Innovative Approaches In The Manufacture Of Zirconium Alloy Components For PHWRs

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Abstract

Selection of an appropriate route for the fabrication of Zirconium alloy fuel components has a direct bearing on the quality of finished product. Many sophisticated and intricate processes such as vacuum arc melting, extrusion, hot rolling and cold working processes – swaging, drawing and sheet rolling are employed. Many advances were made in eddy current and ultrasonic evaluation to meet the stringent quality control requirement and locate the micro flaws. Emphasis was laid on achieving high recoveries and manufacture the product at minimum cost.

Several creative and innovative processes were adopted particularly in the fabrication of end caps and spacers. The spacers were produced through the wire route and subsequently parting them into tiny spacers, which is entirely different from the conventional route of fabricating the sheets followed by blanking and coining. This has improved the material recovery and the lead time has been reduced substantially.

The end caps used for the closure of clad tubes have to meet the most stringent quality requirements to avoid micro-flaws. The manufacturing processes adopted have direct influence on the integrity of the finished product. Special defect standards were developed to identify and eliminate micro-flaws and thereby ensure consistent and repetitive quality product.

The paper brings out the above innovative approaches made in fabrication and quality control techniques in the manufacture of fuel components for PHWR fuel bundles.

INTRODUCTION

Nuclear Fuel Complex is manufacturing zirconium alloy cladding tube, bar for end caps and sheet material for spacers, bearing pads and end plates for PHWR fuel bundles for Indian PHWRs. Fuel bundles for Pressurized Heavy Water Reactor using these components have to withstand highly corrosive environment of elevated temperature, high coolant pressure and neutron flux density. Any failure of zirconium alloy end cap or cladding tube encapsulating natural uranium dioxide fuel during reactor operation is totally undesirable from safety as well as economical point of view. Hence, bar material for machining of end caps and thin walled zirconium alloy fuel cladding tubes require very high degree of structural integrity and dimensional control. This necessitates ultrasonic testing of bars and tubes covering total surface with stringent standards to extremely high degree of reliability.

PROCESS

The operations in fabrication involves intricate and advanced techniques such as multiple vacuum arc melting, hot working (extrusion and rolling), cold working (pilgering, swaging, drawing and rolling) with intermediate vacuum heat treatments. Various destructive and non-destructive techniques are employed to control quality of production with adequate recoveries at a competitive cost. Various fuel components are cladding tubes, end plates, end caps, bearing pads, spacer pads etc. The performance of these components in nuclear reactor depends upon several parameters e.g. dimensions, surface finish, chemical composition, metallurgical condition, soundness of material, corrosion resistance etc. for which very stringent specifications have been imposed by NPCIL. A very high degree of confidence in fuel bundles is essential about their integrity and property. Destructive testing on sample basis and non-destructive tests on 100 % basis are employed for achieving the required quality level. NFC developed necessary expertise and sophisticated facility to meet this challenge by evolving detailed quality control plan for the raw material, intermediates and finished products. Several creative and innovative fabrication processes were adopted in manufacture of the components especially cladding tubes, end plugs and spacers.

PHWR BAR FOR END CAPS

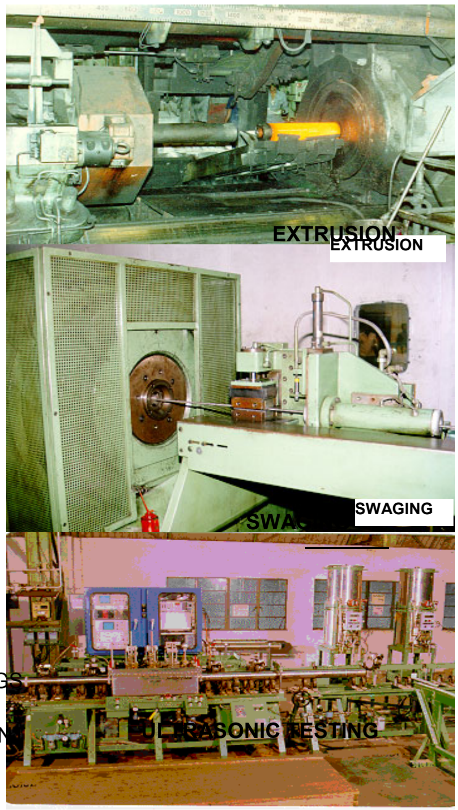
Vacuum arc melted ingots are extruded in multiple stage and are further cold swaged to finished size suitable for machining to end caps. The detailed flow chart shown.

HOT WORKING

VAC.ARC MELTED INGOT
↓
EXTRUSON-I
↓
MACHINING
↓
EXTRUSION-II
↓
VACUUM ANNEALING
↓
COLD SWAGING OPERATION

COLD WORKING

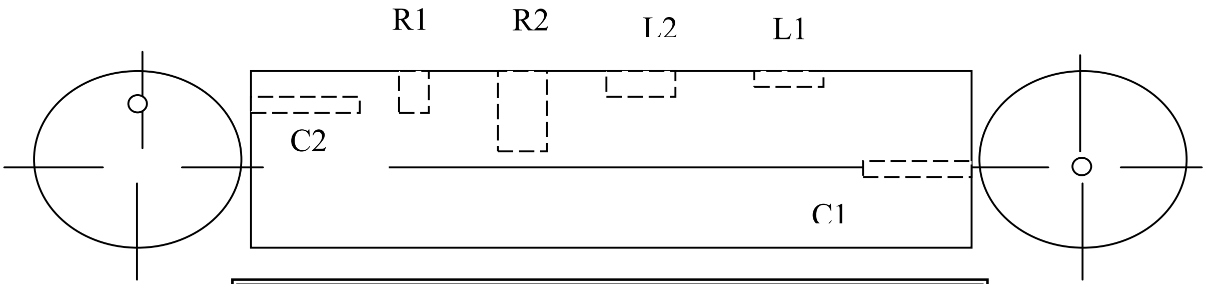
↓
VACUUM ANNEALING
↓
CENTRELESS GRINDING
↓
ULTRASONIC TESTING
↓
MACHINE END CAP CAPPLUGS
↓
SUPPLY TO FUEL FABRICATION PLAN



ULTRASONIC TESTING

To eliminate possibility of any fuel failure during operation in the reactor very stringent quality control steps are employed during NDT of bars before releasing for machining of end caps.

- Ultrasonic inspection at various stages of extrusion during production is employed to eliminate the possibility of existence of voids in the material being processed. Reference standard used for testing of finished bar in ground condition is shown :



	Diameter (mm)	Depth (mm)
R1	0.6	4.0
R2	1.0	8.0
C1	0.2	10
C2	0.2	10
	Length (mm)	**Depth (mm)**
L1	3.0	0.04
L2	3.0	0.07

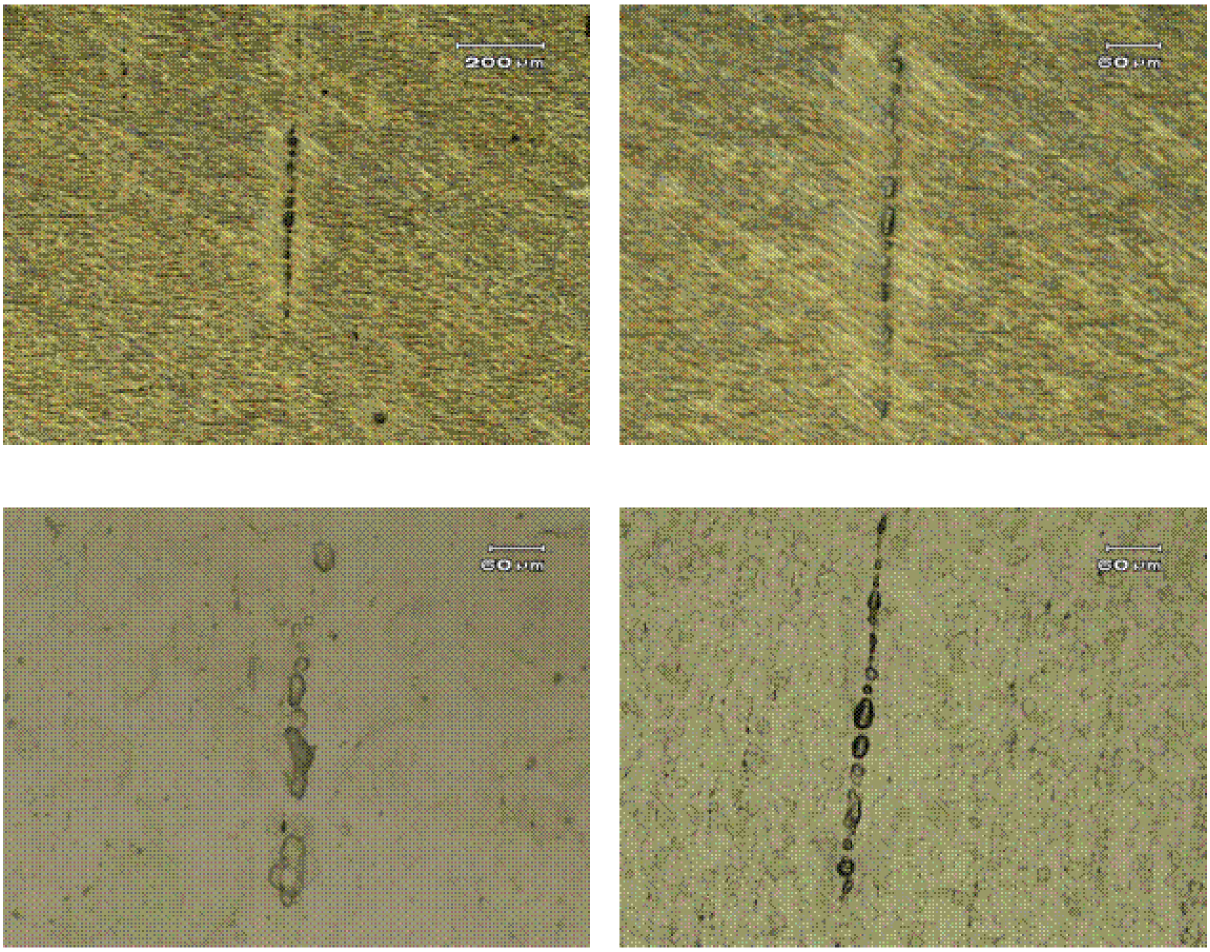
U
R

ULTRASONIC TEST STANDARD FOR PHWR BAR

Axial centered and off-centered hole of 0.2 mm Ø could be fabricated by drilling a hole of larger size in intermediate bar and cold working to finished size. For effective detection of extremely fine defects, calibration of the system is certified using detection of certain natural defects found in bar. Such fine defects could not be fabricated by conventional methods. With this innovative method of Quality Control technique, voids/defects of the order of 10 microns could be detected. This eliminates probability of fine defects getting sensed during helium leak testing of fuel elements after welding of end caps to fuel tubes.

The testing is done on the semi-automatic ultrasonic test station covering complete surface. Any indication observed during testing is closely examined. Two probes of different frequencies are mounted on probe holders in an immersion tank in which bar is rotating as well as moving forward with 50 % over lap. The probes are 90 degree apart under normal beam mode for efficient and reliable detection of defects with their orientation.

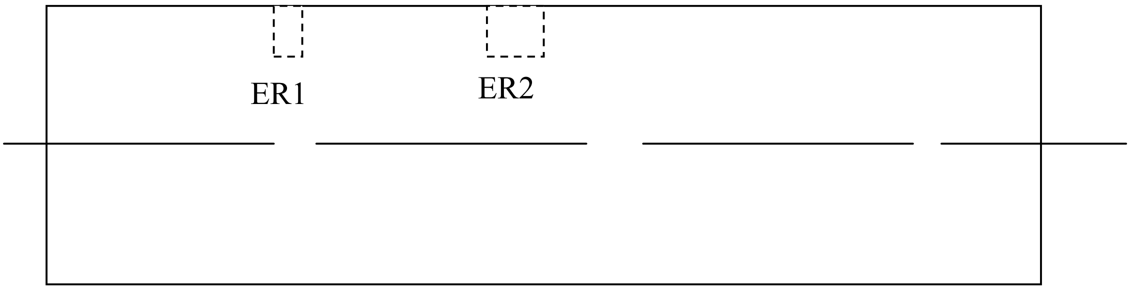
Typical defects observed in bars are shown :



TYPICAL END CAP DEFECTS

- For better confidence of bar material near the surface eddy current test is also employed in addition to ultrasonic testing. The reference standard employed is 0.3 mm and 0.4 mm dia radial holes. The test frequency selected ensures penetration of up to 3 mm distance from the surface to ensure defect free area at land of machined end caps.

Reference standard used for eddy current testing of finished bar in ground condition is shown

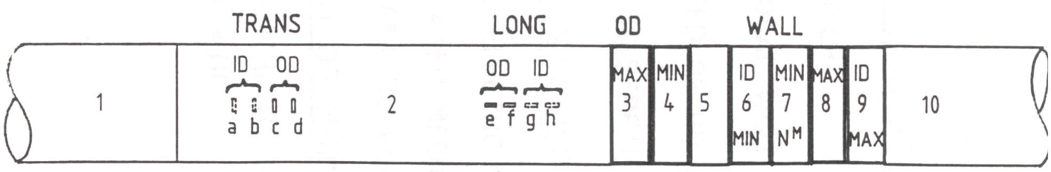


	Diameter (mm)	Depth (mm)
ER1	0.30	3.0
ER2	0.40	3.0

EDDY CURRENT TEST STANDARD FOR PHWR BAR

FUEL CLAD TUBING

Vacuum arc melted ingots are extruded in two stages and further reduced by cold pilgering with intermediate vacuum annealing. The finished tubing are center-less ground on outside and blasted on the inside surface. These tubes are subjected to stringent ultrasonic examination and dimensional measurement on fully automatic computerized ultrasonic test station. Reference standard used for testing these tubes is shown :



S. No.	TYPE	DEPTH	S. No.	TYPE	DEPTH	S. No.	TYPE	DEPTH	S. No.	TYPE	DEPTH
1	SUPPORT TUBE		2e	OD LONG	0.050	4	OD MIN	15.20	9	ID MAX	14.52
2a	ID TRANS	0.038	2f	OD LONG	0.038	5	SUPPORT TUBE		10	SUPPORT TUBE	
2b	ID TRANS	0.050	2g	ID LONG	0,050	6	ID MIN	14.24			
2c	OD TRANS	0.038	2h	ID LONG	0.038	7	WALL MIN	0.406		ALL DIMENSIONS	

Vacuum arc melted ingots are extruded in multiple stage and are further multi-stage cold pilged to finished size. The detailed flow chart shown

PROCESS FLOW SHEET OF FUEL CLAD TUBE (TYP)

HOT WORKING

VAC.ARC MELTED IN

↓

EXTRUSION - I

↓

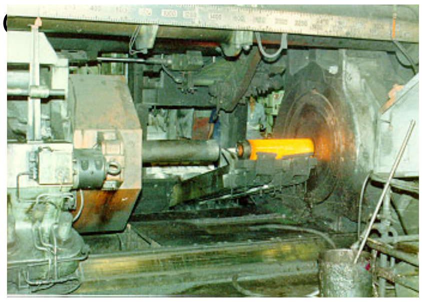
MACHINING

↓

EXTRUSION - II

↓

VACUUM ANNEALING



↓

COLD WORKING

MULTIPLE PILGERING OPERATION WITH INTERMEDIATE VAC - ANNEALING

↓

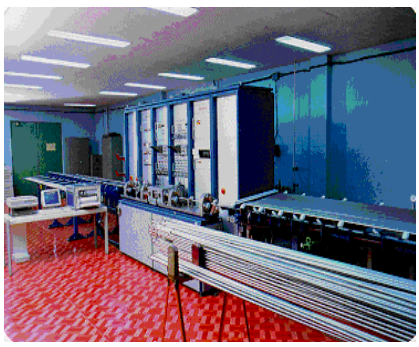
STRESS RELIEF ANNEALING

↓

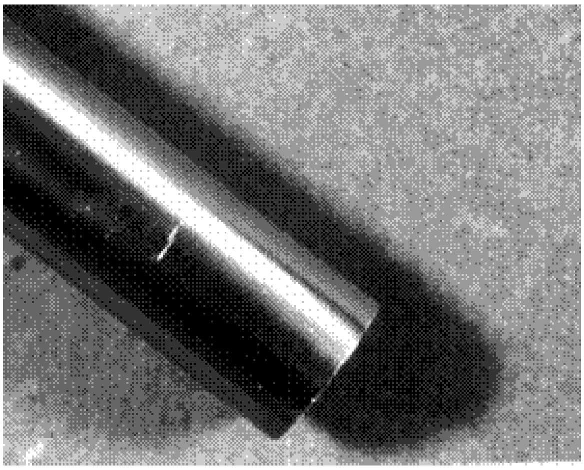
ULTRASONIC TESTING

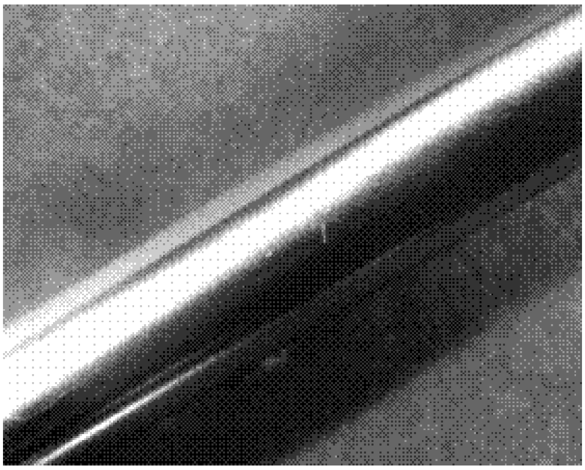
↓

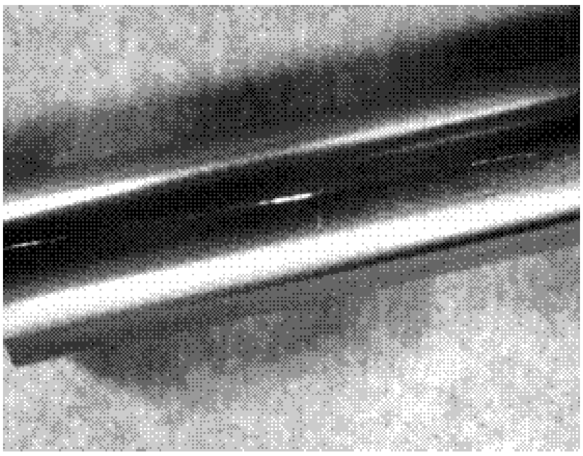
CUT & SUPPLY TO FUEL PLANT

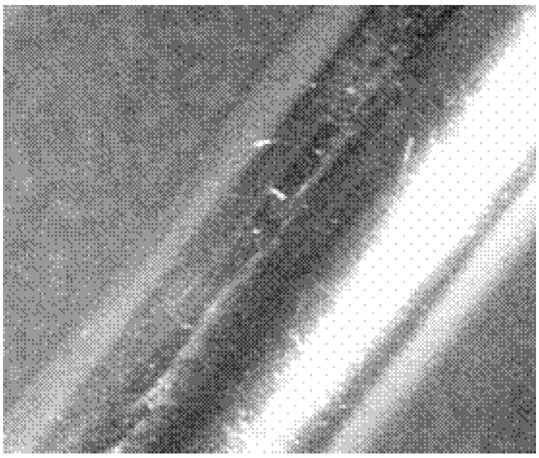


Tubes showing any deviation from the set limits are marked automatically and sorted. Typical defects observed are shown :









Addition of a 0.3 mm Ø x 0.2 mm deep flat bottom hole in conventional reference standards helps in identifying fine pitting on the surface of the tube for better corrosion resistance of material.

SPACERS

3.25 mm thick spacers are conventionally fabricated by coining and punching of the cold rolled sheet material. Since the thickness to width ratio is more than 1,

- frequent breaking of dies and punches
- poor finish due to shear edges during blanking operation
- excessive generation of heat causing oxidation of the punched product.

SPACERS FOR 37 ELEMENT FUEL BUNDLE

PROCESS

BILLET MACHINING
↓
HOT EXTRUSION
↓
COLD SWAGING WITH INTERMEDIATE VAC. ANNEALING
↓
INSPECTION (ULT)
↓
COLD DRAWING

WITH INTER-VAC. ANNEALING
↓
DRAWING TO SQUARE (3 PASSES)
↓
VAC. ANNEALING
↓
INSPECTION (DIMN. VISUAL)
↓
KING
↓
COINING
↓
FINISHING
↓
FINAL INSPECTION

3.25 mm SPACERS

An innovative process was developed for manufacturing of these spacers through a different route which is shown opposite. This process involves drawing a rectangular wire of 2.25 mm x 3.25 mm section from the bar stock. The process involves less number of operations and substantial reduction in lead time. The recovery also is very much high compared to the sheet route. Due to the ease in manufacturing, less number of stages of operations and higher yield of material, this innovate manufacturing route is cost effective.

Conclusion :

The innovative method employed during processing of Zirconium alloy fuel components failure rate of fuel bundles in Indian PHWRs is brought down to almost zero level and the fabrication of fuel has become more cost effective.

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