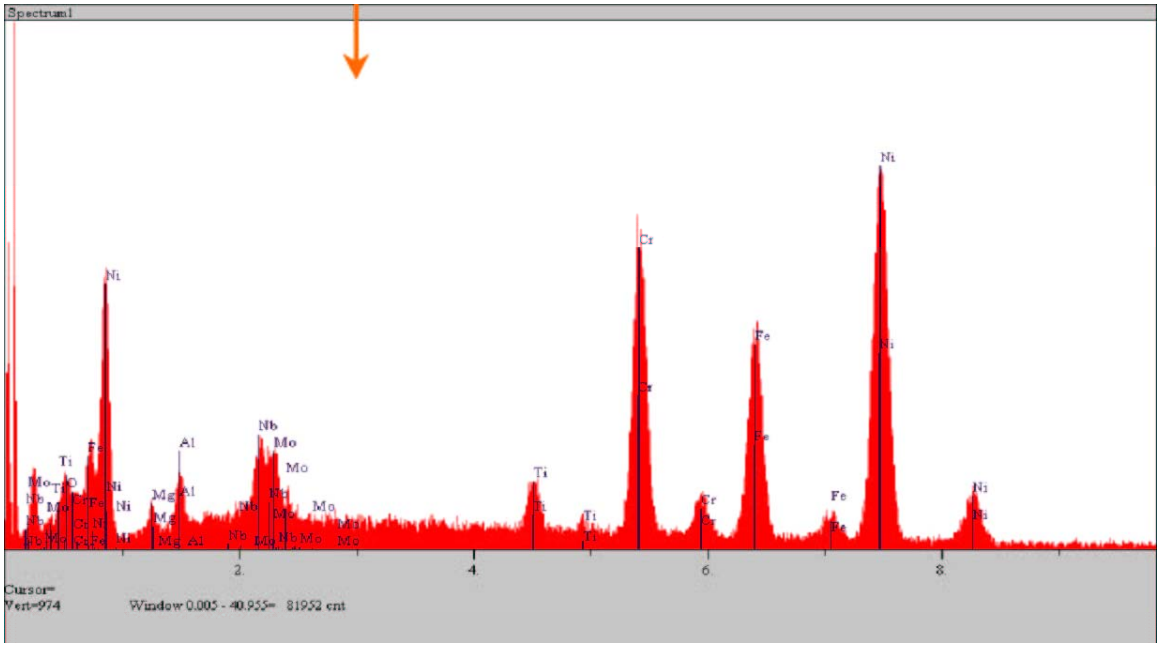




Ni Billet Indication # 3 – SEM analysis

Flaw approximately 0.015” as it appeared after removal of 0.052” of material

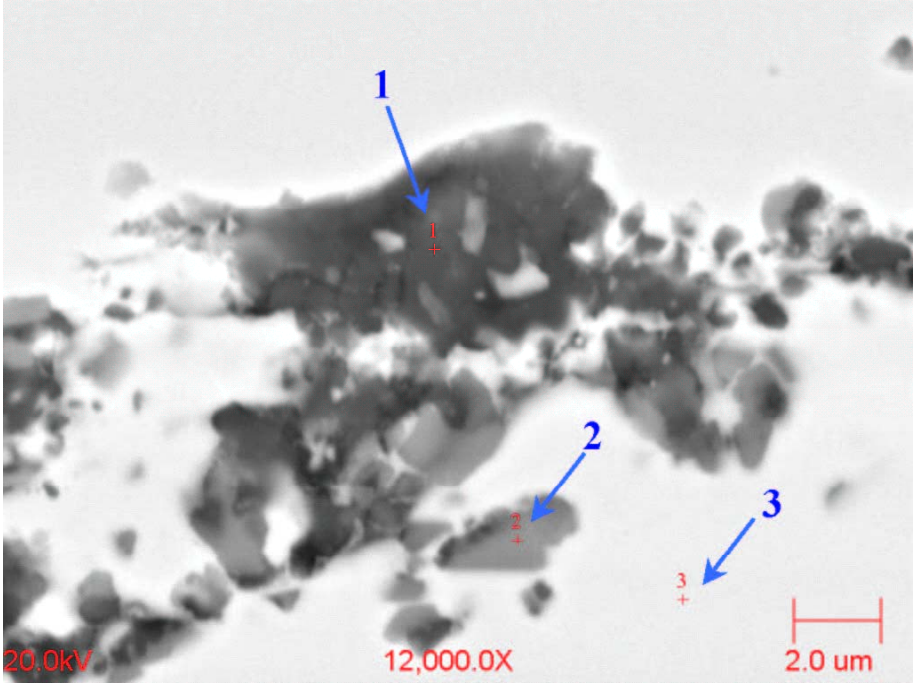


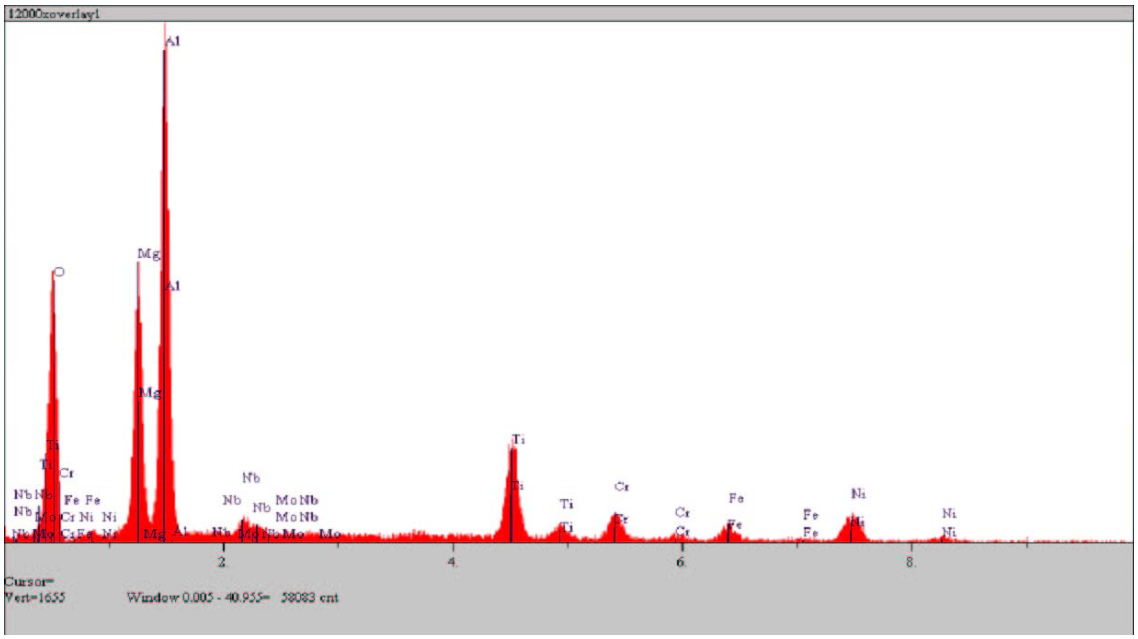


XES analysis of material in the flaw area showed the presence of primarily nickel, chromium, iron, niobium, molybdenum, titanium, aluminum and magnesium.

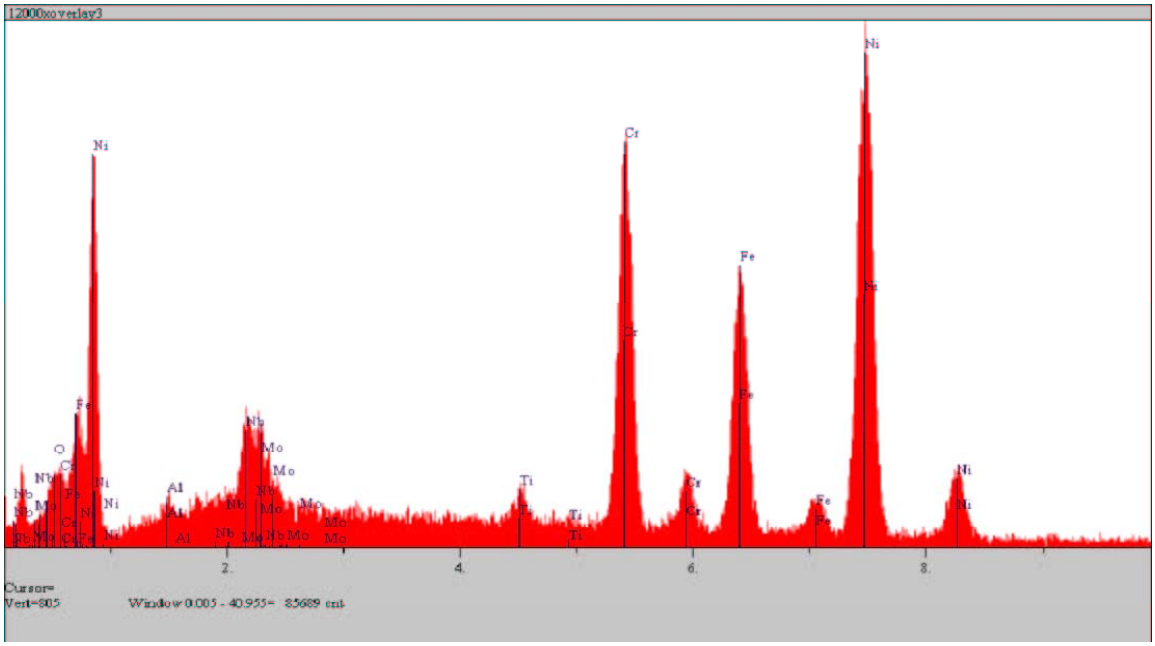
Ni Billet Indication # 3 – SEM analysis

Flaw approximately 0.015” as it appeared after removal of 0.052” of material





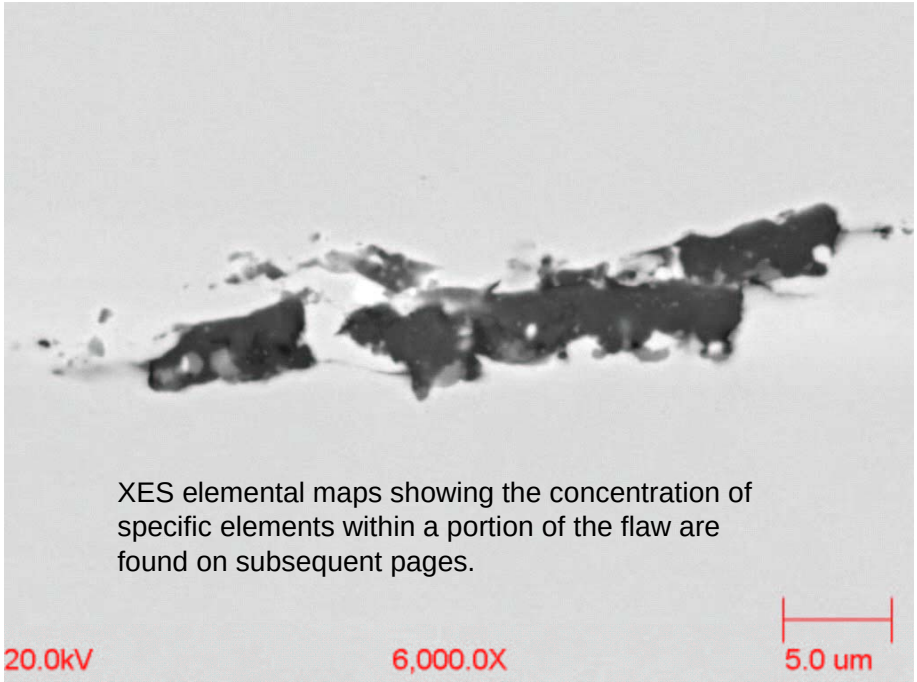
Spot XES analysis within the flaw (location 1 above) showed the presence of primarily aluminum, magnesium and oxygen.



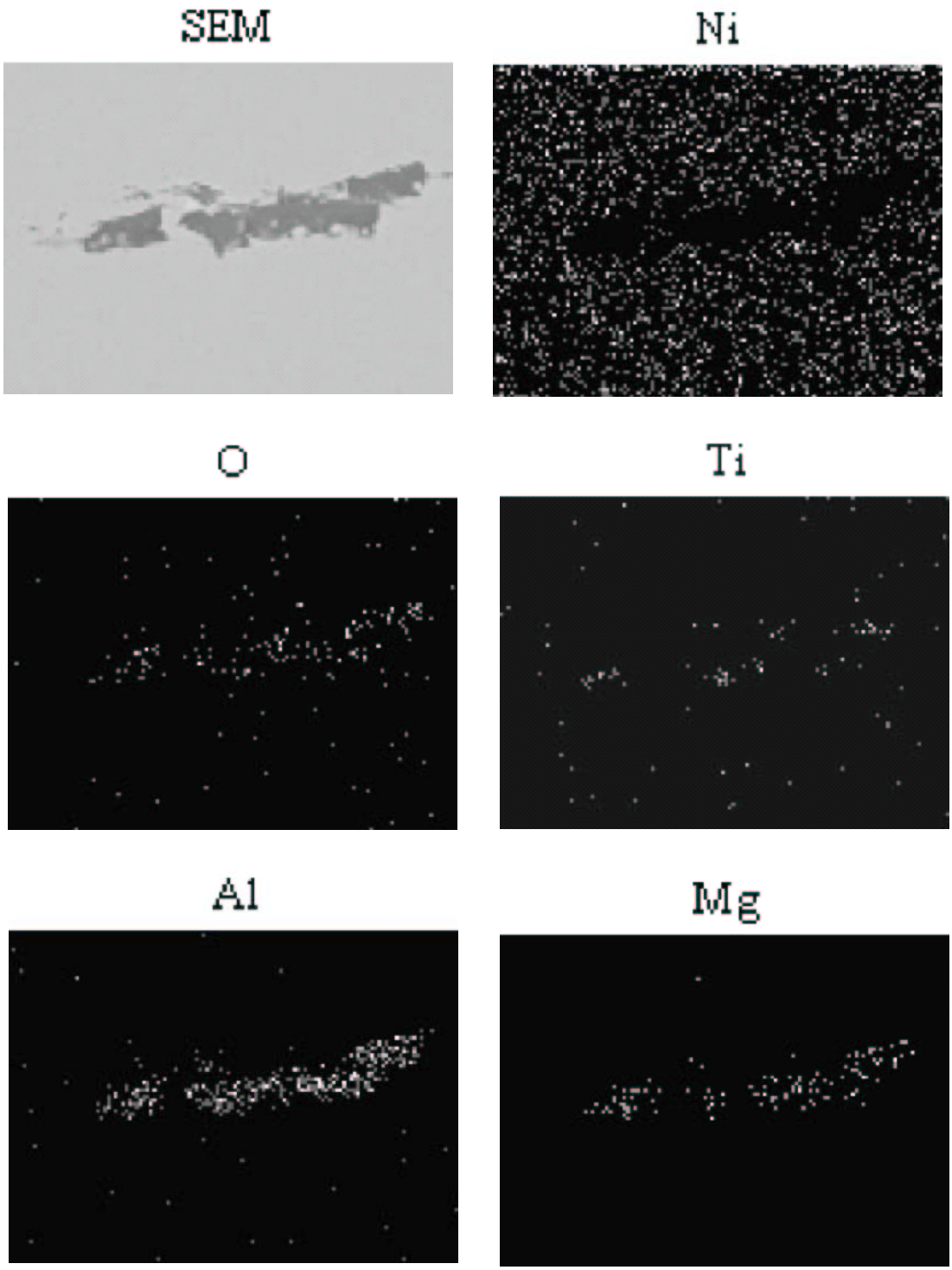
Spot XES analysis within a basemetal area near the flaw (location 3, previous page) verified the surrounding material composition is consistent with IN718.

Ni Billet Indication # 3 – SEM analysis

Flaw approximately 0.015” as it appeared after removal of 0.052” of material



Ni Billet Indication # 3 – SEM analysis

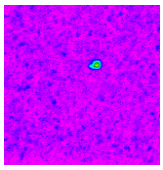


Ni Billet Indication # 3 – Ultrasonic Measurements

Experimental C-scan Images

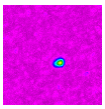
15 MHz

Side 2



0.8” X 0.8”
Gain=40 dB

Side 4



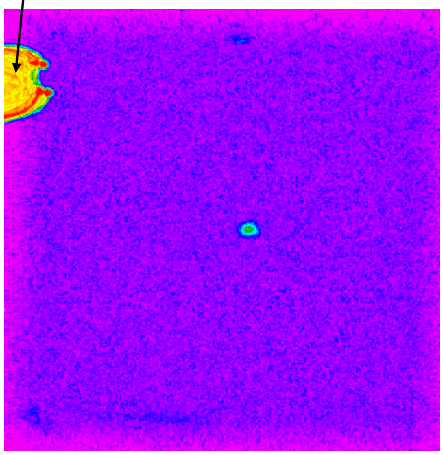
0.5” X 0.5”
Gain=43 dB

Multizone Color Code

Image resolution: All are of 0.005” scan increment (in-between pixels)
Orientation: side 5 on left and side 6 on right for sides 1~4; side 2 on left and side 4 on right for sides 5~6; both images centered w.r.t. cube face

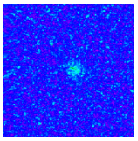
50 MHz

Side 1



1.0” X 1.0”
Gain=36 dB

Side 3



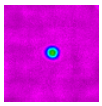
0.3” X 0.3”
Gain=41 dB

Multizone Color Code

Image resolution: 0.002” scan increment (in-between pixels)
Orientation: side 5 on left and side 6 on right; both images centered w.r.t. cube face

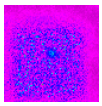
5 MHz

Side 1



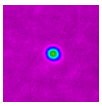
Gain=47 dB

Side 2



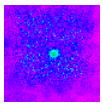
Gain=52 dB

Side 3



Gain=46 dB

Side 4



Gain=55 dB

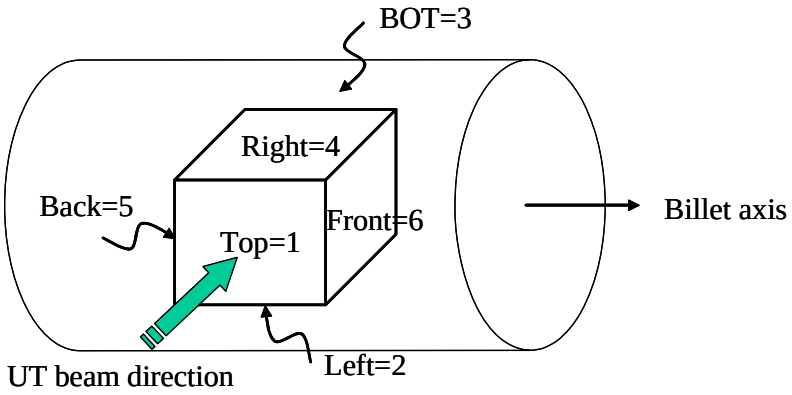
Multizone Color Code

Image resolution: All are 0.8” by 0.8” centered; of 0.01” scan increment (in-between pixels)
Orientation: side 5 on left and side 6 on right ; all images centered w.r.t. cube face

Ni Billet Indication #4 – General Information

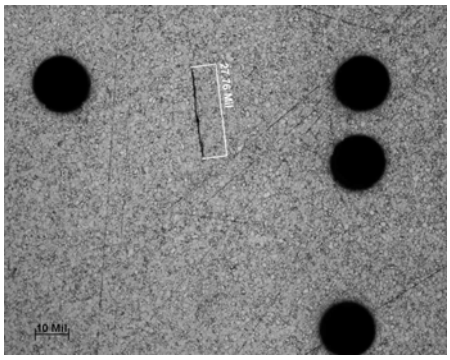
• Alloy	Inconel 718
• Melt method	Double melt VIM/VAR
• Billet diameter	10 inch
• Size of calibration reflector (1/64ths of inch)	#1
• Calibration amplitude (% screen height)	80%
• Indication amplitude before evaluation (% screen height)	20.5%
• Indication amplitude after evaluation (% screen height)	20.5%
• Distance Amplitude Correction (DAC)	No
• Indication Depth	1.7 inches
• Indication Length	0.18 inches
• Transducer information:	
– Frequency	5 MHz
– Transducer Element	1.5 inches circular
– Focal length	7.0 & 13.7 inches
– Lens curvature	bi-cylindrical
– Beam diameter	0.245” axial
– Test mode	longitudinal
– Water Path	3.0 inches

Ni Billet Indication # 4 – Cube orientation naming system

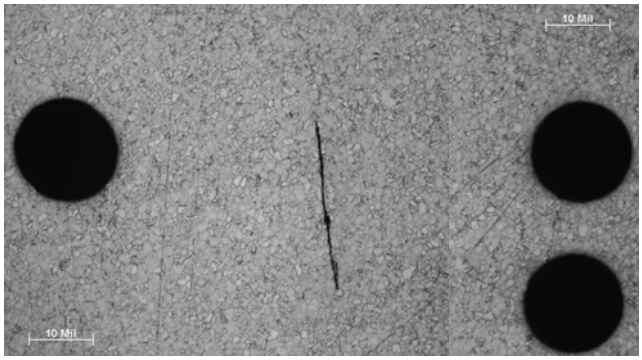


Ni Billet Indication # 4 – composite micrograph

Depth = 40 mils



25X

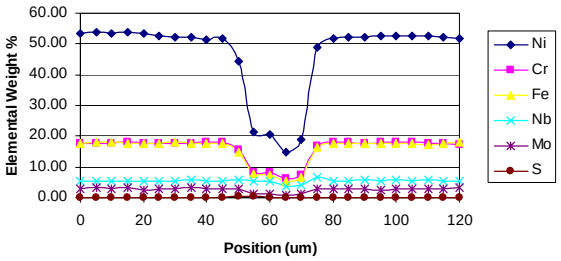


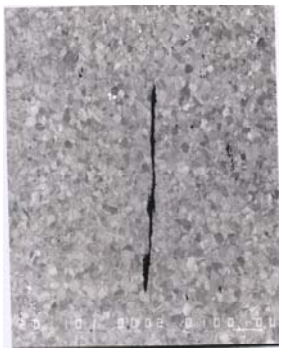
50X

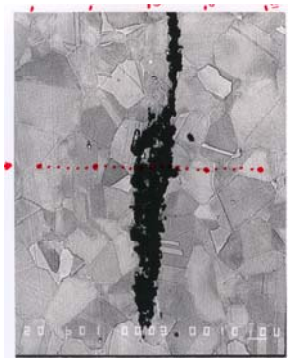
Depth = Distance From Original Surface of Side #2

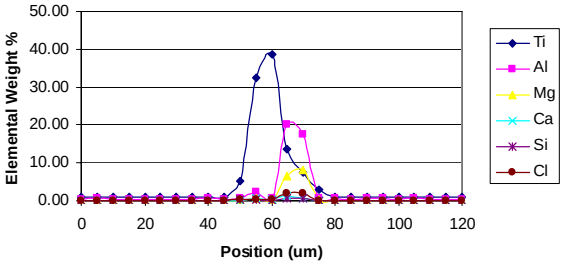
Axial Measurement = Distance along crack length (27.6 Mils)

Ni Billet Indication # 4 – SEM results from slice 1 and depth of 40 mils



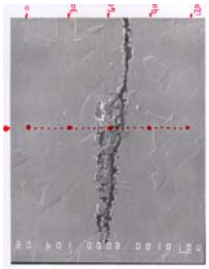




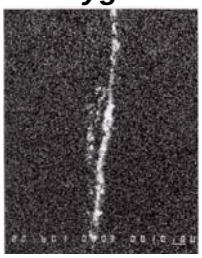


Ni Billet Indication # 4 – SEM results from slice 1 and depth of 40 mils

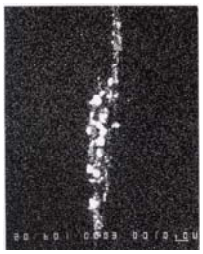
Microprobe Dot Maps



Oxygen



Titanium



Carbon

Nitrogen & Titanium

- ***Oxygen is present in abundance.***
- ***Not clear if Nitrogen is present***
  - ***Could be just Titanium or, Titanium and Nitrogen***

Ni Billet Indication # 4 – SEM results from slice 7 and depth of 50 mils

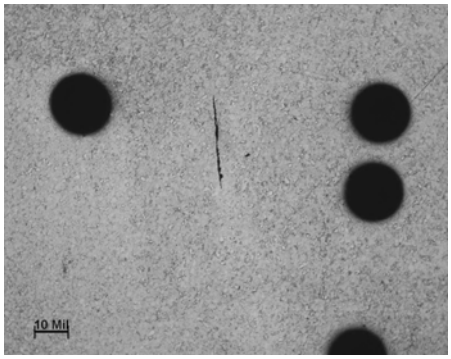
Microprobe data

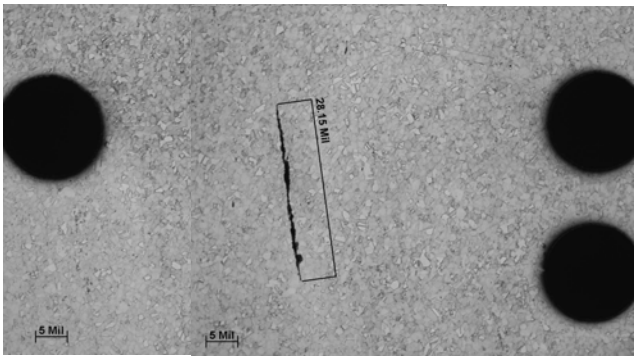
(Step Scan through 120um
using 5x5 rasters)

Step Scan Through Defect (5x5um rasters)																			
Pt#	um	Ni	Cr	Fe	Ti	Mo	Nb	Al	Mn	V	W	Zr	S	Mg	Ca	Na	Si	Cl	Total
1	0	53.29	17.78	17.69	0.98	2.97	5.53	0.46	0.05	0.04	0.01	0.14	0.01	0.02	0.00	0.00	0.09	0.06	99.13
2	5	53.81	17.74	17.93	0.97	3.20	5.48	0.49	0.06	0.06	0.00	0.09	0.08	0.00	0.02	0.00	0.08	0.02	100.04
3	10	53.25	17.71	17.92	0.98	3.01	5.37	0.47	0.07	0.05	0.00	0.04	0.13	0.00	0.00	0.00	0.06	0.05	99.11
4	15	53.65	17.89	17.83	1.00	3.11	5.33	0.43	0.06	0.06	0.00	0.00	0.16	0.04	0.00	0.02	0.11	0.01	99.72
5	20	53.39	17.72	17.74	1.04	2.59	5.52	0.48	0.05	0.03	0.00	0.00	0.10	0.00	0.00	0.01	0.04	0.05	98.76
6	25	52.58	17.67	17.82	0.99	2.83	5.54	0.48	0.04	0.02	0.00	0.18	0.03	0.01	0.00	0.00	0.03	0.03	98.27
7	30	52.06	17.64	17.99	1.00	2.82	5.42	0.48	0.05	0.03	0.00	0.20	0.07	0.00	0.00	0.00	0.05	0.03	97.84
8	35	52.11	17.73	17.65	1.00	3.16	5.72	0.46	0.09	0.03	0.00	0.15	0.08	0.01	0.01	0.00	0.09	0.05	98.31
9	40	51.41	17.92	17.87	1.04	2.90	5.34	0.50	0.04	0.03	0.00	0.00	0.10	0.00	0.00	0.01	0.08	0.08	97.32
10	45	51.70	18.04	17.72	1.08	3.01	5.54	0.49	0.06	0.05	0.00	0.00	0.08	0.03	0.01	0.00	0.05	0.06	97.91
11	50	44.37	15.44	14.68	5.24	2.73	5.57	0.71	0.06	0.03	0.00	0.00	0.36	0.12	0.13	0.08	0.23	0.29	90.04
12	55	21.33	8.40	7.97	32.56	1.10	5.42	2.35	0.02	0.12	0.00	0.15	0.26	0.58	0.81	0.02	0.20	0.32	81.60
13	60	20.46	8.02	7.55	38.76	1.18	5.34	0.76	0.00	0.15	0.00	0.00	0.10	0.04	0.25	0.01	0.06	0.33	83.02
14	65	14.84	5.99	5.47	13.56	0.97	3.90	19.97	0.01	0.05	0.00	0.00	0.14	6.50	1.18	0.03	0.69	1.81	75.10
15	70	18.86	7.32	6.77	7.47	1.07	3.92	17.38	0.01	0.04	0.00	0.06	0.16	8.01	0.70	0.02	0.80	2.10	74.67
16	75	48.86	16.72	16.51	3.01	2.82	6.71	0.62	0.06	0.04	0.02	0.15	0.18	0.38	0.05	0.07	0.09	0.14	96.45
17	80	51.95	17.98	17.84	1.04	2.98	5.50	0.51	0.03	0.06	0.00	0.00	0.06	0.05	0.01	0.05	0.09	0.08	98.22
18	85	52.15	17.90	17.64	0.99	2.95	5.47	0.47	0.04	0.04	0.00	0.15	0.05	0.02	0.00	0.01	0.07	0.02	97.98
19	90	52.32	17.82	17.86	1.01	3.07	5.76	0.49	0.03	0.07	0.00	0.01	0.04	0.00	0.01	0.04	0.05	0.03	98.62
20	95	52.75	17.90	17.65	0.98	2.66	5.46	0.49	0.06	0.00	0.00	0.20	0.09	0.03	0.00	0.00	0.10	0.09	98.48
21	100	52.62	17.94	17.72	1.00	2.92	5.58	0.47	0.05	0.05	0.00	0.16	0.08	0.00	0.00	0.00	0.11	0.06	98.76
22	105	52.67	18.03	17.59	1.02	3.03	5.37	0.49	0.08	0.05	0.00	0.06	0.08	0.00	0.00	0.00	0.07	0.03	98.56
23	110	52.62	17.82	17.27	1.00	3.05	5.82	0.47	0.06	0.03	0.00	0.00	0.05	0.01	0.00	0.00	0.07	0.01	98.28
24	115	52.11	17.83	17.63	1.00	2.74	5.44	0.47	0.09	0.03	0.00	0.00	0.01	0.00	0.00	0.01	0.05	0.02	97.43
25	120	51.62	17.45	18.07	1.01	3.14	5.22	0.48	0.04	0.05	0.01	0.00	0.06	0.03	0.00	0.02	0.09	0.01	97.29

Ni Billet Indication # 4 – composite micrograph

Depth = 41.6 mils

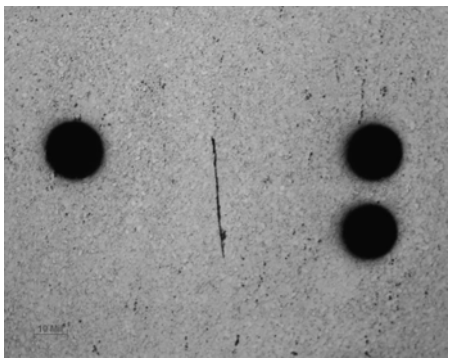


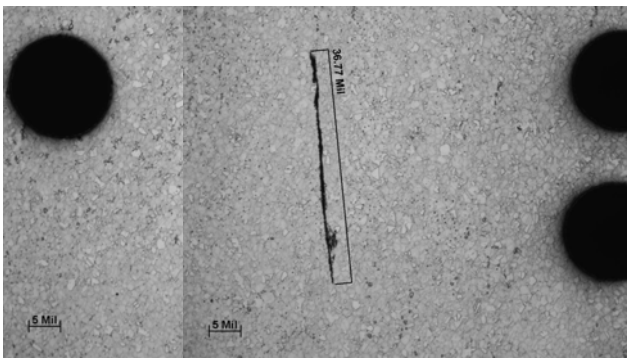


25X ***50X***

Ni Billet Indication # 4 – composite micrograph

Depth = 43.6 mils

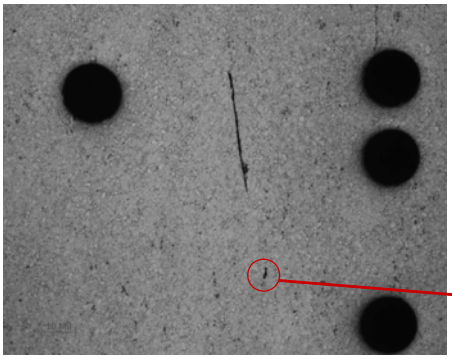




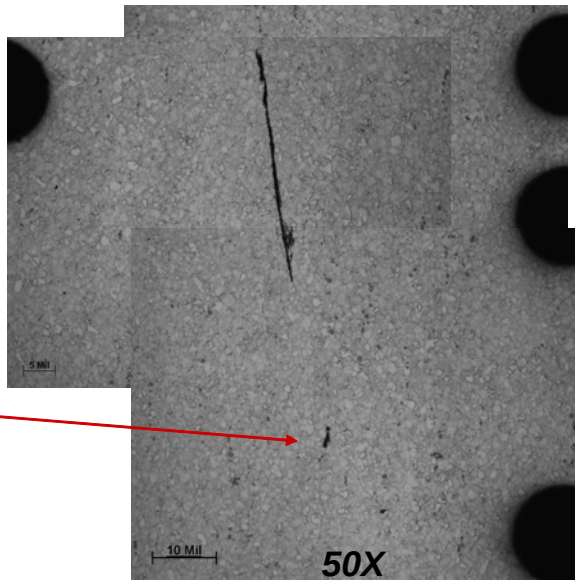
25X ***50X***

Ni Billet Indication # 4 – composite micrograph

Depth = 43.6 mils – appearance of second discontinuity



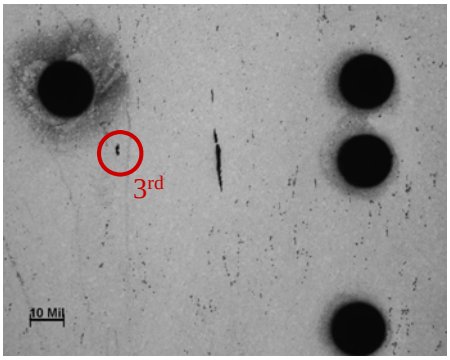
25X



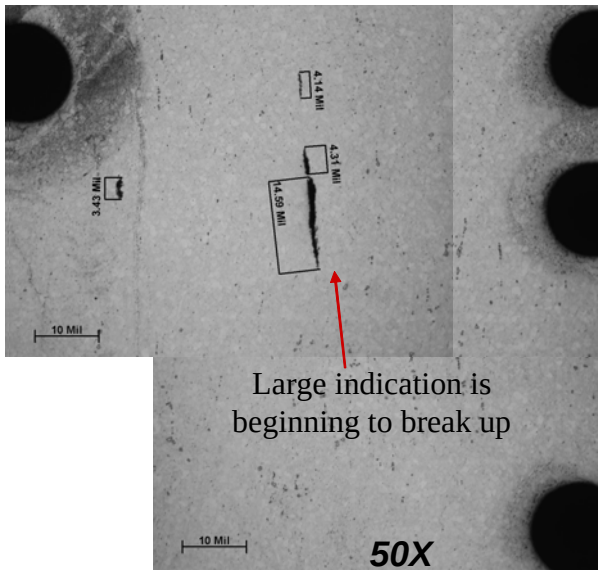
50X

Ni Billet Indication # 4 – composite micrograph

Depth = 45.6 mils – appearance of third discontinuity



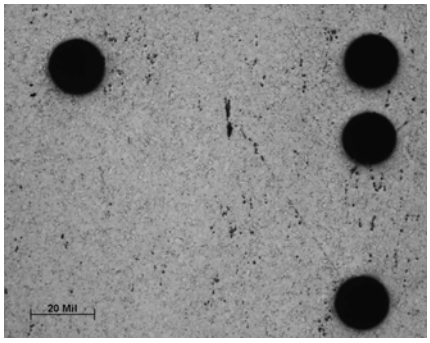
25X



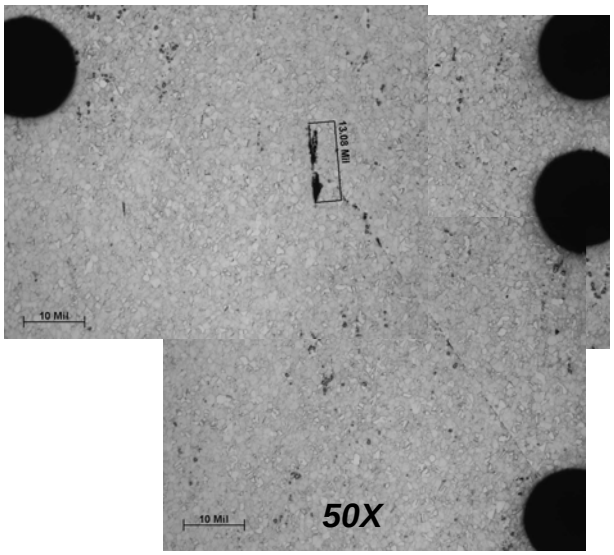
50X

Ni Billet Indication # 4 – composite micrograph

Depth = 47.6 mils



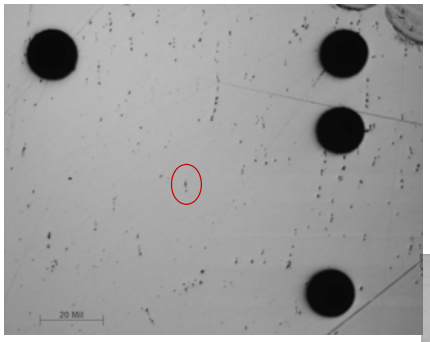
25X



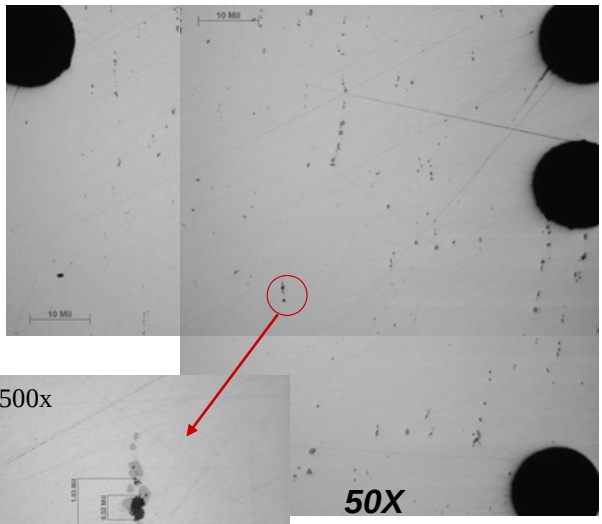
50X

Ni Billet Indication # 4 – composite micrograph

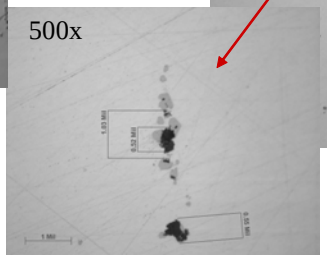
Depth = 49.6 mils – appearance of fourth discontinuity



25X



50X



Sample was unetched because of the number of surface scratches. More material would have to be polished in order to etch.

Ni Billet Indication # 4 – Ultrasonic Measurements

C-scan Images

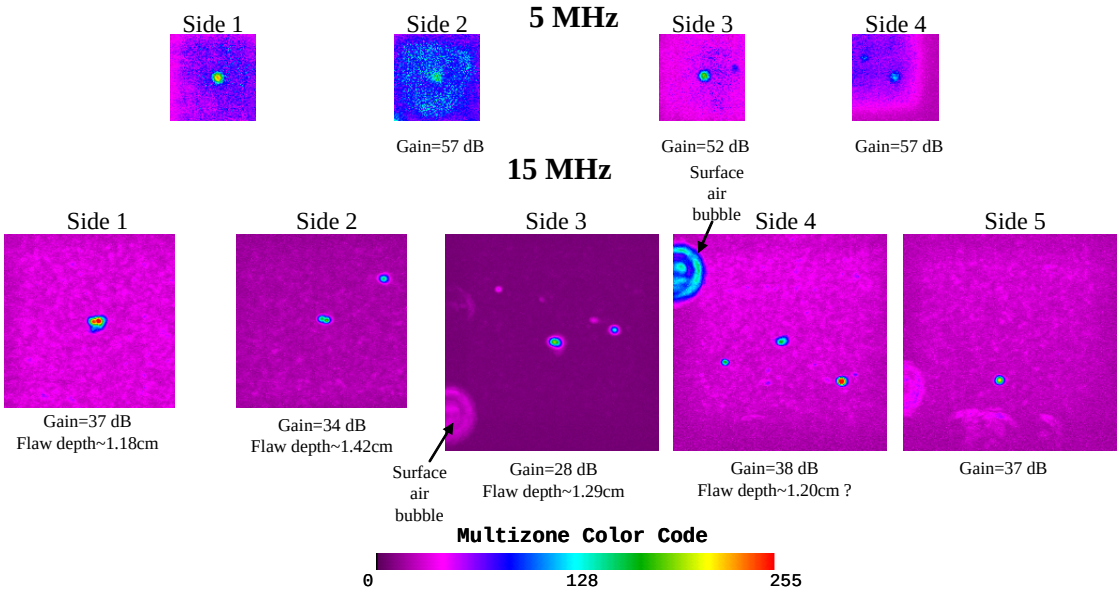
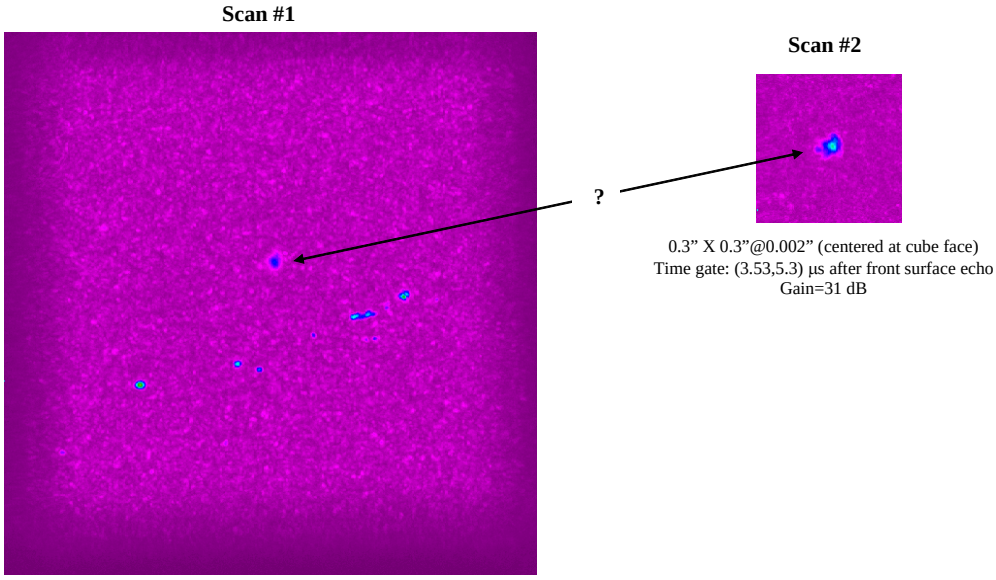


Image size: 5MHz=0.8” by 0.8”; 15MHz=0.8” by 0.8” (sides 1 and 2), 1” by 1” (the rest)
Image resolution: 5MHz=0.01”, 15MHz=0.005”
Orientation: side 5 on left and side 6 on right for sides 1~4; side 2 on left and side 4 on right for sides 5~6
NOTE: (1) Each image is roughly centered at the corresponding cube face
(2) flaw depth is approximated by using time-of-flight of main flaw signal and measured Ni L-wave speed

Ni Billet Indication # 4 – Ultrasonic Measurements

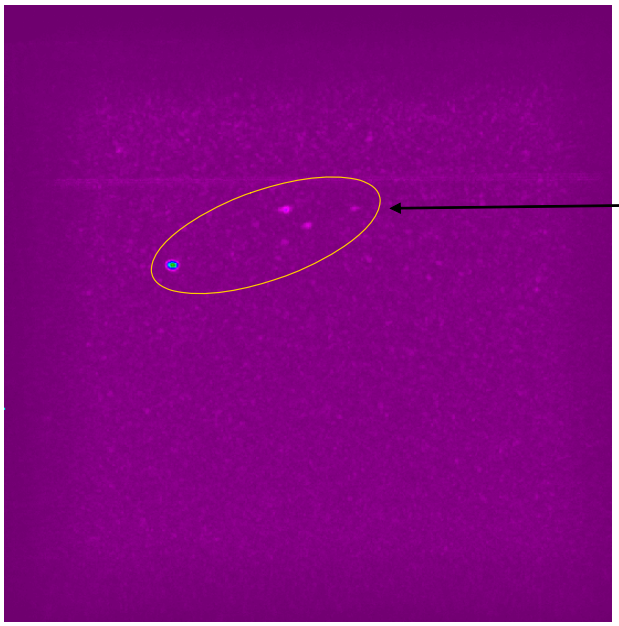
50 MHz side 1



Ni Billet Indication #4 – Ultrasonic Measurements

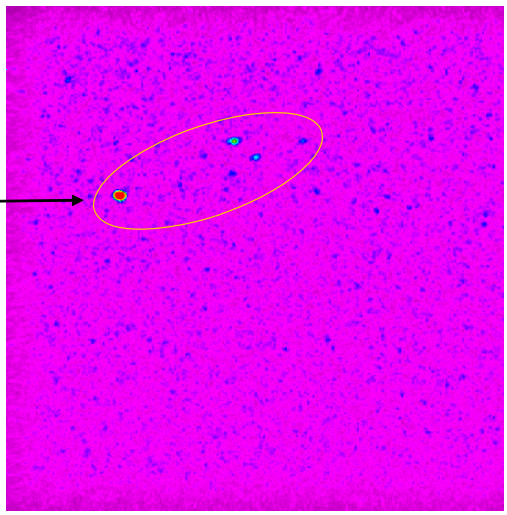
50 MHz side 2

Scan #1



1.1” X 1.1”@0.002” (centered at cube face)
Gain=23 dB

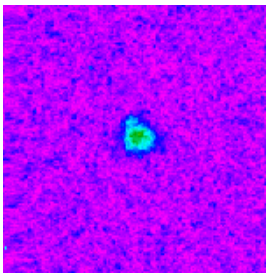
Scan #2



0.9” X 0.9”@0.002” (centered at cube face)
Gain=34 dB

Two flaw depths: ~0.835 cm and ~0.785cm

50 MHz side 3



0.3” X 0.3”@0.002” (centered at cube face with ~0.1” offset toward lower-left corner)
Gain=38 dB

APPENDIX B—DATA ACQUISITION PROCEDURE

UT Data Acquisition Procedure for ETC Real Defects
Using a Sonix Immersion System

by C. Thomas Chiou, Mike Keller, Jeff Umbach and Andrei Degtyar

Last update: 04-17-01

1. Introduction

This procedure is written for internal use in ETC-II Task 1.1.1 Fundamental Studies and other related tasks. The objective is to acquire UT A-scan, C-scan and multiple b-scan (volumetric A-scan) data of naturally occurring defects embedded in a small Ti- or Ni-based cube block. The target readers are NDE staff with sufficient experience in use of a Sonix immersion system. Some technical details has been included here in an attempt to make this document self-contained. Section 2 lists the basic requirements of system components and accessories. Section 3 lays out the experimental setups of the reference and defect data acquisition, for which the step-by-step procedures are described in Sections 6 and 7. Other supporting materials are provided in the remaining sections. For clarification of several key terminologies, the readers are referred to Section 9.

2. System Requirements

The designated scan hardware is a computerized Sonix immersion scan system produced in the 1990's (or later) with three-axis scan capability, controlled by Sonix FlexSCAN-C software version 4.0 (or higher). Sonix default pulser/receiver such as DPR-35+ should be used if equipped, but other typical pulser/receivers such as Panametrics 505x series can be substituted. A standard transducer search tube (mounting pole) and a mechanical transducer manipulator capable of two angular position controls are assumed to be parts of the scan system. The defect specimen should have been sectioned down to a minimum size (typically around 1″ cube) with the defect centered in the block. Knowledge of defect depth on each of the six sides is expected. The front and back surfaces of the defect cube block in the three orthogonal directions should also be made as parallel as possible. The accessories include a sample stand, a thermometer, transducer sets and fused-quartz reference sets. The specifications and usage of each accessory component are as follows.

2.1 Sample stand

A three- or four-legged flat stand of circular (or rectangular) shape with minimal size of 4″ diameter (or side) is needed to support the cube sample and the reference plate in the scan tank. This stand should be made of rust-free materials such as stainless steel, Ti or epoxy glass, and the stand legs must be adjustable with good precision for leveling.

2.2 Thermometer

A thermometer is needed to measure the water temperature of the scan tank from which the water attenuation can be estimated. The precision of the thermometer should be within 1 degree Celsius or Fahrenheit.

2.3 Transducer Set

Minimally, two focused transducers are needed to acquire the UT data. Both should generally be spherically focused with central frequencies around 5MHz for one and at least 15 MHz for the other. Assuming a maximum 0.5″ defect depth below all six sides of the defect cube block, all transducers must have at least a 2″ true focal length (see Section 9.1 for definition) for good focusing. The size and focal length combination of the transducer should be carefully selected so that the beam entry area will not be larger than the 1″ square surface of the defect cube block. The typical transducer set used consisted of a 5MHz, 1″ diameter, 8″ true focal length transducer and a 25 MHz, 0.25″ diameter, 2″ true focal length transducer.

In order to determine the key transducer parameters such as the true focal lengths, geometric focal lengths and equivalent diameters (Section 9.1), all transducers must also be characterized. The transducer characterization task may be performed at ISU before a procedure is specified and tested at other sites in the future.

2.4 Reference Set

Minimally one (two recommended) fused-quartz plate is needed for the above-mentioned transducers to take reference waveforms (A-scans). These reference waveforms will be used by UT models to estimate the system efficiency factor of the scan system (Section 3.1). The plate thickness should be 1″ (used with 5MHz transducer) and 0.5″ (used with 15 MHz transducer and above) for the primary and the second optional plates, respectively. The size of the plate(s), normally 2″-4″ in diameter (or per side), should fit with the service area of the sample stand. Like the defect cube block, the front and back surfaces of the plate(s) should also be parallel.

3. Experimental Setups

3.1 Basic Setups

One of the objectives of acquiring UT data with this procedure is to support UT modeling activities. The UT models used in ETC are based on ISU's Thompson-Gray measurement model framework [1]. In order to predict real defect signals at absolute levels as seen on the oscilloscope, these UT models require a separate reference experiment from which the scan system response or system efficiency factor can be estimated. Thus, the data acquisition actually consists of two parts: the main task is to acquire the defect data from the cube block, and the other is to obtain the reference waveforms from, as mentioned in Section 2.4 above,

the fused-quartz set(s). The setup of these two experiments, both in immersion mode, are illustrated below.

In Figure 3.1, a focused transducer (specified in Section 2.3) is normalized (Section 3.4) to the front surface of a fused-quartz plate of thickness $Y_{r,s}$. Given the UT speeds in water and fused-quartz (Sections 9.2 and 9.3), plate thickness, and the transducer focal length, the water path is set (see Section 9.4 for formula) to $Y_{r,w}$ such that the geometric focal length (section 9.1) is on the back surface of the fused-quartz plate. Echoes from the back surface, i.e. the reference waveforms (A-scans), are to be acquired in this experiment. Note that additional spacers need to be placed between the fused-quartz plate and the stand, which ensures water to be the backing medium. This is important for UT models to set up correct interface parameters without ambiguity.

In Figure 3.2, the <u>same</u> transducer is similarly normalized to the front surface of the defect cube block. However, a different water path $Y_{d,w}$ is used so that true focal length is on the nearest (front) surface of the defect, for which the defect depths $Y_{d,s}$ in all six sides should have been measured (Section 1). Prior to transducer normalization, the stand needs to be leveled with respect to the paths of the scan bridge (Section 3.2). It is also assumed that both front and back surfaces of the defect block are in parallel to the leveled stand surface (Section 1). In this experiment, single-shot A-scans, two-dimensional C-scans, and three-dimensional b-scans (see Section 9.1 for definition) will be acquired.

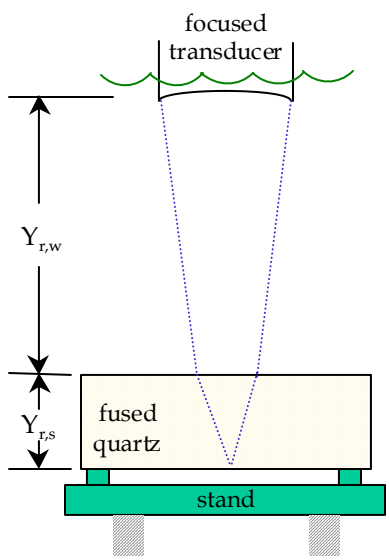


Figure 3.1 Reference Experiment

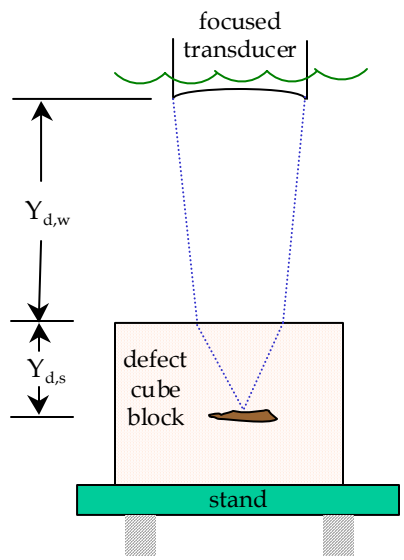


Figure 3.2 Defect Experiment

<u>It should be pointed out that all hardware connections (such as the co-axial cables and transducer search tube) and settings (such as damping, pulse rate, energy level on pulser/receiver unit) must be kept the same for both the reference and defect experiments. The only adjustable setting is the gain (or attenuation on Panametrics models) of the pulser/receiver unit</u>. This is to ensure the accuracy of the system efficiency factor as stated above.

In order to warrant the best possible data obtained in an optimal condition of a given scan system, extra care should also be taken on the specimen placement issues. Specimen placement involves the leveling of the specimen and orienting the specimen with respect to the scan system coordinates. These are the subjects of the following subsections.

3.2 Specimen Leveling

For a typical linear scan, the rule of thumb is to maintain a constant distance between the beam entry surface and the transducer face. This constant distance can in turn be related to the planar path that the scan bridges move about, assuming there is no bending of the scan bridges (see Section 4.2). This ensures the alignment of the specimen and the scan bridges to avoid the fluctuations of beam focusing and signal time-of-flight. This is referred as specimen leveling with constant water path, and the surface to be leveled is often the front surface of the specimen. A common technique of leveling a front surface is to perform a lengthy line scan on that surface. During the scanning, the amount of change in time-of-flight of an echo from the front surface, as seen on the oscilloscope, determines the degree of tilting of the surface. One can then adjust, for instance, the screws of the sample stand to correct the tilt. However, given the relatively large size of the transducer (1″ diameter for the 5MHz transducer) and small dimension of the defect block (~1″ cube), this technique does not work well in this case. The solution here is to level the surface of the sample stand instead. The leveling of the sample stand ensures the same for the front and back surfaces of the defect cube block, since they are parallel to each other as was required (Section 1). For the reference fused-quartz plate, the leveling is not as crucial because only single-shot A-scans are acquired.

3.3 Specimen Orientation

Based on past experience with the Sonix system, issues related to specimen orientation have frequently been the source of error and confusion. Often the C-scan images were rotationally disoriented or mirror-inverted from the actual specimen layout. The problem arises largely from the inconsistency between the specimen orientation (in the water tank) and the Sonix scan plan. To avoid such difficulty, <u>it is recommended that the Sonix scan plan be set up to match exactly with the actual specimen orientation</u>. As an example, Figure 3.3a illustrates a hypothetical specimen orientation and the matching Sonix C-scan line paths (see Section 9.5 for detailed scan/step direction settings under FlexSCAN-C's Scan Setup menu). If the bottom-up image convention (with origin at lower-left corner) is followed, then the orientation of the C-scan image, as depicted in Figure 3.3b, should match correctly with that of the specimen. It is also recommended to keep a drawing of the specimen orientation with respect to the scan plan and a copy of the details of the scan plan settings for future reference.

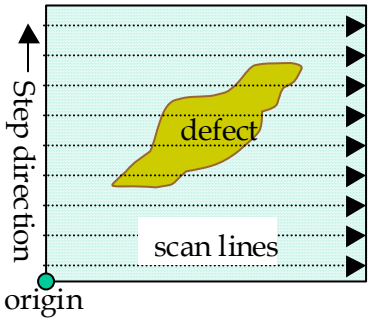


Figure 3.3.a specimen and scan orientations

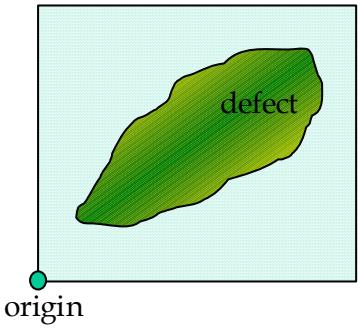


Figure 3.3b resulting C-scan image

3.4 Transducer Normalization

In addition to specimen leveling, the normalization of the transducer is also an important but often difficult task. By normalization we mean to orient the transducer with respect to the beam entry surface in such a way that the sound beam enters the specimen with minimum energy loss and achieves the optimal focusing. For spherically focused transducers, a popular ring wave method of normalization has proven reliable. The ring wave method takes advantage of the time-of-flight difference between the outer transducer ring wave and inner main beam. As depicted in Figure 3.4b, when the transducer is very close to a flat surface, the central main component of the beam takes a longer time to travel back and forth than the outer ring components do. This results in a separation of the time domain front surface echo into a small leading ring signal and a large trailing main signal as shown in Figure 3.4b. If the transducer is well fabricated, the ring signal will reach its maximum when the transducer is perpendicular to the surface such that all ring components travel using the same amount of time. This phenomenon thus provides a practical way to normalize a focused transducer of axial symmetry. The degree of time separation between the ring and main components depends on the size, focal length and frequency of the transducer. For the 5MHz, 1″ diameter, spherically focused transducer with focal length 8″ at about 0.5″ above a flat surface, the time separation is substantial. For a higher frequency transducer with shorter focal length and smaller diameter, the separation becomes less clear. In this case, the inseparable main and ring signals should be viewed as a whole and maximized in the process of transducer normalization.

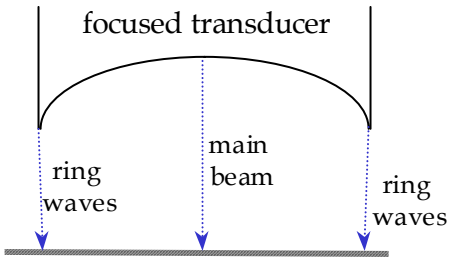


Figure 3.4a “ring-wave” setup

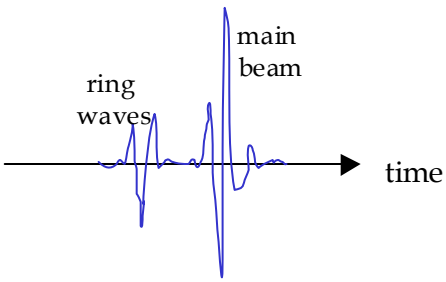


Figure 3.4b corresponding A-scan

4. System Calibration

In addition to an optimal experimental setup, a thorough system calibration process is the key to data accuracy and should be conducted BEFORE any data acquisition. In this procedure, there are three elements in the system calibration process: pulser/receiver, mechanical scan bridges, and oscilloscope. It is also strongly recommended to follow all calibration procedures described in FlexSCAN-C user's guide.

4.1 Pulser/Receiver

Important electronic parts like the pulser/receiver are often overlooked in the calibration process. While the accuracy of other aspects of the pulser/receiver matters, the single most critical function of the pulser/receiver for this procedure is the gain (or attenuation) setting, the only adjustable electronic parameters in the system (recall Section 3.1). Extra care should be taken in operating this setting. For example, the receiver of Panametrics 5052 is rated maximum output voltage of $\pm$0.5 volt into 50 Ohms. Any signal that has peak-to-peak amplitude exceeding 1 volt is subjected to distortion and loss of data accuracy. Thus, it is vital to maintain a linear undistorted operation of the gain (attenuation) setting in the pulser/receiver unit and acquire measurements in this linear range. A simple test of the linearity is to measure the peak-to-peak amplitude of a stationary signal (within the maximum output limit) with a sequence of gain settings that lie in the expected range of operation. The amplitude change in measurement should be linearly proportional to that in the gain settings. Proper remedy needs to be made if significant deviation from the linearity is observed.

Mechanical Scan Bridges

Typical problems with mechanical scan parts are scan bridge bending due to aging and scan backlash effects. Severe scan bridge bending may cause data loss and/or incorrect data registration. For example, heavy weight over time can cause the center of a scan bridge to buckle downward, which leads to a shorter water path in the central portion of scan. For a fixed narrow time gate in which UT data are digitized, a portion of the target UT signal may then shift out in this central scan path depending on the amount of bending. The misalignment problem may also arise when the beam entry surface of specimen has variable curvature. Because of these shortcomings, at most times it is good idea to turn ON the front surface follower feature in Gate Control window of FlexSCAN-C.

The backlash effect frequently originates from excessive looseness in the lead screws of the mechanical scan bridge. This looseness can cause misalignment problem in data when scanned in bi-directional mode (i.e. taking data in both scan and return pass of a scan line). One way to determine the amount of backlash is to scan an object of well-defined shape and examine the degree of distortion in the C-scan image, especially the outlines of the object image. In FlexSCAN-C, the backlash effect may be compensated by software operation (Scan -> Backlash Correction). In any event, it is recommended to scan only in unidirectional mode (scan -> Scan Setup -> Bidirectional OFF) to reduce this effect.

Oscilloscope

The Sonix digital oscilloscope comes with default settings, as seen in the A/D Offset of A/D 8100 window, for the vertical baseline position of signal trace. Normally, these default settings are sufficient to keep the trace baseline in the middle (zero) of the scope display. In situations that the signal baseline deviates substantially from this zero position, the A/D Offset setting must be adjusted accordingly.

Another problem with the Sonix digital scope is a constant time trace offset as seen in some systems using an external pulser/receiver unit. This is possibly due to inconsistent timing between the trigger signal and the initial transmitted pulse in the combination of pulser/receiver and Sonix A/D card. This offset, typically causing 1-2 s longer in a time-of-flight reading, should be pre-determined and compensated as much as possible. One way to determine this time trace offset is to take a time-of-flight measurement from a specimen of known thickness, e.g. the 1″ fused-quartz reference plate. This can be done as follows:

First proceed with the procedures of leveling the sample stand, transducer normalization with respect to sample stand, and determining the water wave speed as described in Sections 3.2, 3.4 and 9.2. Next, place the fused-quartz plate on the sample stand, manually lower the transducer to be in contact with the front surface of fused-quartz plate, and then carefully remove the fused-quartz plate from below. In this way, an exact 1″ water path is readily set for a time-of-flight measurement of the front surface echo from the sample stand surface. Follow Section 9.4 to calculate the time-of-flight and compare that with the Sonix scope reading. The difference is the offset needed to be compensated in all future time-of-flight measurements. Note that this time trace offset depends on system loading (the combination of pulser/receiver, transducer, cables, etc.) and must be re-calibrated if any system component and/or major setting changes.

5. Data Format

Three types of UT data are acquired in this procedure: A-scan, multiple b-scan, and C-scans. By default, FlexSCAN-C generates a UT scan data file using the traditional DOS naming system: XXXXXXXX.YYY where X's are the user supplied file name (8 characters maximum) and Y's are the three-character file extension assigned by FlexSCAN-C.

Files with **CS1** extension are binary C-scans stored either in Sonix proprietary format or TIFF format. The former format can be read by any image processing software supporting RAW format. The actual data follow the first 9276-bytes header. Note that the image origin is at the lower left corner stored in row major. The TIFF format is one of the popular public-domain file formats and should be supported by most image processing software. From the programming point of view, the Sonix proprietary format is the preferred format because it is easier to work with.

Files with **RF** extension are multiple-line b-scans stored in a Sonix proprietary format, which is a special version of multi-page TIFF format. Files of this type can be accessed by FlexSCAN-C directly. Some image processing software also support this format.

Files with **TXT** extension are numeral screen dump of A-scan traces and can be opened by any text file editor. It contains a short header followed by waveform data points in 256-level integer, separated by commas. It is always a good practice to maintain a concise file naming convention and provide such convention along with the corresponding data structure in a readme file for future reference and use.

6. Reference Waveform Acquisition

To ensure best data quality and minimal errors, it is advised to follow the steps below when acquiring the reference waveform. The transducer should have been mounted on the angular manipulator, which is in turn attached to the search tube of the scan bridge.

The following steps need only to be done once for each new fused-quartz plate:

- Measure and record the dimensions and weight of the fused-quartz plate. Deduce the density accordingly and check with the tabulated generic value (Section 9.3) if applicable. Take necessary action if the difference is significant.
- Measure and record the UT speeds of the fused-quartz plate and check with the tabulated generic values (Section 9.3) if applicable. Take necessary action if the difference is significant.

The following steps need to be done for each transducer loaded with the system at the beginning of the scans:

- Determine the time trace offset (Section 4.3).
- Measure and record the UT speed in water (Section 9.2).
- Measure and record water temperature within 1-degree precision.

Steps below are to be done for both low-frequency (5 MHz) and high-frequency transducers with matching fused-quartz plate:

- Measure and record the UT speed in water (Section 9.2) when water quality/temperature changes significantly during the scans. Be sure to update the new water speed in FlexSCAN-C (under Edit->Configuration->couplant velocity).
- Measure and record water temperature within 1-degree precision when temperature changes significantly during the scans.
- Normalize transducer with respect to front surface using ring wave method (Section 3.4).
- Calculate the time-of-flight prediction of the front surface echo so that the *geometric focus* is set on the back surface (Section 9.2). Use the pre-determined plate thickness in the calculation.
- Manipulate FlexSCAN-C's digital scope to locate the front surface echo. Adjust water path until front surface echo appears at the predicted time instance as calculated in the last step. Be sure to account for the time trace offset if any (Sections 3.1 and 4.3, and Figure 3.1).
- Manipulate FlexSCAN-C's digital scope to display the back surface echo.
- Measure the time-of-flight of the back surface echo. Check measurements against the predictions. Make correction if necessary.

- Adjust both pulser/receiver's gain setting (or attenuation setting on Panametrics 505x series) and the A/D Gain setting in FlexSCAN-C's A/D 8100 window so that the peak back surface waveform is about at 80% full screen height. Also set the time scale of FlexSCAN-C's digital scope so that time resolution is sufficient (at least 20 time trace data points across the signal duration).
- Check and adjust the baseline offset (A/D offset in A/D 8100 window) if necessary (Section 4.3).
- Record all Sonix system settings. This can be done by properly arranging all FlexSCAN-C's setting windows on the screen and then print screen from File menu.
- Record all other experimental settings.
- Take single-shot A-scan waveform of back surface echo. The time average feature should be turned ON to reduce noise. Use highest average number available. A-scan waveform data is obtained by entering File -> Export … -> Scope to ASCII. Record peak-to-peak amplitude of the waveform.

6. Defect Data Acquisition

To ensure best data quality and minimal errors, it is advised to follow the steps below when acquiring the defect data. The defect depth in each side of the defect cube block should have been determined previously. The transducer should have been mounted on the angular manipulator, which is in turn attached to the search tube of the scan bridge.

The following steps need only to be done once for each new defect cube block:

- Measure and record the UT speeds of the defect cube block and check with the tabulated generic values (Section 9.3) if applicable. Take necessary action if the difference is significant.
- Measure and record the dimensions and weight of the defect cube block. Deduce the density accordingly and check with the tabulated generic value (Section 9.3) if applicable. Take necessary action if the difference is significant.

The following steps need to be done for each transducer loaded with the system at the beginning of the scans. This step can be skipped if it has been done in reference data acquisition.

- Measure and record the UT speed in water (Section 9.2).
- Measure and record water temperature within 1-degree precision.
- Determine the time trace offset (Section 4.3).
- Go to Edit -> Configuration -> Image Format to set C-scan format to Sonix proprietary format.

The steps below are to be done for both low-frequency (5 MHz) and high-frequency transducers. For each transducer, repeat the applicable steps on every accessible side of the cube block:

- Measure and record the UT speed in water (Section 9.2) when water quality/temperature changes significantly during the scans. Be sure to update the new water speed in FlexSCAN-C (under Edit->Configuration->couplant velocity).

- Measure and record water temperature within 1-degree precision when temperature changes significantly during the scans.
- Level the sample stand and set the defect cube block on the stand (Section 3.2).
- Maintain a consistent and precise orientation of the defect cube block with respect to the scan system coordinates (Section 3.3).
- Normalize transducer with respect to front surface of the defect cube block using ring wave method (Section 3.4).
- Calculate the time-of-flight prediction of the front surface echo so that the *true focus* is set on the nearest defect surface (Section 9.4). Calculate the prediction for the time-of-flight of defect signal from the pre-determined defect depth. Also calculate the prediction for the time-of-flight of back surface echo from the pre-determined cube dimensions.
- Manipulate FlexSCAN-C's digital scope to locate the front surface echo. Adjust water path until front surface echo appears at the predicted time instance. Be sure to account for the time trace offset if any (Section 4.3).
- Manipulate FlexSCAN-C's digital scope to locate the defect signal and back surface echo.
- Measure the time-of-flight of the defect signal and back surface echo. Check measurements against the predictions. Make correction if necessary.
- Adjust both pulser/receiver's gain (or attenuation on Panametrics 5052x series) setting and the A/D Gain setting in FlexSCAN-C's A/D 8100 window so that the maximum defect waveform is about at 80% full screen height (Section 9.5).
- Check and adjust the baseline offset (A/D offset in A/D 8100 window) if necessary (Section 4.3).
- Set proper time gate location and width for defect signal in FlexSCAN-C's Gate Control window. Make sure the sampling rate is at least 100 MHz (Section 9.5). Also turn on Front Follow gate (Sections 4.2 and 9.5).
- Record all Sonix system settings. This can be done by properly arranging all FlexSCAN-C's setting windows on the screen and then print screen from File menu.
- Record the cube block orientation drawing and all other experimental settings.
- Take single-shot A-scan waveform of defect at peak position with time average feature ON. This is done by entering File -> Export … -> Scope to ASCII. Record peak-to-peak amplitude of the defect waveform.
- Turn OFF time average feature (time averaging requires time-consuming multiple data acquisitions at the same scan which is not possible in high-speed scans such as c- or b-scans. The scan speed will be greatly compromised if this feature is not turned off).
- Go to Scan -> Scan Setup. Set all necessary parameters for C-scan. Make sure the scan and step increments are 5 mils for 5 MHz scan, and 2 mils for high-frequency scans, respectively (see example in Section 9.5).
- Go to Scan -> Scan Go to dry run C-scan data acquisition.
- Make changes such as scan sizes (pixels) in Scan Setup if necessary.
- Repeat last three steps until data quality criterion is met.
- Follow the last four steps to acquire b-scan data (see example in Section 9.5).

7. Key Parameter Calculations/Settings

In this section, the methods of calculation for all key parameters used in this procedure are given. In support of these calculations and clarification of the procedure contents, some key terms are first described. Examples of Sonix scan settings are also attached for future reference.

7.1 Key Terminology

Time-of-flight (TOF) in UT NDE is the round-trip time that ultrasound travels in a medium (or media) between transducer face and a point of interest, or between two points of interest. The horizontal time axis as seen on oscilloscope measures the time-of-flight of signals.

Water path is the distance between the transducer face and the front surface of the specimen in an immersion test.

Geometric and true focal lengths and equivalent diameter are the most important transducer parameters for a spherically focused transducer. Geometric focal length is the axial length (measured from the transducer face) as determined by geometric optics with respect to a given lens curvature. True focal length is the one most transducer specifications refer to, indicating the actual focal depth. Usually true focal length is shorter than geometric focal length. Equivalent diameter is the transducer size (diameter) produced by transducer characterization procedure, not necessarily the same as the manufacturer's specification.

Multiple-line B-scan takes an A-scan (waveform) at each scan position in a two-dimensional C-scan path. The results are three-dimensional A-scan data covering the volume being scanned.

7.2 UT speed in water

A simple measurement of the longitudinal-wave speed in water can be done by using two reference signals from a flat surface. In most cases, the front surface echoes are conveniently used as the reference signals. First normalize the transducer with respect to the flat surface (Section 3.4). Measure the TOF, T_1, of a reference point on the front surface echo, say, at the peak position. Secondly, move the transducer up or down a known distance, D, perpendicular to the flat surface. In a Sonix immersion system, this can be easily done by moving the motorized vertical scan bridge on which the transducer search tube attaches. The distance moved can be monitored in the Motor window in FlexSCAN-C. Next, measure the TOF, T_2, of the same peak reference point on the front surface echo at the new position. Finally, by simple physics of motion,

$$\text{water speed} = \frac{2D}{|T_2 - T_1|}$$

where | | means the absolute difference. For example, let D=2 inch=5.08cm, T_1=30 μs (microsecond; 1 μs =10^{-6} second) and T_2=98.65 μs then water speed = 0.148 cm/μs (0.0583 in/μs) which is typical for tap water at 70°F. This water speed should also match with the couplant velocity in FlexSCAN-C (accessed from Edit menu -> Configuration -> Couplant Velocity).

7.3 UT speeds in defect cube block/fused-quartz plate

Longitudinal-wave speed in cube block/fused-quartz plate can be measured similar to that in water. The difference is that the back surface echo taken from the defect cube block or fused-quartz plate (without moving the transducer up or down) replaces the second front surface echo in the case of water. For example, let the TOF of front surface be 20μs and TOF of back surface echo be 28.2 μs. From the above formula, the longitudinal-wave speed in a 1″ Ti-6Al-4V cube block is 0.62 cm/μs. Shear-wave speed, however, requires the use of a shear-wave transducer measured in contact mode. One can take the first and the second bounces of the back surface echoes as the reference signals. If no shear-wave transducer is available, the values in Table 9.1 may be used.

Table 9.1 UT and material properties of several frequently used materials in ETC

Material	**Longitudinal-wave speed (cm/μs)**	**Shear-wave speed (cm/μs)**	**Density (g/cm^3)**
Water	0.148	NA	1.00
Ti-64	0.620	0.319	4.43
IN718	0.610	0.326	7.86
Fused-quartz	0.597	0.309	2.20

7.4 Water path

Given transducer focal lengths, wave-speeds in water and in the specimen, the correct water path and the corresponding TOF can be easily computed. Let the geometric and true focal lengths be F_g and F_t, respectively. Also denote longitudinal wave-speeds in water, fused-quartz and defect cube block as V_w, V_f, and Vs For the reference experiment, the following formula applies:

$$F_g = Y_{r,w} + \frac{V_f}{V_w} Y_{r,s}$$

For the defect experiment, the parameters change slightly in the same formula:

$$F_t = Y_{d,w} + \frac{V_s}{V_w} Y_{d,s}$$

where the subscripted Y's are the water paths and specimen thickness/depths described in Section 3.1 and Figures 3.1 and 3.2. The corresponding TOF_r for the back surface echo (measured from beginning of the time trace) is the sum of TOF for front surface echo (also from beginning) and TOF for the back surface echo (measured after the front surface echo) in the reference experiment:

$$TOF_r = TOF_{r,w} + TOF_{r,s} = \frac{2Y_{r,w}}{V_w} + \frac{2Y_{r,s}}{V_s}$$

Likewise, TOF_d for the defect in the defect experiment is

$$TOF_d = TOF_{d,w} + TOF_{d,s} = \frac{2Y_{d,w}}{V_w} + \frac{2Y_{d,s}}{V_s}.$$

7.5 Examples of Sonix FlexSCAN-C scan settings

Figures 9.1 through 9.5 are the actual scan settings used in the first Ni real defect. Most settings should be suitable for future use except those specifics on transducer characteristics and defect size. Figures 9.1 and 9.2 are examples of the SCAN SETUP menu in Sonix FlexSCAN-C settings for low-frequency (5 MHz) and high-frequency C-scans, respectively. Figure 9.3 shows the SCAN SETUP menu for high frequency b-scan. Figures 9.4 and 9.5 are examples of screen snap shot of Sonix FlexSCAN-C showing the various settings for low-frequency (5 MHz) and high-frequency scans.

8. Further Contact

Questions/corrections/comments are welcome and should be forwarded to

C. Thomas Chiou (515)294-0299 cchiou@cnde.iastate.edu
Mike Keller (513)552-4643 mike_keller@geae.com
Jeff Umbach (561)796-6047 umbachj@pwfl.com
Andrei Degtyar (860)565-3987 degtyaa@pweh.com

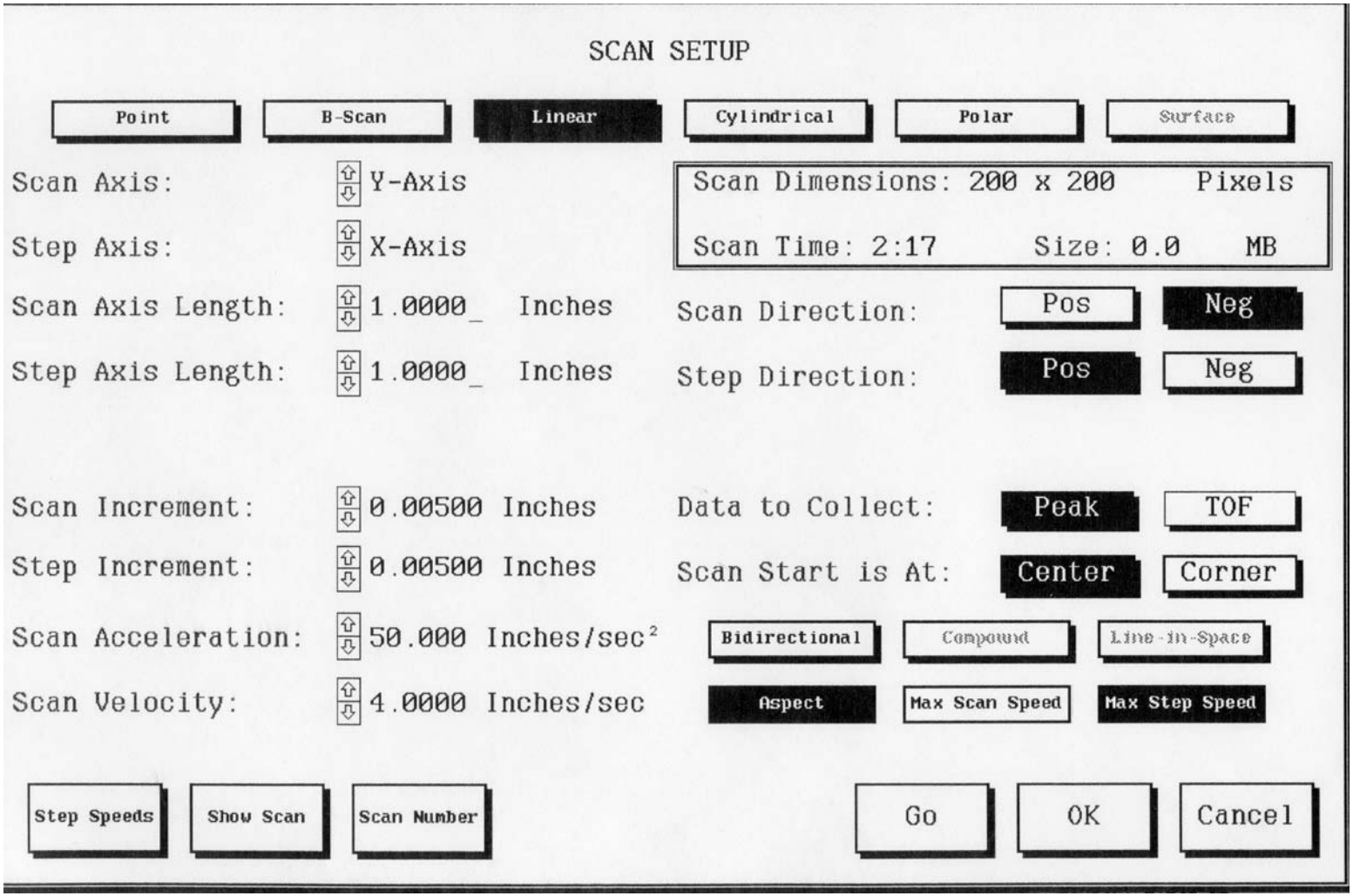


Figure 9.1 The SCAN SETUP menu in Sonix FlexSCAN-C for low-frequency (5 MHz) C-scan settings

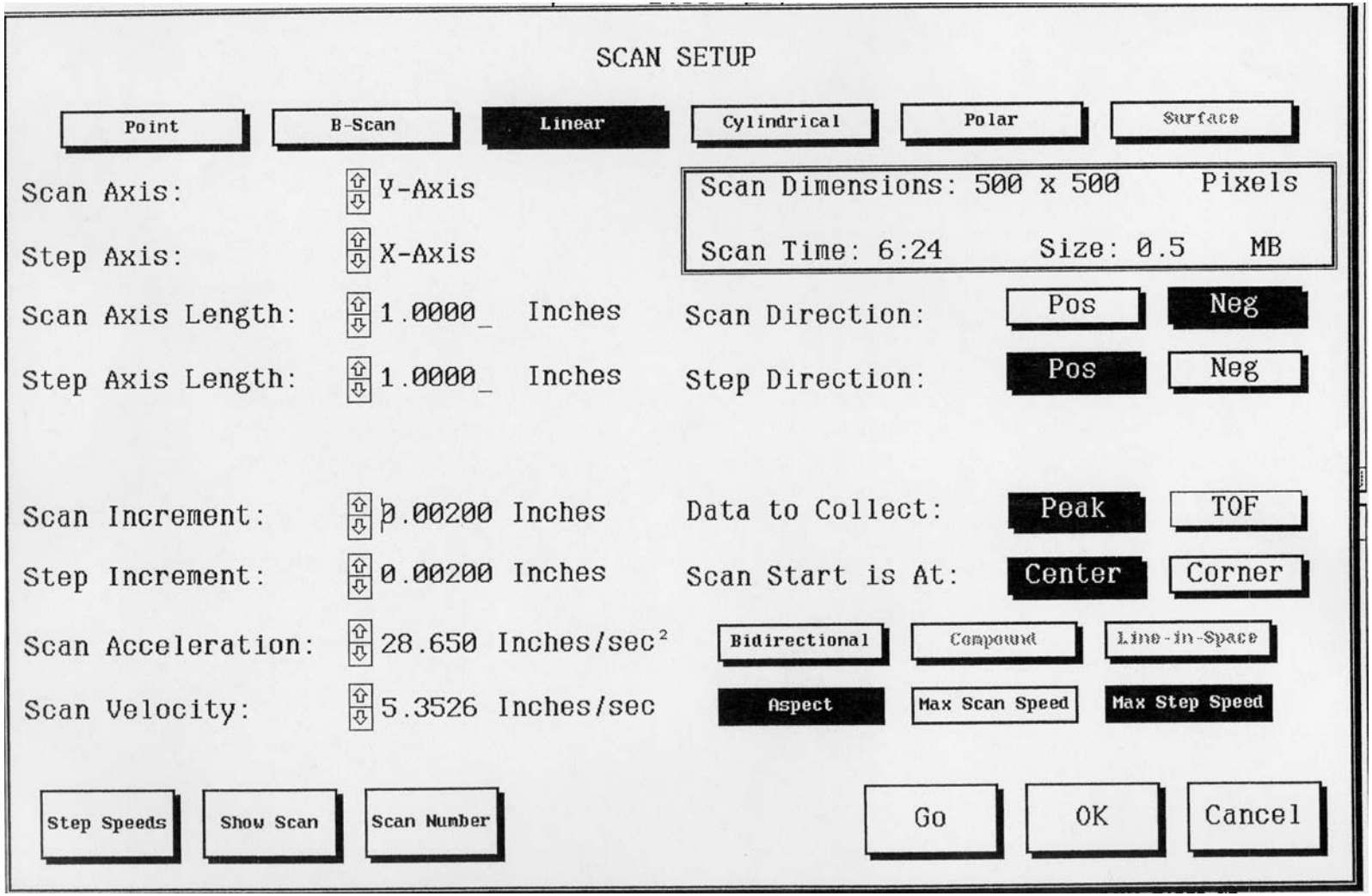


Figure 9.2 The SCAN SETUP menu in Sonix FlexSCAN-C for high frequency C-scan settings

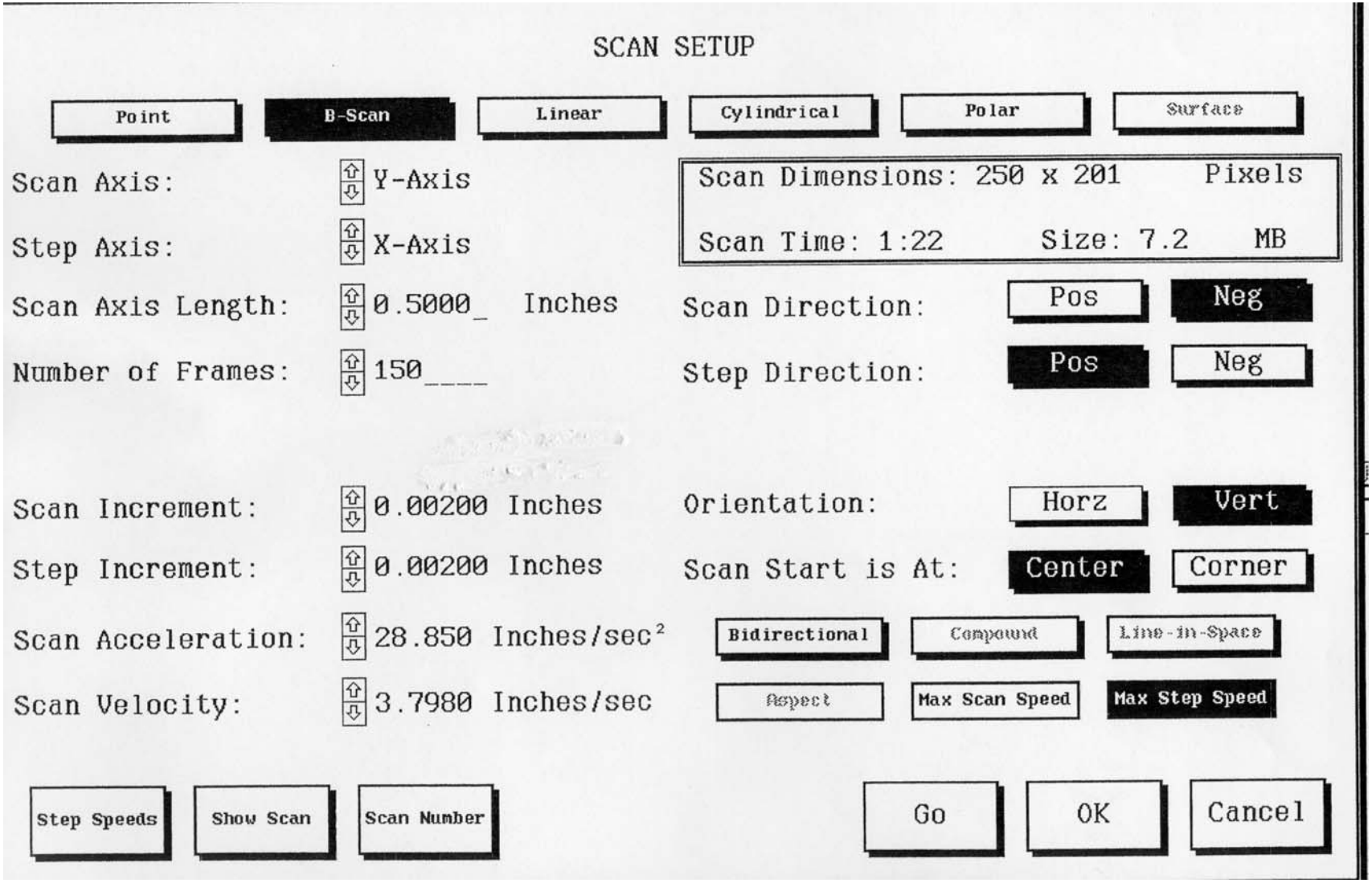


Figure 9.3 The SCAN SETUP menu in Sonix FlexSCAN-C for high frequency b-scan settings

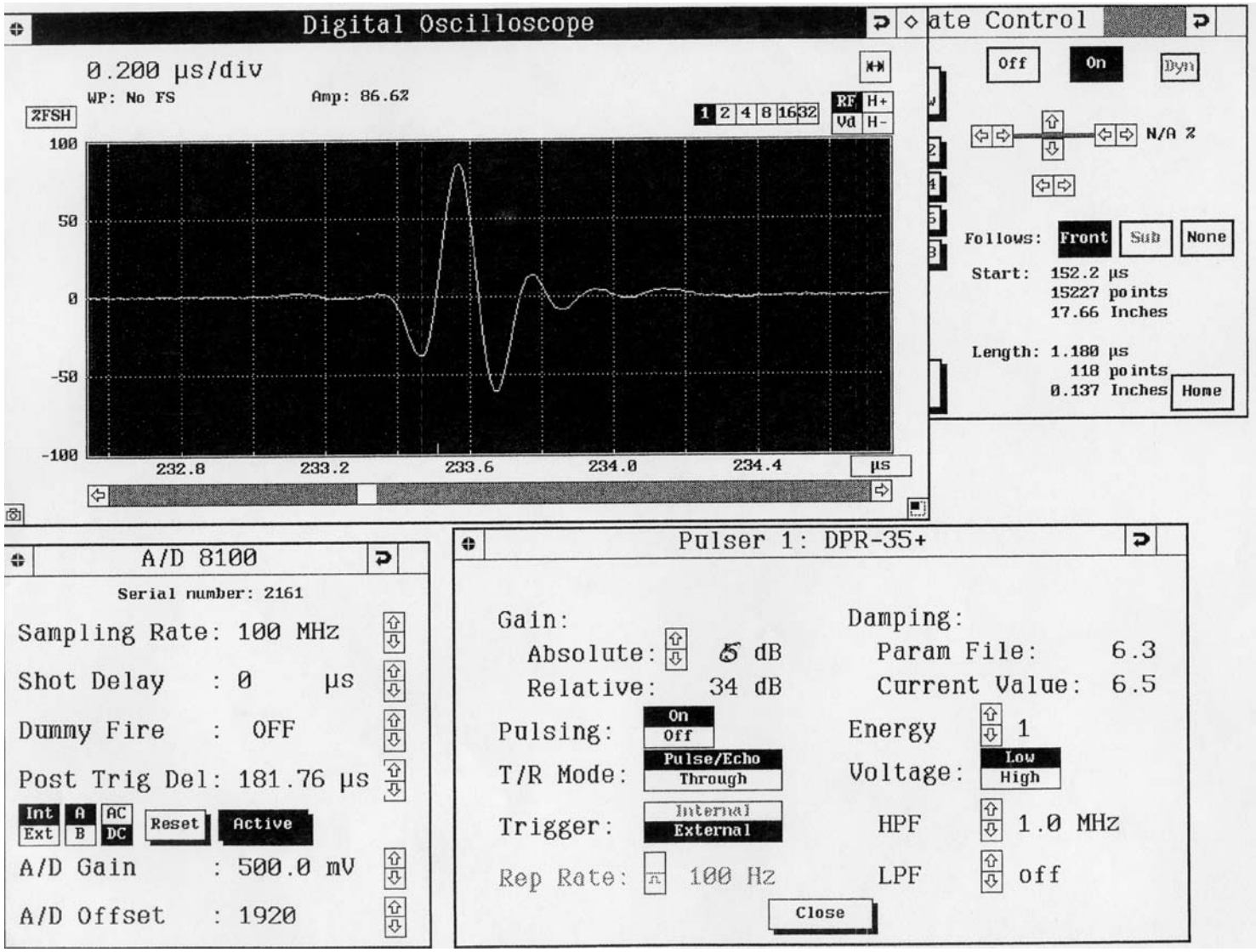


Figure 9.4 A screen snap shot of Sonix FlexSCAN-C shows the various settings for low-frequency (5 MHz) scan

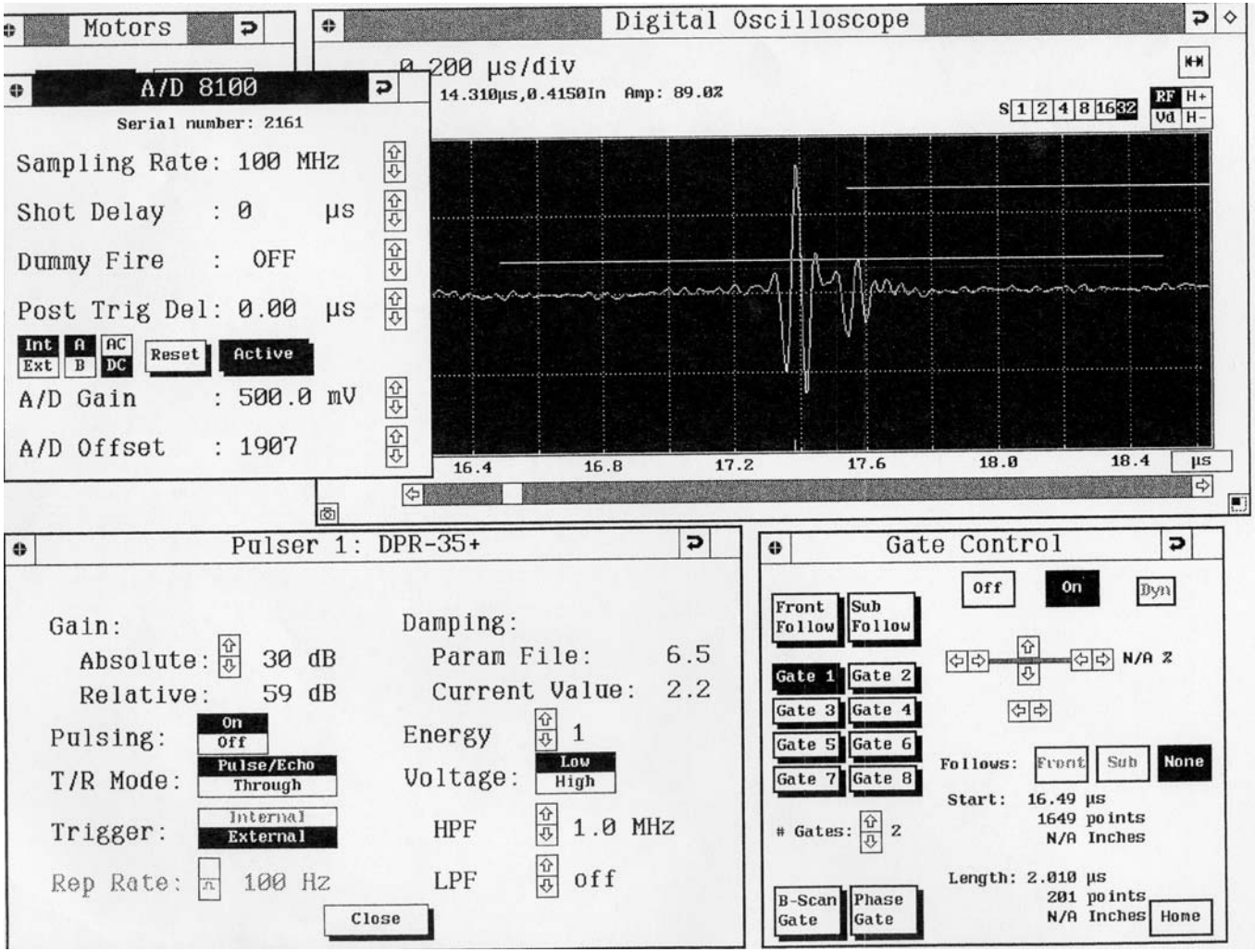


Figure 9.5 A screen snap shot of Sonix FlexSCAN-C shows the various settings for high-frequency scan

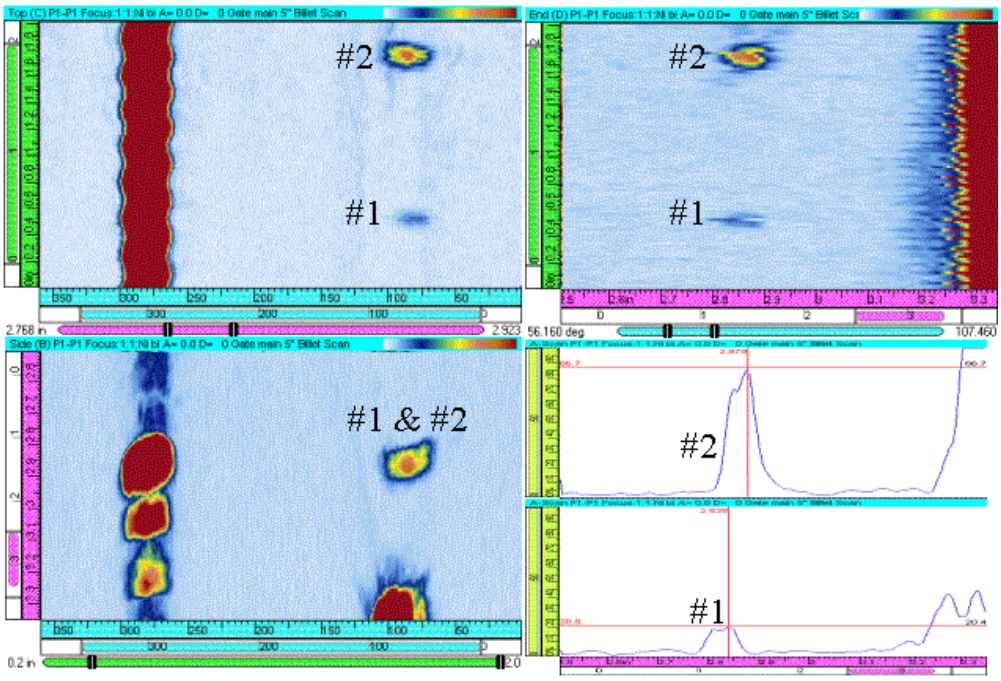
REFERENCE,

1. Gray, T.A., "Application of Measurement Models to Specification of Ultrasonic Inspections," in *Review of Progress in QNDE*, Vol. 16B, D.O. Thompson and D.E. Chimenti, eds., Plenum, New York, 1997, pp. 2061-2068.

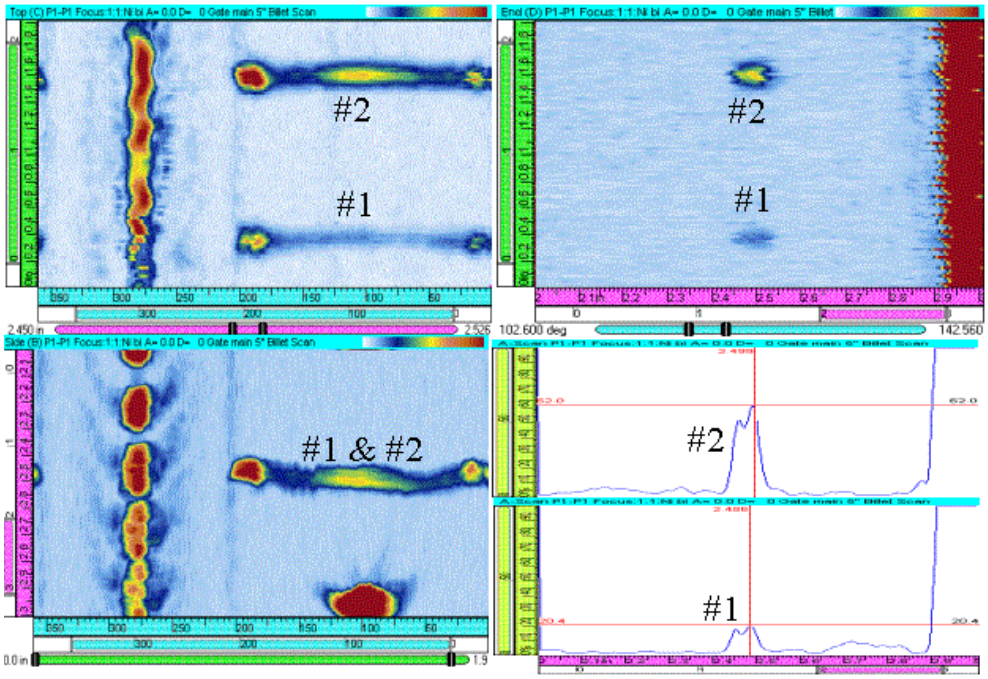
APPENDIX C—NICKEL SMALL-DIAMETER BILLET DATA

The following are the results from the phased array inspection of the 5″ diameter Waspaloy billet reference standard.

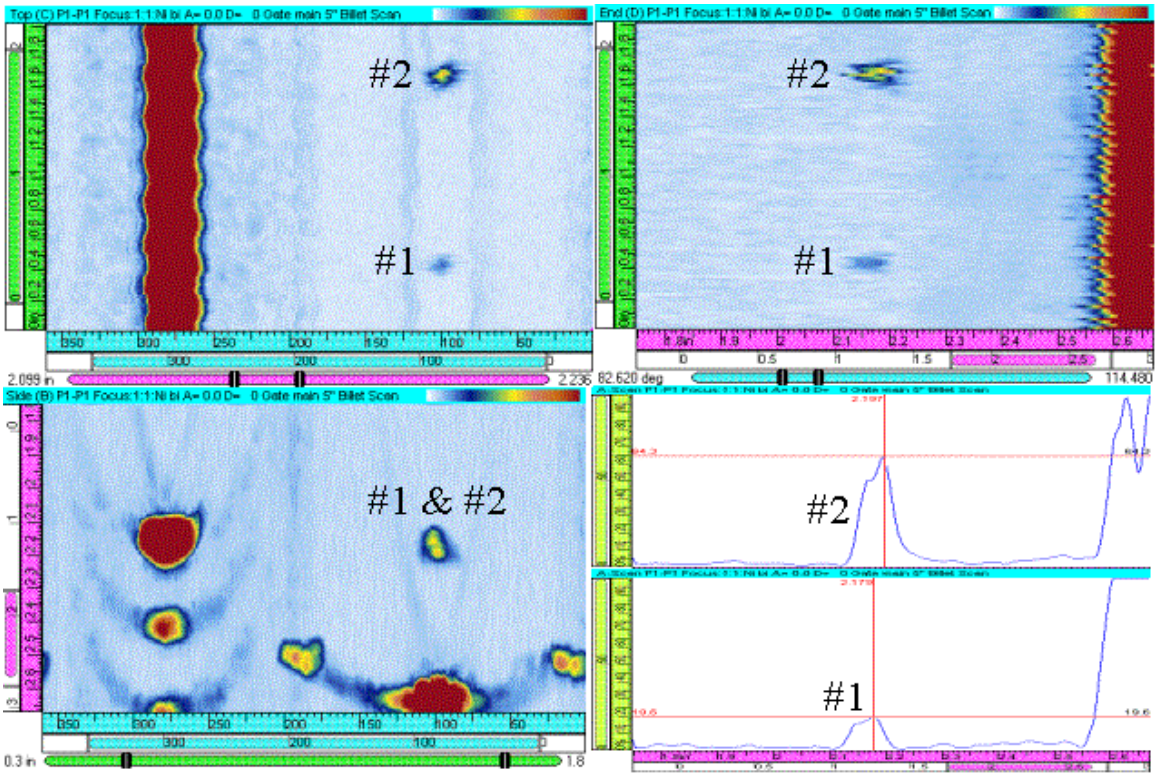
Waspaloy, f = 5 MHz, Depth = 2.63″, ER-focus = 2.63″, WP = 4″, BW = 100 mils, Gain = 15 dB



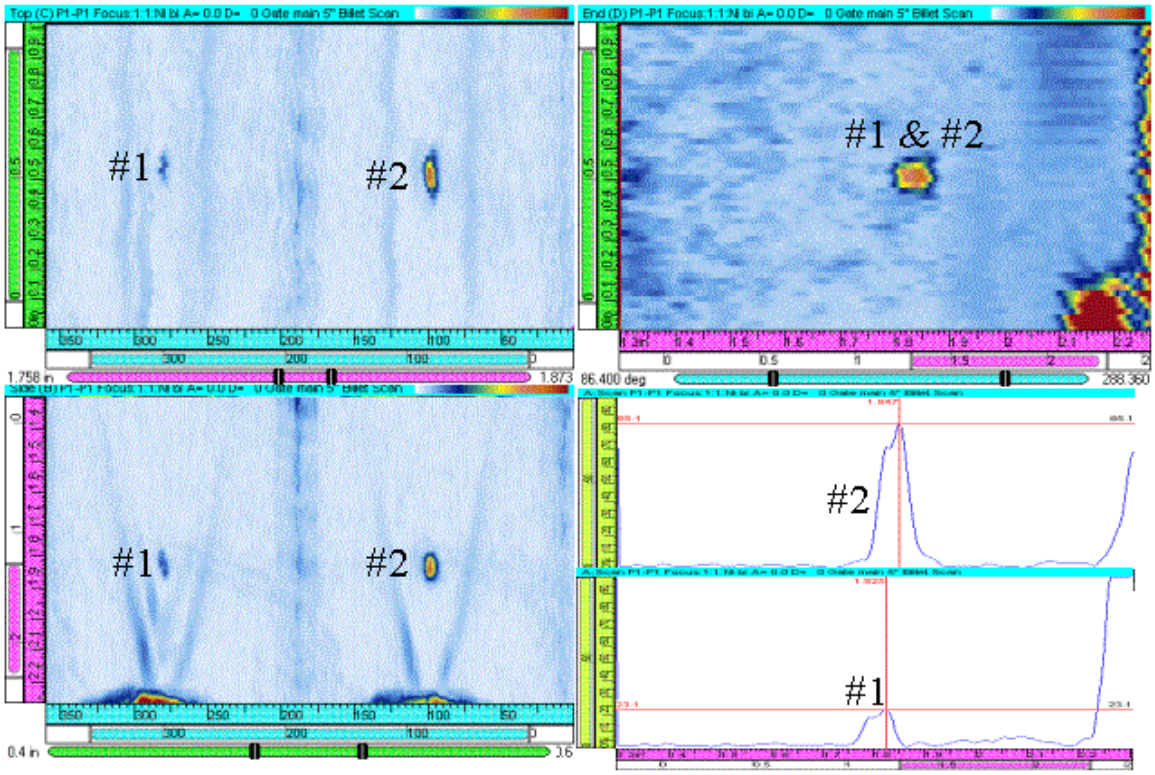
Waspaloy, f = 5 MHz, Depth = 2.25″, ER-focus = 2.25″, WP = 4″, BW = 100 mils, Gain = 10 dB



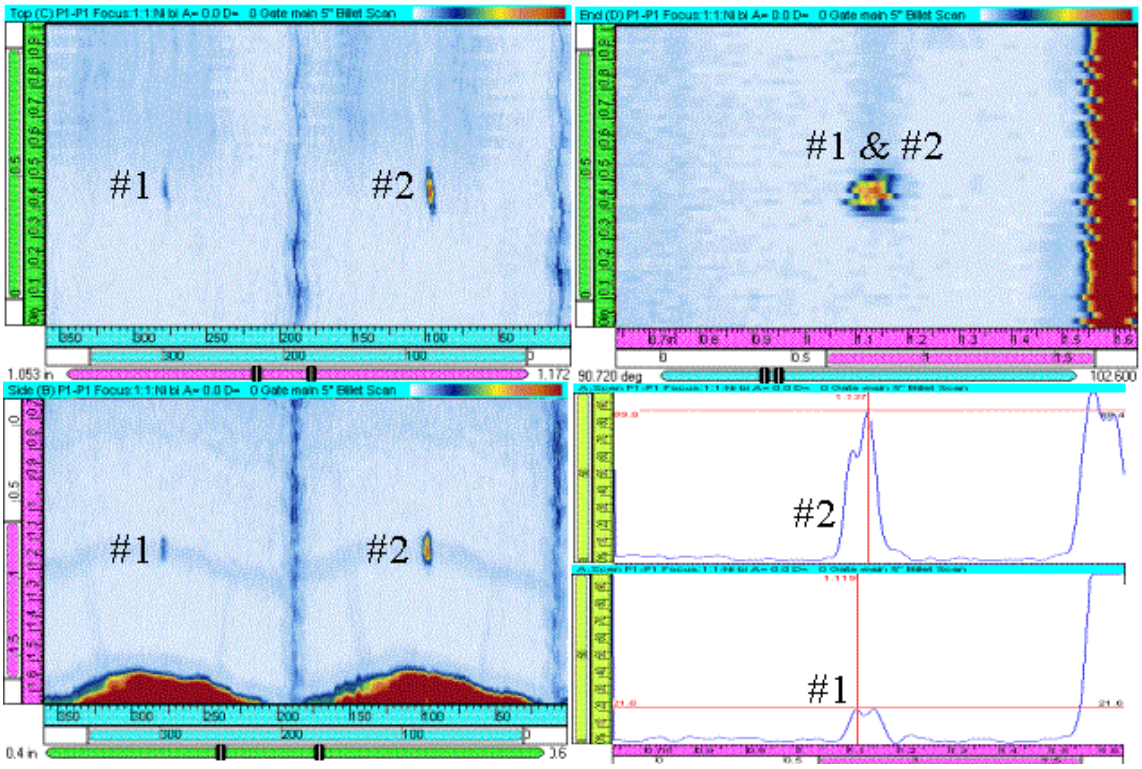
Waspaloy, f = 5 MHz, Depth = 2.25″, ER-focus = 2.25″, WP = 4″, BW = 100 mils, Gain = 10 dB



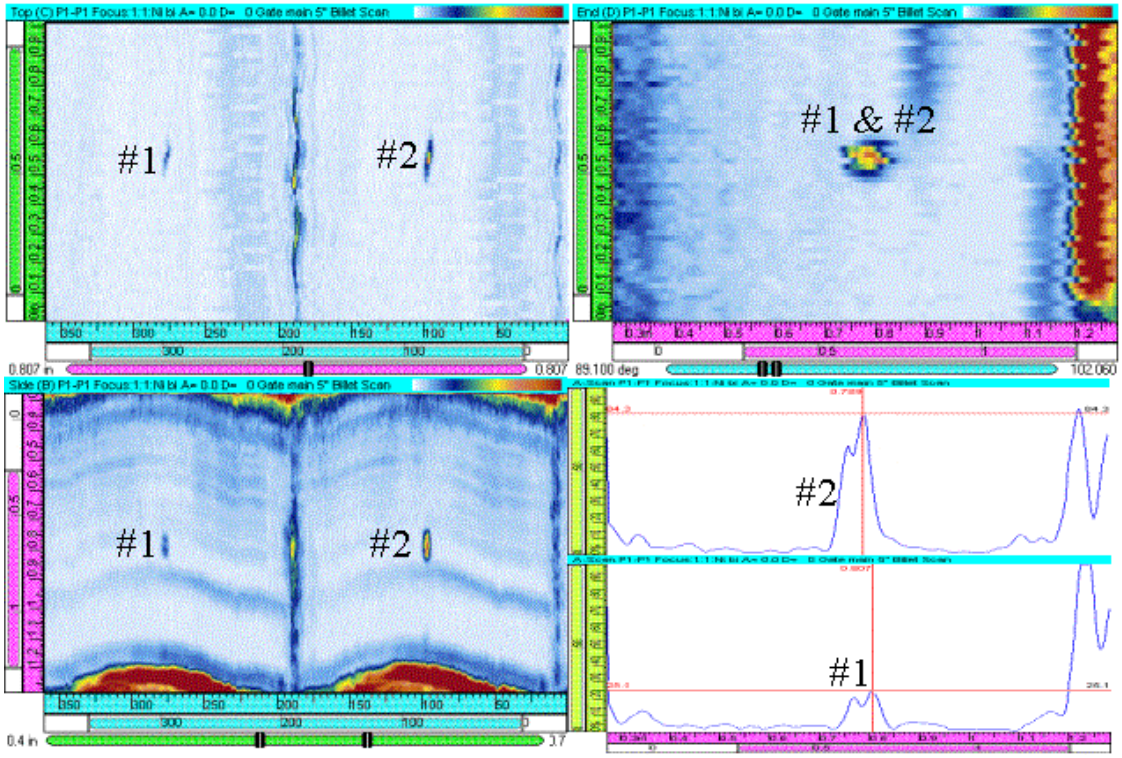
Waspaloy, f = 5 MHz, Depth = 1.87″, ER-focus = 1.87″, WP = 4″, BW 100 mils, Gain = 10 dB



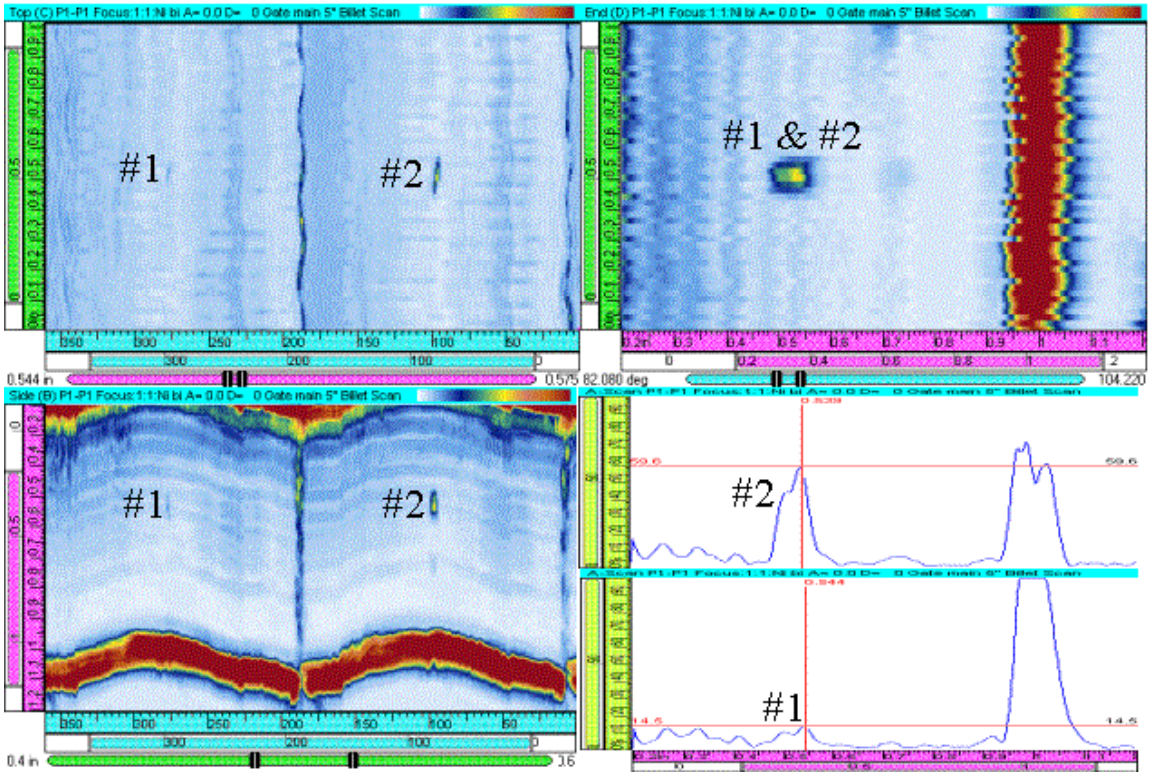
Waspaloy, f = 5 MHz, Depth = 1.13″, ER-focus = 1.13″, WP = 4″, BW = 100 mils, Gain = 13 dB



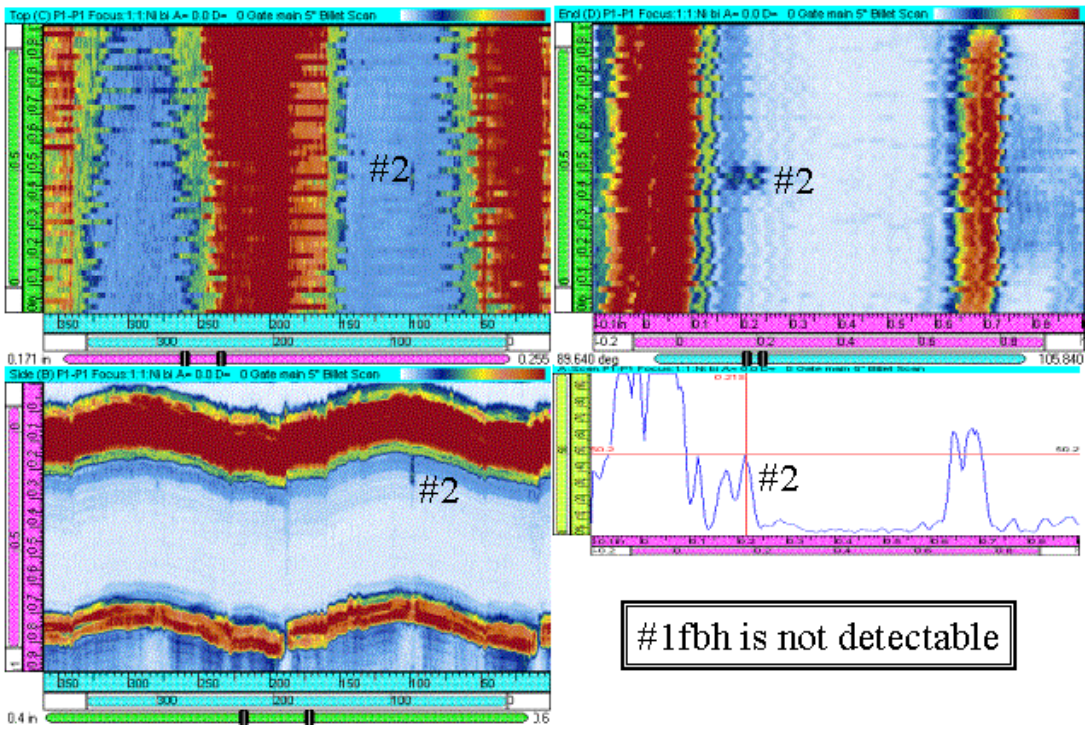
Waspaloy, f = 5 MHz, Depth = 0.75″, ER-focus = 0.75″, WP = 4″, BW = 100 mils, Gain = 13 dB



Waspaloy, f = 5 MHz, Depth = 0.48″, ER-focus = 0.48″, WP = 4″, BW = 100 mils, Gain = 15 dB



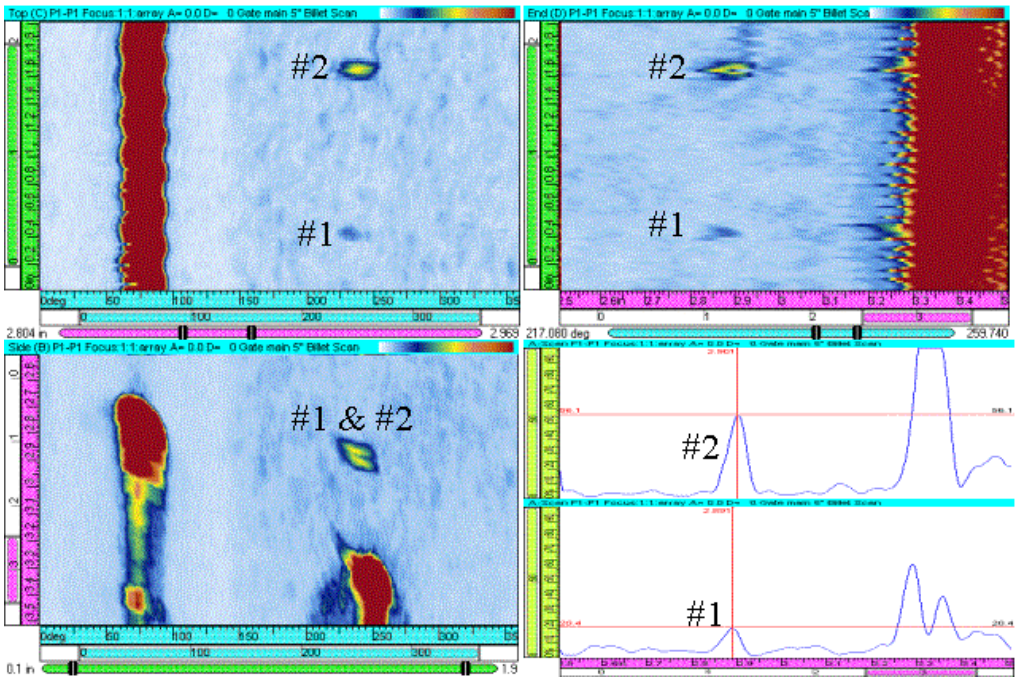
Waspaloy, f = 5 MHz, Depth = 0.2″, ER-focus = 0.2″, WP = 5″, BW = 100 mils, Gain = 20 dB



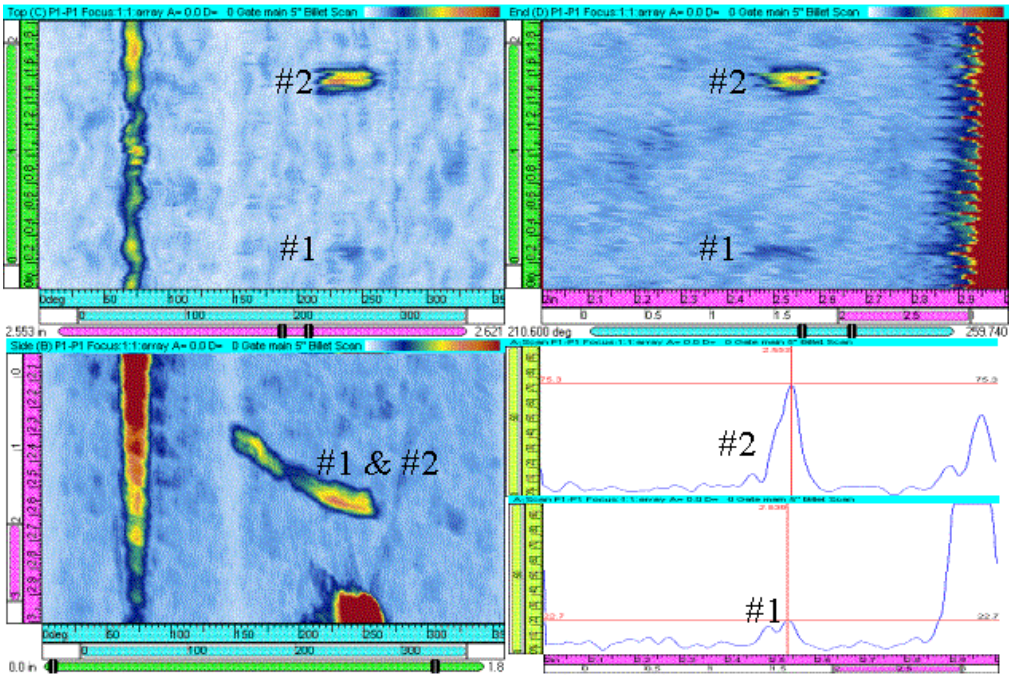
APPENDIX D—TITANIUM SMALL-DIAMETER BILLET DATA

The following are the results from the phased array inspection of the 5″ diameter Ti-6Al-4V billet reference standard.

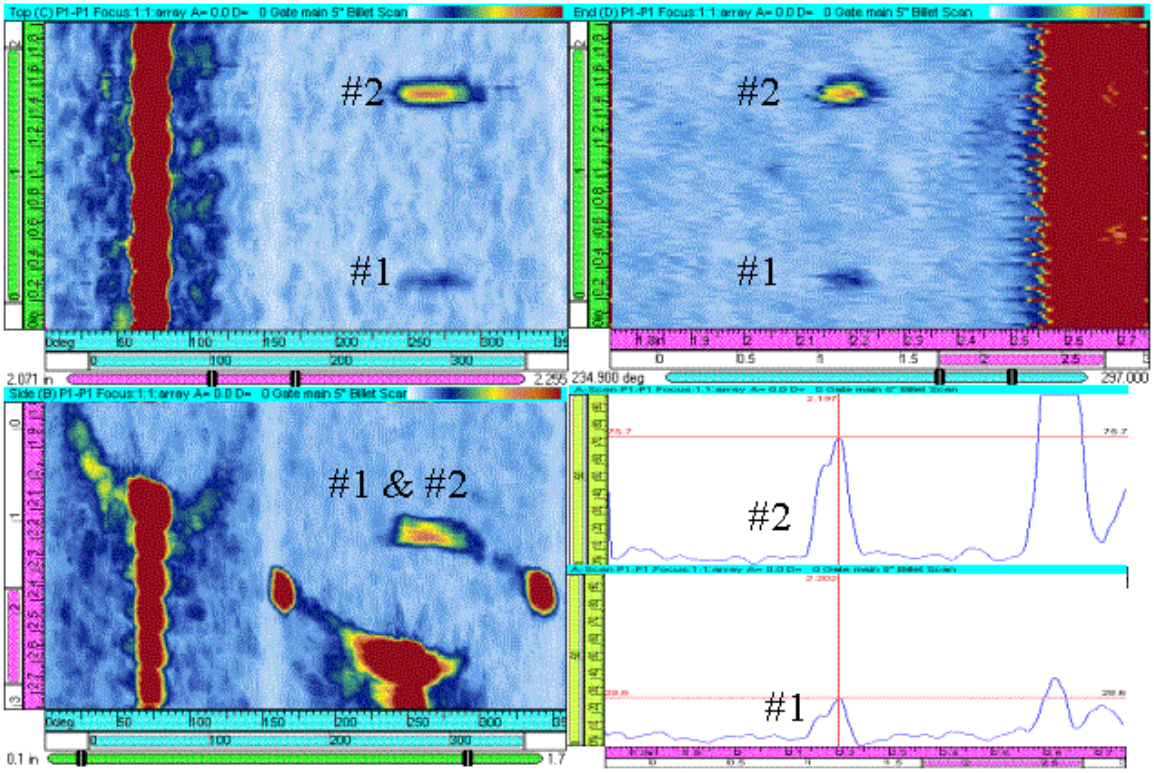
Titanium, f = 5 MHz, Depth = 3.0″, ER-focus = 3.0″, WP = 4″, BW = 100 mils, Gain = 10 dB



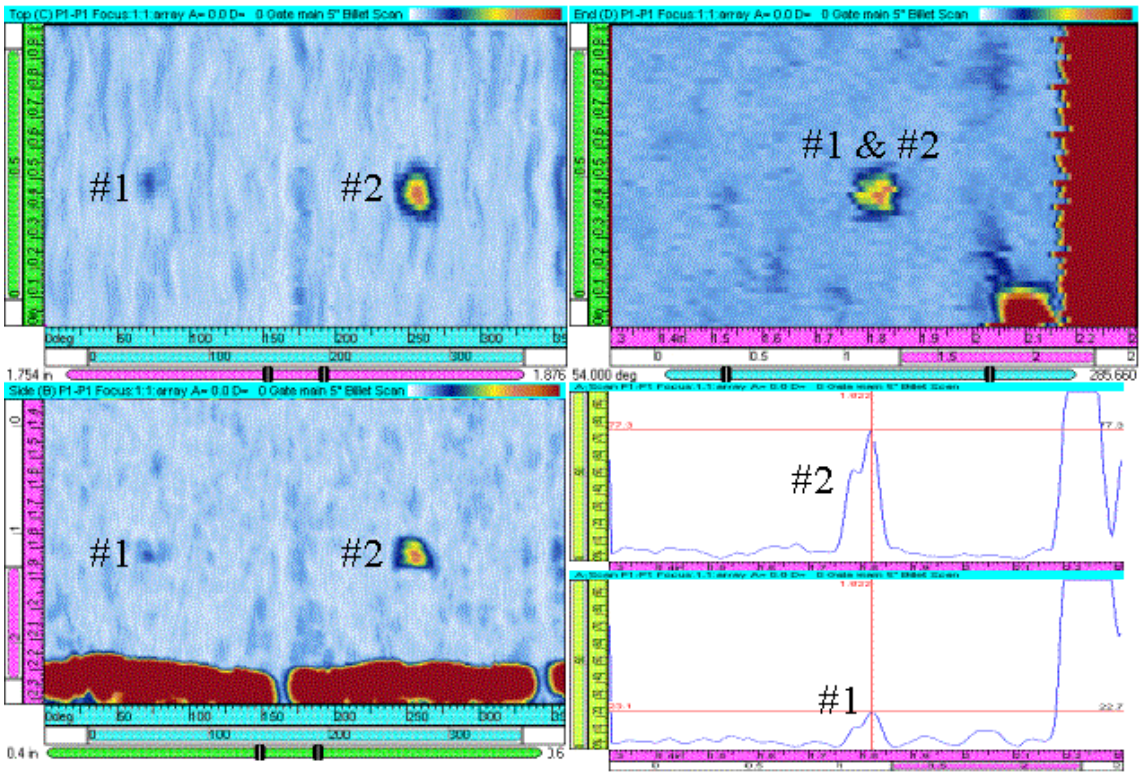
Titanium, f = 5 MHz, Depth = 2.63″, ER-focus = 2.63″, WP = 4″, BW = 100 mils, Gain = 12 dB



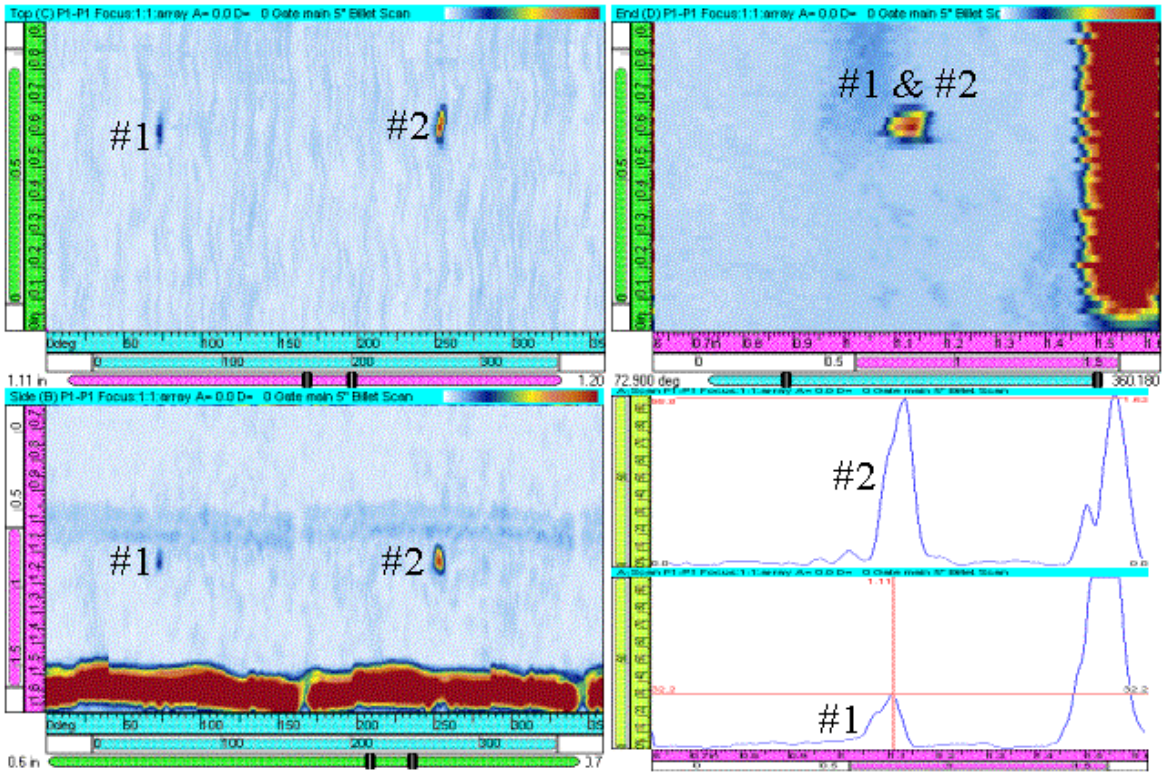
Titanium, f = 5 MHz, Depth = 2.25″, ER-focus = 2.25″, WP = 4″, BW = 100 mils, Gain = 13 dB



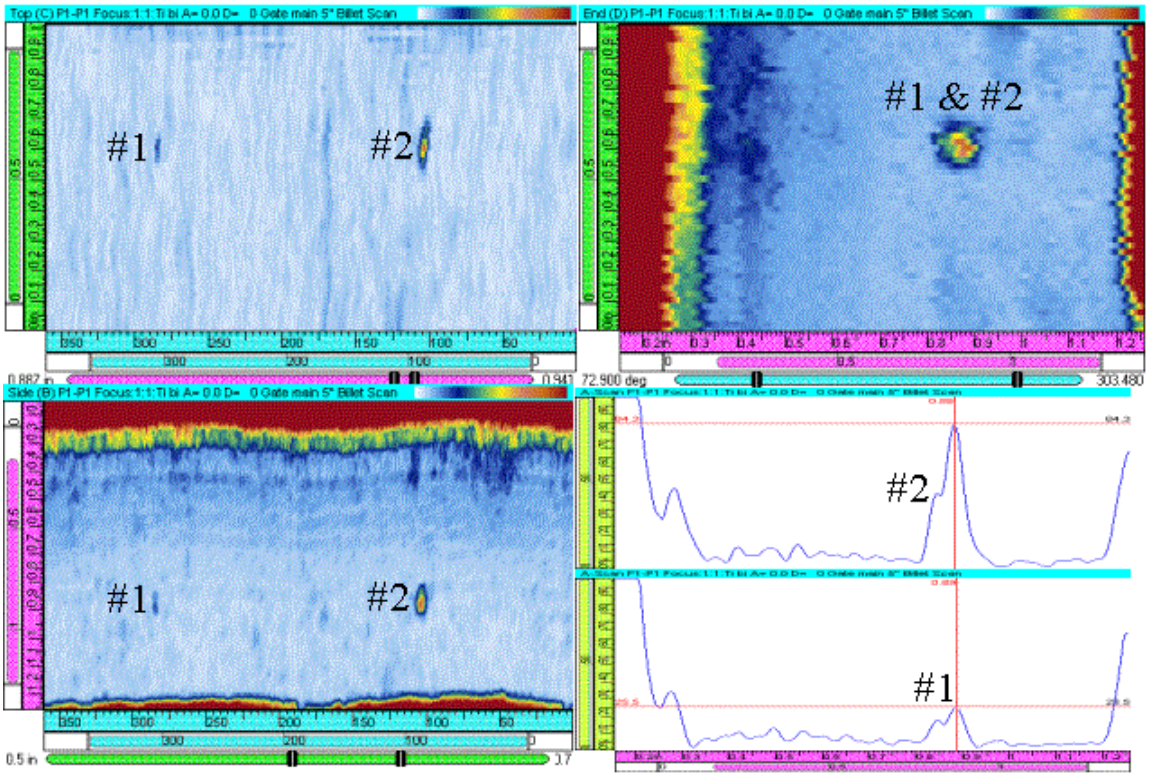
Titanium, f = 5 MHz, Depth = 1.87″, ER-focus = 1.87″, WP = 4″, BW = 100 mils, Gain = 15 dB



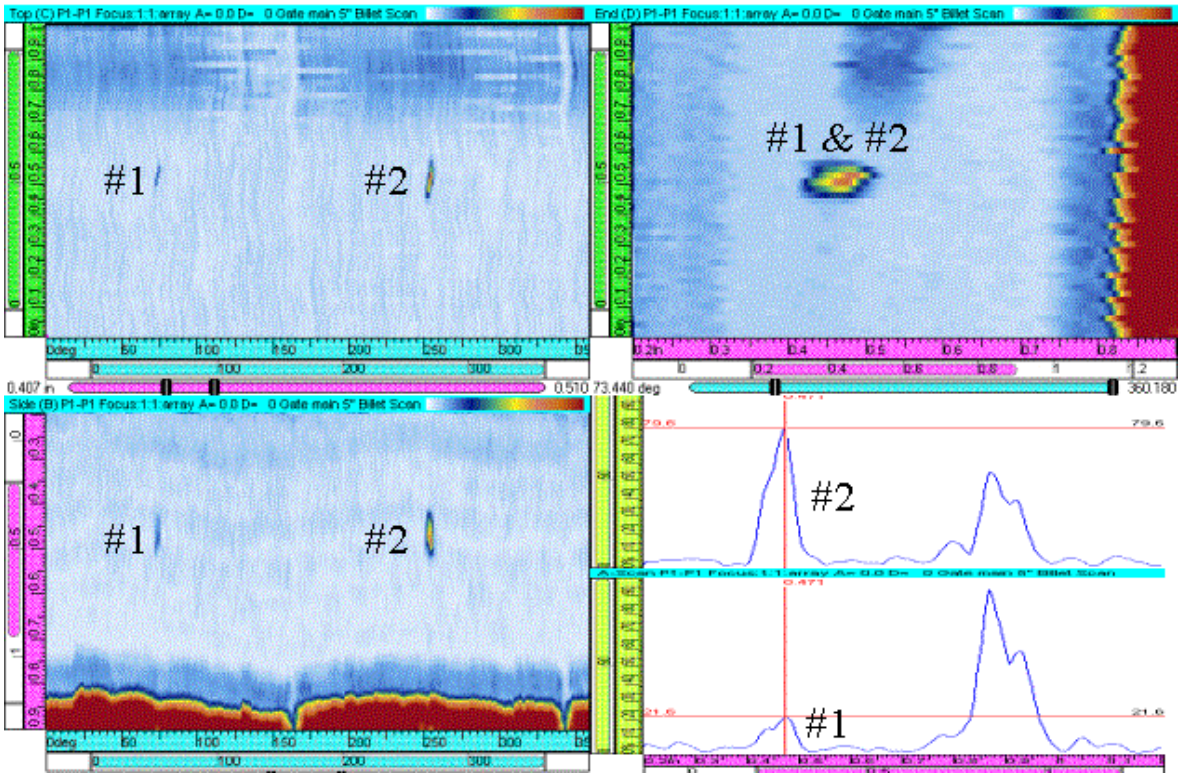
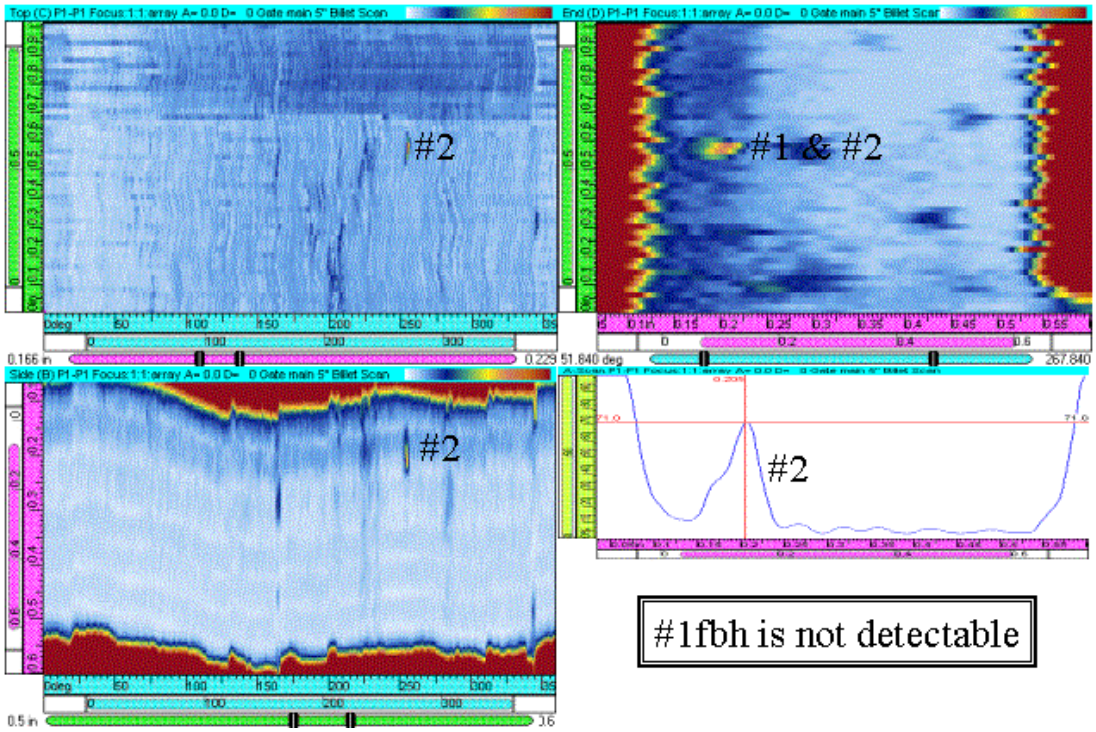
Titanium, f = 5 MHz, Depth = 1.13″, ER-focus = 1.13″, WP = 4″, BW = 100 mils, Gain = 6 dB



Titanium, f = 5 MHz, Depth = 0.75″, ER-focus = 0.75″, WP = 4″, BW = 100 mils, Gain = 15 dB



Titanium, f = 5 MHz, Depth = 0.48″, ER-focus = 0.48″, WP = 4″, BW = 100 mils, Gain = 10 dB



Titanium, f = 5 MHz, Depth = 0.2″, ER-focus = 0.275″, WP = 4″, BW = 100 mils, Gain = 15 dB