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SUPERALLOY KNIFE EDGE SEAL REPAIR.(U)
MAY 78 R E KUTCHERA, P G BAILEY F33615-76-C-5123
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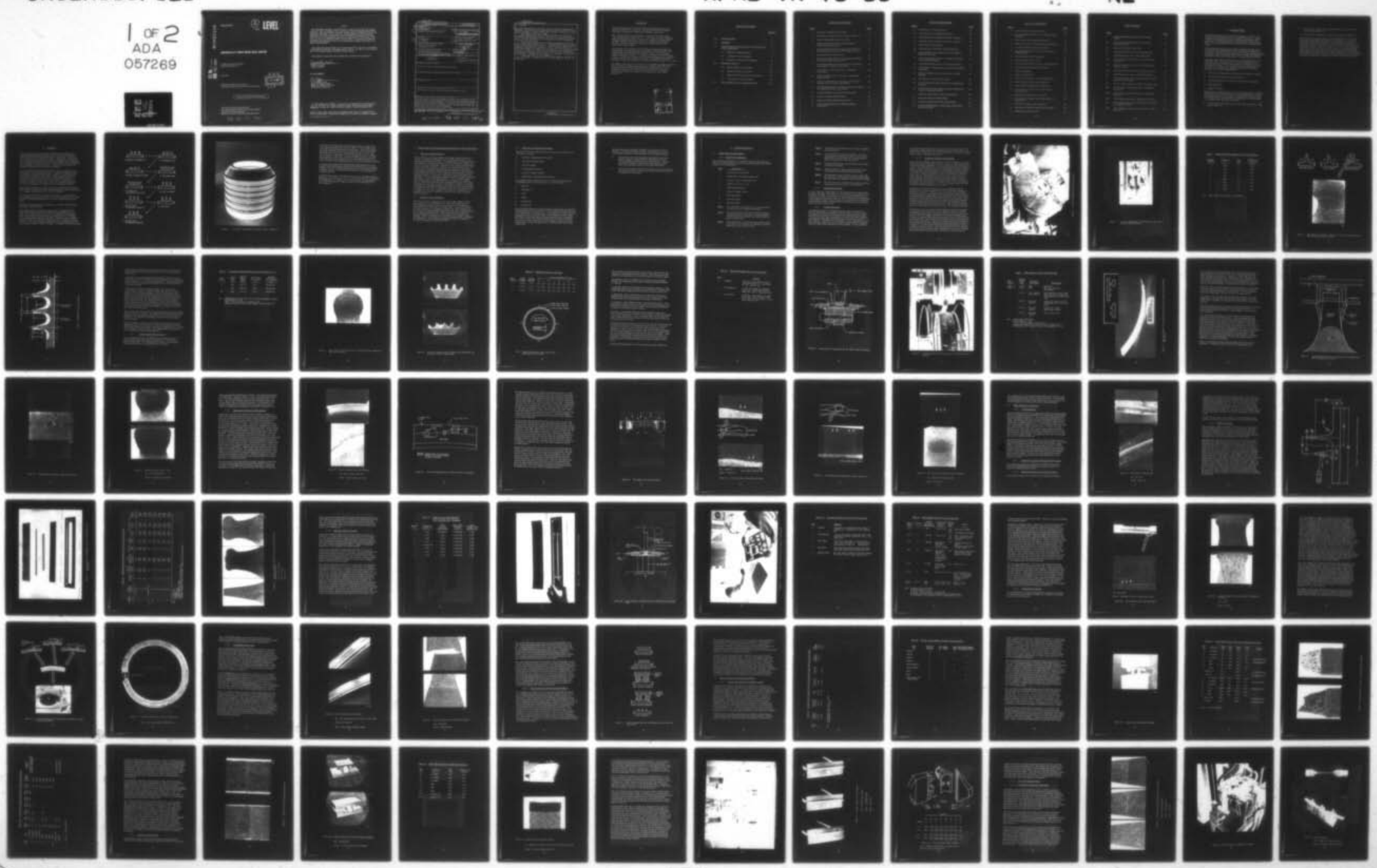

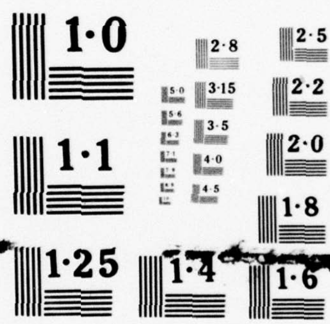

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SUPERALLOY KNIFE EDGE SEAL REPAIR

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GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

MAY 1978

TECHNICAL REPORT AFML-TR-78-56
Final Report for period 1 March 1976 to 31 November 1977

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Donald W. Becker

DONALD W. BECKER
Project Engineer

FOR THE COMMANDER

NG Tupper

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A twenty month effort has successfully demonstrated the feasibility of the Continuous Seam Diffusion Bonding (CSDB) process for repairing knife edge seal teeth on superalloy engine components. Seal teeth rings from the F101, Rene'95, Compressor Rotor Spool (CRS), stages 4-9, containing five representative seal teeth clusters were used for this investigation. The Rene'95 seal teeth were repaired with Inconel 718 tip extension material.

The developed processes were utilized to repair two seal teeth rings machined from the CRS. Isothermal rolling was used successfully to initially widen the

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seal teeth bond interface to facilitate notch-free diffusion bonds after reprofiling. CSDB parameters were established for bonding the Inconel 718 to the René 95 seal teeth. A closure technique was developed to complete the circumferential bonding of a seal teeth ring.

The ultrasonic pulse-echo technique was found to be a useful tool in determining if bonding was successful. The integrities of the bonds were verified by finish machining and fluorescent penetrant inspection of the seal teeth. Additional confirmation of bond integrity was made by metallographic sectioning of the seal teeth.

The processing parameters for the rings were translated to flat seal teeth specimens made from René 95 plate to conduct mechanical testing in the as bonded or heat treated (aged) conditions. The 1200°F tensile and stress rupture strengths of aged bonds were equivalent to that of Inconel 718 sheet. The 1200°F shear strengths of as bonded and aged bonds were 75% of the shear strength of Inconel 718 plate. The thermal fatigue properties of as bonded and aged specimens were equivalent to those of the René 95 seal teeth. At 1000°F, the LCF strengths of as bonded and aged specimens were comparable to each other and slightly below the strength of a new component.

A CSDB repair cost estimate of $2200 was determined for the F101 compressor rotor spool. A projected savings of 90% for salvage vs. new part cost is indicated.

FOREWORD

This Technical Report covers the technical effort performed under Contract F33615-76-C-5123 from 1 March 1976 through 31 November 1977 and is submitted as fulfillment of Exhibit A, Item A002.

This contract with the General Electric Company, Cincinnati, Ohio, was conducted under Project No. 7351. The contract was accomplished under the technical direction of Mr. D. W. Becker of the Processing and High Temperature Branch, AFML/LLS, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio.

The program was conducted by the Material and Process Technology Laboratories of the General Electric Company, Cincinnati, Ohio. The program was conducted under the direction of Mr. E. J. Kerzicnik, Program Manager, and Mr. P. G. Bailey, Technical Program Manager, with R. E. Kutchera serving as the Principal Investigator on the program. A major subcontractor was Solar, Division of International Harvester, San Diego, California with their work under the direction of Mr. F. K. Rose.

The specific objective of the program was to establish a joining procedure and to measure resultant joint properties of repaired knife edge seals using the Continuous Seam Diffusion Bonding (CSDB) process. The program included demonstration of the repair process by buildup of two seal teeth rings from a Rene'95 F101 compressor rotor spool, Stages 4-9.

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1.0 INTRODUCTION

A labyrinth knife edge seal is used in jet engines as a means of restricting airflow between cavities with different pressures. These cavities are usually formed between rotating and stationary turbomachinery. The labyrinth seal forms the interface between these parts, serving a similar function to a piston ring in a reciprocating engine.

The labyrinth seal performs the airflow restriction function by producing a pressure drop through a series of teeth which penetrate a rub surface. Seal teeth are normally provided on the rotating structure to minimize structural damage during contact and provide maximum flexibility in choice and configuration of the stationary rub surface.

Clearance control and engine efficiency are highly dependent on the seal teeth seals. The seal teeth are often an integral part of an expensive rotating component fabricated from a superalloy such as Inconel 718 or Rene'95. Current design practices dictate that the seal teeth be of a knife edge configuration with special attention directed to the following requirements:

- The loads and temperatures to which the seal teeth are exposed.
- The types of stresses and deflection limits.
- The life limiting modes in which the seal teeth must operate.
- Wear protection.
- Design for repair.

Simple seal tooth damage can occur during manufacturing or handling. Tooth cutouts to repair the damage are unacceptable because of their life limiting history. Other forms of damage listed below are also of great concern since they can render an expensive unit unserviceable if no reliable repair technique is available.

- Normal wear of seal teeth due to erosion and rubbing wear during engine operation.

- Abnormal wear caused by secondary damage due to an unbalance from bearing failures, etc.

- Foreign object damage due to ingestion during engine operation.

State-of-the-art seal teeth repair is very limited because of: (1) tooth size which is generally very small and not amenable to conventional weld repair, and (2) material characteristics which result in loss of properties, distortion or sensitivity to cracking during welding or post-weld heat treatment. There are, however, a few low stress applications authorized for Gas Tungsten Arc (GTA) repair. For highly stressed seals, there is clearly a need for a high integrity repair technique that would eliminate the drawbacks of the fusion welding processes and permit the salvage of expensive components containing seal teeth. The techniques which involve solid state bonding show promise in this important area.

2.0 SUMMARY

This program has successfully demonstrated the feasibility of the Continuous Seam Diffusion Bonding (CSDB) process for repairing knife edge seal teeth on superalloy engine components. A schematic of the repair process is shown in Figure 1. Seal teeth rings from the F101, Rene'95, compressor rotor spool (CSR) Stages 4-9, containing five representative seal teeth clusters, were used for this investigation. The component is shown in Figure 2. The Rene'95 seal teeth were repaired with Inconel 718 tip extension material.

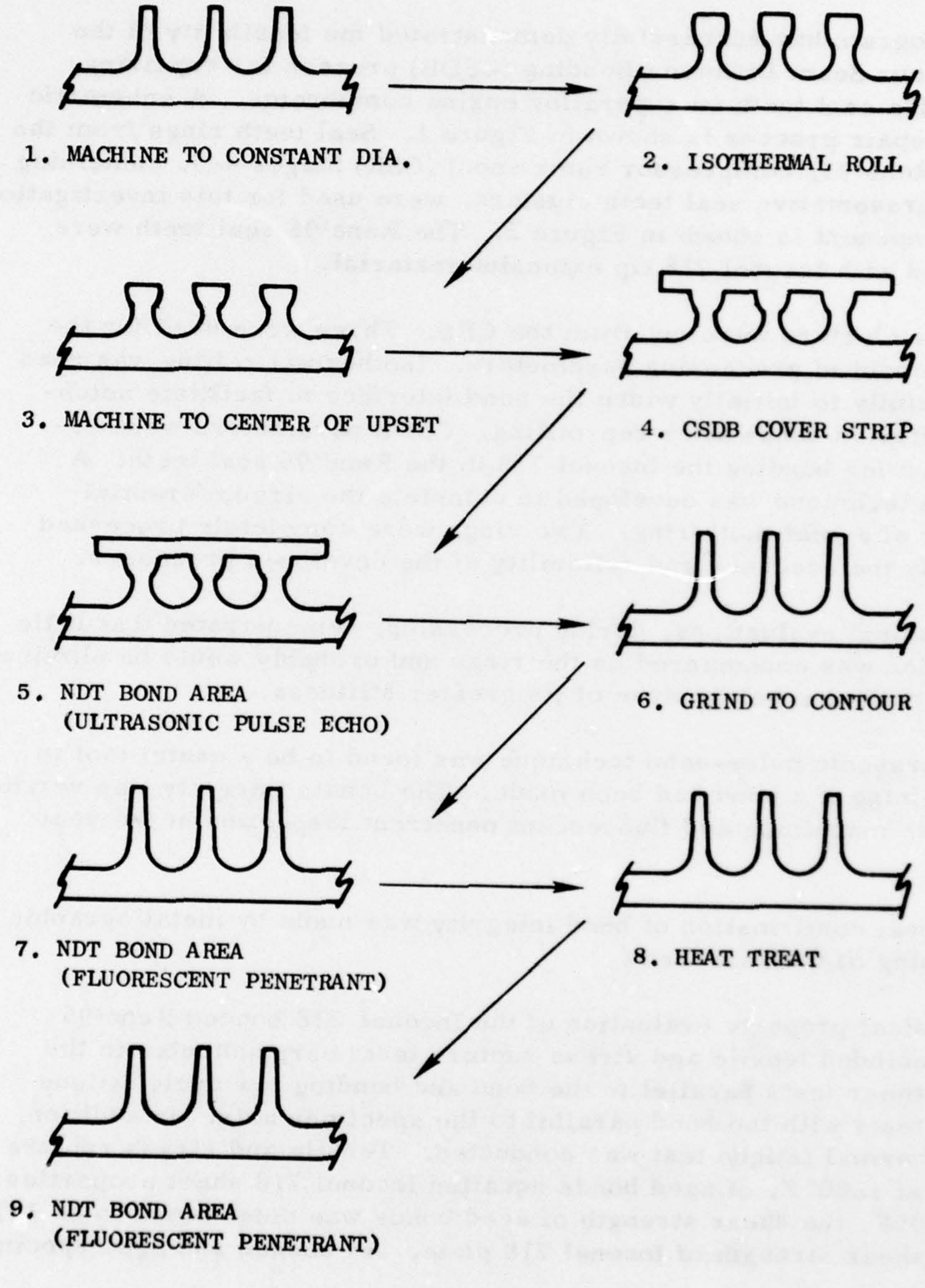
The five clusters were cut from the CRS. Three were used for the development of processing parameters. Isothermal rolling was used successfully to initially widen the bond interface to facilitate notch-free diffusion bonds after reprofiling. CSDB parameters were established for bonding the Inconel 718 to the Rene'95 seal teeth. A closure technique was developed to complete the circumferential bonding of a seal tooth ring. Two rings were completely processed to verify the adequacy and reliability of the developed processes.

Dimensional evaluations, during processing, demonstrated that little distortion was encountered on the rings and probably would be eliminated on a complete spool because of its greater stiffness.

The ultrasonic pulse-echo technique was found to be a useful tool in determining if a bond had been made. The bond's integrity was verified by finish machining and fluorescent penetrant inspection of the seal teeth.

Additional confirmation of bond integrity was made by metallographic sectioning of the seal teeth.

Mechanical property evaluation of the Inconel 718 bonded Rene'95 teeth included tensile and stress rupture tests perpendicular to the bond, shear tests parallel to the bond and bending low cycle fatigue (LCF) tests with the bond parallel to the specimen axis. In addition, a rig thermal fatigue test was conducted. Tensile and stress rupture tests, at 1200°F, of aged bonds equalled Inconel 718 sheet properties. At 1200°F, the shear strength of aged bonds was determined to be 75% of the shear strength of Inconel 718 plate. As-bonded and aged specimens


1. MACHINE TO CONSTANT DIA.
2. ISOTHERMAL ROLL
3. MACHINE TO CENTER OF UPSET
4. CSDB COVER STRIP
5. NDT BOND AREA
(ULTRASONIC PULSE ECHO)
6. GRIND TO CONTOUR
7. NDT BOND AREA
(FLUORESCENT PENETRANT)
8. HEAT TREAT
9. NDT BOND AREA
(FLUORESCENT PENETRANT)

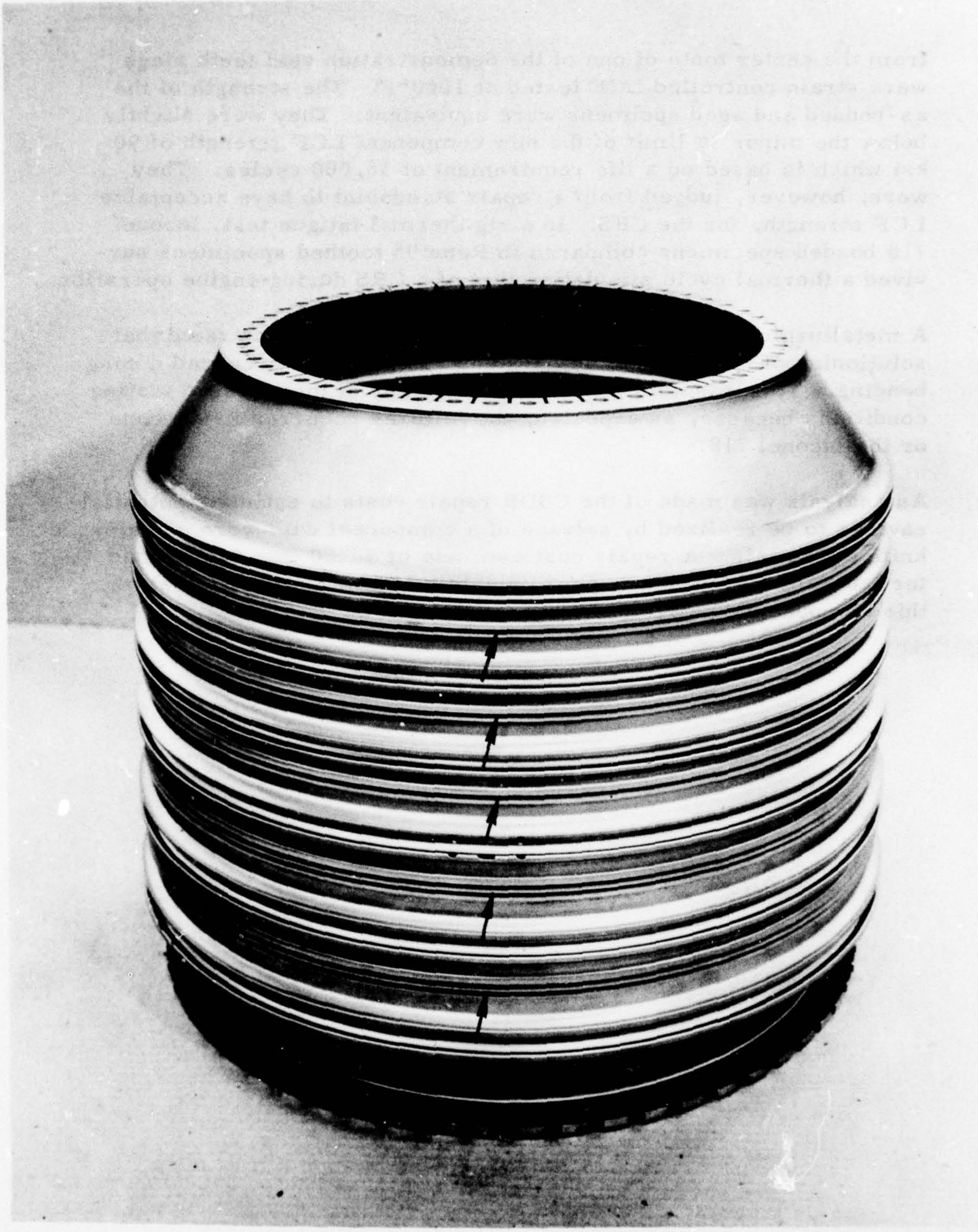


Figure 2. F101 René 95 Compressor Rotor Spool Stages 4 Through 9.

from the center tooth of one of the demonstration seal teeth rings were strain controlled LCF tested at 1000°F. The strength of the as-bonded and aged spcimens were equivalent. They were slightly below the minus 3σ limit of the new component LCF strength of 90 ksi which is based on a life requirement of 36,000 cycles. They were, however, judged from a repair standpoint to have acceptable LCF strength, for the CRS. In a rig thermal fatigue test, Inconel 718 bonded specimens compared to Rene'95 toothed specimens survived a thermal cycle simulating that of a CRS during engine operation.

A metallurgical study of the repaired seal teeth demonstrated that solutioning of the carbides in the Rene'95 seal teeth occurred during bonding. This was not detrimental under any of the imposed testing conditions because, as expected, the failures occurred in the bond or the Inconel 718.

An analysis was made of the CSDB repair costs to estimate potential savings to be realized by salvage of a component with worn or damaged knife edge seals. A repair cost estimate of $2200 was determined for the F101 CRS which is approximately 10% of the initial cost of this component.

3.0 SELECTION OF PROGRAM REPAIR PROCESS & TEST COMPONENT

3.1 Selection of Repair Process

General Electric had accumulated considerable background data on a variety of candidate joining processes for adding extensions to worn superalloy knife edge seal teeth. Conventional fusion welding processes are generally considered unsatisfactory since all involve melting and suffer from loss of properties, distortion, and cracking during welding or post-weld heat treatment. Clearly, the method selected had to be one in which a solid state diffusion bond was produced. The Solar Continuous Seam Diffusion Bond (CSDB) and Continuous Melt Diffusion Bond (CMDB) processes had been evaluated and were found to produce satisfactory bonds. Prior work conducted at Solar demonstrated the capability of the two techniques to diffusion bond two wrought nickel-base superalloys - Inconel 718 and Hastelloy X - in a continuous fashion to Rene'95 seal teeth. The CSDB process was judged to be superior, since it would avoid the braze alloy remnants in the joint. The Linde Ultrapulse process was also given a preliminary evaluation and judged to be inferior. Although excellent upset diffusion bonds were obtained, a continuous bond could not be produced since only short lengths could be bonded one-at-a-time, making the technique too cumbersome and probably less reliable. CSDB was selected as the repair technique for this program.

3.2 Selection of Test Component

The F101, Rene'95, compressor rotor spool (CRS), Stages 4-9 was chosen because of the high payoff for a successful repair process. The multiple seal teeth in this design could result in scrapping an expensive part for tooth wear on a single tooth. It was also selected for other reasons: (1) it contained a typical seal tooth configuration, (2) the one to be used had seen engine operation and was representative of a component needing repair, (3) the seal material is Rene'95, a difficult material to join as it is very sensitive to cracking during welding - success with Rene'95 would predict applicability to virtually all superalloys - and, (4) there are numerous Rene'95 components on the F101 engine that contain seal teeth.

3.3 Selection of Tip Extension Material

Selection of the tooth repair material was based on a number of considerations including:

- Thermal compatibility with Rene'95
- Seal wear characteristics
- Tensile strength
- Creep/rupture strength
- Low cycle fatigue strength
- Fabrication compatibility with Rene'95

Six candidate repair materials were considered based on thermal compatibility and fabrication experience. They included:

- Rene'95
- Hastelloy X
- L605
- HS188
- Inconel 718
- Inconel 600

When compared against the design strength requirements, the limiting strength parameter was found to be low cycle fatigue strength based on a life requirement of 36,000 cycles. This analysis considered thermal compatibility with the Rene'95 spool in establishing the strain range experienced by the seal tooth during each thermal cycle in operation. The results of this study showed only Rene'95 and Inconel 718 tooth material would have sufficient low cycle fatigue strength to meet the requirements, having calculated lives of 100,000 and 62,000 cycles, respectively.

Having narrowed the material candidates to two (Inconel 718 and Rene'95) on the basis of design strength, Inconel 718 was selected as the repair material for this program for the following reasons:

- Inconel 718 shows more favorable rub characteristics than Rene'95 based on General Electric experiences. Inconel 718 does exhibit a greater wear rate than Rene'95, but does not have the tendency of depositing tooth material on the stator seal and generating an accelerated tooth failure.

- Inconel 718 to Rene'95 bonding had been previously demonstrated and a heat treatment defined which would provide the bond joint strengthening of both alloys.

4.0 PROGRAM RESULTS

4.1 Phase I Process Development

4.1.1 Basic Process Sequence

The basic process sequence for the CSDB repair of knife edge seal teeth is described below and was shown previously in pictorial fashion in Figure 1 in the Summary.

Step	Operation
1	Grind O. D. of worn teeth
2	Isothermal roll-widen preshape teeth
3	Grind to center of teeth upset area
4	CSDB cover strip to teeth
5	NDT bond (ultrasonic)
6	Grind to original contour
7	NDT bond (FPI)
8	Heat treat (age)
9	NDT bond (FPI)

Step 1. The seal teeth are machined to a constant diameter to remove any prior damage/degradation.

Step 2. The seal teeth are isothermally rolled/preshaped to increase the width of the teeth, hereby providing a sufficient width to remachine the repaired teeth to their original profile.

Step 3. The seal teeth are ground to the approximate center of the upset area to provide the maximum interface width and a clean bonding surface.

Step 4. The Inconel 718 tip extension cover strip is CSDB'ed to the seal teeth.

Step 5. The bond areas are evaluated by NDT. The pulse-echo ultrasonic technique is ideally suited for this application since the bonds are a constant distance below the top surface of the cover strip.

Step 6. The tip extensions are rough machined and the teeth reprofiled by grinding.

Step 7. The bond areas are again examined by NDT using conventional fluorescent penetrant techniques.

Step 8. The component is heat treated to stress relieve/age the bond area. This may not be necessary depending upon the properties obtained in the as-bonded condition.

Step 9. The bond areas are evaluated by fluorescent penetrant inspection as a final check for bond integrity.

4.1.2 Seal Ring Preparation

A F101, Rene'95, CRS, Stages 4-9 was obtained for the repair effort. At Solar, San Diego, California, five seal teeth rings containing three labyrinth seal teeth were machined from the areas designated by the arrows in previously shown Figure 2. The machining was accomplished by mounting the forward end of the CRS on the face plate of a lathe and progressively making circumferential cuts utilizing a tool post grinder with an abrasive cutoff wheel.

4.1.3 Tooling Fabrication

An expandable fixture was designed and fabricated to be used with either an actual CRS or individual seal teeth rings cut from the spool. This approach was taken so that experience gained with rings during the present contract could be applied to an actual CRS where insertion of an internal expandable mandrel between the spool discs would be more difficult. The fixture was basically a 16-inch diameter by 1-inch thick steel disc made up of one rectangular segment every 90 degrees with two wedge-shaped segments in each quadrant. All the segments are adjustable radially from the central hub and the unit was used for isothermal rolling, CSDB and machining of the seal teeth rings. The fixture shown in Figure 3 was used to grind .030 $\pm$ .002 inch of material from the teeth to simulate worn teeth.

4.1.4 Isothermal Rolling Tooth Widening

The isothermal rolling of the seal teeth rings was conducted on Solar's Isothermal Shape Rolling (ISR) machine, having a 25,000 ampere and 45,000 pound upset capability. Figure 4 shows the setup for isothermal rolling. The temperature and travel speed parameters used on seal ring #1 and the resulting decreases in teeth height are listed in Table I. The temperature was controlled by a feedback signal from an optical pyrometer to control the heating current. An Inconel 718 "thermal strip" band was used between the teeth and upset roll for the first seven settings. Its purpose was to concentrate heating at the tip of the teeth by decreasing roll chill and increasing contact resistance. No thermal strip was used for the eighth setting. An inert protective atmosphere was not necessary. However, a graphite spray lubricant was used to inhibit sticking to the seal teeth.

Evaluation of the microstructures by Solar and General Electric indicated that a rolling temperature of 2025°F was near optimum as illustrated in Figure 5. Although some solutioning of the carbides could be tolerated, at the higher rolling temperature of 2075°F it was too extensive and incipient melting was detected at 500X. At 1950°F, evidence of cold worked grains and shear tears were observed. The microstructure of the center tooth also indicated that it had reached a higher temperature than the outside teeth. The probable cause of the cooler outer teeth was radiation losses. This was not a limiting concern and all three teeth were within a $\pm$ 25°F acceptable tolerance.

Examination of the first isothermally rolled seal teeth ring revealed a nonsymmetrical tooth profile in the originally machined condition. Although the upset profiles of all three teeth, in each set, were comparable, they were judged questionable for subsequent CSDB repair because the rounded edge could leave unbonded areas at the end of the joint after CSDB. This situation and its impact on the rolled teeth are also depicted in Figure 5. The four remaining rings were returned to General Electric for reprofiling before isothermal rolling as shown in Figure 6. The black areas indicate the material that was removed to obtain the proper contour. The reprofiling was done on a vertical turret lathe with the same grinding equipment which is used for finish grinding production CRS seal teeth. It should be realized that the

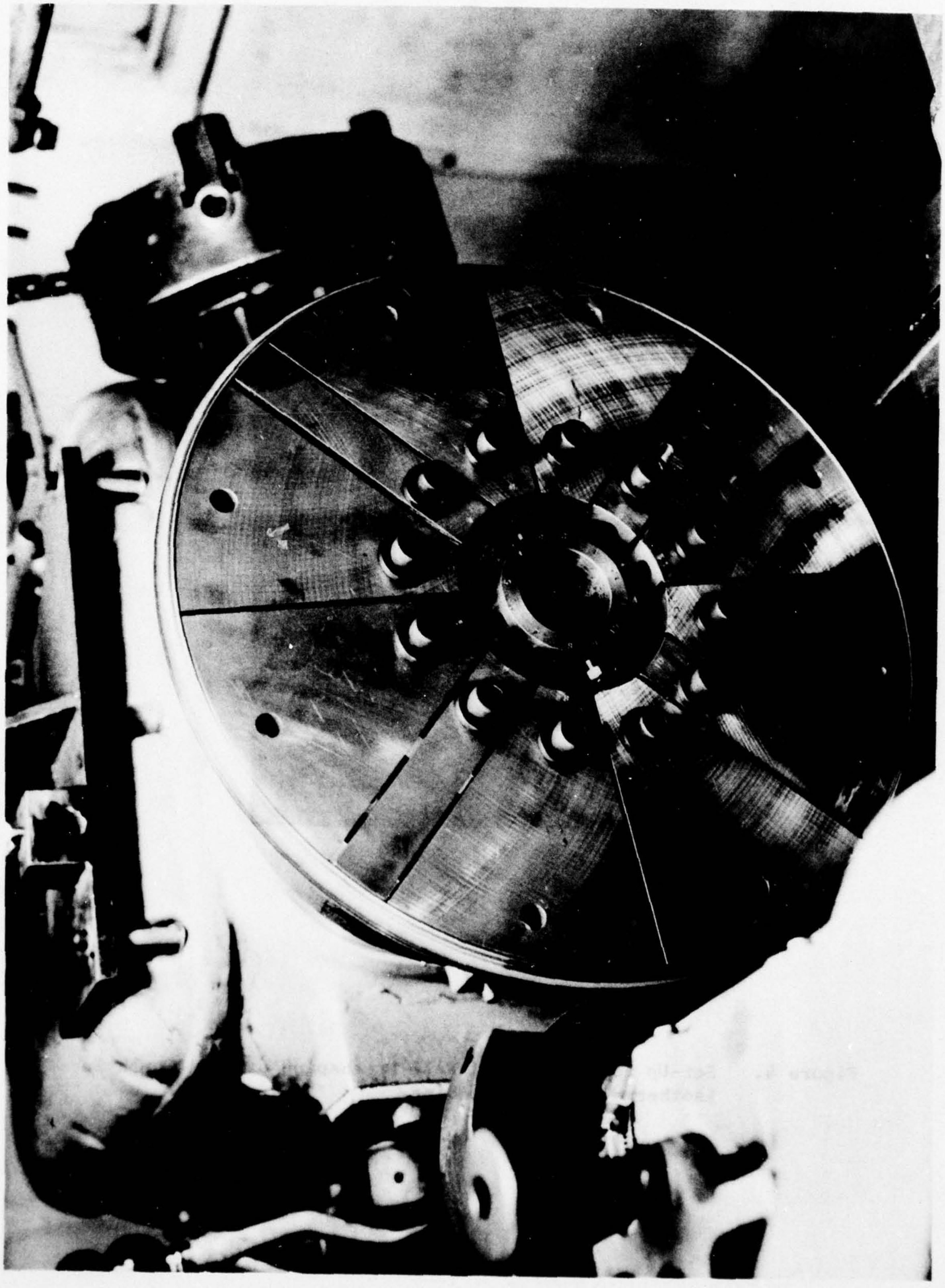


Figure 3. Set-Up For Machining Tips of Seal Teeth.

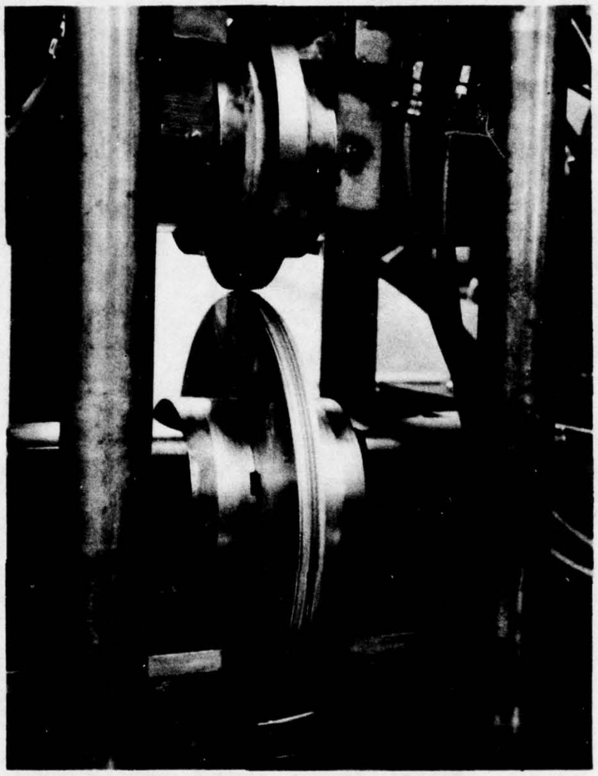


Figure 4. Set-Up For Isothermal Roll Preshaping of Seal Teeth in Isothermal Rolling Machine.

Table 1. Isothermal Rolling Parameters Used on Seal Ring No. 1

Parameter Setting	Temperature (°F)	Speed (ipm)	Decrease of Tooth Height (in.)
1	2025	1.6	0.053
2	2025	3.2	0.042
3	2075	3.2	0.042
4	1950	3.2	0.027
5	1950	1.6	0.034
6	2075	1.6	0.045
7	2026	1.6	0.042
8	2025	1.6	0.047

Note: Squeeze force held constant at 1200 pounds.

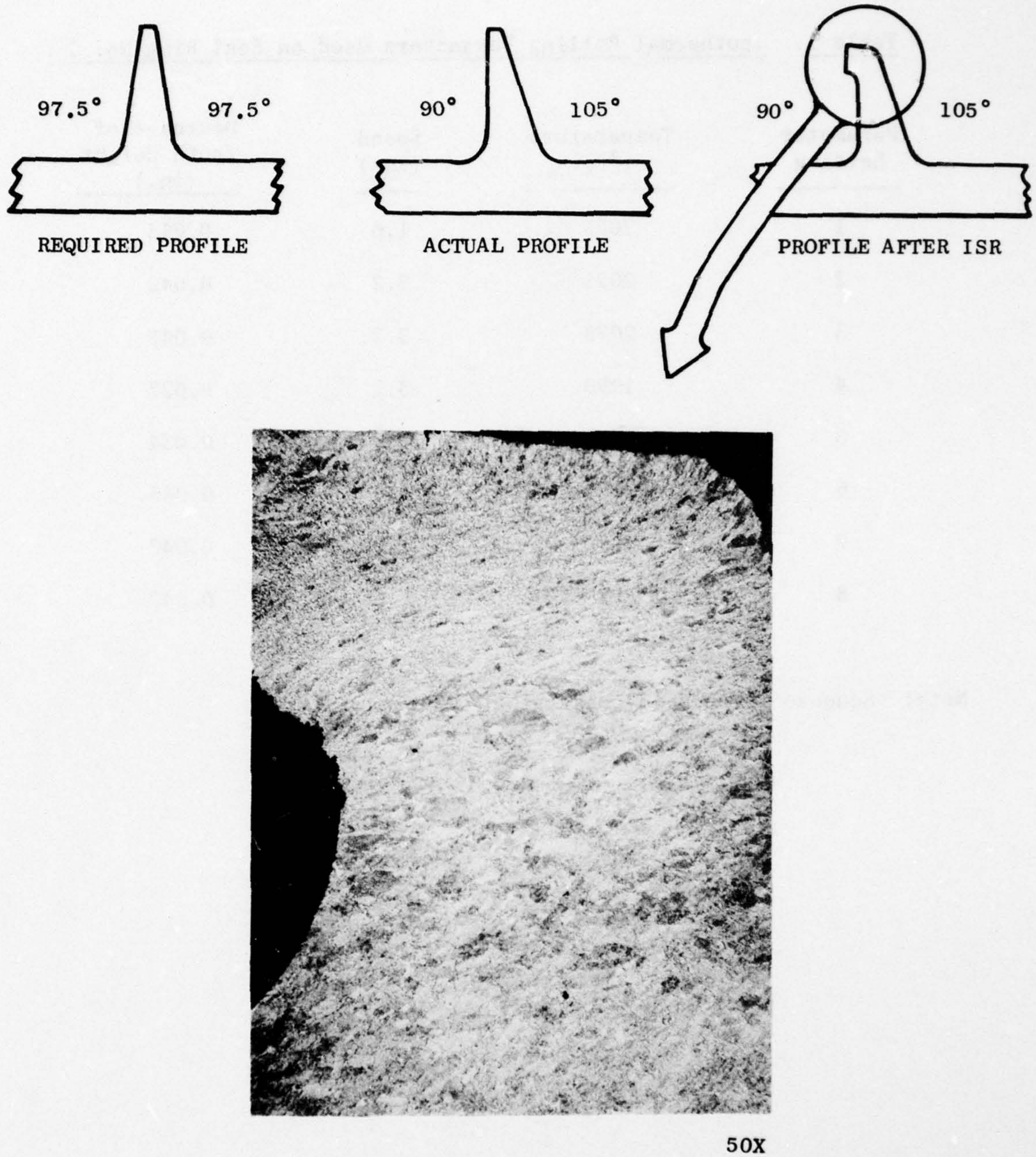


Figure 5. Non-Symmetrical Profiles of René 95 Seal Teeth and Microstructure After Isothermal Rolling at 2025°F.

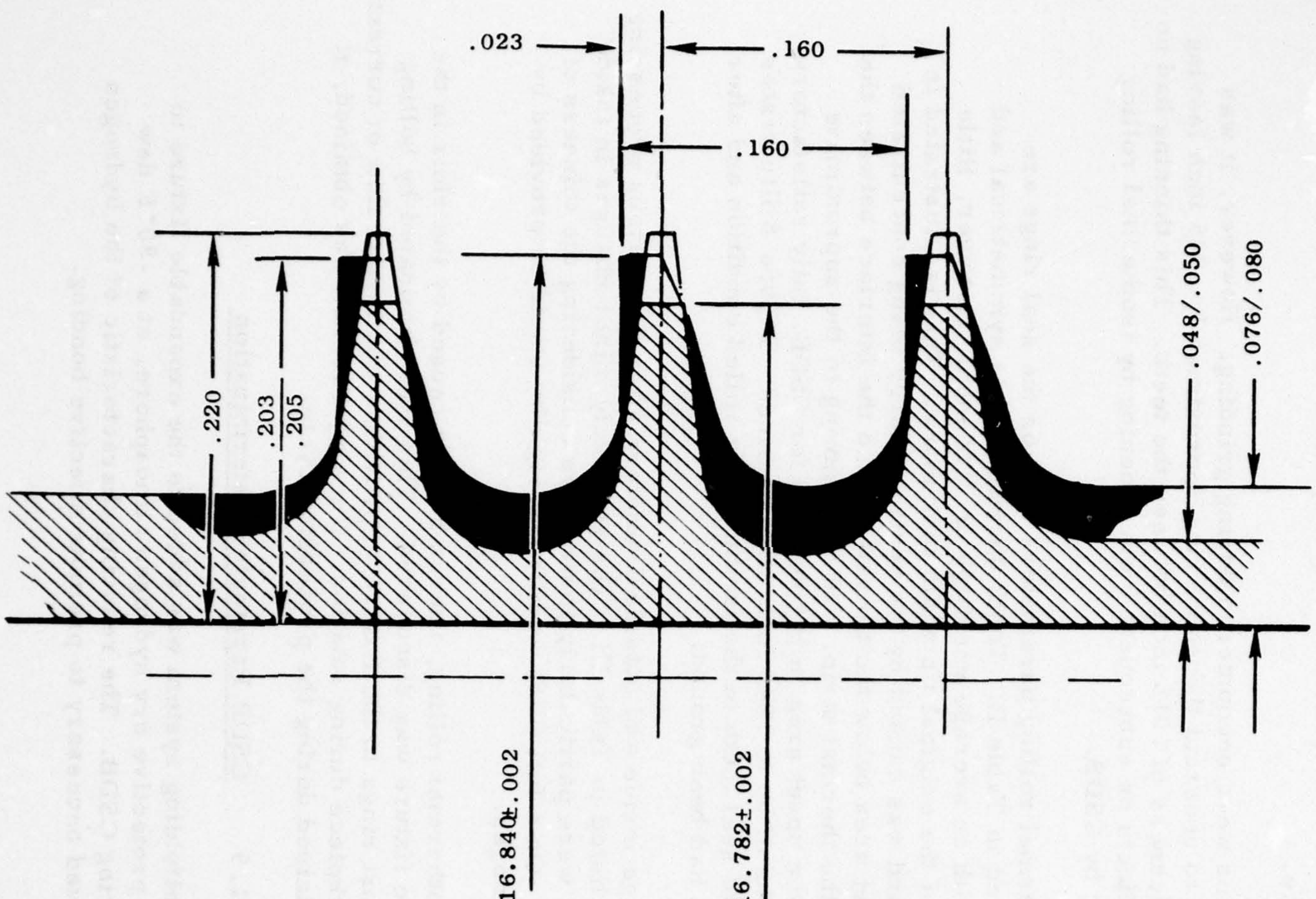


Figure 6 Remachined Seal Teeth Profiles

nonsymmetrical teeth discovered in the program's rotor spool was a highly unusual situation that a repair process would not normally have to face.

No problems were encountered during grinding. However, it was necessary to undercut the spool ring approximately .045 inch leaving a spool thickness of .015 inch between the teeth. This thinning had no adverse effects on subsequent tooth widening by isothermal rolling or bonding by CSDB.

The isothermal rolling parameters used on the seal rings are summarized in Table II. Tooth upsetting was symmetrical and uniform with an average upsetting of .032 inch. However, little widening of the original tip width took place. This is illustrated in Figure 7 and was caused by the heating energy being concentrated in the upset area below the tip rather than the interface between the teeth and the thermal strip. After trimming to the approximate center of the upset area in preparation for CSDB, fully satisfactory crest widths of up to .040 inch were obtained. Figure 8 illustrates a section of seal teeth in the isothermally rolled condition and after the crests had been ground.

The average inside and outside diameters after the various processing steps are listed in Table III. The relatively minor changes in inside diameters were particularly impressive considering the thinness of the rings. On a full CRS, additional rigidity would be provided by internal flanges.

During isothermal rolling, uneven heating caused by the slots in the expandable fixture was discovered. This was eliminated by bolting side support rings to the fixture to provide a continuous flow of current to the workpiece during rotation. Once equilibrium was obtained, it was maintained during the processing cycle.

4.1.5 CSDB Parameter Determination

A gas manifolding system was added to the expandable fixture to provide a protective dry hydrogen atmosphere, at a -80°F dew point, during CSDB. The reducing characteristic of the hydrogen was believed necessary to promote effective bonding.

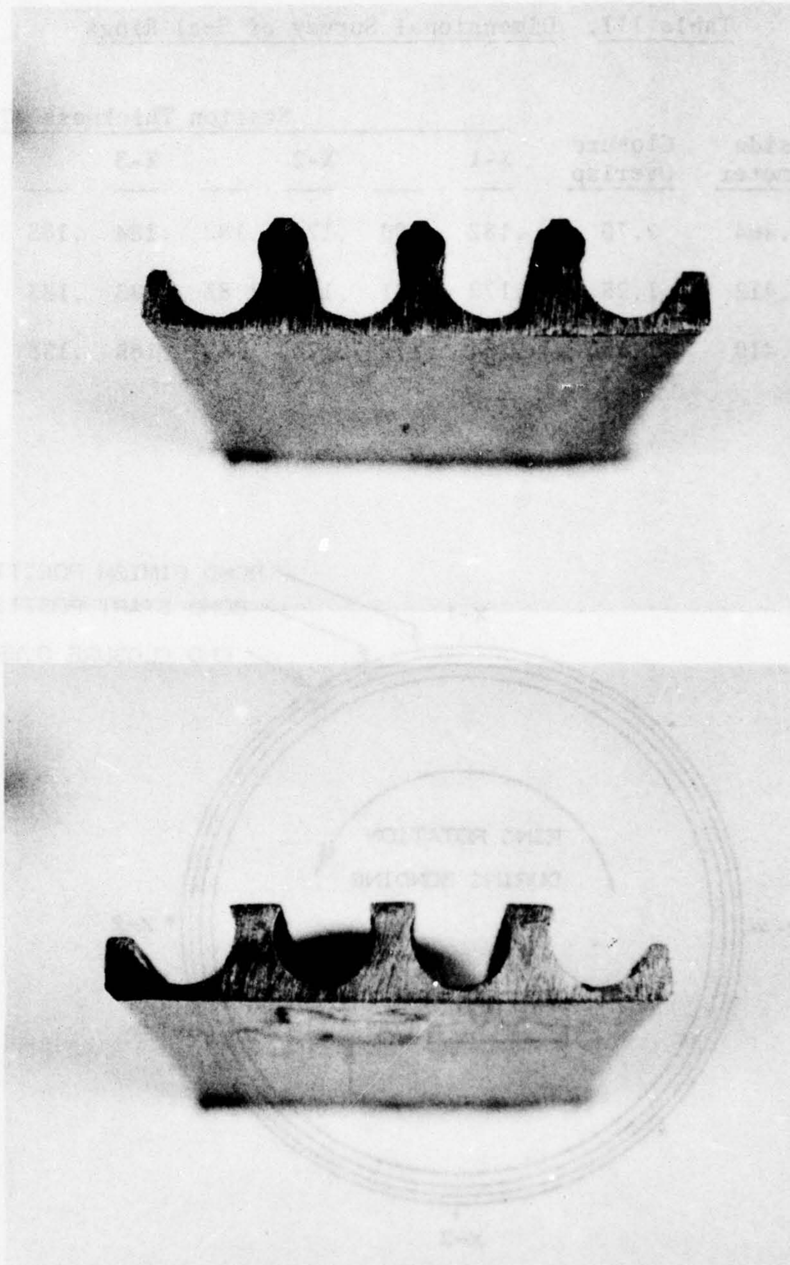
Table II. Isothermal Rolling Parameters Used on Seal Rings Nos. 2-5

Seal Ring No.	Squeeze Force (lbs)	Range of Heating Current (KA)	Decrease Of Tooth Height (in.)	Maximum Tooth Width After Upsetting (in.)
2	1050	1.80/2.21	0.032	055/051/053
4	1230	2.19/2.87	0.034	Not Measured
3&5	1050	1.77/2.73	0.031	053/049/055

Note: Temperature controlled 2025 ± 10°F by Optical Pyrometer Feedback
Rolling Speed 1.6 ipm
.066 x .750 Inch Inconel 718 Thermal Strip
Graphite Lubricant on Seal Ring, Thermal Strip and Form Roll

50X

Figure 7. René 95 Seal Teeth Profile After Isothermal Rolling Symmetrical Seal Teeth at 2025°F.

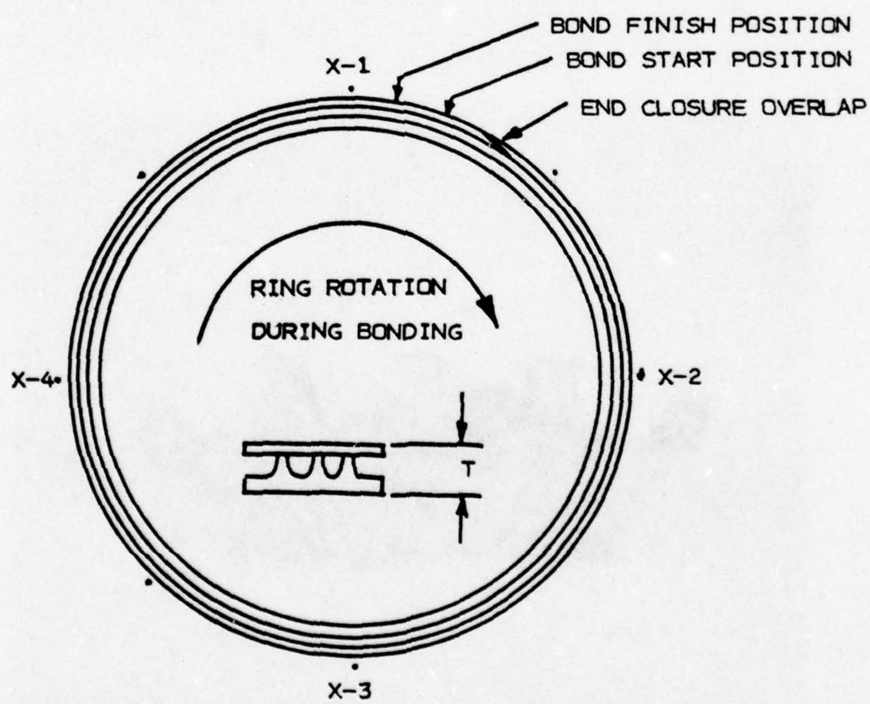


5X

Figure 8. Seal Teeth Profiles After Isothermal Roll Preshaping and Grinding to Center of Upset Area.

Table III. Dimensional Survey of Seal Rings

Seal Ring No.	Inside Diameter	Closure Overlap	Station Thickness (T) inch							
			X-1		X-2		X-3		X-4	
4	16.404	2.70	.182	.180	.174	.182	.184	.185	1.82	.182
3	16.412	1.25	.172	.181	.179	1.83	.183	.183	.182	.177
5	16.410	1.55	.164	.172	.170	.163	.165	.158	.144	.163



Note: Diameter measurements made with π -tape
Measurements are in inches

The thickness of the Inconel 718 cover strip was .066 inch and the alloy was in the solution treated condition. The preference for this condition was determined on a previous program conducted at Solar.

Immediately, prior to assembly into the layup on the expandable fixture, the components were cleaned using the procedure outlined in Table IV.

A schematic section of the bonding layup is shown in Figure 9. The expandable fixture with side rings, gas manifolds and a bonding layup inside .004 inch stainless steel cover foils is shown in Figure 10.

A closed loop current control mode of operation was used during CSDB because optical pyrometry access to the heated surfaces was blocked by the cover foils needed for hydrogen containment.

A summation of the CSDB parameters is presented in Table V. The parameters of squeeze force, travel speed, and hydrogen purge were held constant while current was varied. Peel testing as illustrated in Figure 11 was used to assess bonding.

Indications of good teeth impression and atmospheric protection were achieved on the first segment on seal ring #2 in which the heating current was varied from 2.2 to 2.6 kiloamps (KA), but the bond was weak. Better bonding was achieved on the second segment which was varied from 2.8 to 3.1 KA.

The final processing parameters to be used for the two Phase II process verification rings were to be pinpointed on seal ring #4. A heating current of 2.9 KA was used on the first half of this ring and was stepped to 3.3 KA for the second half. The first half did not bond and the second half appeared to be bonded best over a 6-inch length where the cover strip had slipped so that only two teeth were bonded. These observations indicated the heating current should be increased considerably. Consequently, seal rings #3 and 5, the two rings for the Phase II Process Verification Study were bonded at higher current levels.

A pictorial representation of a section through a typical CSDB seal

Table IV. Cleaning Procedures Used on Seal Teeth Rings

Step		Sequence
A	Degrease	Scrub with cold alakline cleaner (Mission Chemical Co., Concentrate No. 93); warm air dry
B	Electropolish	7 volts, 60 seconds in polishing bath, 120°F (powerclean solution, Molectrics, Inc.,); tap water rinse
C	Acid Pickle	1 part HF, 5 parts HNO_3 in 16 parts water 70°F; 1 min for T430; 5 min for Inconel 718 and Rene'95; DI water rinse; warm dry air.

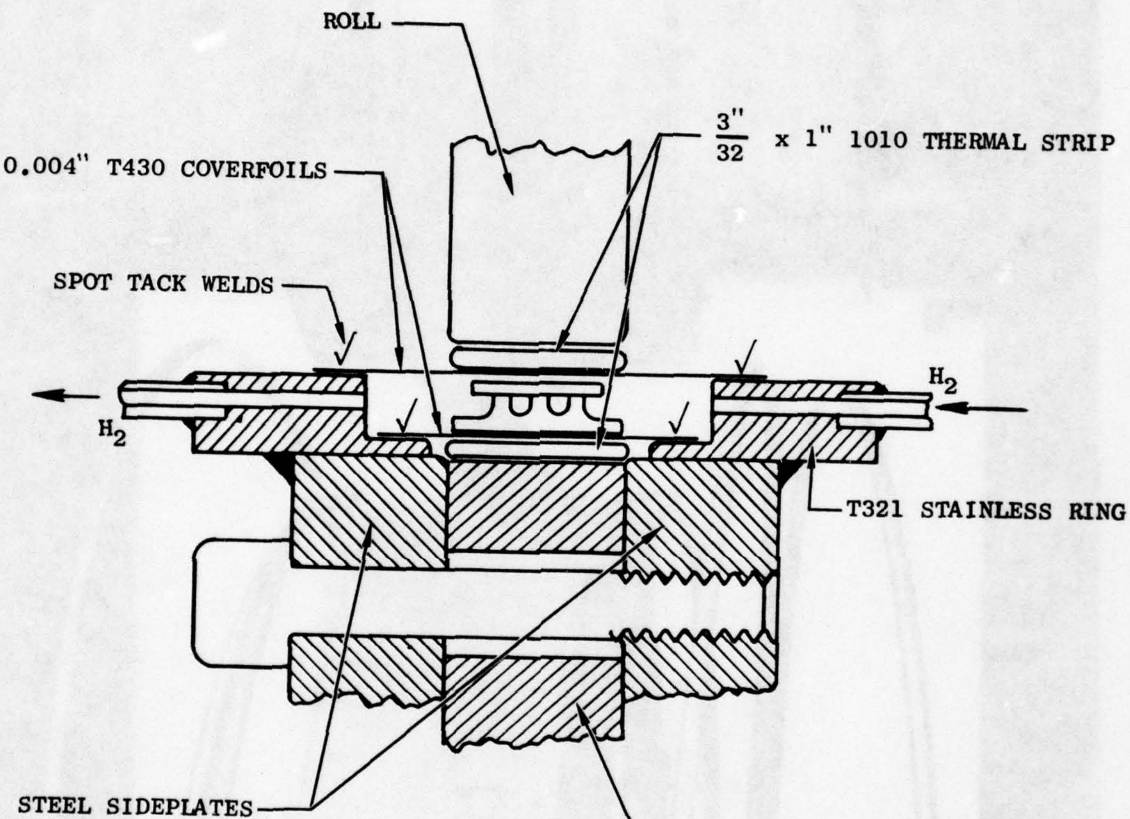


Figure 9. Cross-Section of Bonding Lay-Up For CSDB of Seal Teeth Rings.

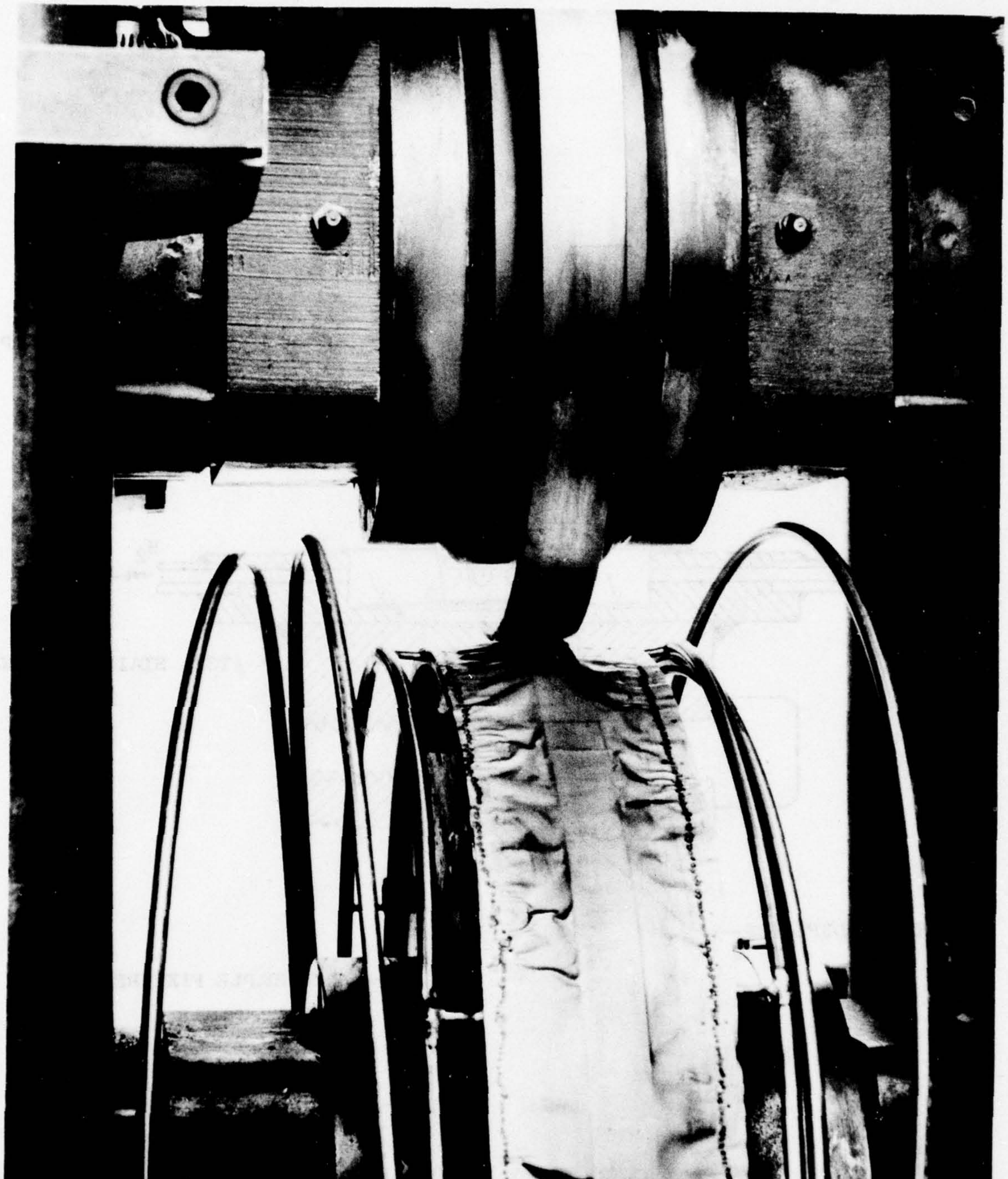


Figure 10. Set-Up For CSDB of Seal Teeth Rings in Isothermal Rolling Machine.

Table V. CSDB Parameters Used on Seal Teeth Rings

Seal Ring No.	Heating Current (KA)	Coverstrip End Closure	Observations
2(Seg. 1)	2.2/2.6	None	Weak bond
2(Seg. 2)	2.8/3.1	None	Peel test indicated Good bonding
4	2.9/3.3	Only starting end scarfed	Good bonding only near finish where coverstrip slipped sideways exposing one of the three teeth
3	3.8/4.5	Both ends scarfed	Appears well bonded but with overtemperature in localized areas
5	3.6/4.0	Both ends scarfed	Appears well bonded. Good closure overlap.
2	3.6/4.0	Both ends scarfed	Trial closure bond

Note: Squeeze Force 1050 Pounds
Rolling Speed 3.2 IPM
.066 x .750 Inch Inconel 718 Coverstrip
Graphite Lubricant Only on Thermal Strip and Bonding Roll
Dry Hydrogen (-80°F Dewpoint) Purge at Approximately 10 SCFH.

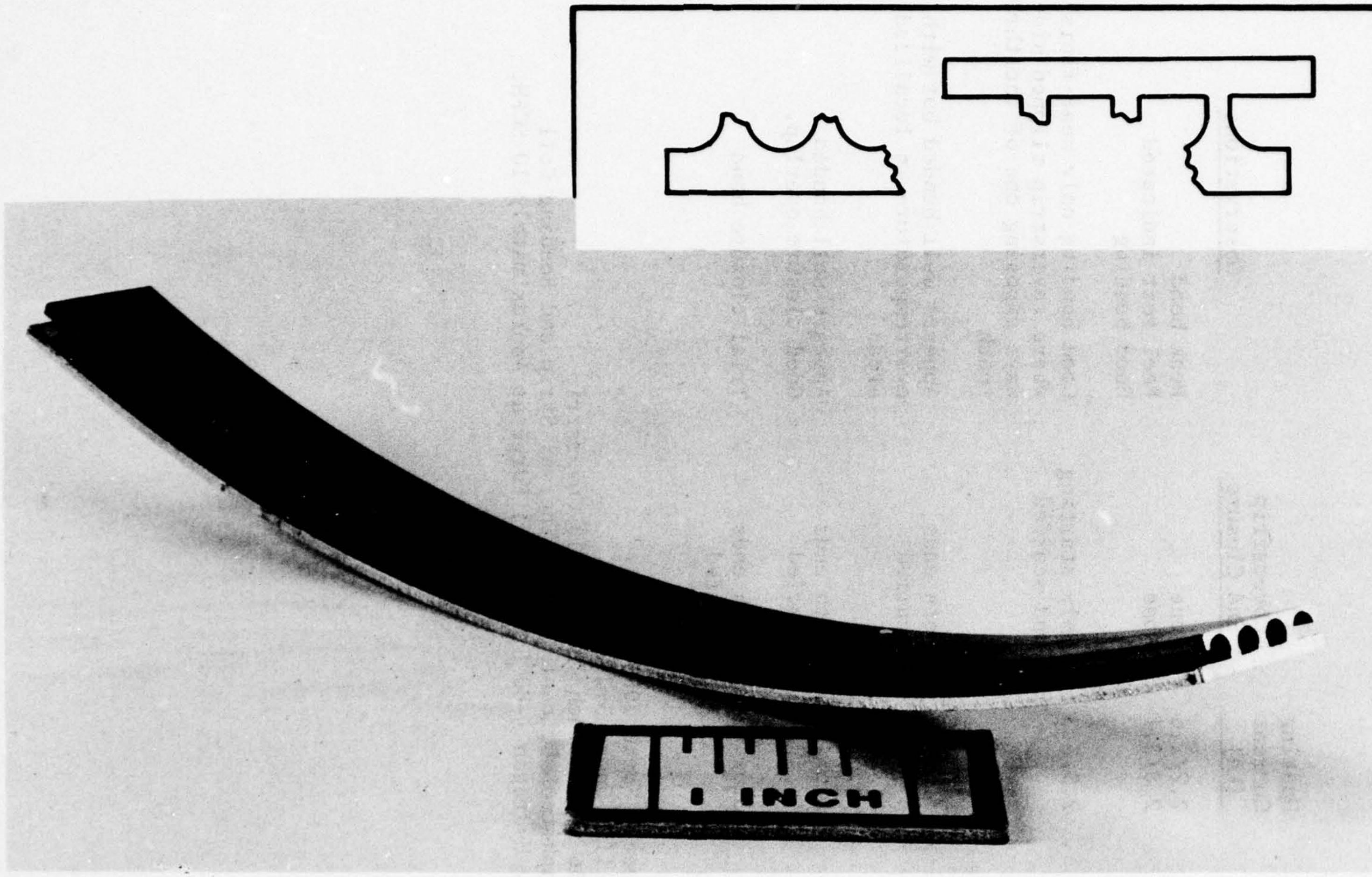


Figure 11. Section of CSDB'ed Seal Teeth Ring and Peel Tests Initially Used to Evaluate Bond Quality.

tooth obtained during the parameter study is illustrated in Figure 12. In some instances, the Rene'95 tooth was simply compressed with little change in microstructure. However, in most cases the area under the bond line showed some solutioning. The solutioning was not considered excessive as long as the mechanical properties of the Rene'95 were not degraded and it was not accompanied by a significant amount of incipient melting, a condition which is shown in Figure 13.

Generally, there was little change in the microstructure of the Inconel 718 cover strip in the bond area. No grain growth was encountered unless the bonding parameters were excessive. This also produced excessive solutioning in the Rene'95 which was unacceptable.

The contour of the bond line was interesting because there was little lengthening of the original contact interface after CSDB. The tooth width, prior to bonding, was indented into the Inconel 718 cover strip material.

These two tendencies were consistent throughout the program. However, they did not present any problems because the bond interface was sufficiently widened by isothermal roll preshaping to cover the width after machining.

The center tooth was judged to be most subject to solutioning since it got hotter than the two outside teeth. The heat generated during CSDB was increased due to the foil encapsulation required hydrogen atmosphere control. The heating current was believed to have been evenly distributed between the three teeth. However, it could have been concentrated in the center tooth. Solutioning could have occurred during the isothermal rolling or CSDB processing alone, or in combination with each other, but in all probability, it occurred during CSDB. During isothermal rolling the temperature was controlled by optical pyrometry since there was access to the area being heated. This luxury was not available during CSDB due to the necessity of hydrogen containment. More sophisticated control of the CSDB parameters might have eliminated overheating.

Figure 14 illustrates the microstructures discussed in the previous paragraphs. In Figure 14 top, the Rene'95 is compressed in the

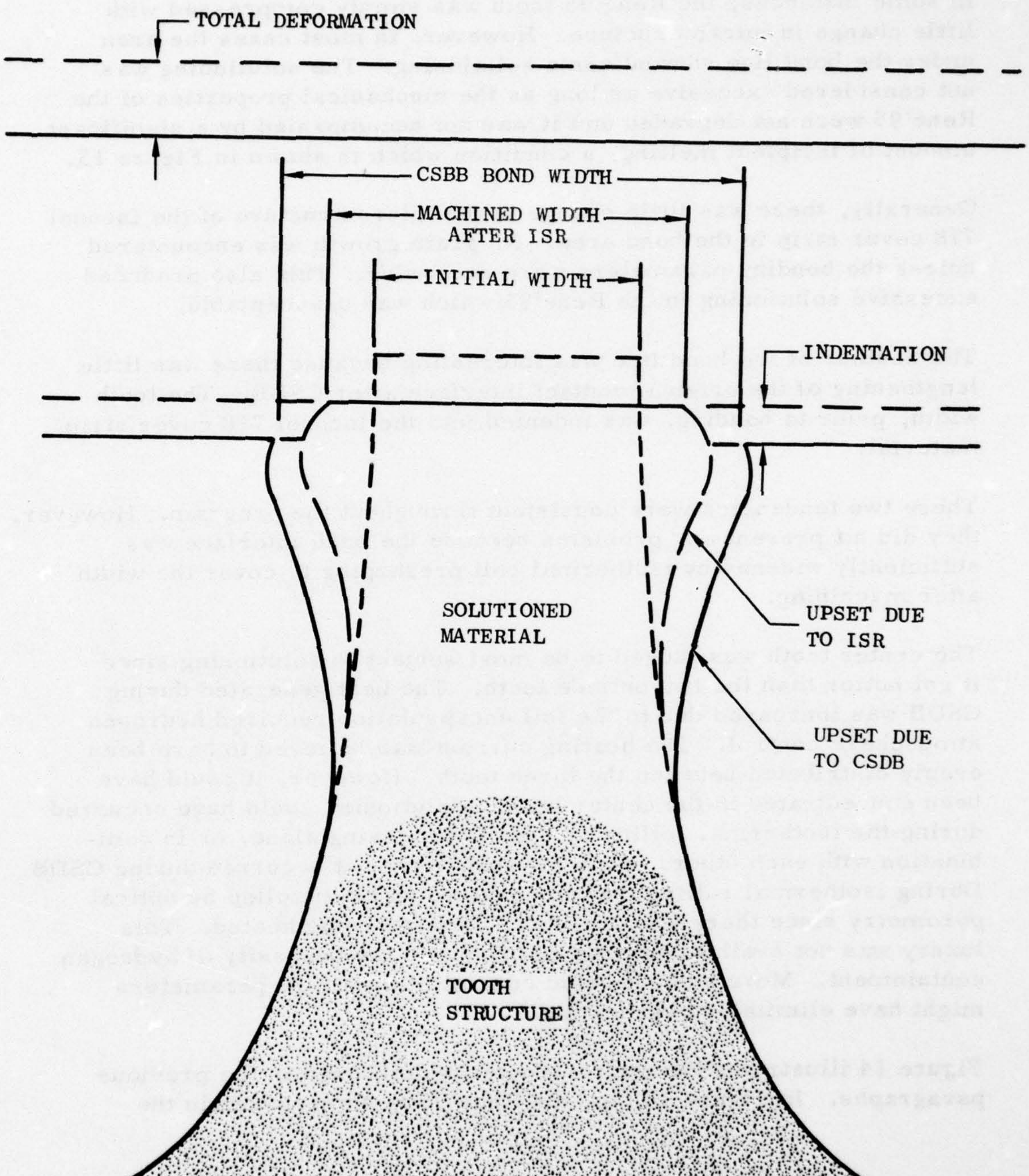


Figure 12. Pictorial Representation of Isothermal Roll Preshaping and CSDB Processing on Seal Teeth.

100X

Figure 13. Incipient Melting Found in René 95 Seal Teeth.

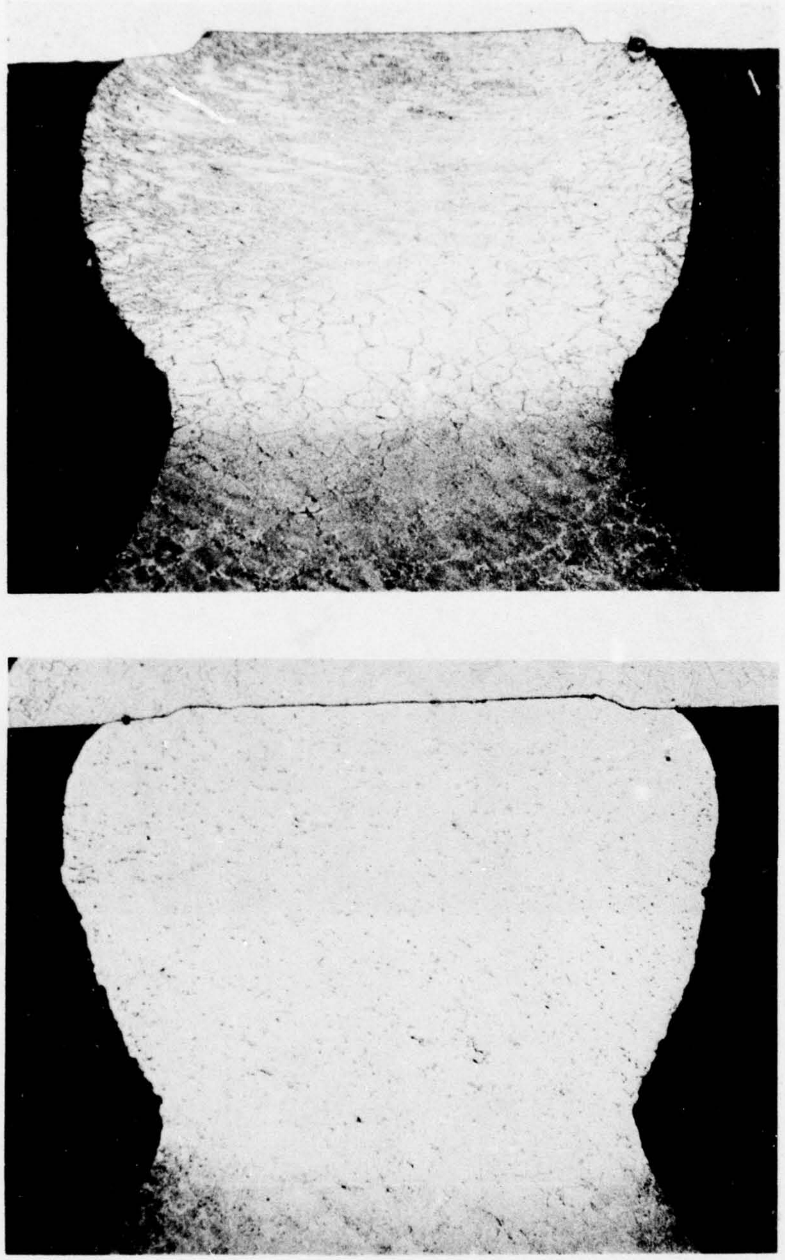


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Figure 14. Sections Through CSDB Seal Teeth.

Top: Little Solutioning

Bottom: Considerable Solutioning

upset area and little solutioning is evident. This section was through an outside tooth. Figure 14 bottom is from a center tooth and there is considerable solutioning of the carbides in the upset area. The temperature of the solutioned material was estimated to have been around 2050°F which was judged acceptable. No differences could be detected between the bonds in the two sections and they were judged to be satisfactory, pending the mechanical evaluation study.

4.1.6 End Closure Parameter Determination

Completing a full 360° tooth repair involves a butt or overlap joint in the cover strip material and to this end, two designs of end closure joints were evaluated: single and double overlap scarf joints as shown in Figure 15. The scarves were made by machining the ends of the cover strip from the full thickness of .065 inch to a knife edge in 1.5 inch, generating a 2.5° bevel. The closure was produced using the approach pictorially presented in Figure 16. Bonding was started beyond the closure, continued around the ring over the closure, ending 1 to 2 inches past the starting point. Rather than use a "running start", the CSDB parameters were brought to the full value before travel was initiated. The same parameters of heating current, force and travel speed, as applied to bonding the cover strip to the teeth, were used for the closure. This technique was used because varying the parameters in the 1.5 inch length of the closure was impractical and unnecessary. The scraf interface in the closure produced an additional resistance/ voltage drop in the bonding circuit. Consequently, it was bonded in the same manner as the original interface because a constant current was being used during bonding. Additional power was required which was supplied by the ISR machine. The length of the cover strip was determined by calculating what its mean length would be after CSDB. This length was shorter than the measured length prior to CSDB due to the compression/distortion of the teeth. Therefore, there was a slight gap between the tapered surfaces of the closure in the bonding layup. However, it closed during CSDB.

The trial closure from ring #2 had the double overlap joint while that of ring #4 had the single overlap as previously shown in Figure 15. Visually, they both appeared to be bonded. However, considerable deformation resulted in the seal teeth under the single overlap joint.

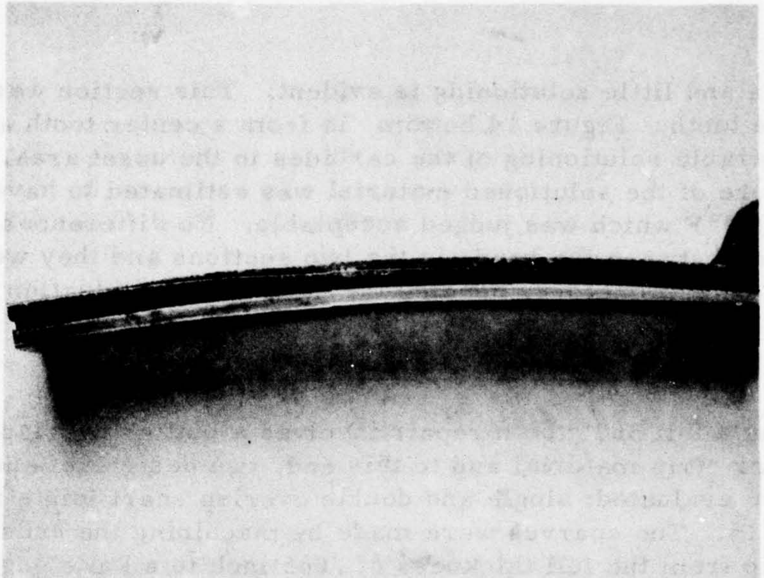

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Figure 15. Single and Double Overlap End Closures.

Top: Double Overlap Scarf Joint

Bottom: Single Overlap Scarf Joint

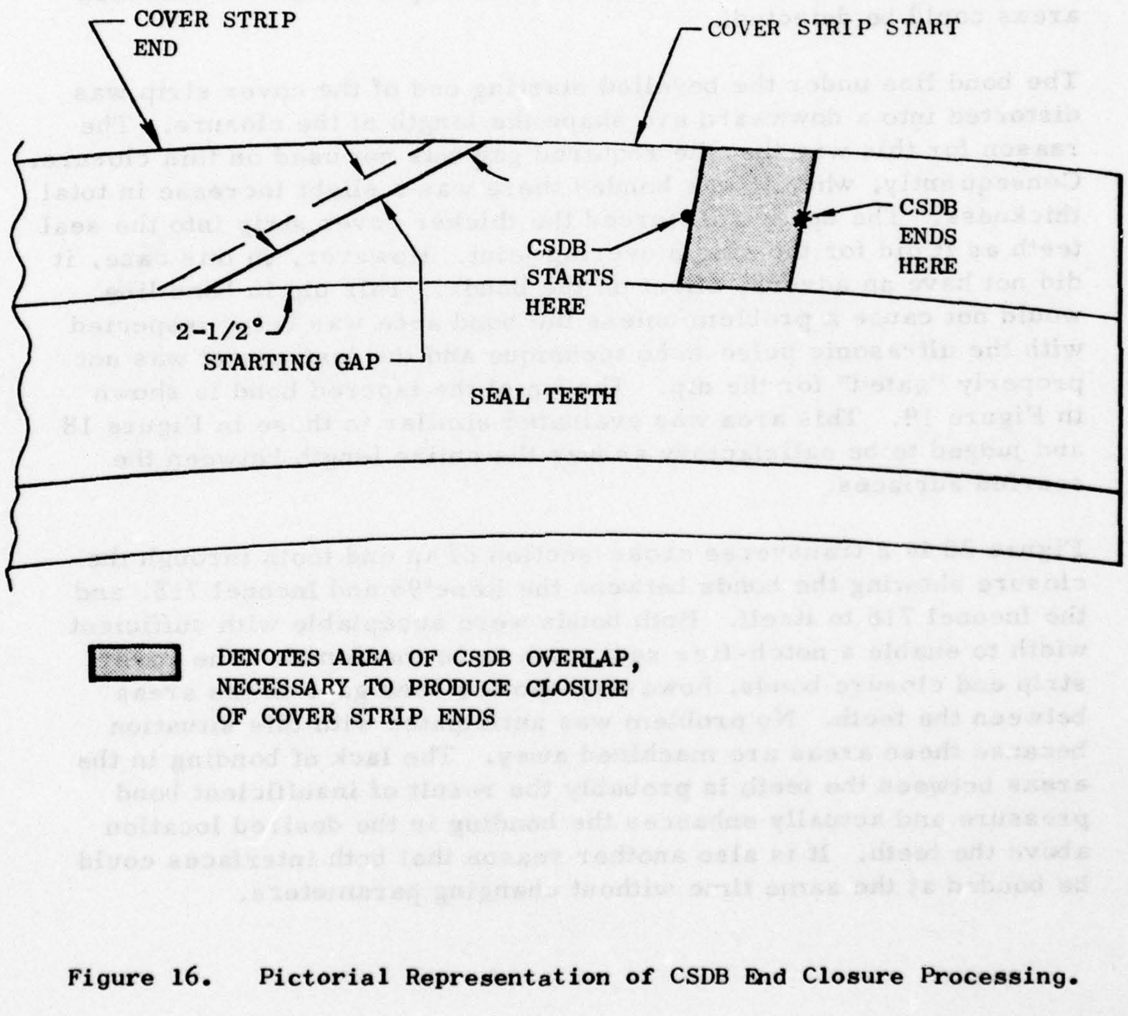

Figure 16. Pictorial Representation of CSDB End Closure Processing.

The upper bonding roll was actuated by hydraulic pressure. As the single overlap closure passed under the roll, it did not compensate quickly enough for the thickness increase and forced the cover strip into the seal teeth. Consequently, the double overlap was judged to be the better approach. Figure 17 shows the top surface of the trial closure with notations of the areas that were sectioned. Longitudinal Sections 7 and 10, at the starts of the taper of the cover strip and the seal teeth on an outside and a center tooth, are shown in Figure 18. In both cases, the feather edge of the starting end was sharp enough to eliminate the tendency to form voids on either side of it. The bonds were judged to be satisfactory as in the polished condition they could not be detected by optical microscopy. The metallographic sections were also fluorescent penetrant inspected and no unbonded areas could be detected.

The bond line under the bevelled starting end of the cover strip was distorted into a downward arc shape the length of the closure. The reason for this was that the required gap was not used on this closure. Consequently, when it was bonded there was a slight increase in total thickness. The upper roll forced the thicker cover strip into the seal teeth as it did for the single overlap joint. However, in this case, it did not have an adverse effect on the bonds. This dip in bond line would not cause a problem unless the bond area was being inspected with the ultrasonic pulse-echo technique and the instrument was not properly "gated" for the dip. The tip of the tapered bond is shown in Figure 19. This area was evaluated similar to those in Figure 18 and judged to be satisfactory as was the entire length between the scarfed surfaces.

Figure 20 is a transverse cross-section of an end tooth through the closure showing the bonds between the Rene'95 and Inconel 718, and the Inconel 718 to itself. Both bonds were acceptable with sufficient width to enable a notch-free seal tooth to be machined. The cover strip end closure bonds, however, showed bond gaps in the areas between the teeth. No problem was anticipated with this situation because these areas are machined away. The lack of bonding in the areas between the teeth is probably the result of insufficient bond pressure and actually enhances the bonding in the desired location above the teeth. It is also another reason that both interfaces could be bonded at the same time without changing parameters.

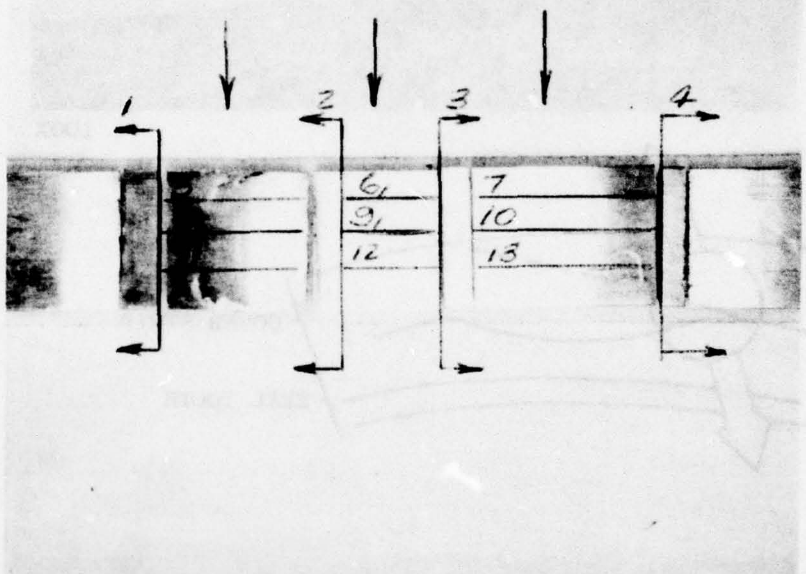

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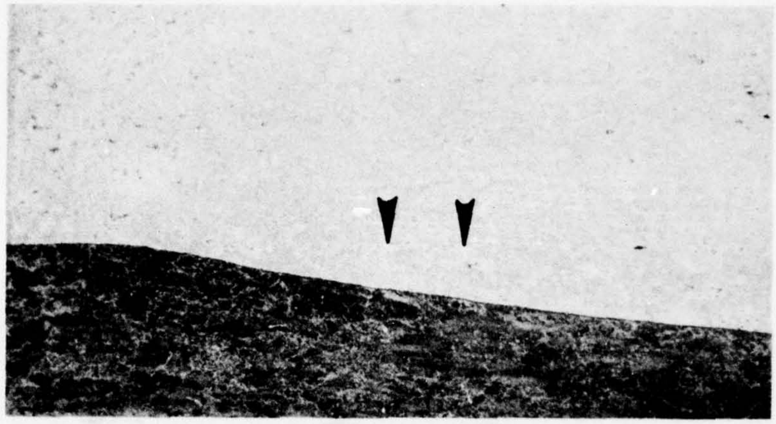
Figure 17. Top Surface of Trial End Closure.



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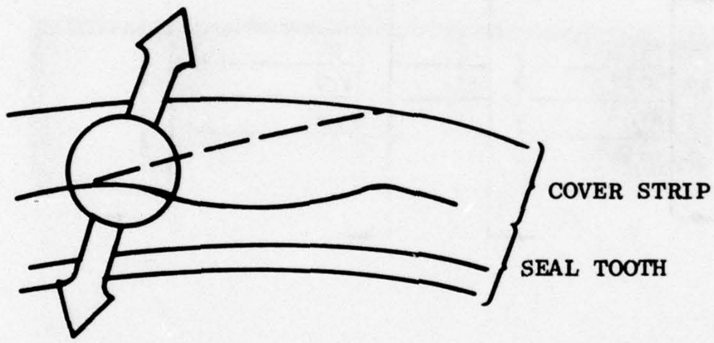

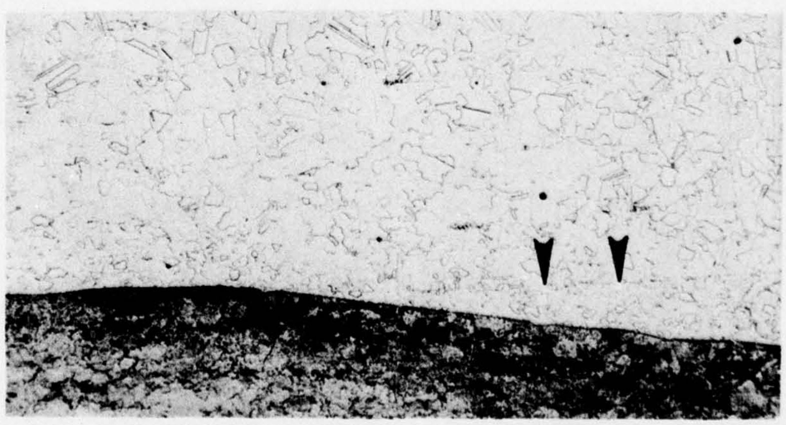

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Top: Location 7

Bottom: Location 10

NOTE: ARROWS INDICATE BOND

Figure 18. Trial End Closure Longitudinal Sections.

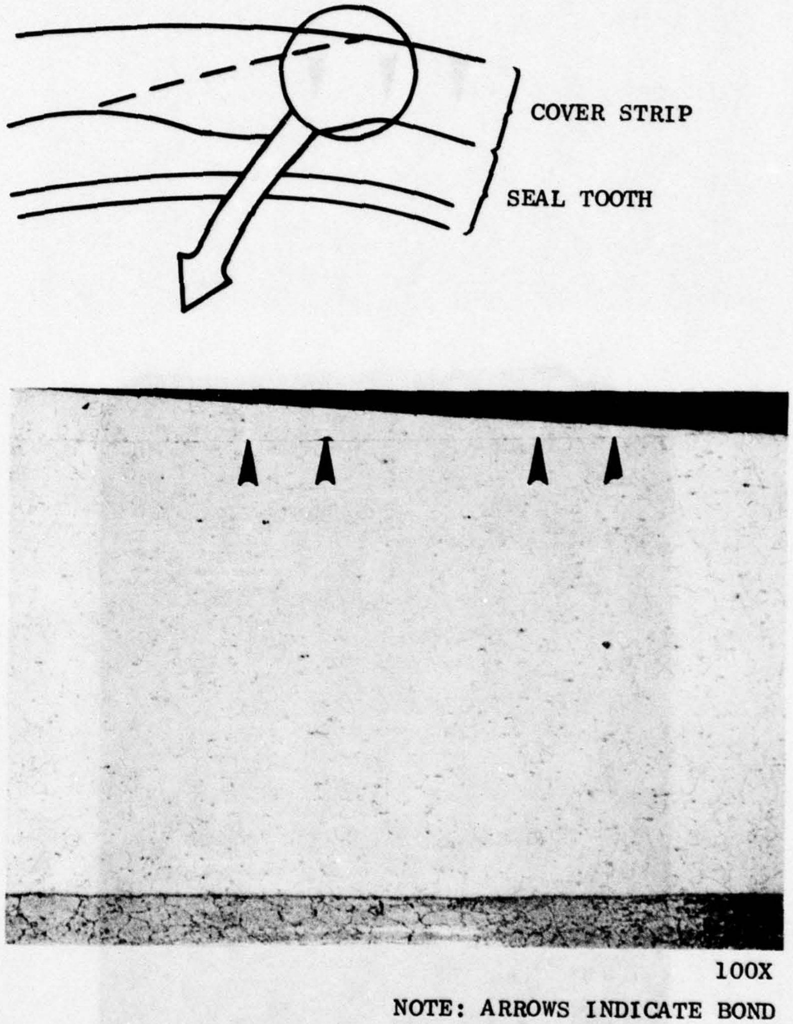
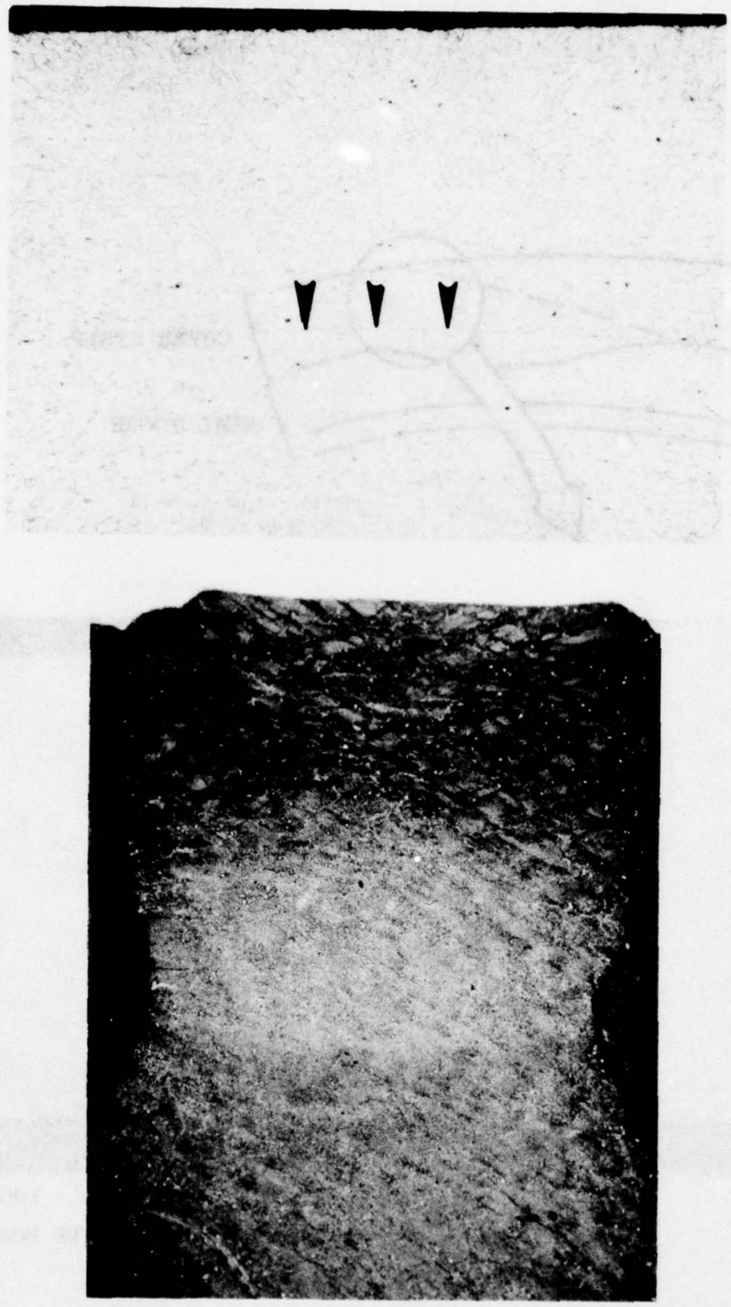


Figure 19. Trial End Closure Longitudinal Section, Location 5.



75X

Figure 20. Trial End Closure Transverse Section, Location 2.

Top: Tapered Cover Strip Bond Area

Bottom: Seal Tooth

The results of the closure study demonstrated that an effective bond could be produced using a double overlap scarf joint. Consequently, this type closure was used on seal rings #3 and 5, the two rings that were fabricated for the Phase II Process Verification Study.

4.2 Phase II Process Verification

4.2.1 Full Ring Repair

Seal teeth rings #3 and 5 were completely processed on the expandable fixture to verify the repair capability of the isothermal rolling/CSDB processes developed in Phase I. The isothermal rolling parameters noted previously in Table II, were used to preshape the teeth prior to CSDB. The bonding parameters developed in Phase I appeared to be inadequate, as noted in Section 4.1.5. Consequently, seal rings #3 and 5 were bonded at higher current levels. Seal ring #3 was the first to be bonded using a heating current of 4.15 $\pm$ .35 KA. The ring appeared to be well bonded, but localized shear type deformation in the upset area of the outer teeth surfaces suggested that the current was excessive. The length of the overlap of the closure was 1/4 inch short of the calculated length. Consequently, there was a depression due to lack of sufficient material.

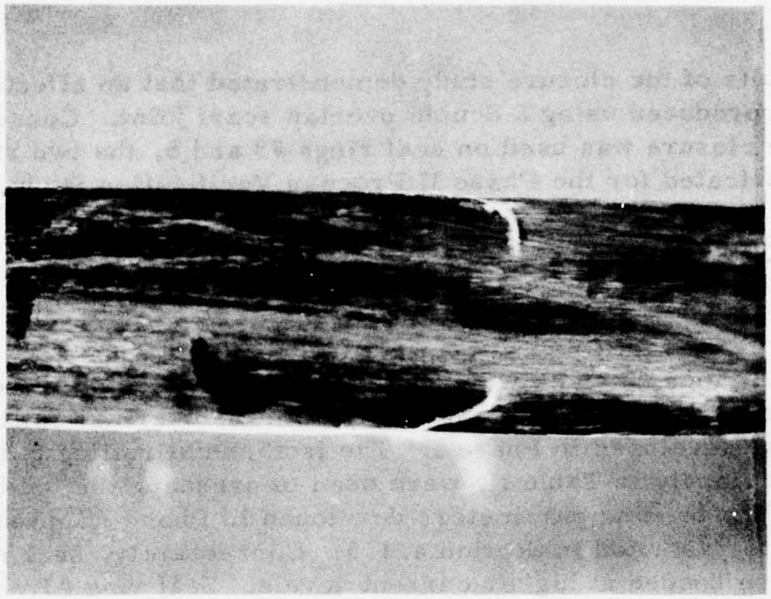
The final seal ring #5 was bonded at 3.8 $\pm$ .2 KA. It appeared to be well bonded and had no localized shear type deformations. The overlap length of the closure was within .050 inch of the calculated length. Figure 21 contains two views of the seal ring #5 closure. The top view was taken after it had been fluorescent penetrant inspected and indicated the tip end of the cover strip above the seal teeth had been bonded. Exesss fluorescent developer can be seen in the unbonded areas beyond the teeth. The two seal rings were not sectioned at this time; they were first inspected and reprofiled as discussed further in the text.

4.2.2 Sample Processing for Phase III Test Program

The sample preparation for Phase III is included in the Phase II section because additional knowledge was gained on isothermal rolling and CSDB during this effort.

4.2.2.1 Material Selection and Tooling Fabrication

The seal teeth samples for a portion of the mechanical property



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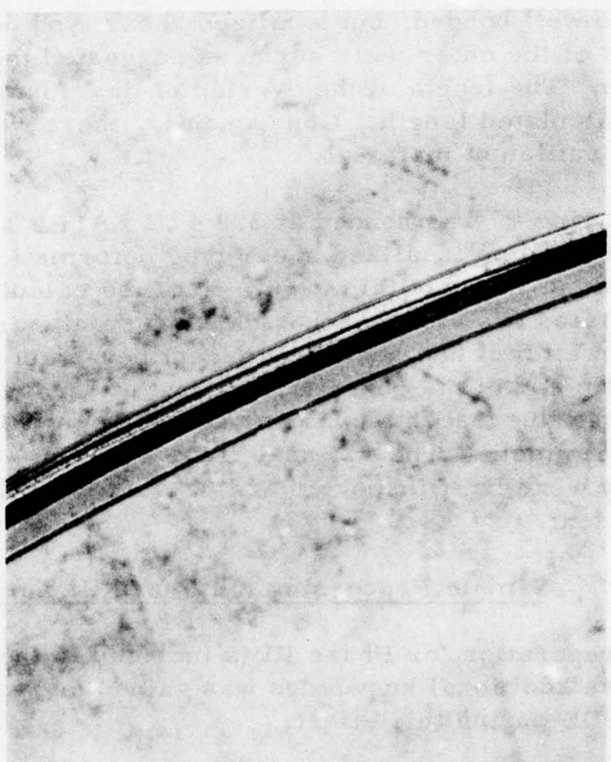


2X

Figure 21. End Closure of Seal Ring #5.

Top: Top View

Bottom: Front View

evaluation were obtained from flat Rene'95 plate. A two-teeth configuration was selected over one containing three teeth: (1) because of the simpler machining involved, and (2) to demonstrate the versatility of the CSDB process. The seal teeth contour was electrochemically ground (ECG) into bars .250 x .750 x 12 inches long, resulting in the cross-section shown in Figure 22. Some warpage was encountered during grinding. However, it did not hamper the isothermal rolling or CSDB. A containing fixture, as shown in Figure 23, was fabricated to position and hold the components for the CSDB layup.

As with the seal rings, a gas manifold was incorporated into the system to provide a protective hydrogen environment during CSDB.

4.2.2.2 Isothermal Rolling

The isothermal rolling and CSDB of the flat bars was conducted on Solar's CSDB machine. The unit has a 10,000 ampere and 3500 pound upset capability and was more suited to flat bars because it comprises a flat table and a cylindrical molybdenum alloy wheel. The pressure and electrical capacity were also less which was more compatible with the two teeth configuration to be bonded.

Approximately .020 inches of material was ground from the tips to simulate worn material and true up the strips. Table VI contains the isothermal rolling parameters and the upsetting achieved. All isothermal rolling was conducted at a rolling speed of 1.6 inch/minute using a .062 x .750 inch wide Inconel 718 thermal strip between the roll and the tooth crests. As was done with the seal teeth rings, the tooth temperature was controlled by means of a feedback signal from an optical pyrometer. The objective was to control the upset temperature in the range of 2000 to 2050°F. The tooth upset ranged from .022 to .032 inch. Some upset variations were encountered in the final five specimens which was probably due to variations in temperature and slight variances in starting crest width. Figure 24 contains cross-sections from the ends of bars #2 and 6. Solutioning of the carbides is evident in the worked area of bar #2, while none was found in bar #6. Solutioning was found in several of the other bars. In some cases, one tooth of a bar was not solutioned while the other was. This was judged to be due to the variances in temperature and crest width. However, it did not cause any serious problems during CSDB.

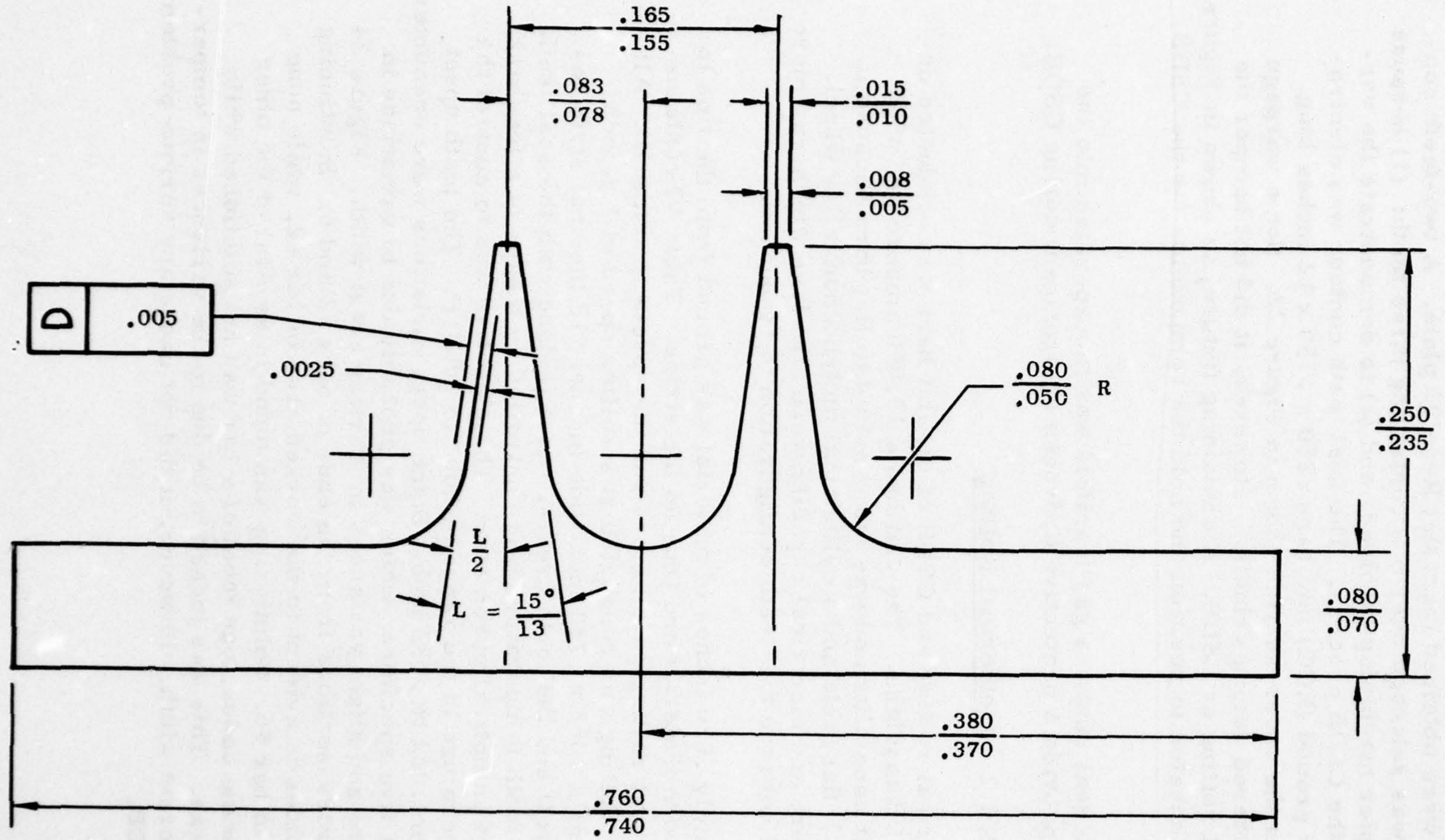


Figure 22. Cross-Section of Flat René 95 Seal Teeth Bars.

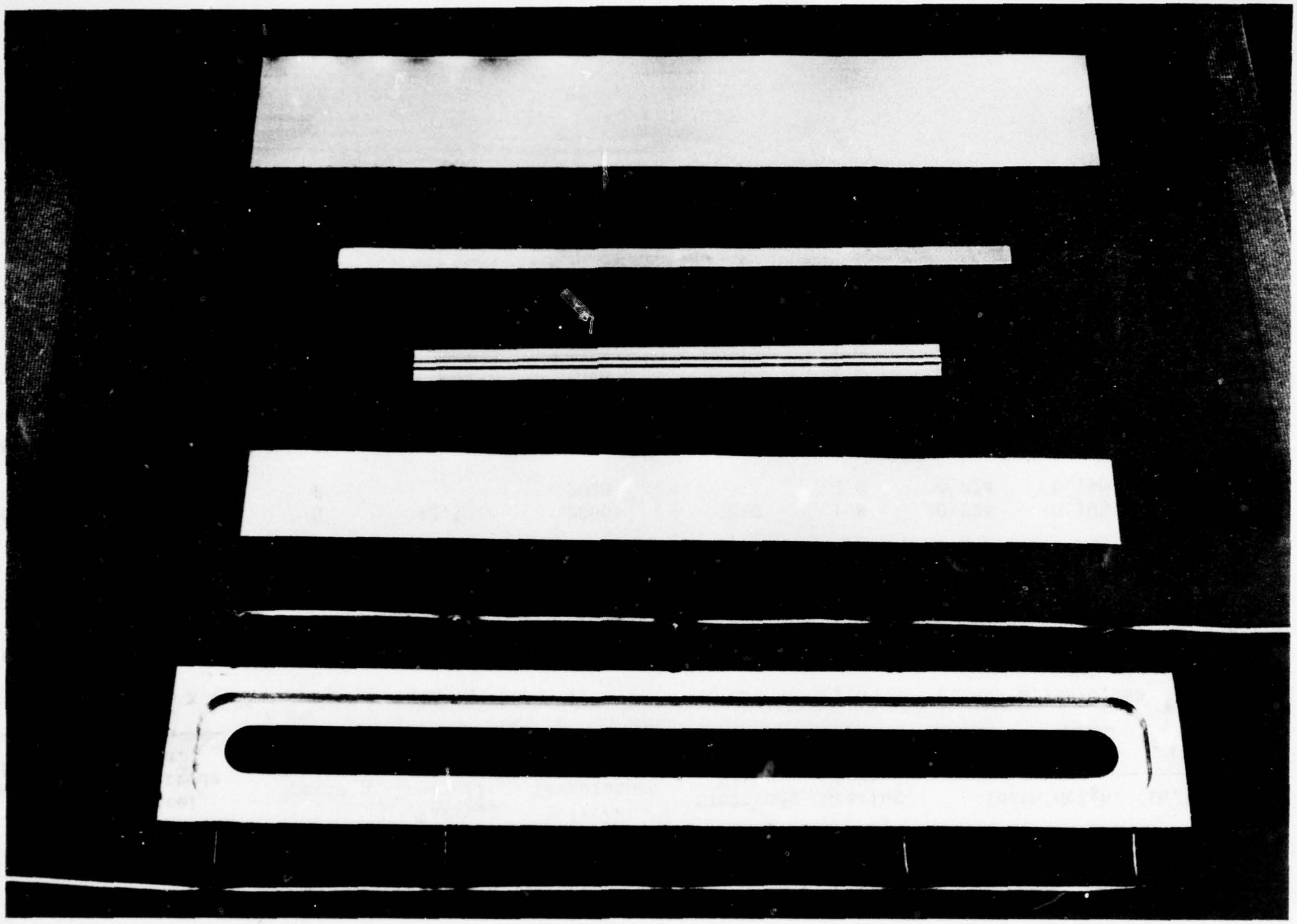


Figure 23. Bonding Fixture and Component Parts For CSDB of Flat Seal Teeth Bars.

Table VI. Isothermal Rolling Parameters Used on Flat Seal Teeth Bars

Specimen No.	Wheel Electrode (in.)	Specimen Position	Paramac Controller Setting (%)	Ircon Temperature Monitor (°F) ε = 0.7	Electrode Force (lb)	Heating Current (KA)	Tooth Height (in.) Intial	Final	Change
1	11.5 dia x 0.75	M	45.0	1970	650	1.6	0.244	0.188/0.200	0.056/0.044
4		S	45.0	2030	925	2.5	0.210	0.170	0.040
		F	42.5	2030	925	3.0	0.210	0.160	0.050
7		S	45.0	2100	750	3.0	0.210	0.170	0.040
		F	42.5	2060	750	2.4	0.210	0.160	0.050
6	12 dia x 0.43	S	42.5	2060	650	1.8	0.224	0.195	0.029
		F		2010		2.0	0.224	0.189	0.035
8		S		2030		1.6	0.218	0.201	0.017
		F		1990		2.0	0.218	0.190	0.028
5		S		2080		1.5	0.212	0.191	0.021
		F		2030		1.9	0.212	0.182	0.030
2		S		2030		2.0	0.216	0.192	0.024
		F		2030		2.3	0.216	0.182	0.034
3		S		1990		2.0	0.223	0.194	0.029
		F		2010		2.2	0.223	0.189	0.034

Note: S-Start End
M-Middle
F-Finish End
Rolling Speed 1.6 ipm
.062 x .740 Inch Inconel 718 Thermal Strip
Graphite Lubricant on Seal Teeth Bars, Thermal Strip and Form Roll

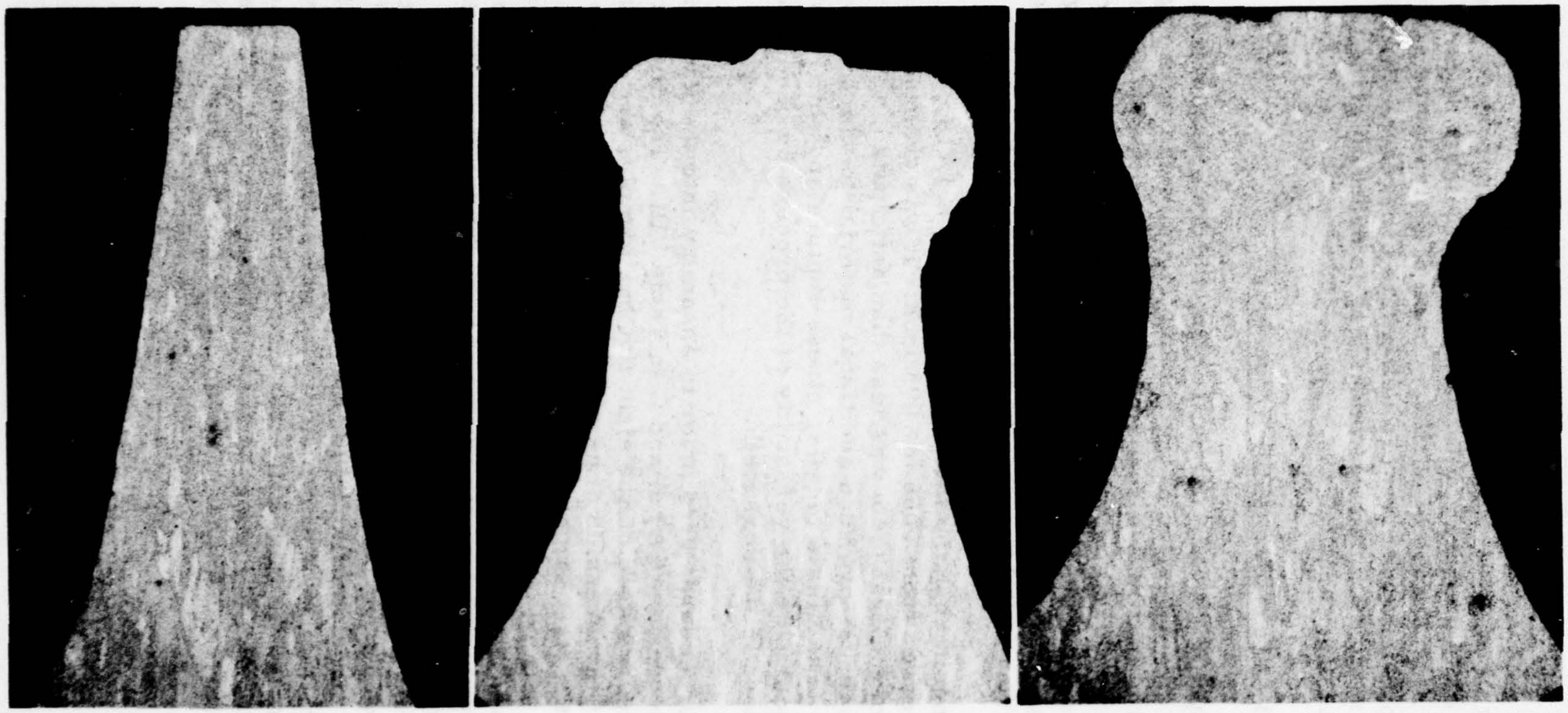


Figure 24. Contours and Microstructures of Flat Seal Seal Teeth Bars After Isothermal Rolling.

Left: Prior to Rolling

Center: Bar #2

Right: Bar #6

After upsetting, the seal teeth were ground to the approximate center of the upset area in preparation for CSDB to the heights noted in Table VII. The total thicknesses of each specimen are also listed after each processing step. There were deliberate differences in overall heights of the samples which was necessary in order to grind to the center of the widened area.

4.2.2.3 Test Bar CSDB Processing

The sample layup for CSDB and the bonding fixture are shown in Figure 25. A cross-section of the bonding layup is shown in Figure 26. The bonding fixture and supporting steel rail with side plates were designed to closely simulate the thermal, electrical and protective atmosphere conditions employed when previously bonding the seal teeth rings on the expandable fixture. Figure 27 depicts the bonding of the flat samples on the CSDB machine.

For the test specimens, the thickness of the Inconel 718 cover strip was increased from .066 to .093 inch. It was changed because: (1) the height of the seal teeth was less than anticipated, (2) the increase in thickness provided additional material to which to weld extension tabs to facilitate tensile, stress rupture and shear testing, and (3) to demonstrate the versatility of the process by bonding a greater thickness to the seal teeth.

The cleaning procedures used prior to assembly into the flat fixture are listed in sequence as A, B and C in Table VIII. The diffusion bonding parameters used on the eight flat bar samples are tabulated in Table IX. A progression of heating currents was used on seal teeth bar #2, the first sample bonded. The portion bonded at 2.5 KA had good peel strength and it appeared that one additional run would be required to pinpoint the optimum current with upper and lower limits. However, due to a cleaning problem with the Rene'95, the next four runs produced samples with poor bond strengths. No difficulties were encountered in cleaning the Inconel 718 at any time. However, an abnormal response was encountered with the Rene'95. In the earlier cleaning of Rene'95, during Phases I and II, the electropolishing operation left a brown smut that was subsequently removed by the acid pickle. In Phase III test sample preparation, it was found necessary to employ mechanical procedures to remove the smut. It was particularly tenacious on the upset area of the teeth. A wet

Table VII. Heights of Flat Seal Teeth Bars After Isothermal Roll Processing

Specimen No.	As Received (±0.001 in.)	After 1st Grind (±0.001 in.)	After Tooth Preshaping (in.)	After Preshape Grind (±0.001 in.)
1	0.244	Not ground	0.188/0.200	0.180
2	0.235	0.216	0.182/0.192	0.178
3	0.231	0.223	0.189/0.194	0.186
4	0.244	0.210	0.160/0.170	0.156
5	0.230/0.235	0.212	0.182/0.191	0.180
6	0.241	0.224	0.189/0.195	0.186
7	0.250	0.210	0.160/0.170	0.161
8	0.236	0.218	0.190/0.201	0.188

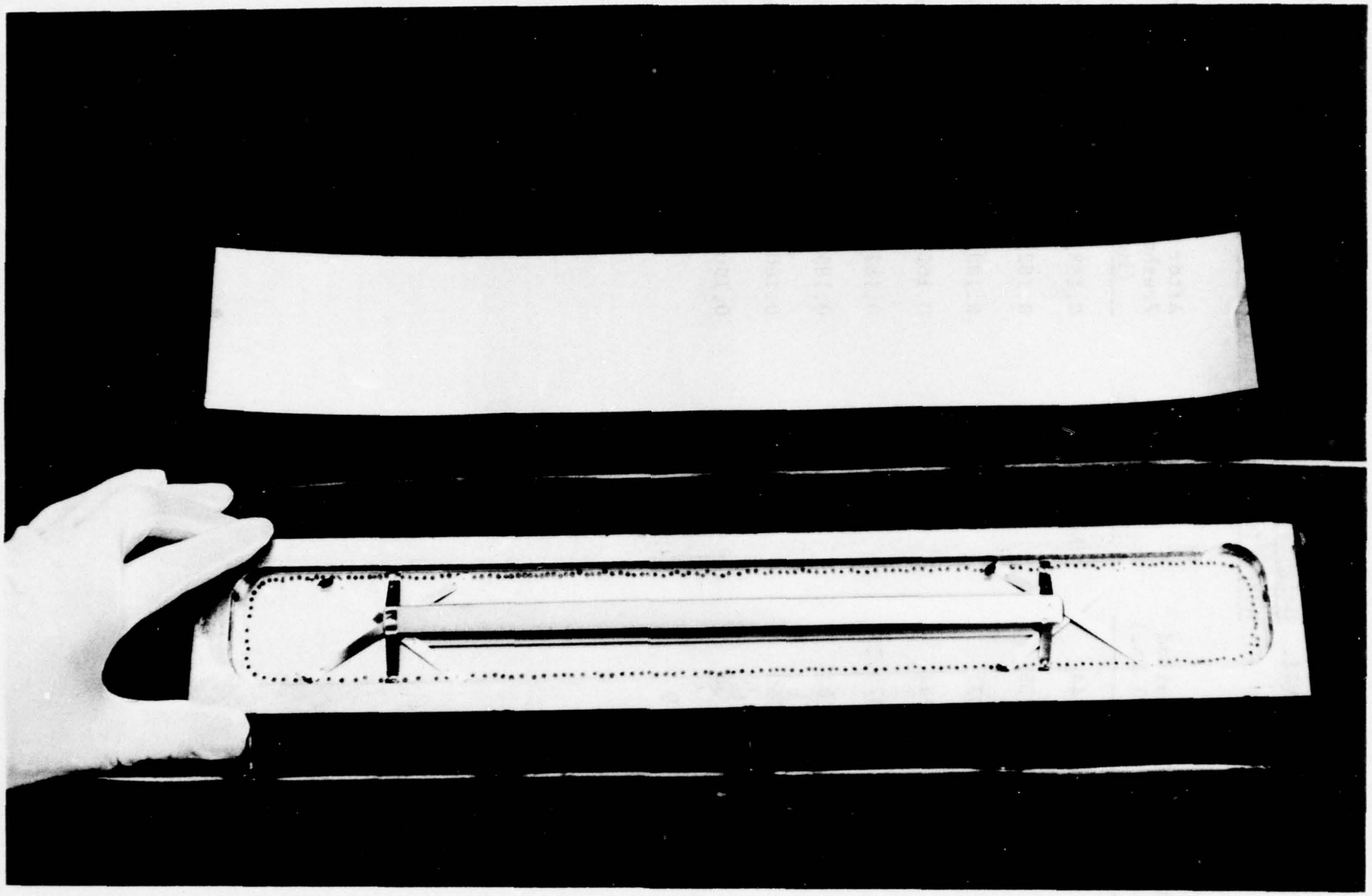


Figure 25. Assembled Bonding Lay-Up For Flat Seal Teeth Bars.

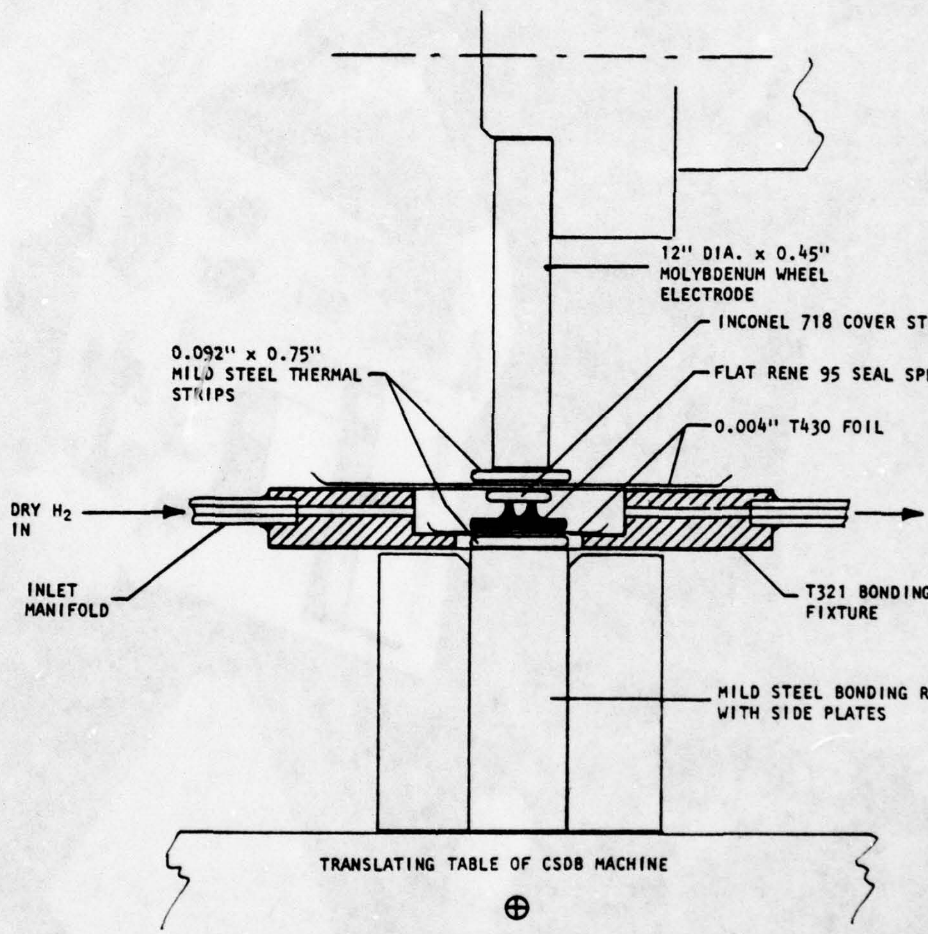


Figure 26. Cross Section of Bonding Lay-Up For CSDB of Flat Seal Teeth Bars.

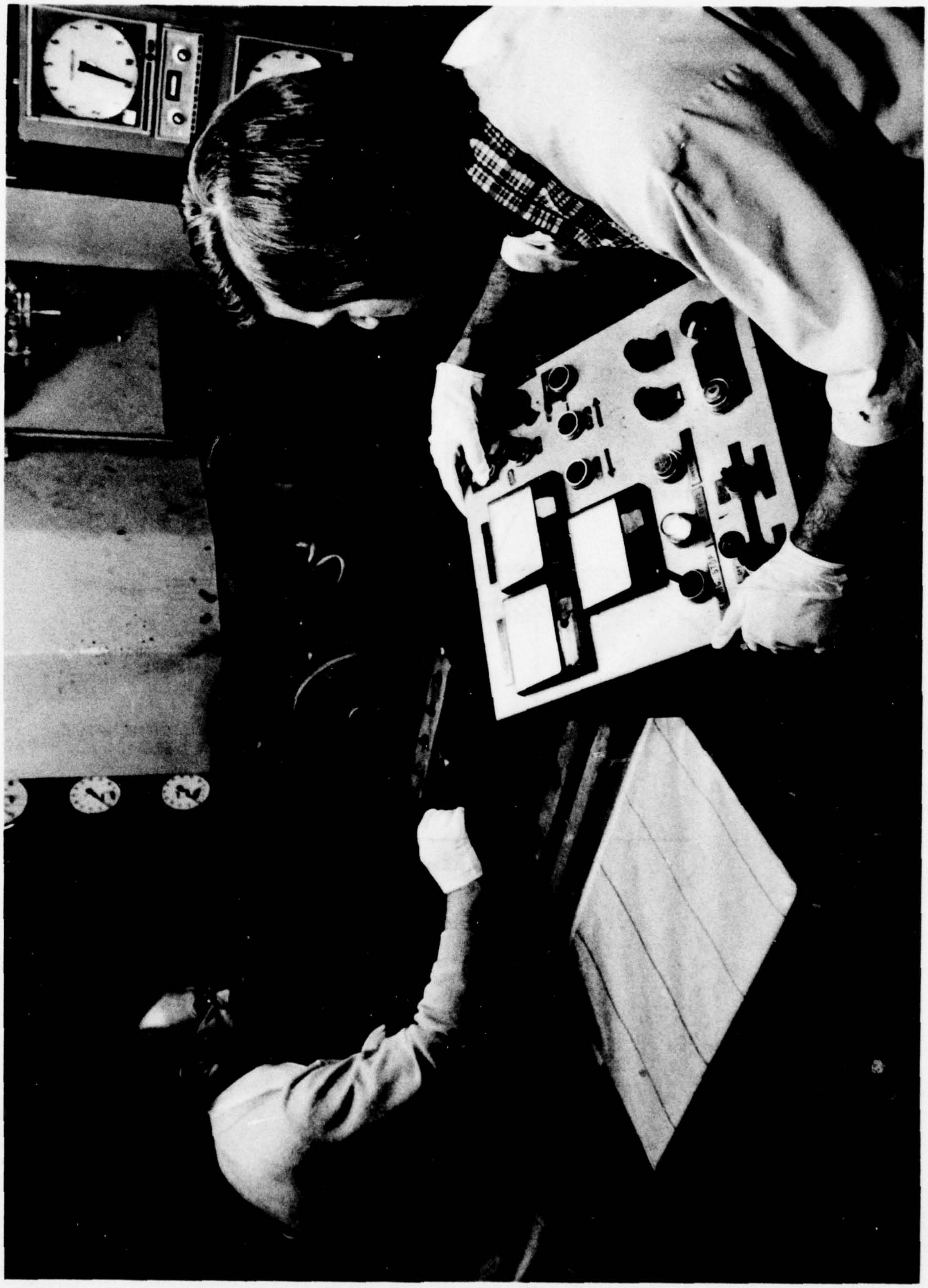


Figure 27. Simulated CSDB of Flat Seal Teeth Bar Samples in CSDB Machine.

Table VIII. Cleaning Procedures Used on Flat Seal Teeth Bars

Step		Sequence
A	Degrease	Scrub with cold alkaline cleaner (Mission Chemical Co., Concentrate No. 93); warm air dry
B	Electropolish	7 volts, 60 seconds in polishing bath, 120°F (powerclean solution, Molectrics, Inc.); tap water rinse
C	Acid Pickle	1 part HF, 5 parts HNO_3 in 16 parts water 70°F; 1 min for T430; 5 min for Inconel 718 and Rene'95; DI water rinse, warm dry air.
D	Wire Brush	Brush smut from Rene'95 manually with stainless steel bristle brush; tap water rinse.
E	Abrasive Blast	Wet blast Rene'95 teeth with 400 mesh alumina at 60 psi; DI water rinse; warm air dry.

Table IX. CSDB Parameters Used on Flat Seal Teeth Bars

Code No. 4505-	Specimen	Surface Preparation (See Table 8)	Inconel 718 Cover Strip (inch)	Heating Current (KA)	Results
5-4-1	2	ABC	0.092 x 0.75	2.10 2.30 2.50	Poor peel strength Very good peel strength
5-5-1	3	ABC-DBC	0.092 x 0.75	2.30 2.50 2.70	Rene' discolored, poor peel strength at all currents
6-3-1	6	ABC-DBC	End closure Specimen 0.092 x 0.75 1.8 in. overlap	2.50	INCO 718 overlap not bonded. Localized discoloration on Rene' teeth.
6-6-1	4	ABC-DBC	End closure specimen 0.092 x 0.75 1.8 in. overlap reduced to 0.240 width at overlap	2.50	Some localized discoloration of Rene' teeth. Appeared well bonded
6-6-2	7	ABC-DBC	No closure. Width reduced from 0.75 to 0.53	2.50	Same as 6-6-1
7-27-1	1	ABCE	0.092 X 0.510	2.55	No discoloration of Rene'. Peel specimen 1-3/4 in. from finish end had very good strength.
8-2-1	5 & 8	ABCE	0.092 x 0.510	2.55	Same as 7-27-1
8-3-1		ABCE	0.092 x 0.510	2.55	Same as 7-27-1

Note:
- Squeeze Force 810 pounds
- Rolling Speed 3.21 PM
- .066 x .750 Inch Inconel 718 Coverstrip
- Graphite Lubricant Only on Thermal Strip and Bonding Roll
- Dry Hydrogen (-80F Dewpoint) Purge at Approximately 10 SCFH

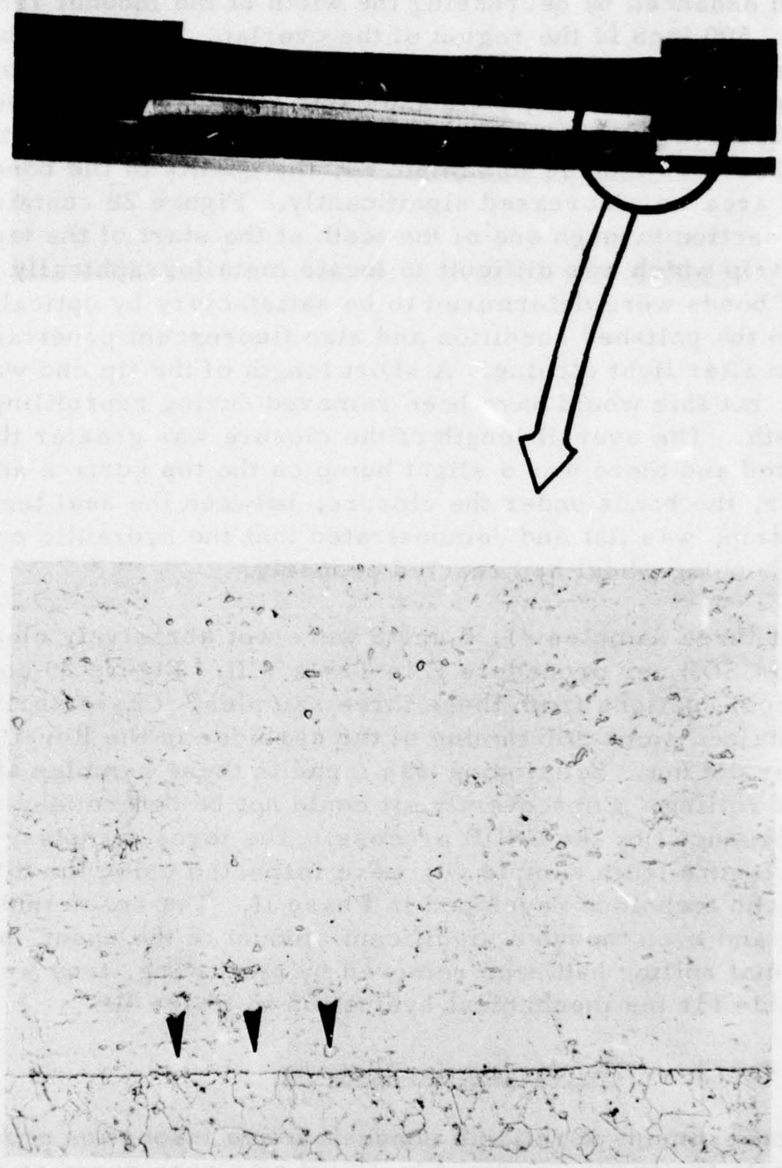
abrasive blast was found to be effective. However, the prior cleaning was probably negated.

Despite the cleaning problem, samples #6 and 4 demonstrated that the diffusion bonding of the samples, including the end closures, could be enhanced by decreasing the width of the Inconel 718 cover strip to .500 inch in the region of the overlap. The bonds between the cover strip and the seal teeth as well as those of the closure on sample #6, were very poor and came apart when sectioned with a wet abrasive cutoff wheel. When the width of the cover strip was reduced to .500 inch as in sample #4, the quality of the bond in the closure area was increased significantly. Figure 28 contains a longitudinal section through one of the teeth at the start of the tapered cover strip which was difficult to locate metallographically. The tapered bonds were determined to be satisfactory by optical microscopy in the polished condition and also fluorescent penetrant inspection after light etching. A short length of the tip end was not bonded, but this would have been removed during reprofiling of the seal teeth. The overall length of the closure was greater than calculated and there was a slight hump on the top surface at the end. However, the bonds under the closure, between the seal teeth and cover strip, was flat and demonstrated that the hydraulic control for the bonding wheel had reacted properly.

The last three samples #1, 5 and 8 were wet abrasively cleaned prior to CSDB per procedure E in Table VIII. Figure 29 contains two typical sections from these three samples. Characteristically, one contained some solutioning of the carbides in the Rene'95, while the other did not. Solutioning was found in these samples after isothermal rolling. Consequently, it could not be determined whether it was produced by the CSDB process. The three samples, as well as the closure from sample #4, were inspected using the ultrasonic pulse-echo technique developed in Phase II. The scans indicated bonding and even though a significant amount of the upset due to isothermal rolling had been removed by machining, they were judged acceptable for the mechanical evaluation in Phase III.

4.2.3 Nondestructive Testing

The establishment of reliable nondestructive inspection procedures to evaluate the bonds produced by CSDB was considered an integral part of the overall program.



Top: End Closer

Bottom: Longitudinal Section Through Cover Strip.

Figure 28. End Closure For Flat Seal Teeth Bars.

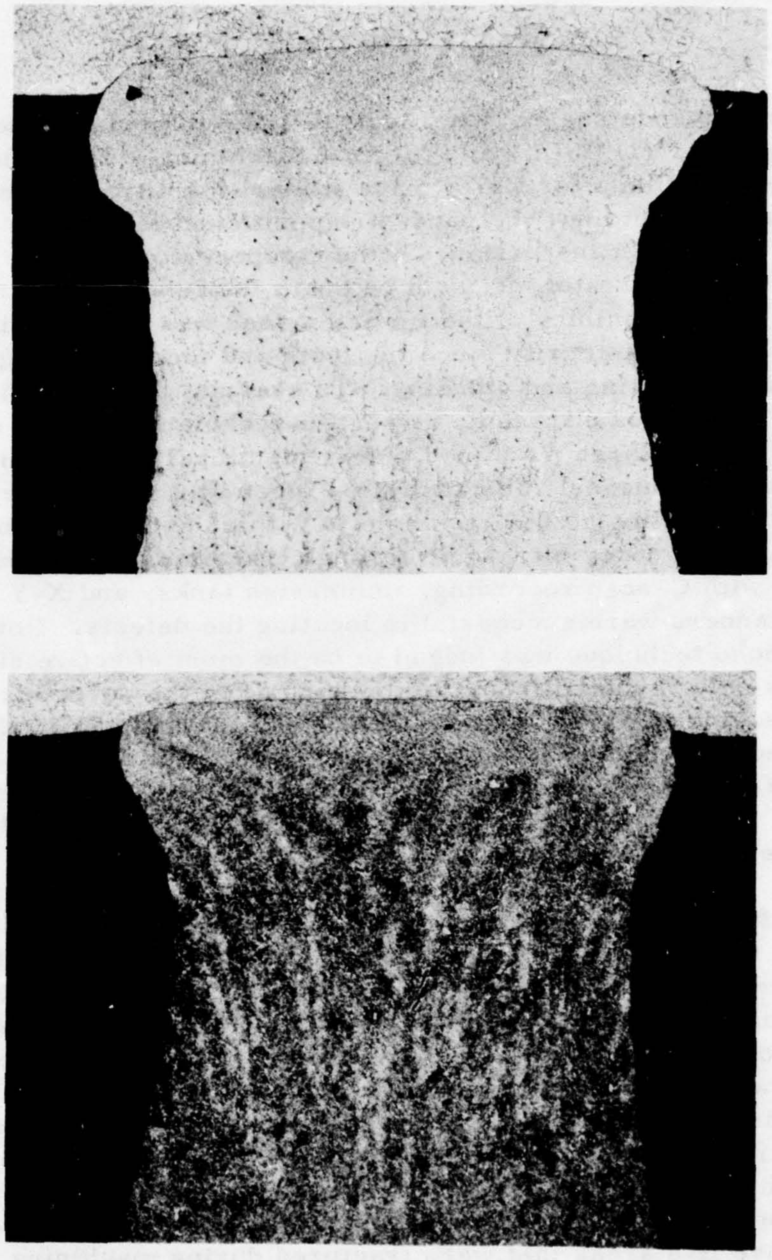


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Figure 29. Sections Through Flat Seal Teeth Bars For Mechanical Evaluation.

Top: Bar #5

Bottom: Bar #8

The repair sequence suggests two logical times to perform the inspections, after: (1) CSDB, and (2) final machining. The bonds location and position after CSDB make it ideal for ultrasonic evaluation. After machining, the bonds are positioned ideally for fluorescent penetrant inspection. If the component containing the seal teeth was heat treated, it could be again fluorescent penetrant inspected. The machining of the tip extensions was also considered a test of the bond's integrity since the teeth and the cover strip were highly loaded in cutting and grinding. To evaluate the capability and sensitivity of various ultrasonic inspection techniques, a test segment was CSDB'ed with three machined slots (intentional defects) in the center tooth. An Inconel 718 calibration block was made to serve as a standard by drilling a .030 inch hole to within .065 inch of the surface. Both the high frequency ultrasonic through transmission and pulse-echo techniques with C-scan recording, immersion tanks, and X-Y and rotation scanners were successful in locating the defects. However, the pulse-echo technique was judged to be the most effective since access was only required from the top surface of the cover strip. A typical C-scan of the test segment with intentional defects made with the pulse-echo technique is shown in Figure 30. The figure also contains sketches of the three defects and the ultrasonic setup. The instrument used was a 725 Immerscope with a 25 MHz transducer focused to concentrate the energy into a small beam pattern.

Seal rings #3 and 5 were evaluated with the through transmission and pulse-echo techniques. The C-scans for seal ring #5 indicated that all three teeth were bonded. However, the C-scan for seal ring #3 indicated that the center tooth had questionable areas. Also, some scattering of the beam was caused by remnants of the foil wrap adhering to the cover strip. This was reduced by removal of the foil by hand-grinding. The C-scan of seal ring #3 is shown in Figure 31. The black lines indicate nonbonded areas and it can be seen that the center tooth contained sections that were marginally bonded at best. As discussed in the following Section 4.2.4 of this report, the center tooth did have five areas that were fractured during machining or were not bonded. This attests to the usefulness of the pulse-echo technique as a poor bond indicator.

The quality of the bonds in the end closures of seal rings #3 and 5 was undeterminable by NDT because of roughness of the top surfaces. This is shown in Figure 31. A trial closure from seal ring #2 was scanned with the pulse-echo technique prior to its being sectioned.

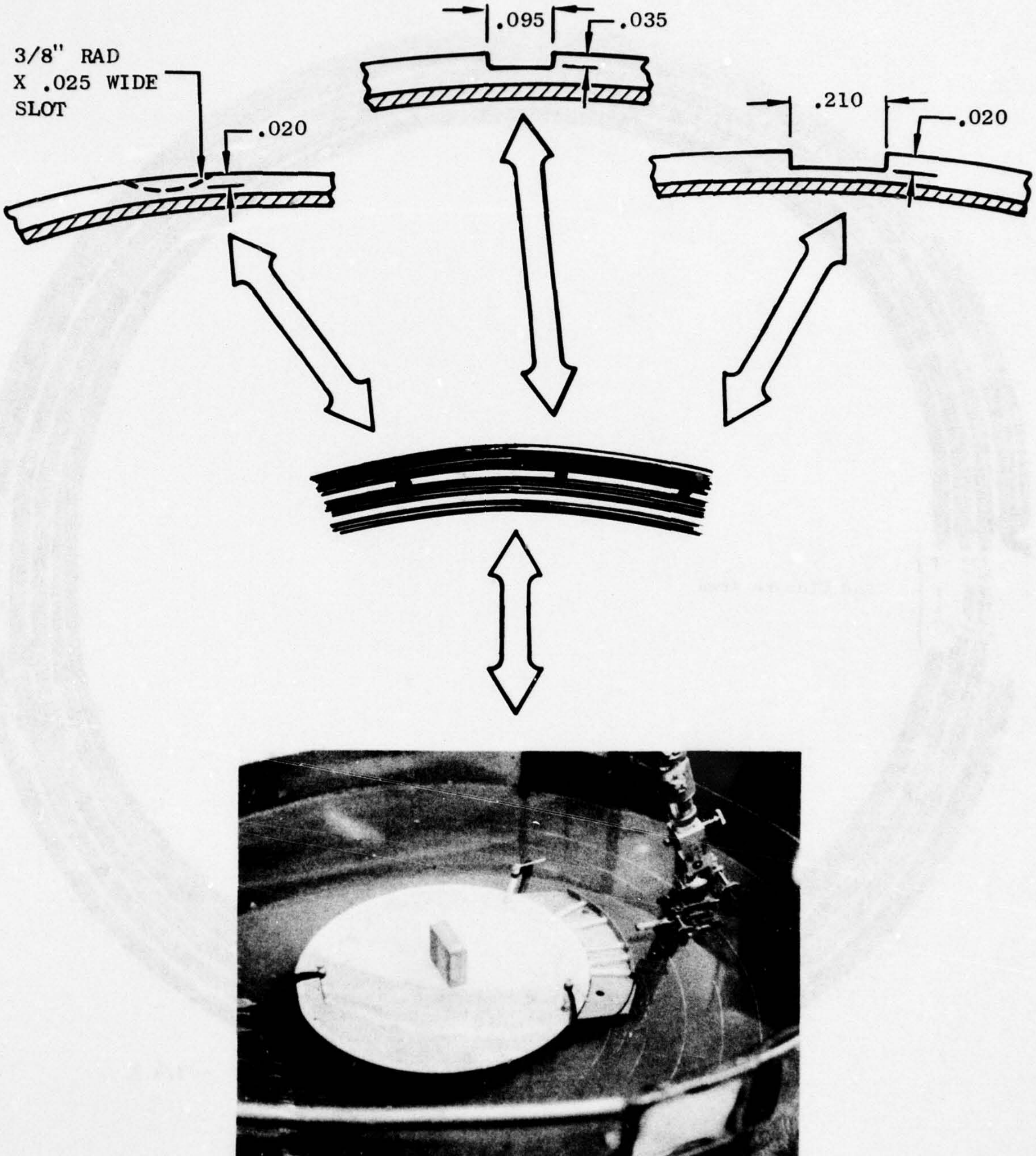

Figure 30. Ultrasonic Pulse-Echo Set-Up, Prelocated Defects and C-Scan of Prelocated Defects.

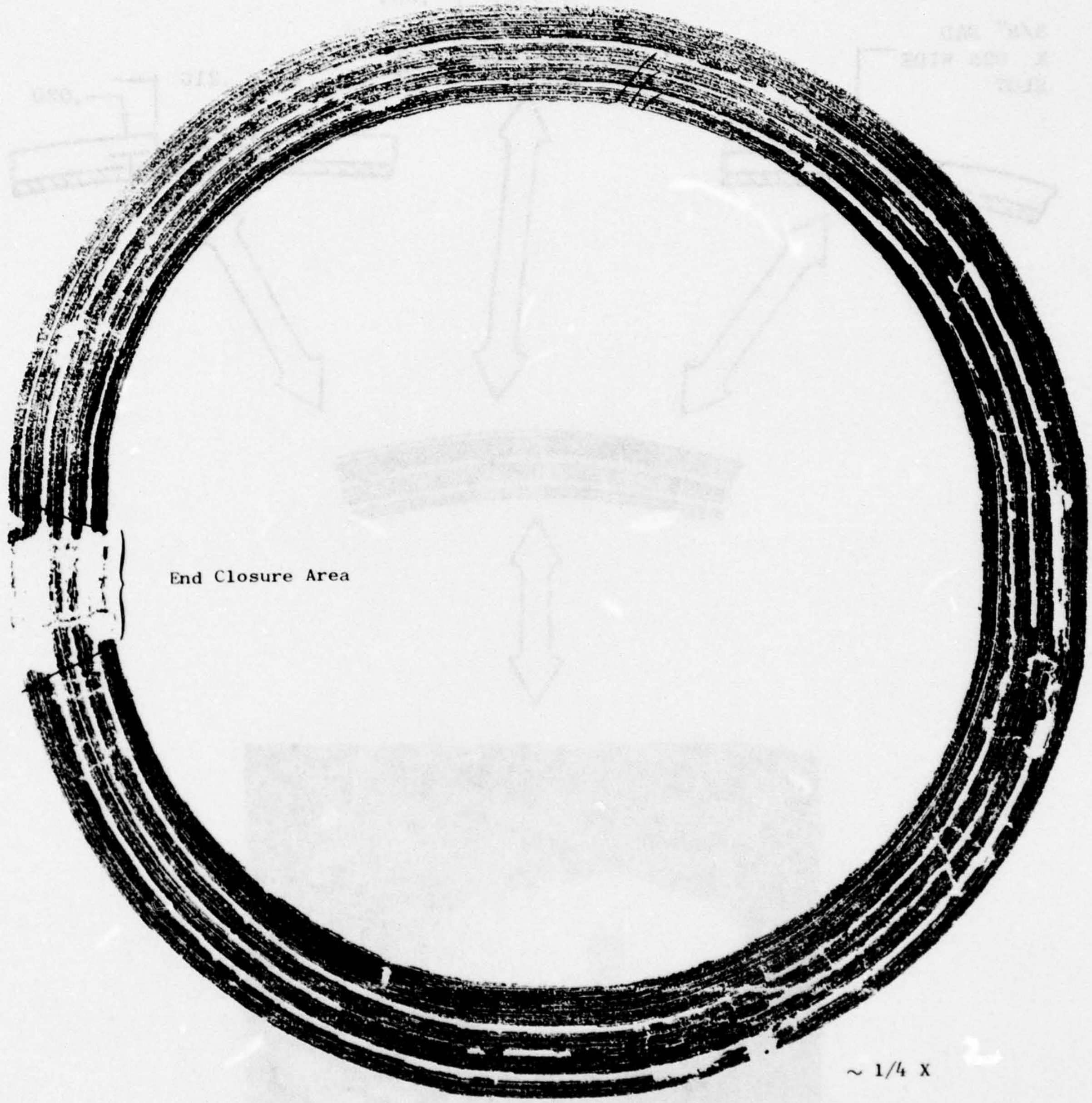

Figure 31. Ultrasonic Pulse-Echo C-Scan of Seal Ring #3.

Note: White Lines Indicate Bonded Areas

The C-scans of the closure indicated that the bonding had been achieved as was verified by the sections that were made and discussed in the Section 4.1.6 on end closure parameter determination.

4.2.4 Reprofiling of Seal Teeth

The machining procedure of the seal teeth on a CRS is to rough turn their contour and then finish grind. This procedure was also used on the seal teeth rings. The seal rings were not heat treated prior to machining because of the potential danger of cracks initiating from the ends of the bond interfaces. The rough contour turning was accomplished in a lathe using a single point tool. Seal ring #5 was machined first without any problems. During the machining of seal ring #3, the center tooth appeared to be bent and rolled over with the bond separated in five areas. The lengths of the separations were readily determined as the machined tip extensions were sider in these areas as shown in Figure 32. Finish ground seal teeth from seal ring #5 is shown for comparison purposes.

A contributing cause of the separations was found to be an excessive lateral/side force on the tip extension through the use of the single point tool. The bonds in the separated areas did not possess adequate shear strength and failed in a shear mode. A possible alternative to the single point tool to eliminate the lateral pressure would be a contoured tool. Both faces would be machined at the same time with this approach. Its use was contemplated. However, it was disregarded in favor of the single point tool because of the possibility of seizing and/or tearing the cover strip which would have been more harmful.

Figure 33 contains sections through the center tooth in separated and nonseparated areas. The nonseparated section vividly illustrates the results of the tool lateral/side force on the Inconel 718 tip extension. The Inconel 718 appears to have been pushed in sideways and is not in line with the Rene'95. In machining the Rene'95 upset area, the lathe operator had to apply considerable pressure since the Rene'95 was more difficult to machine than the Inconel 718. As the single point tool started to machine the Inconel 718, the resistance to tool pressure was reduced and it cut deeper, but the operator could not compensate fast enough. Other than possible contamination on the bonding surfaces, no reason could be found for the weakness in this particular bond. A good diffusion bond is obviously necessary to withstand the rigors of the reprofiling operation.

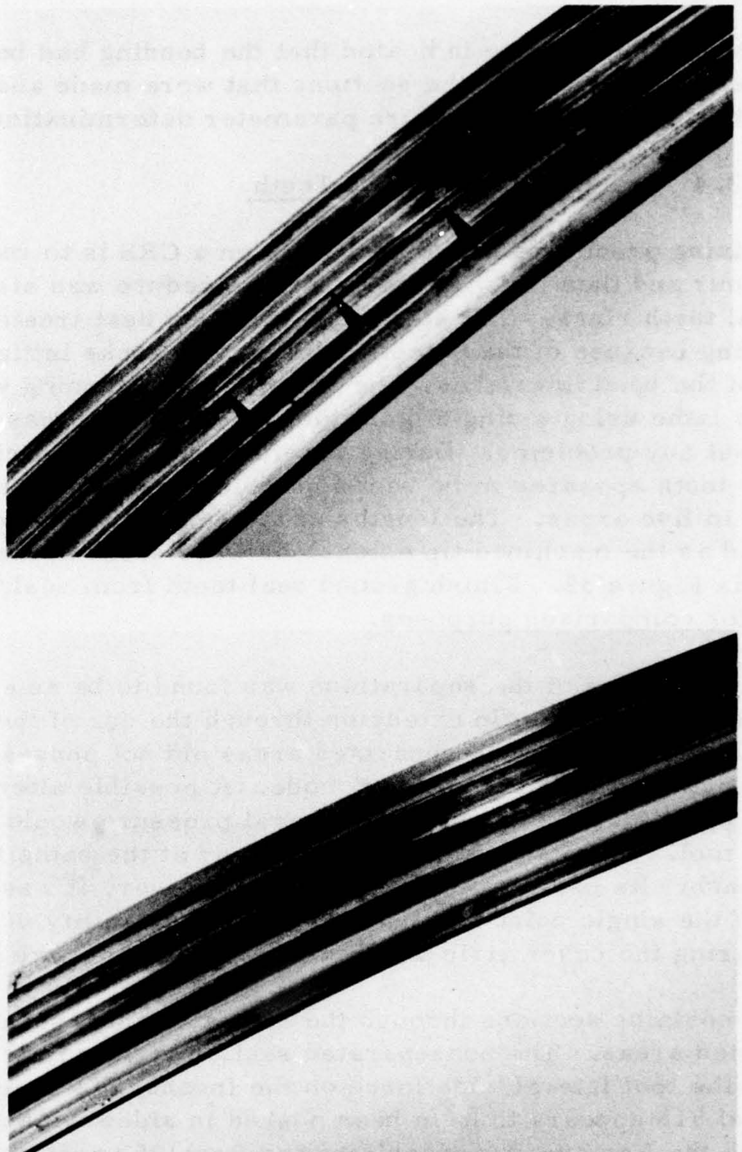

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Figure 32. Seal Teeth Rings After Reprofiling.

Top: Seal Ring #3 Showing Failed Area in Center Tooth

Bottom: Seal Ring #5

Note: Arrows Indicate Separated Length

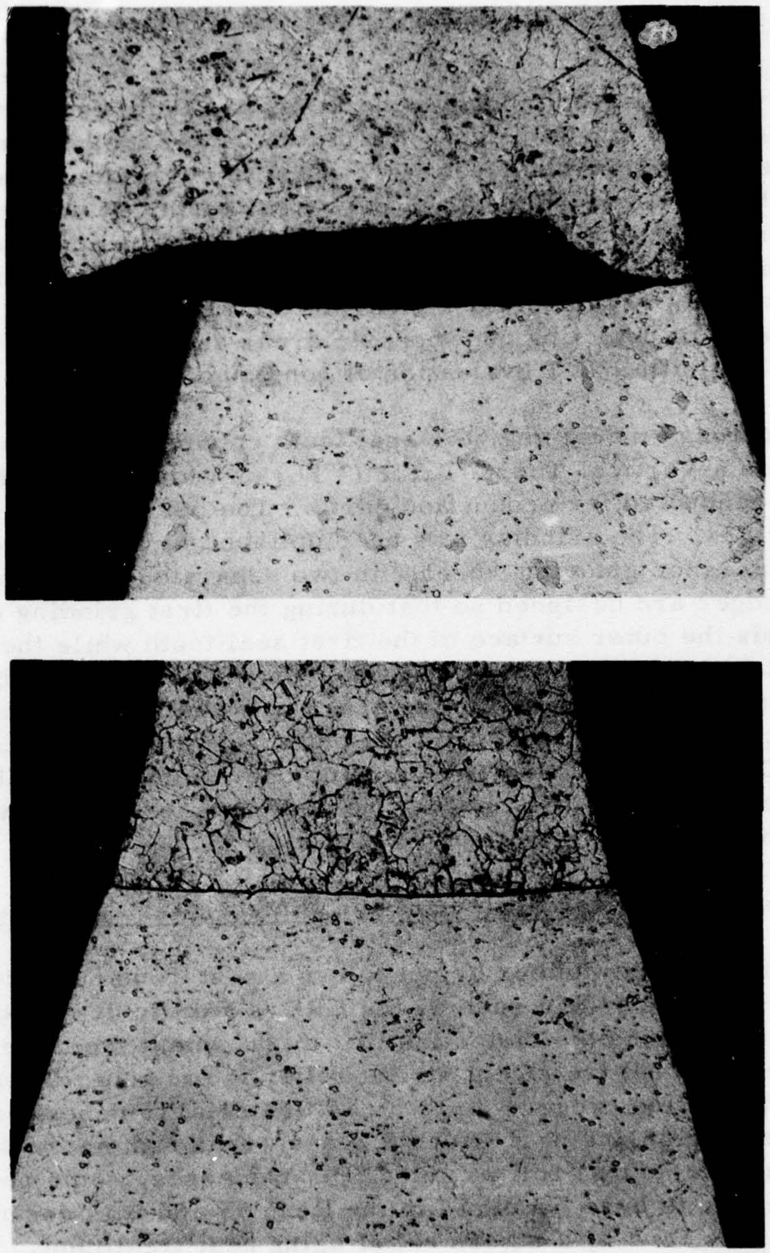

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Figure 33. Sections Through Center Tooth of Seal Ring #3.

Top: Failed Area

Bottom: Non-Failed Area

The previous ultrasonic pulse-echo scans had indicated that there were areas with questionable bonds in the center tooth of seal ring #3. These questionable areas were found to correlate closely with the machining debonded areas in the center tooth. It was impossible to determine whether the failed areas were due to a nonbonded condition or a weak bond that failed due to the lateral/side force. However, the C-scans did demonstrate that the pulse-echo technique was capable of detecting questionable areas and would be a useful tool for the initial NDT evaluation of bond quality.

After the rough machining, the seal teeth contour was ground into seal ring #5 on a Vertical Turret Lathe (VTL) on which the grinding of the teeth is conducted for production parts. The operations are illustrated in Figure 34. The grinding was accomplished by a unique technique using a Borazon grinding wheel with two separated shaped edges. The shaped edges are designed so that during the first grinding operation one grinds the outer surface of the first seal tooth while the second grinds the total area between the second and third seal teeth. During the second grinding operation the areas between the first and second seal teeth are ground along with the outer surface of the third seal tooth. Consequently, only two grinding operations are employed to completely form the three teeth. No problems were encountered during the grinding of the teeth in seal ring #5.

4.2.5 Heat Treatment and Dimensional Evaluation

The question as to whether or not to use a post-bond heat treatment on a complex component such as the CRS is a difficult one to resolve because of the possible distortion that might result from the heat treatment. A heat treatment stress relief age is generally required with a fusion weld process since a cast material is deposited with the associated fusion and heat affected zones. Although no melting occurred during the isothermal rolling and CSDB processes, some solutioning was observed to have occurred in the Rene'95 and it is desirable to stabilize this zone by a stress relief aging heat treatment. This would restore any possible degradation in properties. Since LCF testing was to be conducted on specimens in the as-bonded and aged condition on sections from seal ring #5, it was not heat treated as a full ring to enable specimens to be made in the as-bonded condition. The center tooth from seal ring #3 had bond tears which eliminated any testing potential. Therefore, it was heat treated to determine the effects on dimensional stability.

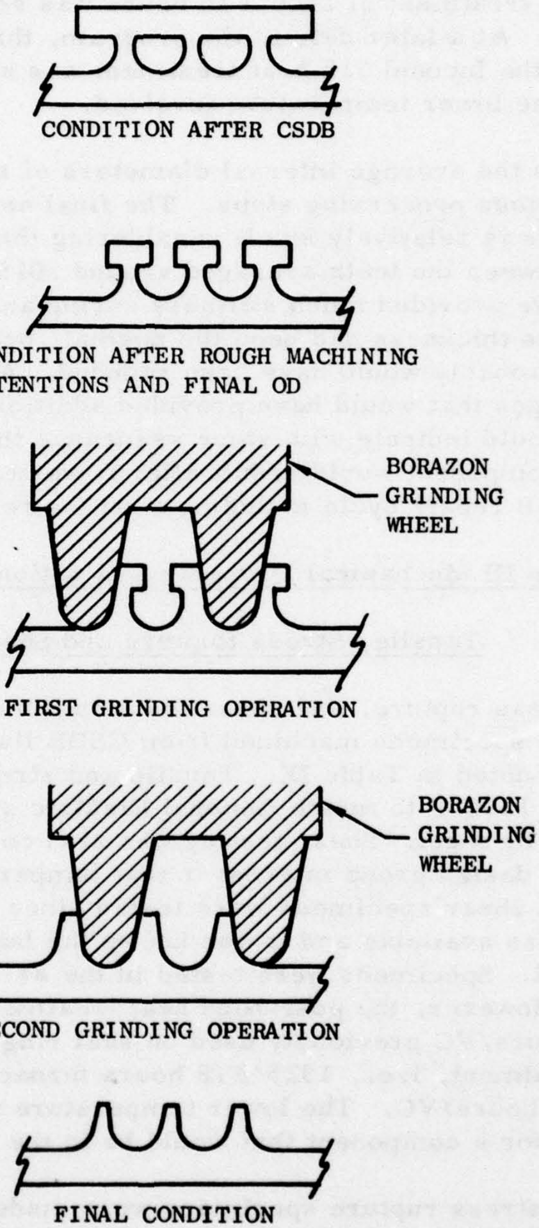

Figure 34. Pictorial Representation of Machining of Seal Teeth From Cover Strip.

Since a bimetal joint was involved with two different aging temperatures (for Rene'95, 1400°F/16 hours and for Inconel 718, 1325°F/8 hours furnace cool at 100°F/hour/to 1150°F/8 hours), a compromise vacuum heat treatment of 1400°F/6 hours was selected and imposed on seal ring #3. At a later date in the program, this selection was revised and the Inconel 718 heat treatment was used on the test specimens because of the lower temperature involved.

Table X lists the average internal diameters of seal rings #3 and 5 after the various processing steps. The final net changes in diameter for both rings is relatively small considering that the thicknesses of the spool between the teeth averaged around .015 inches. These areas could not have provided much stiffness during any of the processing steps. If this thickness had been the normal .060/.070 inch, the final net change probably would have been reduced. Also, the CRS contains internal flanges that would have provided additional stiffening. Altogether, these data would indicate with some assurance that a dimensionally acceptable component would result after it was completely processed with the CSDB repair cycle including a stress relief heat treatment.

4.3 Phase III Mechanical Property Evaluation

4.3.1 Tensile, Stress Rupture and Shear Testing

Tensile, stress rupture, and shear tests outlined in Table XI were conducted on specimens machined from CSDB flat bar samples #5 and 8 previously noted in Table IX. Tensile and stress rupture testing was conducted at 1200°F to match General Electric specification requirements for Inconel 718 sheet. Shear testing was also conducted at 1200°F because of a design group interest in that temperature. Inconel 718 parent metal shear specimens were tested since little comparative shear data was available and it was known the failure would occur in this material. Specimens were tested in the as-bonded and aged condition. However, the post-bond heat treatment was changed from 1400°F/6 hours/VC previously used on seal ring #3 to the GE Inconel 718 heat treatment, i.e., 1325°F/8 hours furnace cool at 100°F/hour to 1150°F/8 hours/VC. The lower temperature was judged to be more appropriate for a component that would be in the fully machined condition.

Tensile and stress rupture specimens were made by cutting lengths, .150 inch long, from samples #5 and 8 and grinding them to .125 inch. Tabs, 3/4 inch wide, were EB welded to the Rene'95 and Inconel 718

Table X. Average Inside Diameters After Isothermal Rolling/CSDB Processing Steps

Ring No.	Initial Diameter	Isothermal Rolling	CSDB	Machining	Grinding	Heat Treatment	Net Change
3	16.419	16.420	16.412	16.420	--	16.418	-.002
5	16.428	16.430	16.410	16.416	16.416	--	-.012

Note: Measurements made with π - tape
Measurements are in inches

Table XI. Tensile, Stress Rupture, and Shear Testing Schedule

Type Test	Specimens Required	Test Temp. RT	Test Temp. 1100°F	Post Bond Heat Treatment None	Post Bond Heat Treatment GE Inconel 718 H.T.
Tensile	3	X		X	
Tensile	3	X			X
Tensile	3		X	X	
Tensile	3		X		X
Stress Rupture	4		X	X	
Stress Rupture	4		X		X
Shear	3		X	X	
Shear	3		X		X
Shear Inconel 718 Parent Metal	2		X		X

sides. Parallel sided columns .030$\pm$.001 inch wide x .125 inch long were EDM'ed into the seal teeth contour resulting in the configuration shown in Figure 35. Prior to heat treatment, the specimens were lightly vapor blasted, immersion etched, and fluorescent penetrant inspected. Four specimens were found to have small fluorescent penetrant indications. However, they were tested to determine the effect on tensile properties. In the defective areas: (1) excessive isothermal rolled material had been removed prior to CSDB, and (2) the columns were slightly offset leaving a slight nonbonded length. All the stress rupture specimens were defect-free as determined by fluorescent penetrant inspection.

Room temperature and 1200°F tensile test data are presented in Table XII. The specification points for Inconel 718 and Rene'95 are also included. The tensile strengths of the defect-free aged CSDB specimens were 100 and 95% of the Inconel 718 specification points at RT and 1200°F. However, all failures of the aged specimens occurred in the bonds indicating that the Inconel 718 parent metal was slightly stronger. This was not the case with the as-bonded specimens as some failures occurred in the Inconel 718 parent metal as shown in Figure 36, demonstrating that the bonds were stronger than the parent metal. The microstructure of the bonded area is also shown and illustrates the bond obtained. Little data are available on the RT and 1200°F tensile strength of solution treated Inconel 718. Consequently, the data obtained for the defect-free as-bonded specimens are probably very close to that value.

The notch effect of the unbonded defect area on the tensile strength was expected and is dramatically shown by the values obtained on samples #35, 10, 22, and 20. The strengths were reduced by as much as 60%. This is much more than can be tolerated and makes the requirement of a notch-free bond an absolute necessity. The tensile ductilities of the as-bonded specimens were greater than those of the aged specimens at RT. However, at 1200°F, they were comparable. The overall ductility is encouraging because it demonstrates that the bonds had measurable ductilities and were not brittle.

The 1200°F stress rupture data are presented in Table XIII. The specification points for Inconel 718 and Rene'95 are also included. The aged CSDB specimens came very close to meeting the requirements for Inconel 718 as indicated by specimen #12, which lasted 26.9 hours at 100 ksi. Specimen #32 lasted 51 hours at 100 ksi after being loaded at 90 ksi for 211 hours, probably, indicating a strain strengthening effect. Other strain strengthening effects, presumably due to aging

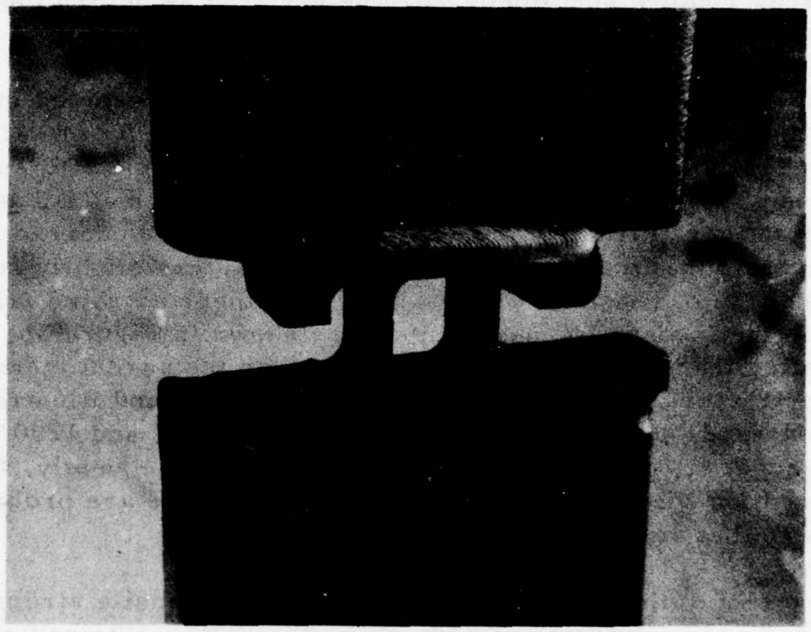

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Figure 35. Tensile and Stress Rupture Specimen

Table XII. RT and 1200°F Tensile Properties of CSDB Seal Teeth Bars

Spec No.	Condition	Temp °F	Load Lbs.	Stress KSI	Elong %	Comments
13	As Bonded	RT	850	118.2	11.2	
33	As Bonded	RT	900	119.4	16.0	
35	As Bonded	RT	610	67.6	19.0	Contained Defect
10	AGED	RT	910	132.1	NA	Contained Defect
14	AGED	RT	1380	191.9	5.6	
17	AGED	RT	1270	184.4	NA	
	Inconel 718	RT		180.0		GE Specification
	Rene'95	RT		190.0		GE Specification
15	As Bonded	1200	610	84.1	12.8	
22	As Bonded	1200	218	34.8	12.8	Contained Defect
31	As Bonded	1200	725	91.2	18.4	
20	AGED	1200	580	84.2	8.5	Contained Defect
16	AGED	1200	1040	140.9	18.4	
18	AGED	1200	960	133.7	12.0	
	Inconel 718	1200		145.0		GE Specification
	Rene'95	1200		180.0		GE Specification

Note: NA (Not Available)

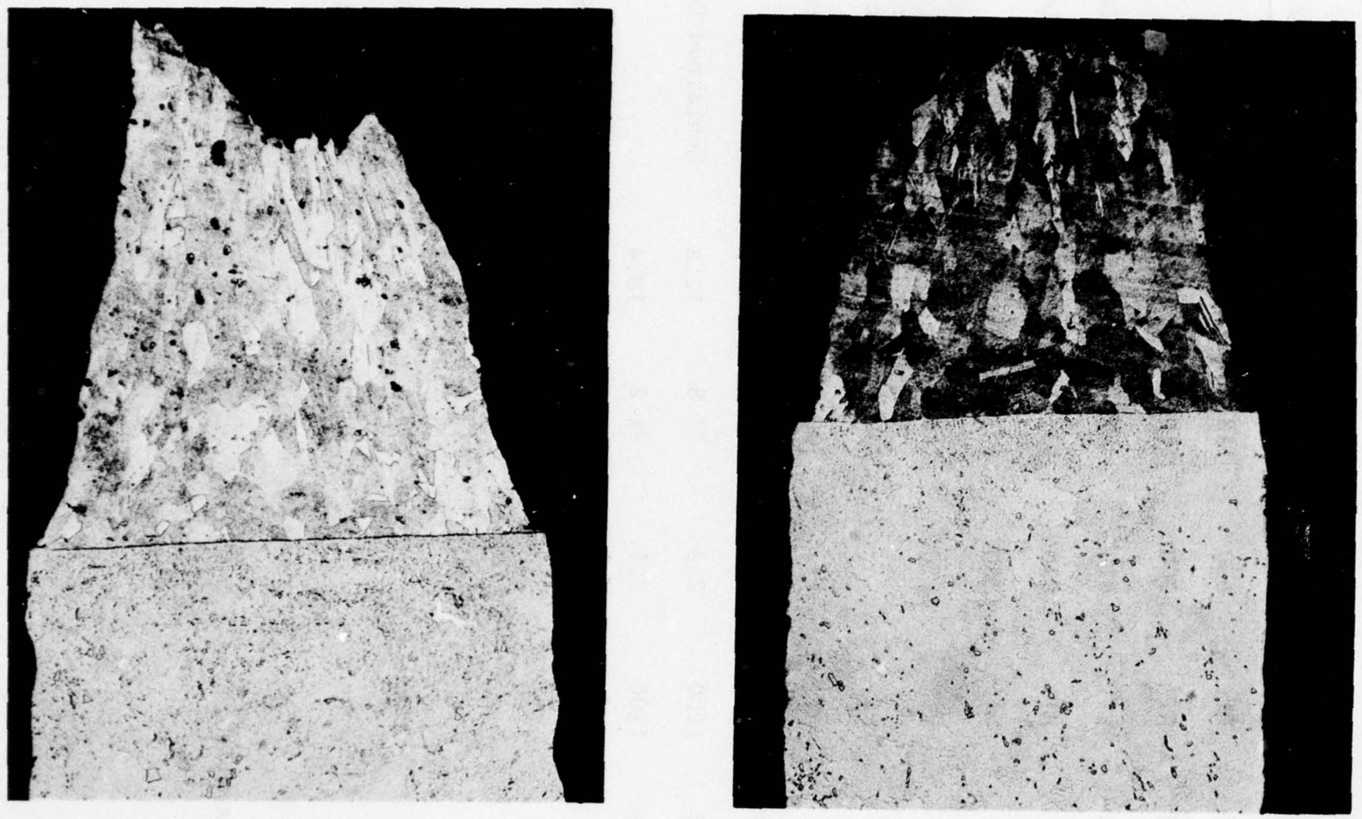

Figure 36. Room Temperature Failures in As-Bonded Tensile Specimen.

Table XIII. 1200°F Stress Rupture Properties of CSDB Seal Teeth Bars

Spec No.	Type	Stress KSI	Time Hrs	Stress KSI	Time Hrs	Stress KSI	Time Hrs	Elong %	Failure Location	Comments
9	As Bonded	50	64.9	+ 70	48.9	+ 80	24.4→	--	--	Testing Discontinued for Met. Sectioning
34	As Bonded	50	234.5	+ 100	1.3			NA	Bond	
11	As Bonded	70	.3					NA	Bond	
21	As Bonded	60	.2					NA	Bond	
32	Aged	90	211.0	+ 100	51			NA	Bond	
12	Aged	100	26.9					NA	Bond	
2	Aged	100	.1					NA	Bond	
19	Aged	100	.1					NA	Bond	
	Inconel 718	100	25.0							GE Specification
	Rene'95	150	50.0							GE Specification

Note: NA (Not Available)

at the test temperature, were evident in two of the as-bonded specimens, #9 and 34. Specimen #34 lasted 1.3 hours at 100 ksi after being loaded at 50 ksi for 234.5 hours. Specimen #9 was capable of being step loaded to 80 ksi and held for 24.4 hours, when testing was discontinued, while specimens #11 and 21 failed shortly after being loaded at 70 and 60 ksi, respectively. The two bonded areas in specimen #9 are shown in Figure 37. Some solutioning of the carbides is evident in the Rene'95 in both teeth which demonstrated, from a stress rupture standpoint, the solutioned structure was not detrimental since it was not loaded to its full capability.

The CSDB shear specimens were made by cutting .530 inch lengths from samples #5 and 8 and grinding them to .500 inch. Cross-sections similar to those of the tensile and stress rupture specimens were EDM'ed into the seal teeth; cutouts were also made at the ends to initiate failure in the center of the bond. The Inconel 718 parent metal specimens were fabricated in a similar manner from blocks .310 x .750 x .500 inches long. Figure 38 shows both types of specimens. Tabs 3/4 inch wide were EB welded longitudinally to the Rene'95 and Inconel 718. The appropriate specimens were heat treated and fluorescent penetrant inspected and all were found to defect-free.

The 1200° F shear data are presented in Table XIV. On the average, the as-bonded, aged, and parent metal Inconel 718 specimens had shear strengths of 59, 62 and 80 ksi, respectively. Thus, the shear strengths of the CSDB joints, either as-bonded or after aging, were approximately 75% of the parent metal strength. It was surprising that aging did not improve the strength of the bond more than an average of 3 ksi. An explanation for this can be derived from the failures that occurred. In the as-bonded specimens the failures generally occurred through the bond. However, most of them contained slight remnants of the Inconel 718 material adhering to the Rene'95 as is illustrated in Figure 39. The figure also contains a section through the bond showing the remnants of Inconel 718. This would indicate the bond and Inconel 718 were close in their resistance to the shear forces being imposed. When the Inconel 718 was aged, its shear strength was improved, thus inducing the failure to occur entirely in the bond. In either case, the bond's shear strength was judged to be adequate.

4.3.2 Thermal Fatigue Testing

General Electric has a unique testing facility (a Simulated Engine Thermal Shock (SETS) machine) that simulates the thermal environment

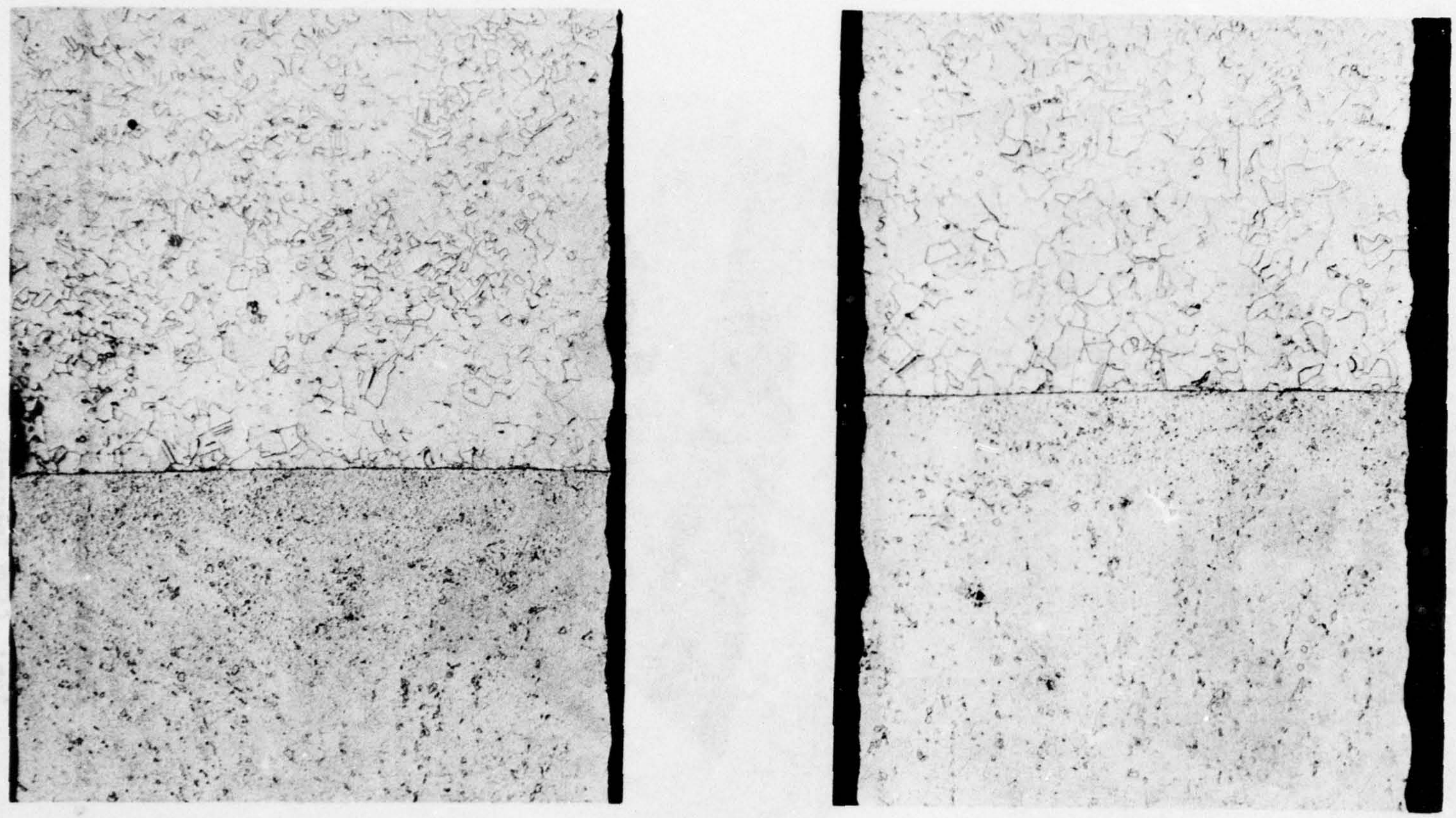

Figure 37. Bond Areas of Stress Rupture Specimen #9.

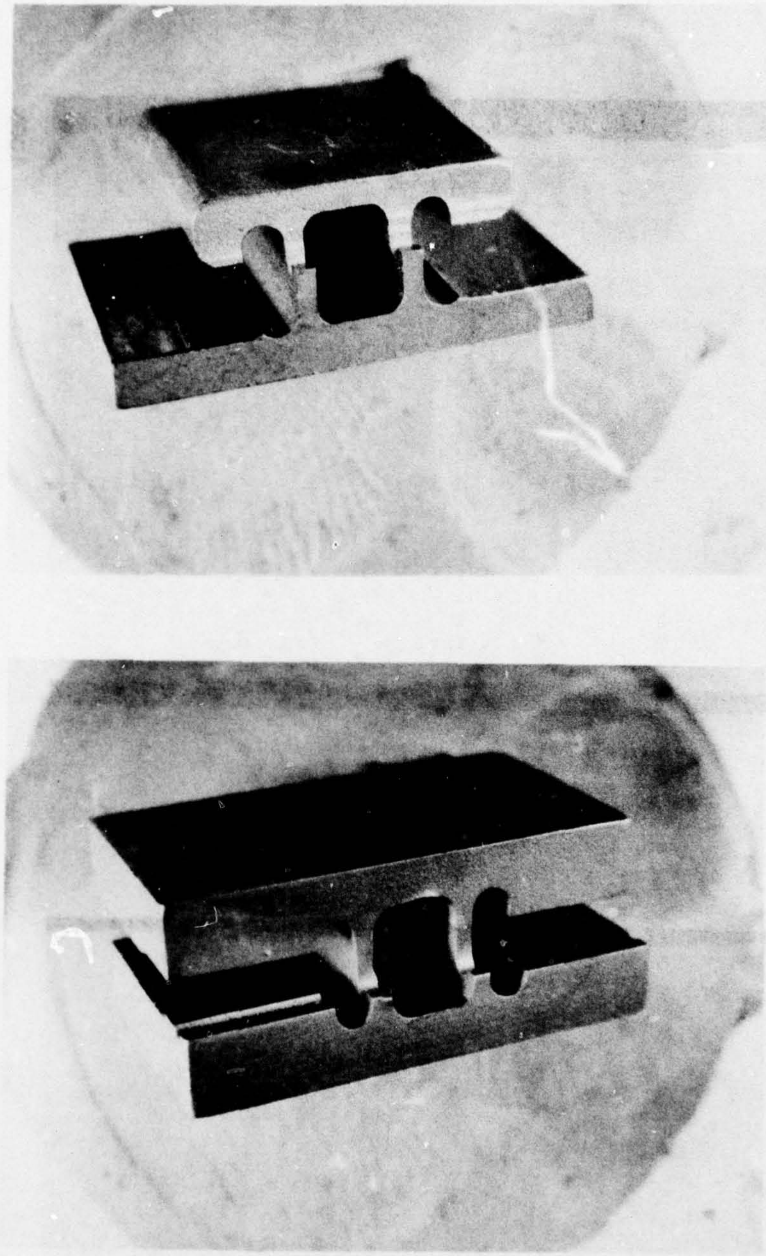

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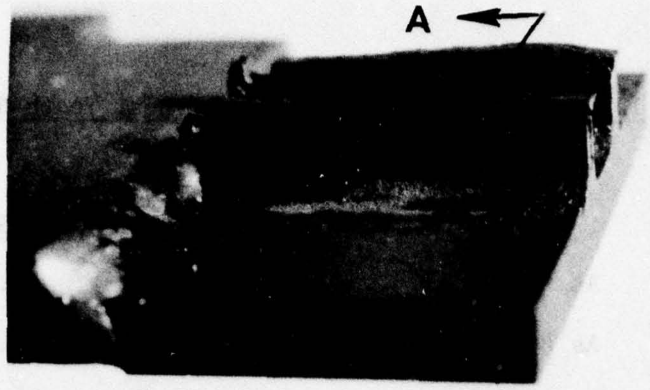
Figure 38. CSDB and Inconel 718 Parent Metal Shear Specimens.

Top: CSDB Specimen

Bottom: Inconel 718 Parent Metal Specimen

Table XIV. 1200°F Shear Properties of CSDB Seal Teeth Bars

Spec No.	Condition	Load Lbs	Shear Stress KSI
24	As Bonded	1298	55.7
26	As Bonded	1400	62.0
29	As Bonded	1168	59.4
25	Aged	1480	64.5
27	Aged	1398	62.9
28	Aged	1305	58.8
PM 1	Inconel 718	1850	83.3
PM 2	Inconel 718	1702	76.7



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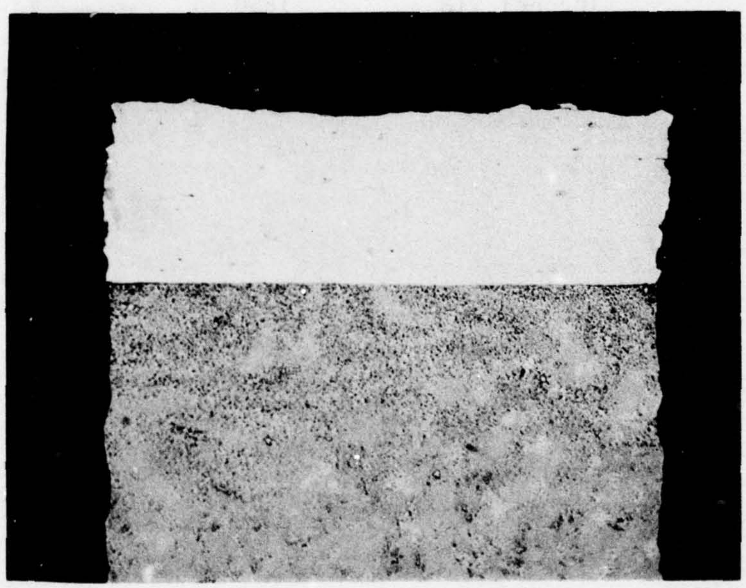

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Figure 39. As-Bonded CSDB Shear Specimen Failure.

Top: Remnants of Inconel 718 Cover Strip on René 95 Seal Tooth

Bottom: Bond Area Through Section A-A

a component experiences during engine operation. The rig consists of an indexing table that repeatedly heats and cools a specimen or simulated part configuration according to a prescribed thermal cycle. The revolving table has eight stations, i.e., one heating station, five "soaking" stations, and two cooling stations. A maximum of eight specimens can be positioned around the table and tested concurrently. The test equipment is shown in Figure 40.

Four 2-inch long specimens were cut from CSDB samples #1 and 5. Only one of the two teeth was reprofiled for thermal cycling because the desired temperature control could not be attained on the two teeth configuration. Single tooth Rene'95 parent metal specimens were machined in the same manner to provide baseline data. Positioning legs were welded to the backs of the specimens as shown in Figure 41, and the assemblies positioned in the SETS machine.

Two as-bonded, two aged specimens, and four Rene'95 parent metal specimens were thermally cycled. The SETS cycles are described in Figure 42 along with the temperatures attained by optional pyrometry. The time interval at each station for Cycle 1 was eight seconds, consequently, the thermal shock produced by the heating and cooling cycles closely approximated what the CRS actually encounters during engine operation.

At appropriate intervals, the testing was stopped and the specimens removed from their stations, lightly vapor blasted, and inspected. The inspection consisted of viewing the seal tooth tip and bond length optically at 20X. An arbitrary numbering system corresponding to a crack index has been established from previous testing. However, it could not be used for this program. After 4000 cycles, no degradation could be found on any of the specimens. In an attempt to increase the severity of the thermal shock, the time interval was reduced from eight seconds to six seconds and the cooling temperature reduced to room temperature, as noted for Cycle II. The maximum temperature of 1100°F was not changed at the request of the design group. Cycle II was imposed for 3000 additional cycles and again no degradation could be found on any of the specimens. Testing was discontinued because the design data point of 5000 cycles had been exceeded. Although no failures had occurred, the testing procedure demonstrated that the as-bonded and aged specimens were capable of operating along side Rene'95 specimens and surviving a thermal cycle that a CRS would encounter during engine operation.

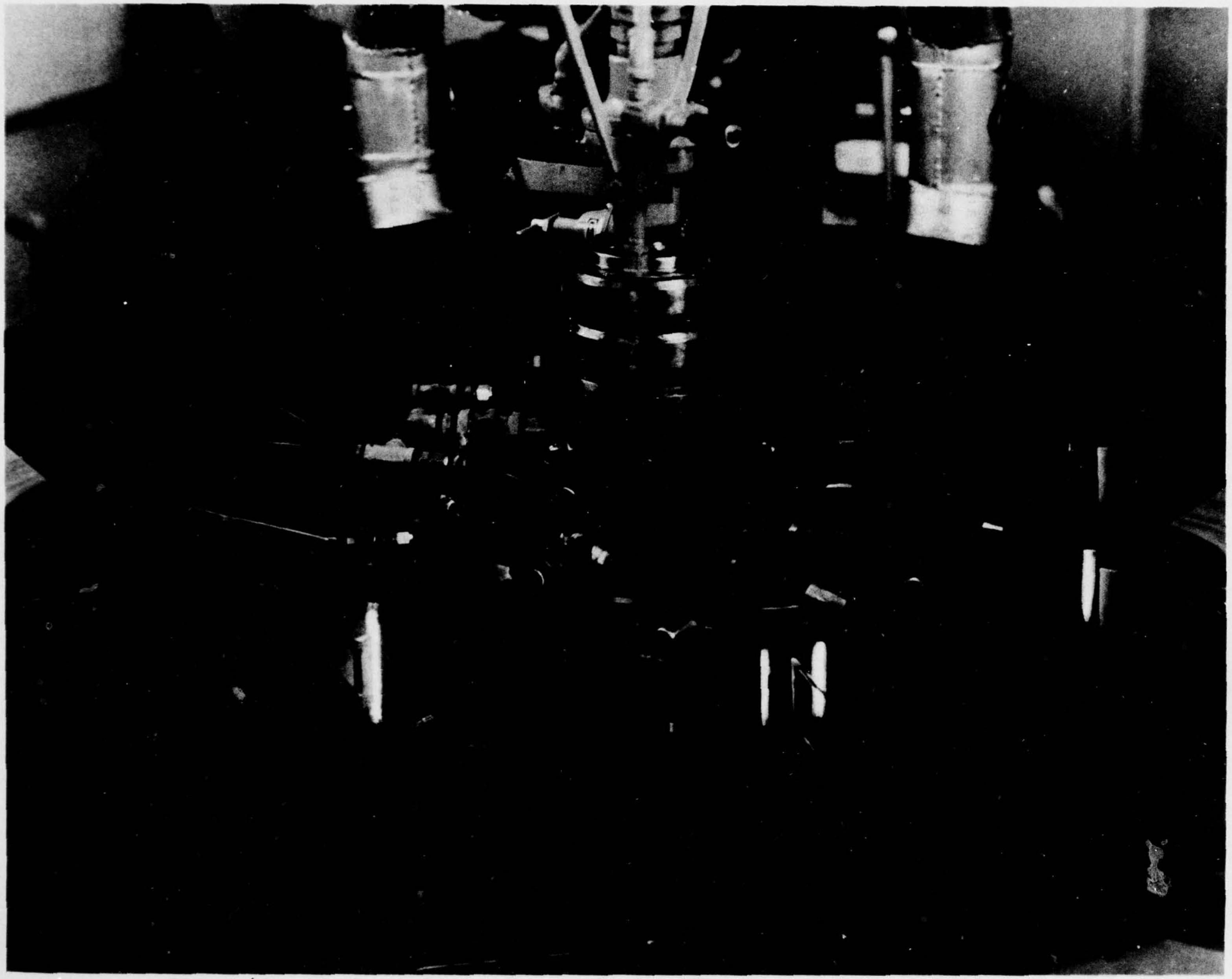

Figure 40. Simulated Engine Thermal Shock, SETS, Thermal Fatigue Machine.

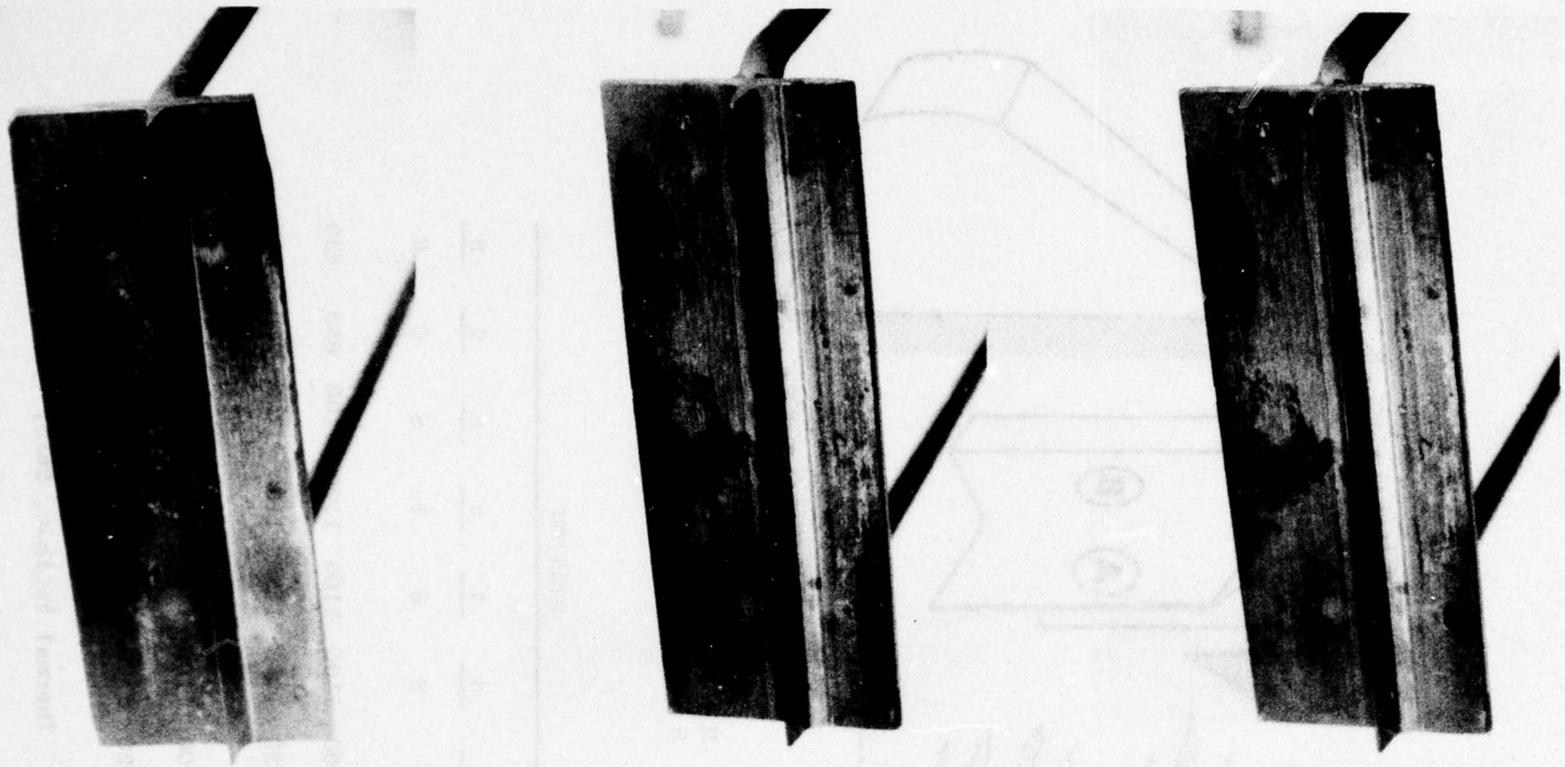

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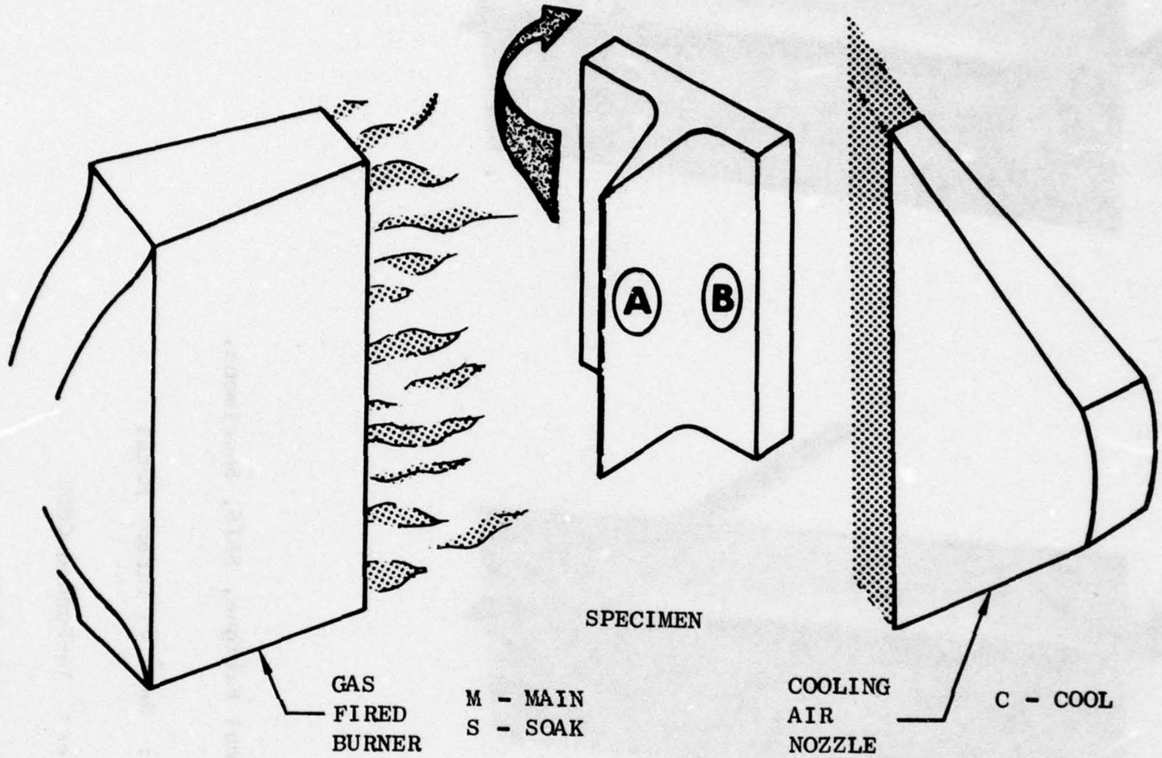
Figure 41. Thermal Fatigue, SETS, Specimens.

Left: René 95 Parent Metal

Center: As-Bonded CSDB

Right: Aged CSDB



		STATION							
		1	2	3	4	5	6	7	8
CYCLE		M	S	S	S	S	S	C	C
I	A	1100	1100	1100	1100	1100	1100	650	450
	B	980	1130	1090	1130	1100	1100	700	480
II	A	1100	1100	1100	1100	1100	1100	425	80
	B	970	1120	1100	1120	1100	1110	475	85

Figure 42. Thermal Fatigue, SETS, Cycles.

Top: Temperature Measurement Locations A and B

Bottom: Station Temperatures

Figure 43 contains sections through the bond areas of the as-bonded, aged, and parent metal specimens. Solutioning of the carbides in the Rene'95 is evident in both the as-bonded and aged specimens demonstrating that in this thermal fatigue test the solutioned structure did not have any adverse effect. The bond line of the aged specimen makes an abrupt angle at one face of the tooth. This is the area where the tip of the teeth indents into the cover strip. No degradation resulted from this and the bond was judged to be adequate.

4.3.3 Low Cycle Fatigue Testing

4.3.3.1 Equipment and Specimen Preparation

The strain controlled LCF properties of the as-bonded, aged and Rene'95 parent metal seal teeth were determined in bending fatigue. The testing equipment, shown in Figure 44, is a deflection controlled unit that subjects the specimen to four-point bending, while maintaining a minor axial load on the specimen. The defelction was established by a spherometer that measures the radius of curvature of the specimen. A triangular wave form was obtained with the standard frequency of 20 cpm (.33 Hz). The specimens were resistively heated to 1000°F. Both temperature and displacement of the gage section were continuously recorded on strip chart recorders with crack initiation (N_i) being determined from the displacement strip chart.

The two teeth configuration used to determine the other mechanical properties did not lend itself to the single tooth testing procedure. The three-seal teeth configuration from seal ring #5 was judged to be more appropriate since: (1) it truly represented a repaired component, (2) it could easily be machined enabling the critical center tooth to be tested, and (3) sufficient test material was not available from the flat seal teeth bars.

Three inch-long segments were cut from seal ring #5 and extensions, 3/4 inch wide, EB welded longitudinally to both ends to produce the CSDB test specimens. The specimen configuration and welding fixturing used for the CSDB specimens are shown in Figure 45. Cylindrical seal teeth for the Rene'95 teeth were not available so flat specimens with identical gage sections were low stress ground from the Rene'95 cross-rolled plate for the other mechanical properties. The Rene'95 teeth test specimens were fabricated similarly to those of the CSDB as shown in Figure 46. Eight parent metal and six CSDB specimens were fabricated. Three of the CSDB specimens were aged by the

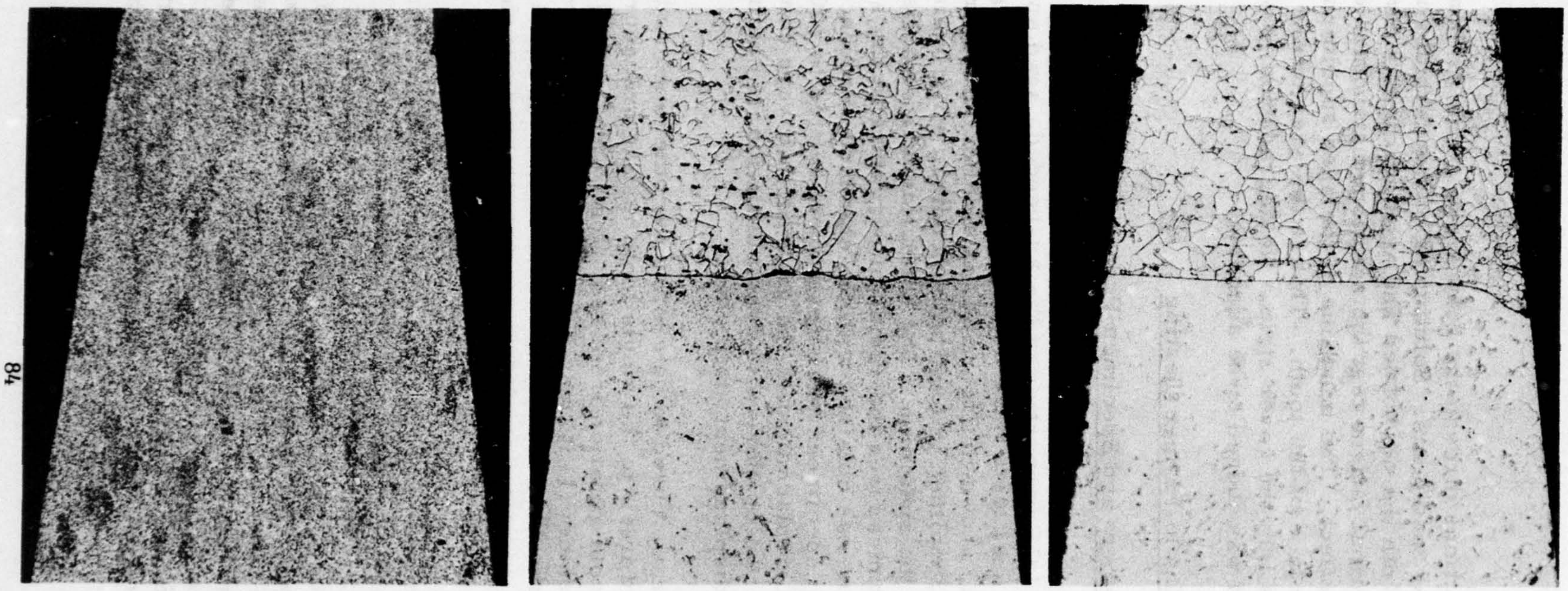


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Figure 43. Sections Through Thermal Fatigue, SETS, Specimens.

Top: René 95 Parent Metal

Center: As-Bonded CSDB

Bottom: Aged CSDB

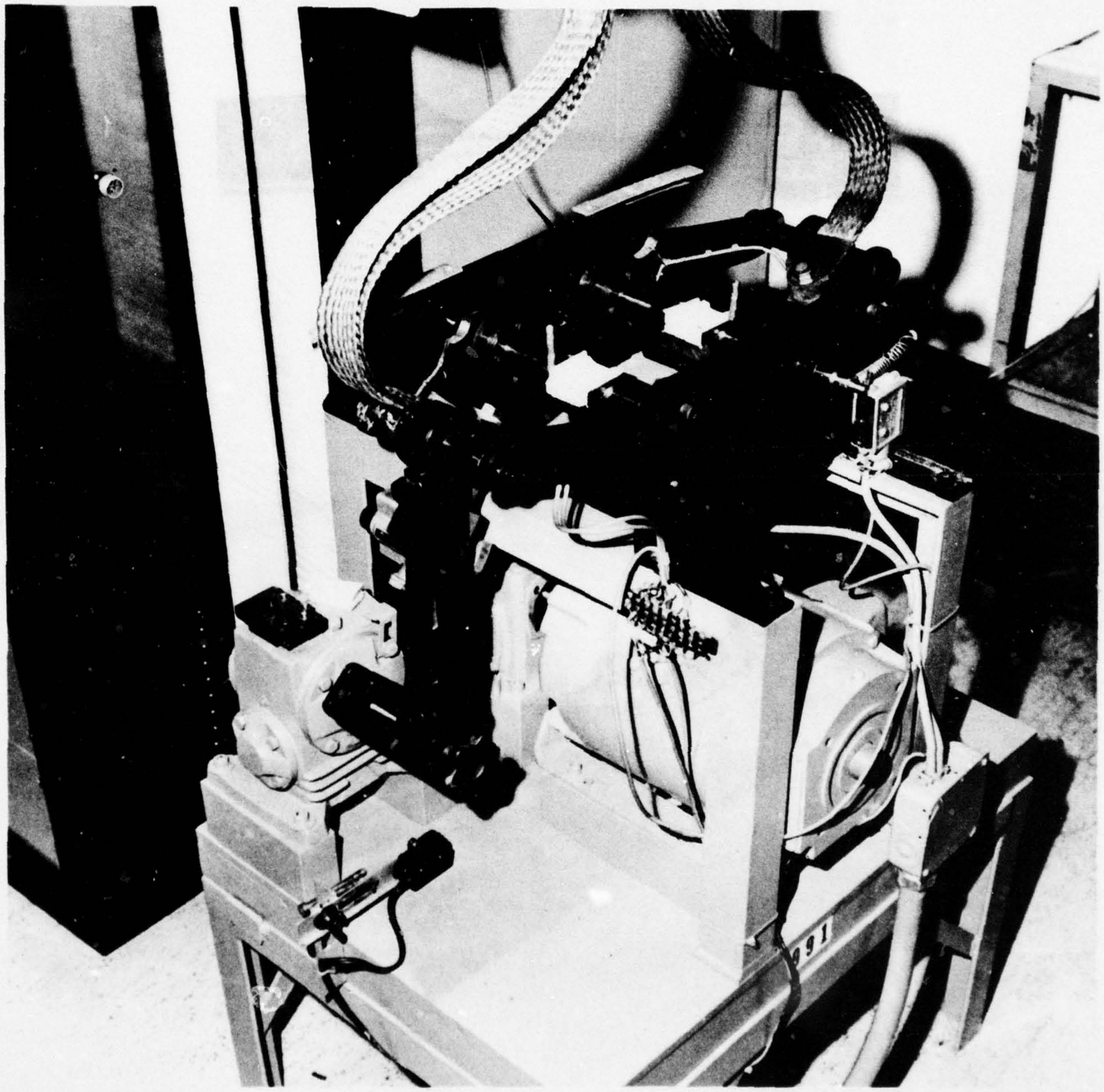

Figure 44. Forrest Four Point Bending LCF Machine.

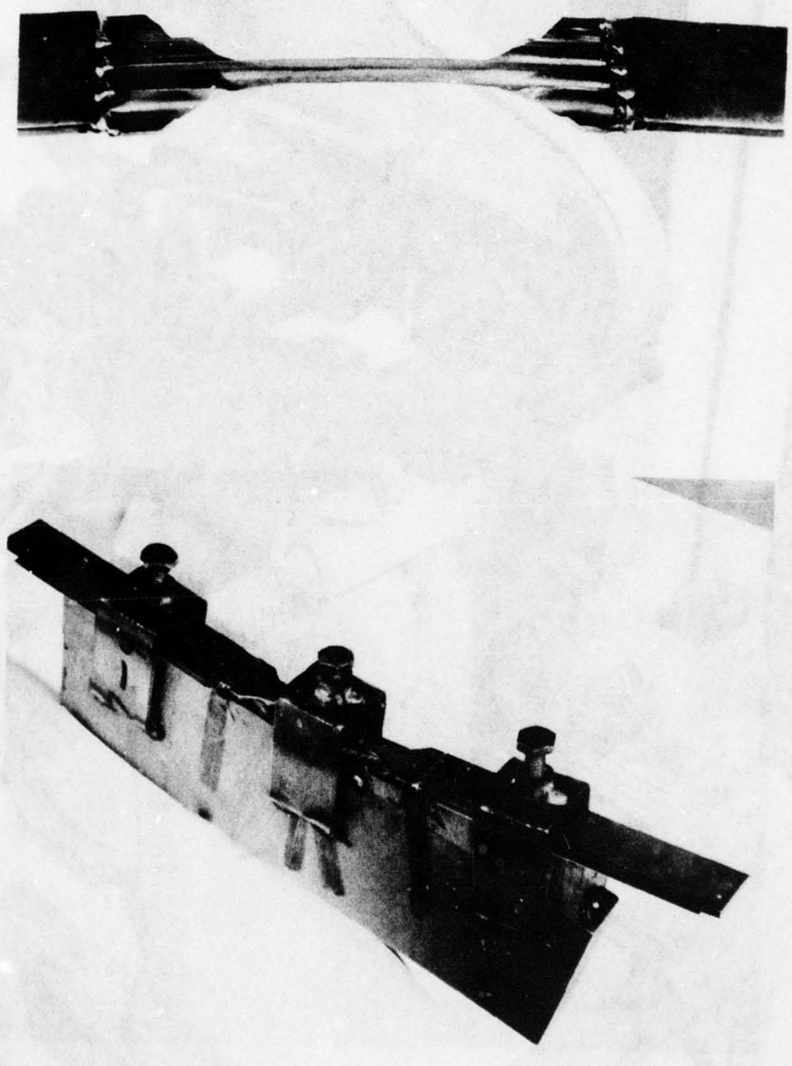

Figure 45. CSDB LCF Specimen.

Top: Specimen Cut From Seal Ring #5

Bottom: Specimen in Welding Fixture

AD-A057 269 GENERAL ELECTRIC CO CINCINNATI OHIO MATERIAL AND PRO--ETC F/G 11/6
SUPERALLOY KNIFE EDGE SEAL REPAIR.(U)
MAY 78 R E KUTCHERA, P G BAILEY F33615-76-C-5123

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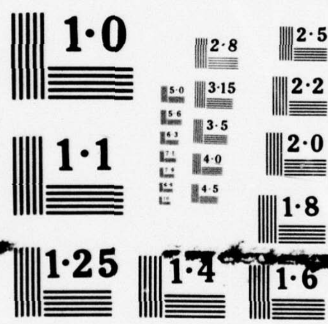


NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

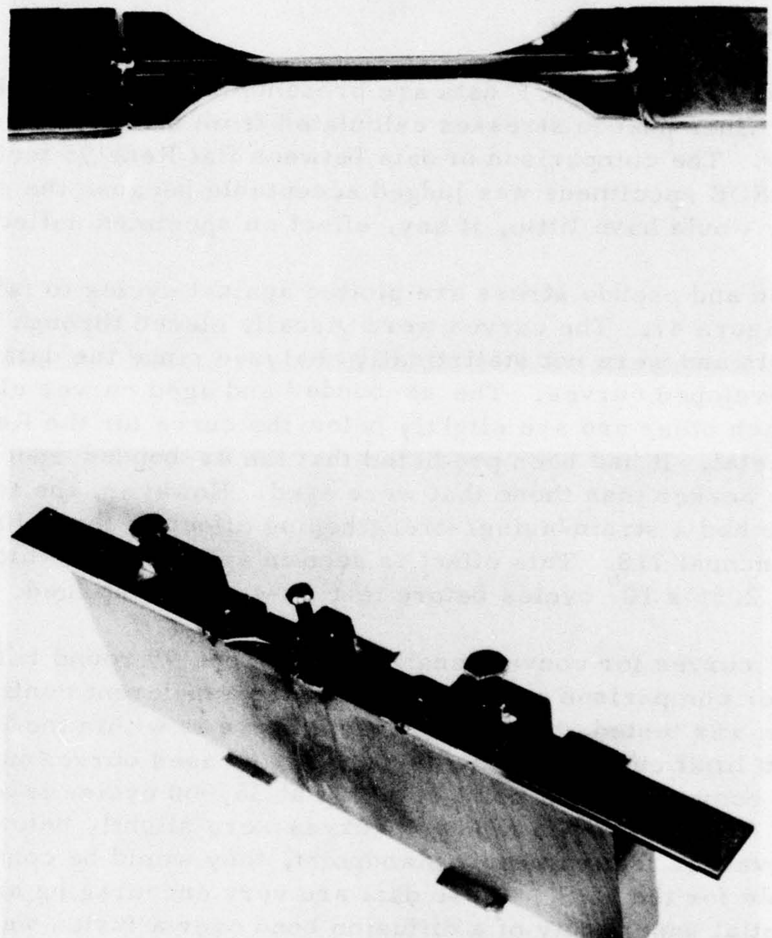


Figure 46. René 95 LCF Specimen.

Top: Specimen Machined From Plate

Bottom: Specimen in Welding Fixture

previously noted post-bond heat treatment. All 14 specimens were periodically fluorescent penetrant inspected during the processing cycles and all were found to be defect-free.

4.3.3.2 Testing

The strain controlled LCF data are presented in Table XV along with the outer fiber pseudo stresses calculated from strain and modulus of elasticity. The comparison of data between flat Rene'95 teeth and curved CSDB specimens was judged acceptable because the starting geometry would have little, if any, effect on specimen deflection.

Deflection and pseudo stress are plotted against cycles to failure (N_f) in Figure 47. The curves were visually placed through the data points and were not statistically analyzed since the data followed easily developed curves. The as-bonded and aged curves closely follow each other and are slightly below the curve for the Rene'95 parent metal. It had been predicted that the as-bonded specimens would be weaker than those that were aged. However, the test cycle may have had a strain/aging/strengthening effect on the solution treated Inconel 718. This effect is seen in specimen #3 which was tested to 2.56×10^6 cycles before testing was discontinued.

The LCF curves for conventionally forged Rene'95 round bar are plotted for comparison purposes. Although a different configuration specimen was tested, the Rene'95 teeth curve is within the Rene'95 minus 3σ limit curve with the as-bonded and aged curves just below. The new component data point of 90 ksi at 36,000 cycles is also plotted. The as-bonded and aged curves were slightly below the 90 ksi. However, from a repair standpoint, they would be considered acceptable for the CRS. These data are very encouraging and indicate the potential superiority of a diffusion bond over a fusion weld. In the CSDB process a wrought structure was added to the seal teeth rather than cast structure as would be deposited by a fusion welded process. The fatigue strength of the wrought structure is usually significantly greater than that of the cast.

In general, the failures that occurred in the specimens were in the gage section as shown in Figure 48 with crack initiation starting in the Inconel 718 at the tip of the tooth. Some cracking initiated at the

Table XV. 1000°F Strain Controlled LCF Properties of Rene'95 and CSDB Seal Teeth

Spec No.	Type	Stress Alt. KSI	Deflect Inches $X10^3$	Nf $X10^3$	Ni $X10^3$	Comments
1	Rene'95	90.0	19.0	3.8	NA	Radius Failure
2	Rene'95	45.0	9.5	56.7→	--	Runout
3	Rene'95	78.2	16.5	56.7→	--	Runout
4	Rene'95	132.2	27.9	1.0	.8	
5	Rene'95	100.9	21.3	24.1	13.6	
6	Rene'95	90.0	19.0	7.8	5.8	
7	Rene'95	99.5	21.0	1.1	.8	Radius Failure
8	Rene'95	84.8	17.9	74.5	NA	
3R	Rene'95	85.3	18.0	10.9	NA	Rerun of No. 3
AB1	As Bonded	83.8	17.7	8.7	6.7	
AB2	As Bonded	75.8	16.0	50.3	37.0	
AB3	As Bonded	74.8	15.8	256.0→	--	Runout
A	Aged	88.1	18.6	3.9	2.5	
B	Aged	78.2	16.5	28.3	15.1	
C	Aged	77.7	16.4	27.9	6.7	

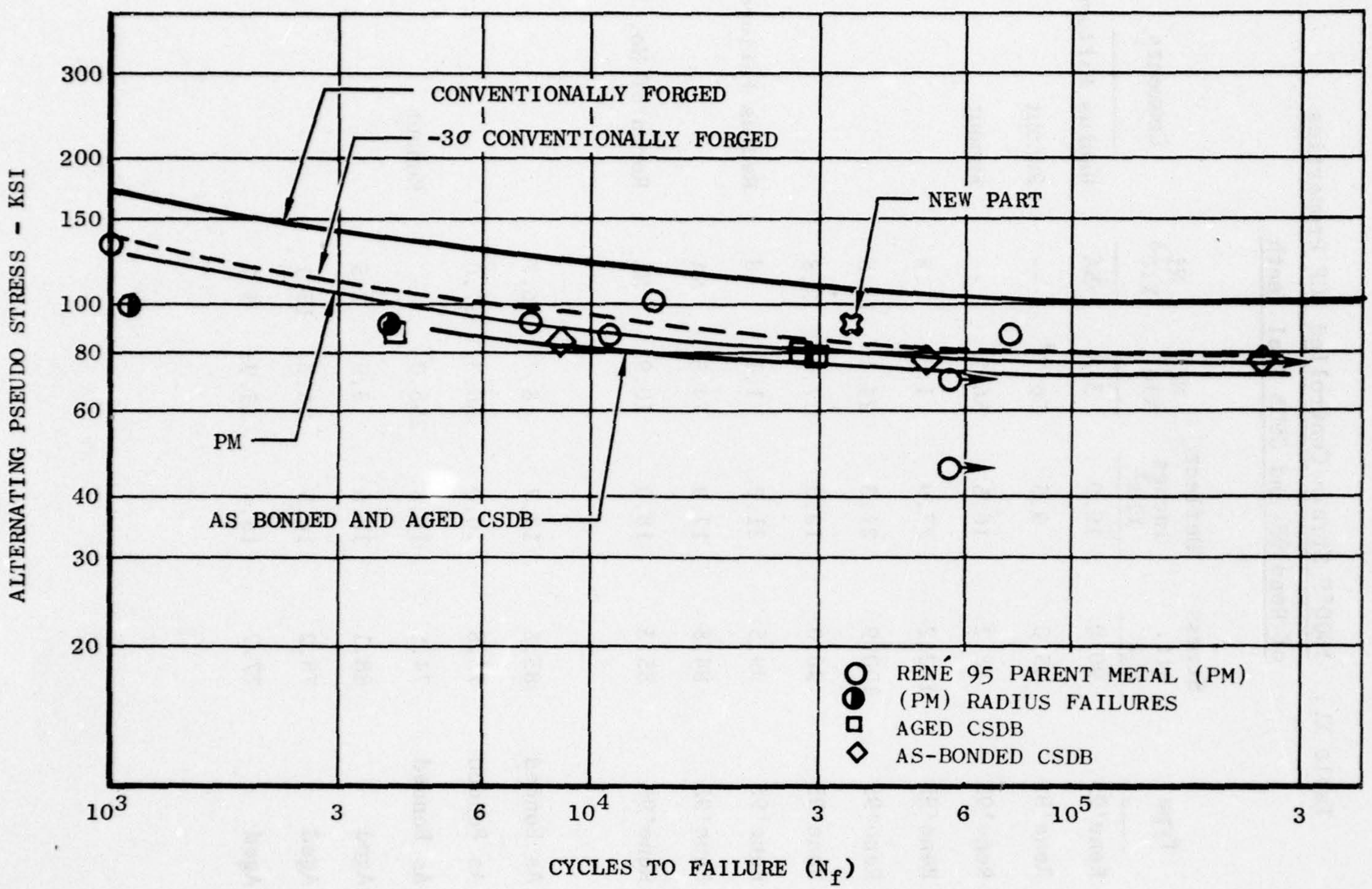


Figure 47. 1000°F LCF Properties of Seal Teeth Specimens (A = .95, 20 CPM).

10X

Figure 48. Typical Failure Modes of LCF Specimens.

Right: As-Bonded CSDB

Left: René 95 Parent Metal

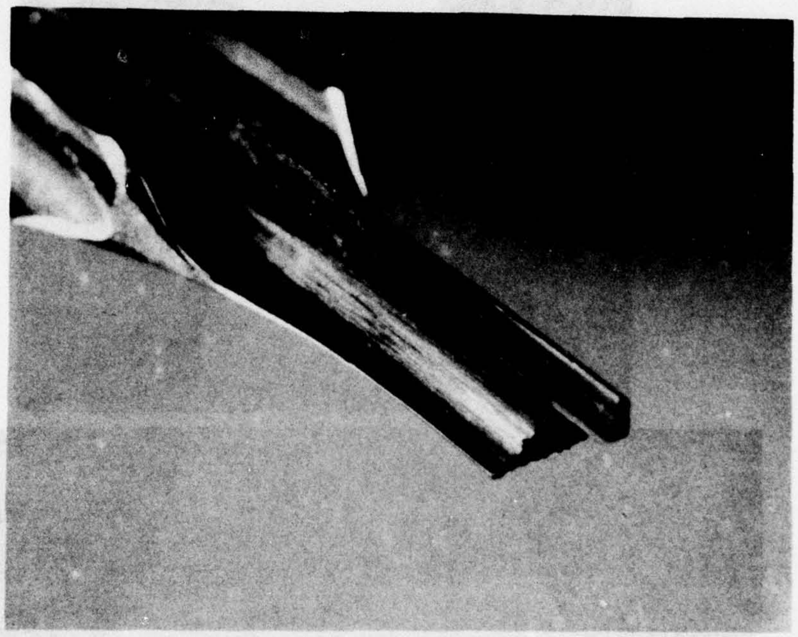
gage section radii or just out of the gage section. These are noted in Table XIV and Figure 47. Two of the three aged specimens failed in the mode shown in Figure 49. Cracking initiated in the tip of the tooth, through the tip extension to the bond, along the bond for a short distance and then through the tooth. This type of failure was not degrading and could be beneficial because of its crack arresting characteristics; depending upon the loading on the seal teeth, a crack could initiate in the tip extension and stop at the bond line and not continue into the component where it could cause serious damage.

Cross-sections at two locations of the center tooth that was LCF tested are shown in Figures 50, 51, 52, and 53. The optimum bond is shown in Figures 50 and 51, whereby the Rene'95 is not solutioned in the bond area. Some expected solutioning occurred under the bond as shown in Figures 52 and 53. This did not cause any integrity problems as the bond area was of excellent quality and no incipient melting or other degrading effects could be found in the Rene'95. This again indicated that there was some latitude in the parameters to produce acceptable bonds. The LCF data obtained from the specimens demonstrated that excellent properties can be obtained from them.

4.4 Cost Analysis for Spool Repair

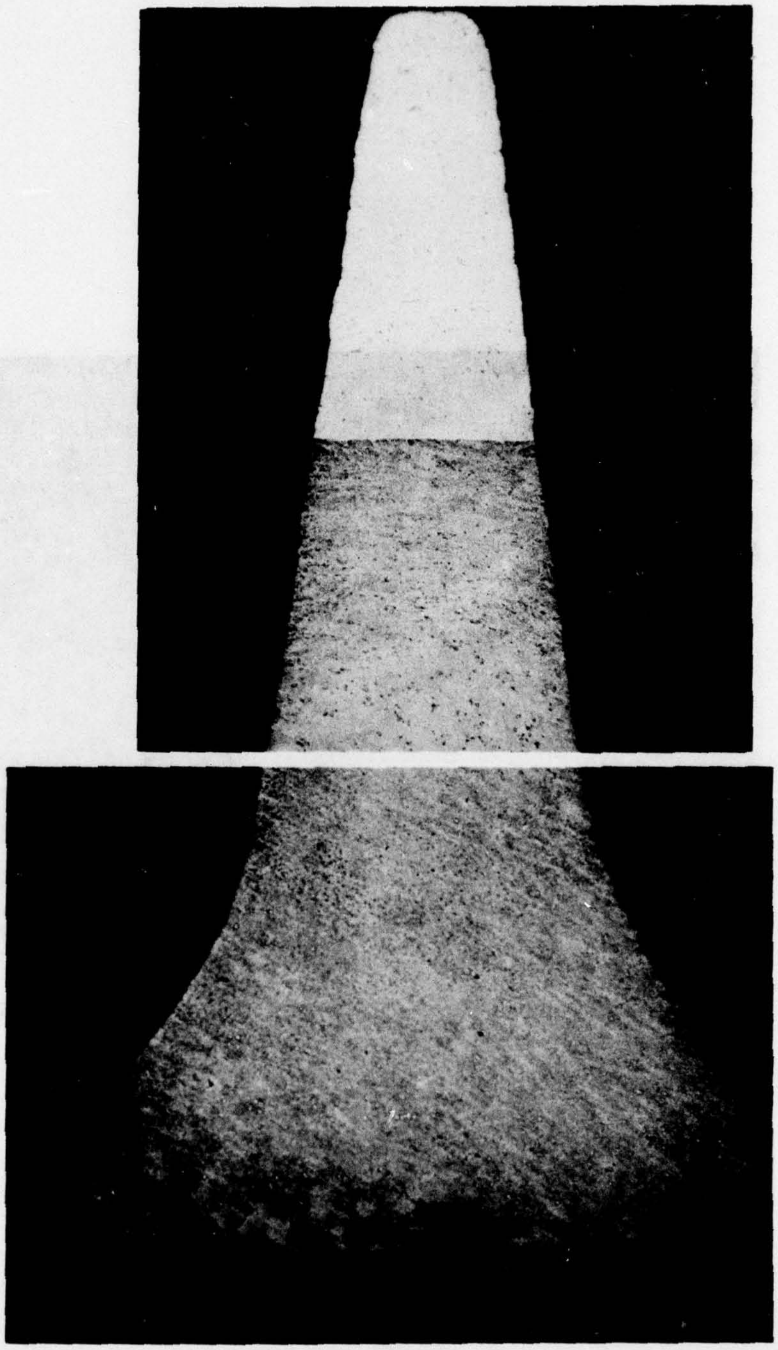
A detailed cost analysis was conducted for CSDB repair of an F101, Rene'95, CRS, Stages 4-9. By necessity, such an analysis must initiate with a conceptual design of the fixturing to be used. Such a conceptual design of the fixturing for the repair of the seal teeth on the CRS is shown in Figure 54. The design locates cover strips and thermal strips at all the seal teeth stages. The expandable tooling is located by Stage 9 assuming that it is the one being repaired. It would be necessary to have an expandable fixture located under each stage requiring repair.

A flow chart describing the approach for the repair of worn seal teeth on the CRS is shown in Figure 55. The estimated costs expressed in labor hours are listed in Table XVI. They are estimated under the assumption that one stage of seal teeth is to be repaired. Costs are not included for the Inconel 718 cover strip and thermal strip, or blade split rings, which provide support for the cover foil. Costs are also not included for expendible items such as cover foil, foil strapping material, hydrogen and argon gases, etc. However, a conservative estimate would be $500.



6X

Figure 49. Failure Mode of Aged CSDB LCF Specimens.



50X

Figure 50. Cross Section of Center Tooth of Seal Ring #5 at Location X-3.

(see Table III)

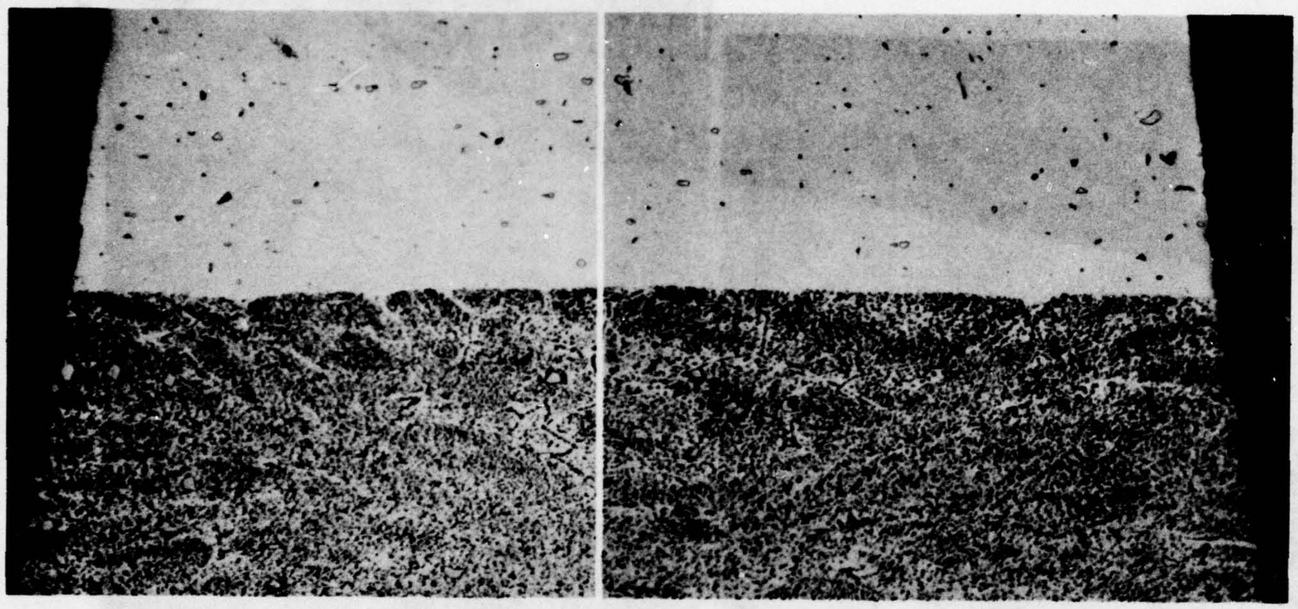


Figure 51. Bond Line of Center Tooth of Figure 50.

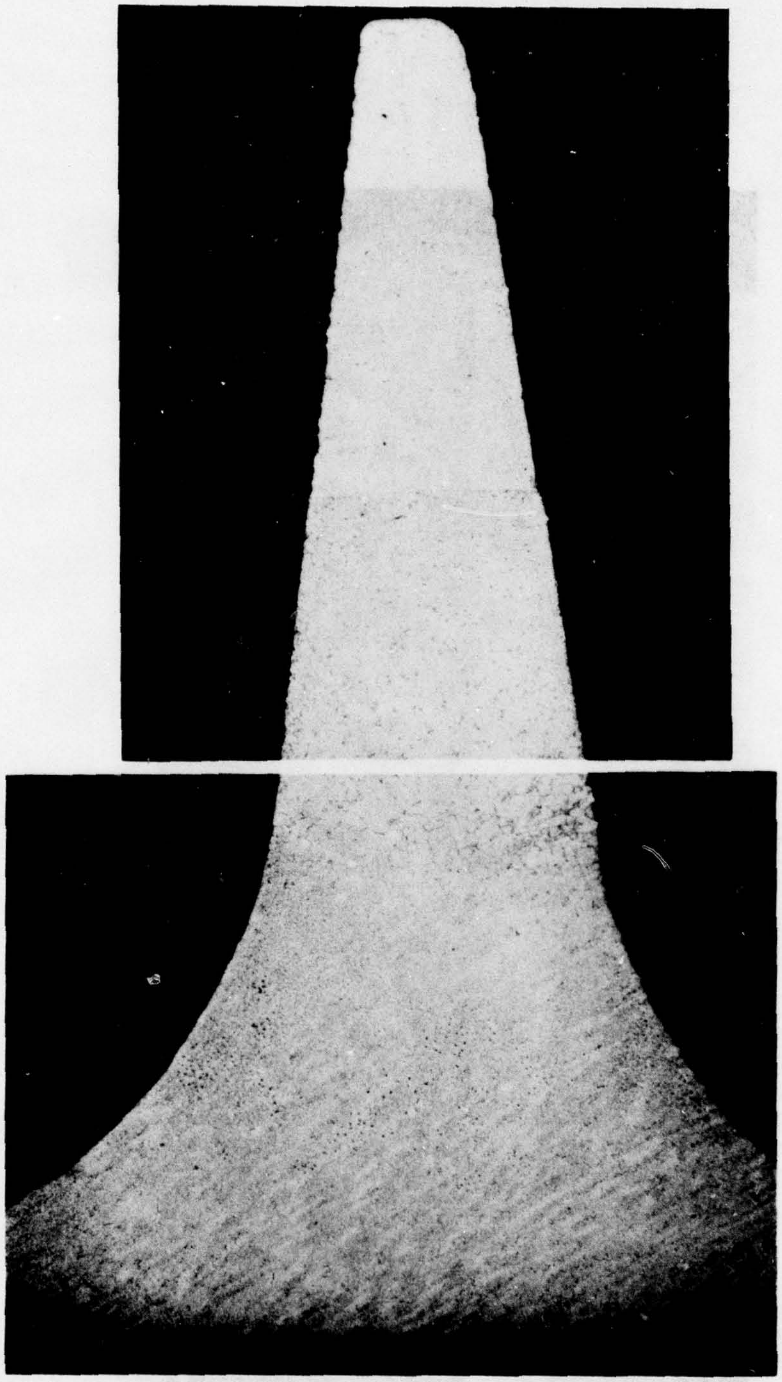


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Figure 52. Cross Section of Center Tooth of Seal Ring #5 at Location X-2.

(See Table III)

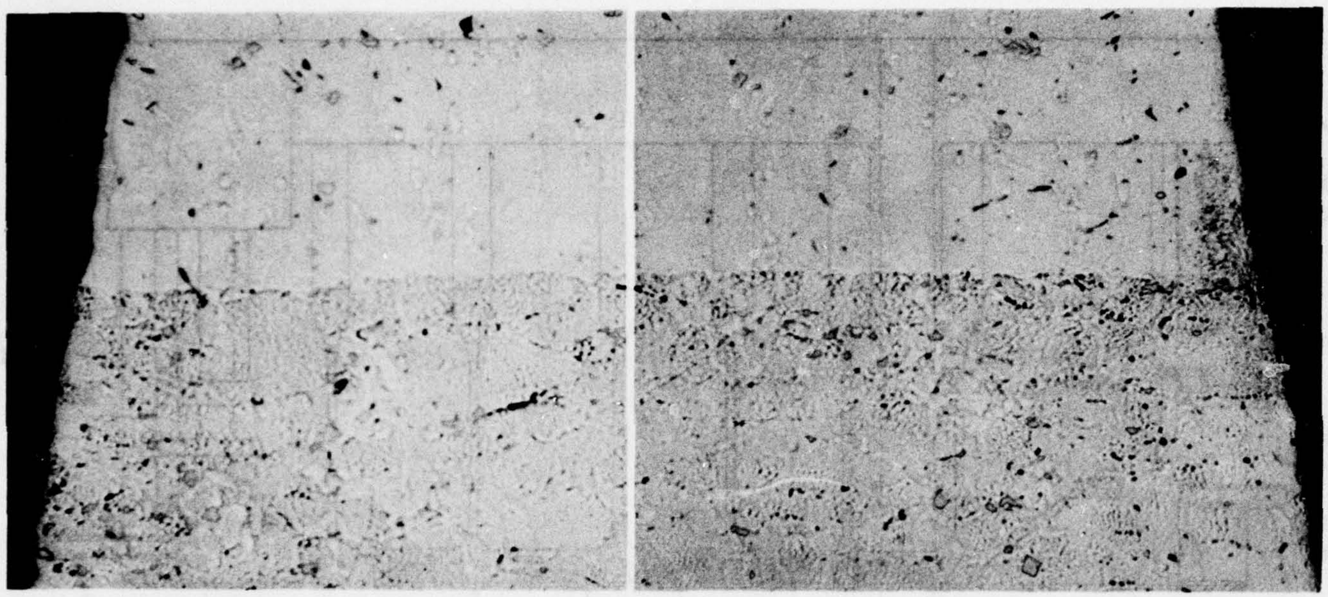

Figure 53. Bond Line of Center Tooth of Figure 52.

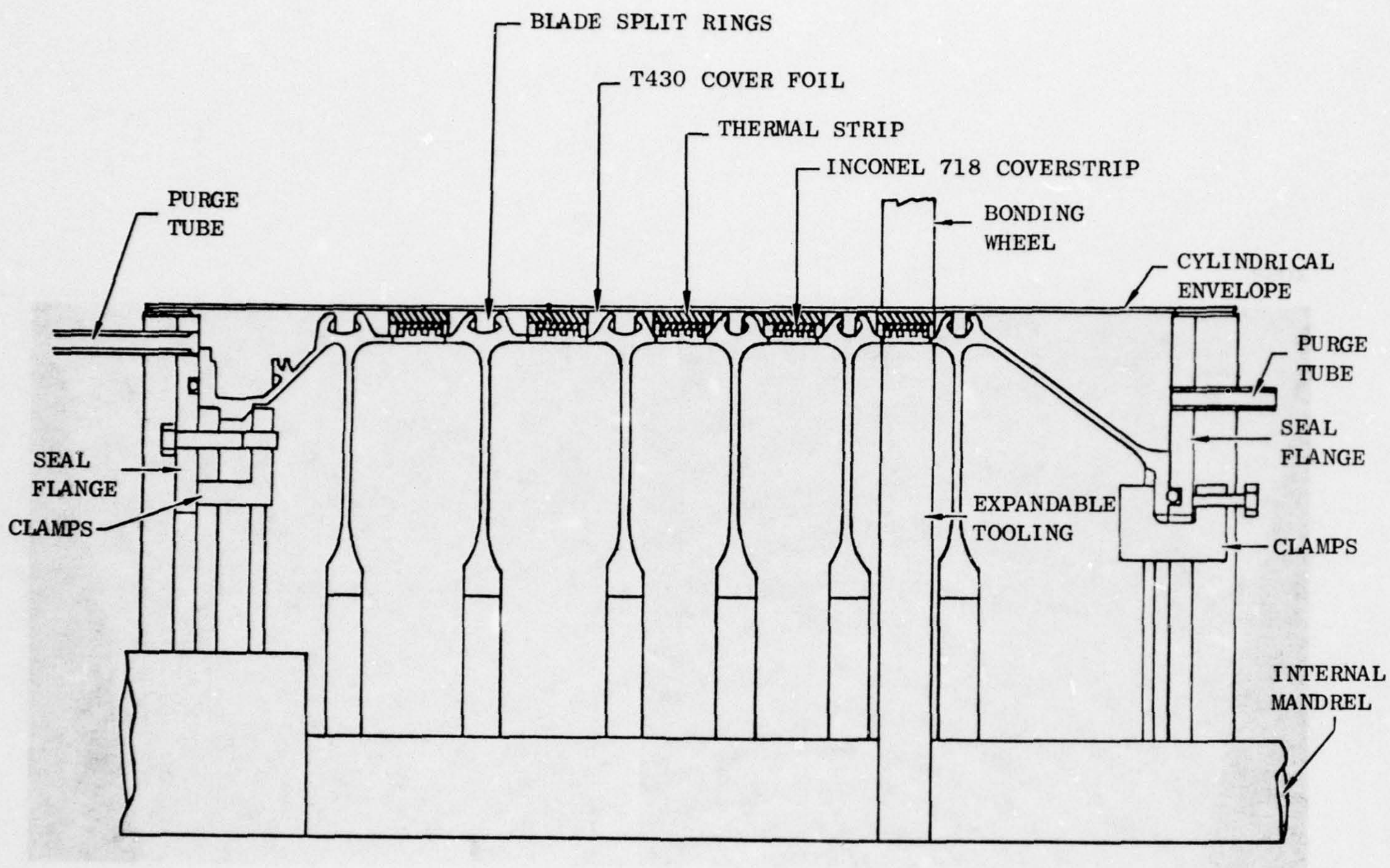

Figure 54. Fixturing For Complete Compressor Rotor Spool.

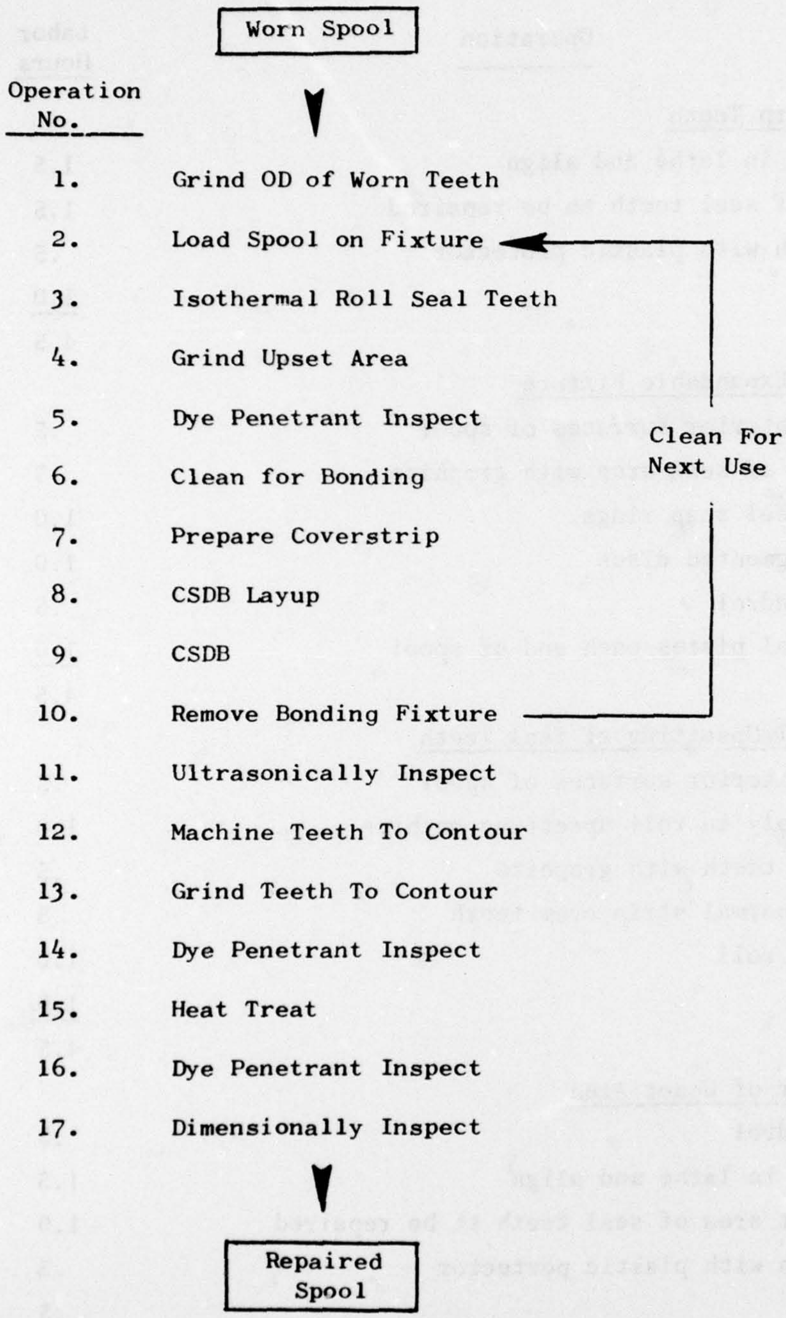

Figure 55. CSDB Processing Flow Chart

Table XVI. Cost Estimate for Repair of F101, Rene'95, CRS

No.	Operation	Labor Hours
1.	Grind OD of Worn Teeth	
	a. Loads pool in lathe and align	1.5
	b. Grind OD of seal teeth to be repaired	1.5
	c. Cover teeth with plastic protector	.5
	d. Unload	1.0
		4.5
2.	Load Spool on Expandable Fixture	
	a. Degrease interior surfaces of spool	.5
	b. Spray I.D. of seal area with graphite	.5
	c. Install steel snap rings	1.0
	d. Install segmented discs	1.0
	e. Install mandrel	.5
	f. Install seal plates each end of spool	1.0
		4.5
3.	Isothermal Roll Upsetting of Seal Teeth	
	a. Degrease exterior surfaces of spool	.5
	b. Load assembly in roll upsetting machine	1.0
	c. Spray seal teeth with graphite	.5
	d. Position thermal strip over teeth	.5
	e. Isothermal roll	1.0
	f. Unload	1.0
		4.5
4.	Grind to Center of Upset Area	
	a. Remove mandrel	.5
	b. Load spool in lathe and align	1.5
	c. Grind upset area of seal teeth to be repaired	1.0
	d. Cover teeth with plastic portector	.3
	e. Unload	.5
	f. Install mandrel	.5
		5.3

Table XVI. Cost Estimate for Repair of F101, Rene'95, CRS (continued)

No.		Operation	Labor Hours
5.		Dye Penetrant Inspect	
	a.	Wash, dye penetrant inspect and wash	2.0
			2.0
6.		Clean for Diffusion Bonding	
	a.	Degrease exterior surfaces of spool	.5
	b.	Vapor hone seal teeth to be repaired	.5
	c.	Rinse with D.I. water/air blast	.5
	d.	Dry with warm air	.5
			2.0
7.		Prepare Cover Strip for Bonding	
	a.	Shear 3/4 wide x 50^{+} inch length	.3
	b.	Grind reverse tapers on ends	1.5
	c.	Roll into ring	.5
	d.	Clean	.2
			2.5
8.		Layup for Diffusion Bonding	
	a.	Load assembly into layup arbour cradle	1.0
	b.	Install end seal flanges and clamps	1.0
	c.	Position cover strip over teeth/s to be repaired	.5
	d.	Position thermal strip/s	.5
	e.	Position blade split rings in blade grooves	1.0
	f.	Spot tack straps between blade split rings and to thermal strip to position and hold it	1.0
	g.	Stretch wrap T430 foil over flanges thermal strips and manifold split rings and spot tack to flanges and split rings	2.0
	h.	Unload	1.0
			8.0
9.		Diffusion Bond	
	a.	Load layup assembly into CSDB machine	1.0
	b.	Purge air space between OD os spool and cover foils with H_2	1.0
	c.	CSDB stage or stages of seal teeth to be repaired	.5

Table XVI. Cost Estimate for Repair of F101, Rene'95 CRS (continued)

No.		Operation	Labor Hours
	d.	Purge with Argon	.5
	e.	Unload	1.0
			4.0
10.		Removal of Bonding Fixtures	
	a.	Load assembly into layup arbour cradle	1.0
	b.	Strip cover foils	.5
	c.	Strip thermal strip, blade split rings straps, etc. off spool	.5
	d.	Strip end seal flanges and clamps	1.0
	e.	Remove mandrel segmented discs and strap rings	2.0
	f.	Load into protective container	2.0
			6.0
11.		Ultrasonically Inspect	
	a.	Load, Ultrasonically Pulse Echo Inspect and Unload	4.0
			4.0
12.		Machine Teeth to Contour	
	a.	Load spool in lathe and align	1.5
	b.	Rough machine tip contour	3.0
	c.	Unload	1.5
			6.0
13.		Grind Teeth to Contour	
	a.	Load spool in VTL	1.0
	b.	Set up for grinding	2.0
	c.	Grind contour	4.0
	d.	Unload	1.0
			8.0
14.		Dye Penetrant Inspect	
	a.	Wash, dye penetrant inspect and wash	2.0
			2.0
15.		Heat Treat	
	a.	Load spool in fixture in vacuum furnace	1.0

Table XVI. Cost Estimate for Repair of F101, Rene'95 CRS (continued)

No.	Operation	Labor Hours
	b. Heat Treat	6.0
	c. Unload	1.0
		8.0
16.	Dye Penetrant Inspect	
	a. Wash, dye penetrant inspect and wash	2.0
		2.0
17.	Dimensionally Inspect	
	a. Load in inspection fixture	1.0
	b. Dimensionally inspect and record data	2.0
	c. Unload	1.0
		4.0
	Estimated Labor Hours	67.3
	10% Contingency	6.7
	Total Labor Hours	74.0

The estimated labor hours total 67.3 hours plus a 10% contingency of 6.7 hours or 74 hours. Based on an estimated shop labor charge, including overhead, of $30.00/hour, the cost to repair a single stage of a CRS would be $2200. Naturally, the cost for repairing two or more stages would not be twice the amount, but an estimated increase of 10% for each additional stage repaired.

Assuming a total cost of approximately $3000 for repairing several seal rings on a compressor rotor spool, this is a small fraction of the replacement cost of such a complex part. This repair process is judged to have high payoff potential.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the work on this program:

- CSDB was demonstrated to be a feasible repair process for worn or damaged Rene'95 seal teeth.
- Inconel 718 is an acceptable tip extension material since diffusion bonds between it and Rene'95 are metallurgically sound and possess excellent mechanical properties and provides adequate wear rates as determined by prior engine experience.
- The CSDB process has an inherent advantage over fusion welding processes in that a wrought structure, rather than a cast structure, is bonded to the Rene'95. Fatigue strength and uniform quality are important properties in which the wrought structure would be significantly greater than that of a cast weld.
- Isothermal rolling was proven effective in preshaping the seal teeth to provide sufficient material, after CSDB, to reprofile to accurate teeth contours without unmachined notches at the buildup interface.
- Acceptable 360° bands can be made by a double-scarved end closure.
- The ultrasonic pulse-echo NDT technique is an effective means of determining if bonding was successful. Fluorescent penetrant NDT is an effective method of determining the integrity of the bond.
- A minimum amount of distortion is experienced during complete CSDB processing. This should provide a stable component.
- As-bonded and/or aged bonds possess excellent thermal fatigue and LCF properties. However, aging the component would be recommended because the failures in the LCF study indicated the aged bonds had crack arresting characteristics.

- Isothermal Rolling/CSDB tooth repair processing is very cost effective. The F101, Rene'95, CRS, Stages 4-9, is an excellent example in which the projected costs to repair one of the seal ring clusters would be less than 10% than that of a new part.

Though feasibility of the isothermal rolling/CSDB process was demonstrated in this program, it is recommended that a follow-on manufacturing technology program be instituted to establish the reproducibility of the repair process. In such a program the isothermal roll, CSDB, and end closure processes would be thoroughly developed to establish parameter limits. Improved temperature control would be sought. Open air gas shielding would be one method studied. Process modifications, including single versus multiple tooth bonding would be evaluated.

The program would also evaluate the rub characteristic advantages of an "original equipment" Inconel 718 tip on Rene'95 rotor seals.

Another area a manufacturing methods program should define is the probable advantage of the solid state CSDB process in Powder Mettalurgy (P/M) disk alloys. P/M parts are susceptible to thermally induced porosity (TIP) which could occur in fusion processes.

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