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Thematic Articles on Manufacturing

Indigenous Design, Development and Manufacture of fighter aircraft aero-engines in India

Plasma Electrolytic Polishing: Advanced post-processing technique for achieving high-quality metallic surfaces

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Inkjet Printing: New Manufacturing Paradigm for Organic Light Emitting Diodes

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Contents

Volume I | Issue II
August 2025

Featured Articles

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Editorial Desk

We are pleased to share with you the latest edition of INAE TechFrontier, the quarterly e-magazine of the Indian National Academy of Engineering (INAE). With the first volume on Quantum Technology successfully launched this year on April 20, 2025, during the INAE Foundation Day, the magazine continues to serve as a platform for showcasing recent advancements and innovations across the engineering and technology landscape. This edition focuses on the theme of Manufacturing, a sector that plays a pivotal role in India's pursuit of technological self-reliance and economic growth.

With national initiatives such as Atma Nirbhar Bharat, India is steadily moving towards becoming a global manufacturing hub. The country is actively working to develop indigenous capabilities in critical areas, reduce dependence on imports, and enhance its industrial infrastructure. In this context, the current edition of INAE TechFrontier presents a selection of insightful articles that reflect the breadth and depth of manufacturing-related research and development taking place across the nation.

The lead article presents a strategic roadmap for developing indigenous gas turbine engines for fighter aircraft. It highlights the importance of establishing specialized design and testing infrastructure for aero-engines, emphasizing their significance in strengthening national defence and achieving technological autonomy.

Another article introduces Plasma Electrolytic Polishing (PeP)—an emerging surface engineering technology known for delivering high-precision, environmentally friendly surface finishes. The article discusses its working principles and potential applications in sectors such as aerospace, biomedical devices, and defence manufacturing.

The third contribution focuses on the indigenous manufacturing of Alloy-800 Steam Generator tubes for Indian nuclear power plants. The article illustrates how in-house capabilities have been developed to meet the growing demand for high-performance components under the government's fleet mode PHWR program.

The final article showcases pioneering work from IIT Kanpur on inkjet printing technology for OLED fabrication. This digital and scalable process offers a cost-effective and environmentally sustainable alternative to traditional display manufacturing methods, opening up new possibilities for flexible electronics and smart displays.

Through these diverse contributions, this edition of INAE TechFrontier aims to highlight the ongoing progress and future potential of manufacturing in India. We trust that readers from academia, industry, and the broader engineering community will find this issue both informative and inspiring.

The next issue due in October 2025 shall focus on *Cyber Physical Systems*. We are actively inviting engaging and original articles from interested contributors. Submissions may be sent to *publications@inae.in*.

Prof. Amit Agrawal
FNAE, Vice-President (Publications), INAE

Indigenous Design, Development and Manufacture of fighter aircraft aero-engines in India

Shri Debashis Deb, FNAE, Former Executive Director, HAL Koraput

Shri Debashis Deb, FNAE,
a distinguished metallurgical engineer, retired as Executive Director of HAL, Koraput. An IIT-BHU (B.Tech) and IIT-Madras (M.Tech) alumnus, he has over 37 years of experience in aero-engine design, manufacturing, and overhaul. He played a pivotal role in setting up HAL's vacuum investment casting foundry, and was instrumental in indigenous development of turbine blades for aircraft and cryogenic engines. Currently Advisor & Consultant at BDL, Hyderabad, he is a Fellow of INAE, IIM, and IE(I). His contributions have earned him several national awards, including Metallurgist of the Year, 2002 and the Distinguished Alumnus Award from IIT-BHU.

Abstract

This paper presents a comprehensive roadmap for achieving indigenous capability in the design, development, and manufacture of fighter aircraft gas turbine engines in India. Propulsion technology is highlighted as a cornerstone of national aerospace capability, with modern engines pushing the limits of material science, thermodynamics, and precision engineering. Despite India's progress in airframe and avionics development, the country remains dependent on foreign suppliers for advanced engine technologies.

The author emphasizes the strategic need to establish a dedicated **Aero-Engine Design Bureau** within the private sector, in collaboration with HAL's AERDC, GTRE, or international OEMs. A **three-phase plan** is proposed: (1) establish core design groups and simulation capabilities; (2) build component-level test facilities; and (3) set up full-scale engine test infrastructure, including sea-level and high-altitude test beds. Parallel to this, a manufacturing facility with the capacity to produce 24 engines annually for 5th generation fighter aircraft is recommended.

The engine comprises around 40,000 individual parts, made from complex materials such as nickel and cobalt-based superalloys, titanium, MMCs, and CMCs. While India has a robust supply chain for basic forgings, castings, and machining, it lacks critical infrastructure for advanced processes such as single crystal casting, vacuum brazing, isothermal forging, and high-temperature coatings. The author suggests sourcing these components internationally in the short term while building local capabilities over time.

A key barrier to progress is the **lack of dedicated testing infrastructure**, which has historically delayed projects like the indigenous Kaveri engine. India currently lacks facilities to validate engine performance at altitude or under combat-like conditions. The paper argues that without proper facilities for iterative testing and validation, even the best engineers are hindered in innovation and optimization.

In conclusion, the paper calls for a **strategic, phased investment** in design talent, manufacturing capability, and test infrastructure. Only through coordinated effort between government, industry, and academia can India realize true self-reliance in fighter aircraft propulsion systems—a critical element of national defense and technological sovereignty.

1. Introduction:

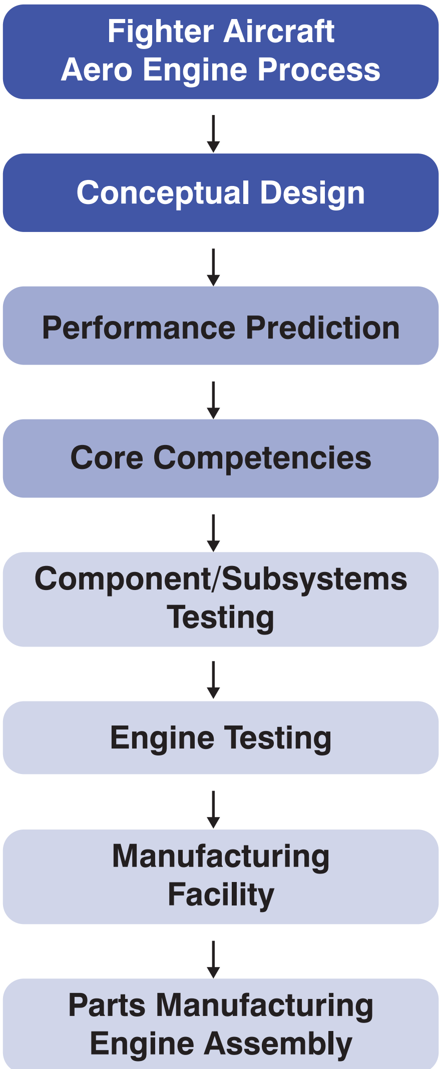
Propulsion technology offers the greatest single contribution to the improvement of fighter/ commercial aircraft.

The past three generations of gas turbine engines have incorporated increased turbine inlet temperature, increased compressor pressure ratio, increased bypass ratio, improved fan and nacelle performance, reduction of noise and emissions, and improved reliability[1].

These gains rest on continued development of new and improved materials and material-processing techniques, the clearly available advances in turbomachine technology, promising progress in combustion technology, and vastly improved utilization of computational fluid dynamics (CFD) in engine design procedures. Finally, there is the unknown impact of novel technologies, such as "smart engines" and magnetic bearings that may completely change the course of engine development [2-4].

Appendix-1 presents a quick glimpse on the process of indigenous engine design, development and manufacturing.

Appendix-1



2. *Pre-requisites of Engine Design and Development:*

- Shortened development cycle
- Improved computational capabilities for propulsion
- Improved testing facilities for propulsion
- Technology validation

The state of the art in new engines is characterized by an installed propulsion system cruise-specific fuel consumption of 0.54–0.56, including nacelle drag but not customer bleed. The installed thrust-to-weight ratio is about 4.5. Cycle pressure ratios are 36–38; the compressor discharge air temperature is 750ºC; and the turbine rotor inlet gas temperature is 1250ºC [5-7].

3. *Core Engine Technologies [8-9]:*

- Improved metallic materials, coatings, and fabrication techniques.
- New engineered materials such as 4th generation nickel base super alloy, polymer matrix composites (PMC) titanium metal matrix composites (MMCs), titanium aluminides, nickel aluminide and ceramic matrix composites (CMC).
- Fiber-reinforced metal and ceramic high-temperature materials.
- More efficient turbine blade cooling; possibly cooling air coolers; advanced, more efficient, high-speed turbomachinery.
- Turbomachinery with "smart" controls and combustors to reduce take-off emissions.
- Integrated fan aeroacoustics for higher efficiency and lower source noise.
- Advanced materials for higher-temperature, lighter-weight fan turbines, composite fan blade development.
- Advanced gearbox systems employing new materials, bearing technology, and lubricants.
- Simpler higher-reliability variable pitch actuation systems and lower-cost designs and manufacturing.

4. *Requirements of an Aero-engine Design Agency:*

In view of the above Propulsion Technology challenges, it is recommended to set up a JV (Joint Venture) of Aero-engine Design Bureau in the private sector in technical collaboration with either Aeroengine Research & Development Centre (AERDC), HAL (Hindustan Aeronautics Limited) / GTRE (Gas Turbine Research Establishment) / foreign OEM (Original Equipment Manufacturer).

The infrastructure and the investment can be made in phases:

- ***PHASE 1:*** Recruitment of designers, procurement of design simulation packages and establishment of the design groups.

These design groups will help in the areas of conceptual design, performance prediction of gas turbine engines, and in the development of core competencies in the different fields of gas turbine technologies.

In Phase 1, the design engineers of different groups will be trained along with the designers of AERDC / GTRE / foreign OEM and design software simulation packages will be procured under their guidance. The test facilities of AERDC / GTRE / foreign OEM will be utilized as and when required, until the facilities are established in the new Design Agency.

- ***PHASE-2:*** The Component / subsystems test facilities will be established in collaboration with AERDC / GTRE / foreign OEM.
- ***PHASE-3:*** The following facilities will be planned for complete engine testing in collaboration with AERDC / GTRE / foreign OEM:

- Sea Level Universal Engine Test Bed

- High Altitude Engine Test Bed

5. *Proposed Aero-engine Manufacturing Facility in the Country:*

An Engine manufacturing facility for 5th generation fighter aircraft aero-engines of 90 KN - 120 KN thrust with a capacity to manufacture 24 engines annually should be set up in the private-sector. Figure 1 shows a 5th generation fighter aircraft engine.

Fig-1: 5th generation fighter aircraft engine

Each engine consists of approximately 5,000 detail parts / sub-assemblies / assemblies totalling to about 40,000 parts count approx. The Gas turbine engine consists of modules such as Low-pressure Compressor, High-pressure Compressor, Intermediate Casing, Bypass Casing, Combustion Casing, High-pressure & Low-pressure Turbine, Exhaust Cone, Jet Pipe, Engine Gear Box, Line Replaceable Units (LRUs) like Lubrication System, Engine Fuel Control System, Instrumentation, Electronic Control Units, etc.

Aero-Engine manufacturing consists of the following activities:

1. Manufacturing of castings, forgings, sheet metal stampings, ring rolled parts and resistance welding / TIG (tungsten inert gas) welding / electron beam welding / laser beam welding / friction welding / high- temperature vacuum brazing of components.
2. Machining of barstock, castings, forgings, and sheet metal stampings.
3. Vacuum heat treatment.
4. Electroplating, thermal barrier coating, abradable, non-abradable & wear resistant coatings.
5. Metallurgical testing & quality control checks.
6. Engine sub-assemblies making.
7. Functional testing of sub-assemblies in dedicated rigs.
8. LRU testing in dedicated rigs.
9. Engine assembly from modules.
10. Engine testing.

The engine components are made from exotic alloys of titanium, aluminium, magnesium, steels, cast iron, nickel and cobalt base superalloys, specialized rubber & graphite compounds, metal matrix composites (MMC), ceramic matrix composites (CMC), polymer matrix composites (PMC).

The country has a good number of private sector vendors for manufacture of simple forgings, rubber seals, graphite seals, machining of barstock / castings / forgings / spur gears / bevel gears / sheet metal stampings, which include conventional machining, CNC (Computer Numerically Controlled) machining / CNC grinding, jig boring, superfinishing operations like lapping / honing, metrological measurements, etc.

But the country lacks in the following infrastructural state of the art facilities:

1. Vacuum investment casting of titanium alloys, nickel base superalloys of equaxed, directionally solidified and Single Crystal turbine blade castings.
2. Precision Forgings & Isothermal forgings.
3. Isothermal Sheet Metal stampings & Superplastic sheet metal stampings.
4. Composites manufacturing (MMC & CMC).
5. TIG welding of large engine casings in argon welding chamber.
6. Vacuum heat treatment and Vacuum brazing.
7. High frequency brazing.
8. Heavy forgings for discs, shafts, casings.
9. Broaching of discs and blades.
10. Creep feed grinding of blades.
11. Manufacture of LRUs (Line Replaceable units) and its testing.

However, the castings, specialized / heavy forgings, composites and complicated sheet metal parts can be sourced from vendors abroad, till the above-mentioned facilities are set up within the country. A bulk of the machining operations can be outsourced to qualified vendors within the country.

6. *Conclusion:*

One of the reasons for the delay in developing the indigenous Kaveri Engine for fighter aircraft is the lack of testing facilities in the country. A facility to test each of the modules - the fan, compressor, combustor, turbine and nozzle, before validation, is necessary. With the best of the engineers, one has to go through three or four iterations. Even for a small test, one has to go to Russia or elsewhere, making it a time-consuming process and leaving very little opportunity to scale up or down, test and validate the components.

India does not even have a fully

functional wind tunnel facility. Nor does it have a facility to simulate an engine that will work at 40,000 to 50,000 feet above the ground.

Talking about the Gas Turbine Engine, which is being developed by multiple defence laboratories and similar indigenous programmes, infrastructure needs to be created, manpower trained, technology developed and only then can one get into the project of indigenous design, manufacture and testing of the engine modules and the assembled engine.

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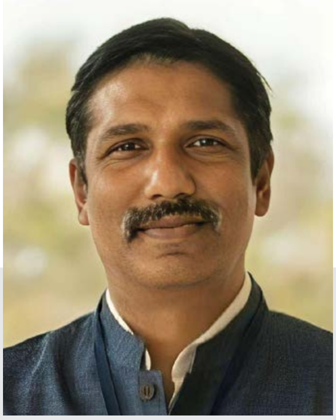

Prof. J Ramkumar, FNAE,
(Satish Chandra Agg. Chair) at IIT Kanpur has more than two decades of experience in research, academics, and industry. He has mentored and nourished more than 15 start-ups spread across the nation who had been exceptional in providing novel products and have stepped up into the market. Prof. Ramkumar is a frugal innovator, with a deep interest in manufacturing sciences. He has brought out eight MOOCs courses (having over 48 lakhs views) including international audience, conducted & organized 100+ workshops in Design Thinking to propagate science & research among students, scholars, industrial practitioners and faculties.

Plasma Electrolytic Polishing: Advanced post-processing technique for achieving high-quality metallic surfaces

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Abstract

This article explores plasma assisted polishing technique, also known as plasma electrolytic polishing (PeP), is an advanced surface engineering technique for high precision and good surface finish. The manufacturing of metallic components by conventional machining processes and additive manufacturing processes tends to have poor surface finish and requires further post processing treatments before their operational use.

Among various methods used to perform the post processing, PeP has emerged as an efficient method. PeP is an emerging method for producing finished metal and alloys due to various advantages such as highly polished surface and use of eco-friendly solutions. This article highlights the important aspects of the PeP such as working principle, basic components, and its potential applications.

Globally, the manufacturing sector is undergoing a shift and India is steadily positioning itself to grab the opportunity to become the manufacturing hub for the world. As per the IBEF report, India's manufacturing exports are expected to reach 1 trillion dollars by FY28 [1]. Furthermore, an increase in capacity utilization to approximately 76.8%, along with industrial workforce underline the expanding momentum of the manufacturing sector.

Driven by expanding research capabilities and increasing industrial demand, India holds significant potential to lead advancements in plasma electrolytic polishing (PeP) technology. As surface quality emerges as a critical requirement across sectors such as aerospace, biomedical, and defence, PEP offers a cleaner, faster, and more environmentally friendly alternative to traditional polishing methods.

1. *Introduction*

Post processing is a critical step in manufacturing workflow, widely used in several industries such as automotive, aerospace, biomedical and marine to remove the surface irregularities like protrusions on the surface of a component. Polishing plays an important role in modifying the tribological properties of the surface, reducing friction between interacting components, facilitating metallographic analysis and enhancing the corrosion and wetting properties. It also prepares components for surface engineering operations and contributes to their aesthetic appeal [2]. Polishing is defined as the process whereby fine abrasive particles are dispersed in fluid or paste and applied to the surface to achieve smoothness with minimal changes to the component mass, dimensions or geometry. Polishing techniques are classified based on mechanical, physical, chemical and process assisted methods as shown in Figure 1. Traditional polishing methods such as buffing and grinding remains commonly used in industrial application.

Conventional polishing techniques such as mechanical buffing, abrasive flow finishing, and electrochemical polishing have been used for decades. However, these techniques face challenges such as difficulty with complex shapes, inconsistent material removal, residual stresses, and environmental concerns associated with waste generation [3]. Mechanical buffing necessitates rigid tools and controlled settings, making it unsuitable for delicate or irregular surfaces. It often induces surface scratches and thermal damage thereby compromising surface quality. Abrasive flow finishing offers greater flexibility but necessitates customized fixtures for each component geometry, thus increasing both operational complexity and expense. Additionally, the flow of media can result in uneven polishing in intricate areas [4]. The surface roughness in Abrasive flow finishing is largely influenced by the grain size of abrasive particles used. Electrochemical polishing is restricted to conductive materials and can lead to non-uniform finishes in multi-phase alloys due to preferential dissolution. Furthermore, Electrochemical polishing utilizes harsh acidic electrolytes, raising significant environmental and safety risks. Contact-based methods are inadequate for delicate components or scenarios where ultra-smooth finishes at micro or nanoscale dimensions are required. Wear and electrolytic polishing have emerged as a promising, contactless approach to eliminate surface damage, tool wear, and need of complex fixtures. It enables the uniform as well as precise polishing of complex and freeform surfaces which are often unattainable though traditional methods [5]. PeP can reduce the surface roughness value up to 10nm or less. Unlike Electrochemical polishing, electrolyte used is mild, and non-toxic which reduces the environmental and safety concerns related to its disposal.

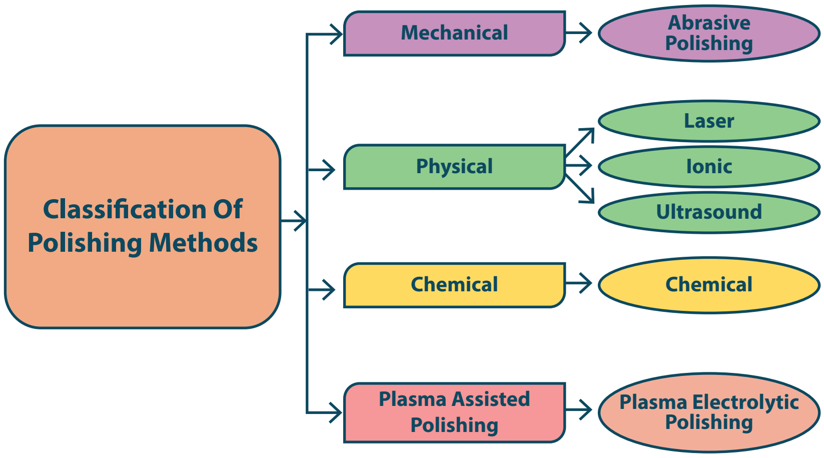

Fig-1: Classification of polishing methods

2. *Working principle and components of PeP process*

PeP works by applying a high voltage to a metal workpiece submerged in a mild electrolyte, where the workpiece acts as the anode. Operating voltages typically between 200 to 400 V, the surface heats rapidly forming a vapor-gas envelope (VGE) around the component (as shown in Figure 2). This envelope generates micro-plasma discharges that remove surface material through localized melting and vaporization. The process combines physical erosion from charged particles with electrochemical (1) and chemical (2) reactions at the surface [6]. Material removal is primarily focused on surface peaks, resulting in surface leveling and a smooth, glossy finish. The effectiveness of PeP depends on the electric field strength, electrolyte composition, and the interaction between the plasma, gas layer, and metal surface [7].

$$2M + nH_2O = 2MO_{n/2} + 2ne^- + 2nH^+aq \quad (1)$$

$$2MO_{n/2} + 2zA^- + 2nH^+aq + (2m - n)\,H_2O = 2(MA_Z \cdot mH_2O)^{(n-z)+} \quad (2)$$

where, M is the metal to be polished, A is the anion of the electrolyte.

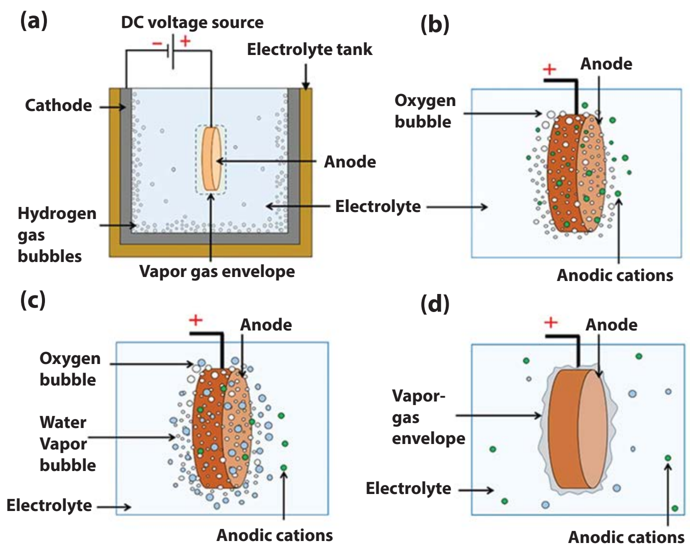

Fig-2: Schematic showing mechanism of PeP process [3]

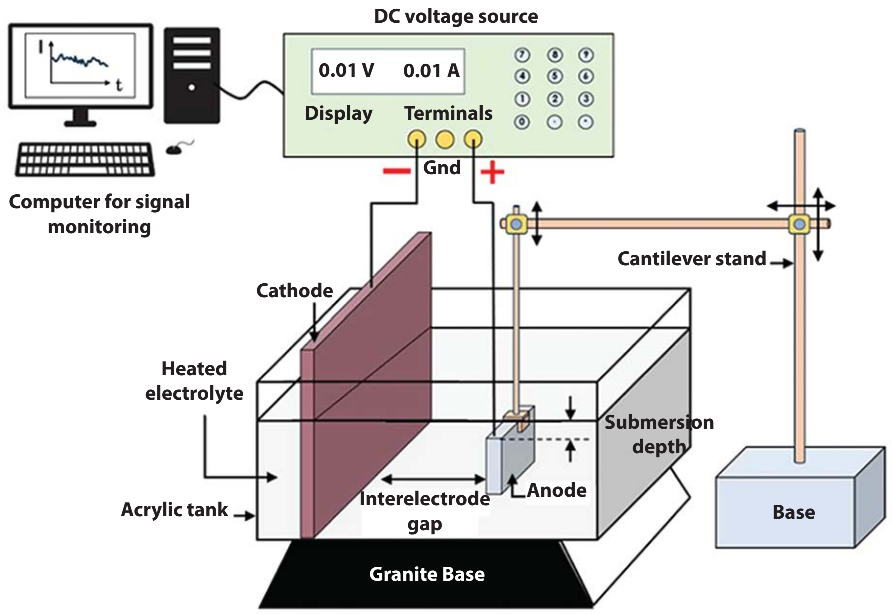

Fig-3: Schematic showing setup of PeP process [3]

Figure 3 presents a schematic of PeP system used for surface finishing or polishing the component. Setup consists of a DC voltage source connected to the anode (workpiece) and cathode (counter electrode) both immersed in a heated electrolyte within an acrylic tank. The workpiece (anode) is held by a cantilever stand to control its submersion depth, while the entire system rests on a granite base for stability. Plasma discharge occurs at the anode surface, smoothing and brightening it. A computer-based monitoring system is integrated to track current and voltage, ensuring precise control of the polishing process.

3. *Potential applications*

Plasma electrolytic polishing offers wide-ranging applications due to its ability to achieve smooth, reflective surfaces without physical contact or harsh chemicals. Its precision and biocompatibility make it particularly well suited for medical implants, dental instruments, and surgical tools. In demanding sectors like aerospace, electronics, and optics, PeP enhances corrosion resistance and surface integrity, attributes critical for performance and component longevity. It is also used for polishing complex shapes and micro-components in high-tech industries [8]. The schematic in Figure 4 illustrates key application sectors where PeP is currently implemented or has strong potential, highlighting its growing relevance in advanced and sustainable manufacturing environments.

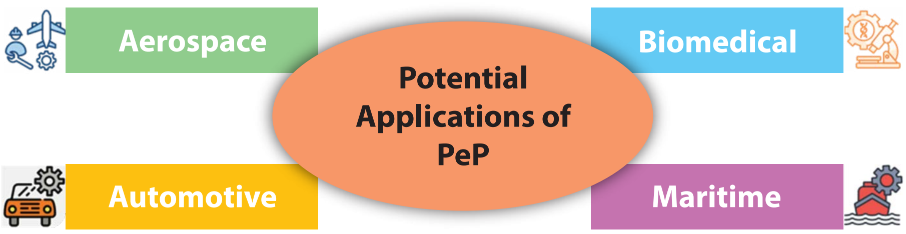

Fig-4: Potential areas of application of PeP technique.

4. *Conclusions*

Plasma Electrolytic Polishing has emerged as an advanced surface finishing technique that effectively addresses the limitations associated with conventional polishing techniques. Its non-contact, environmentally sustainable procedure facilitates high-precision polishing of intricate geometries, concurrently enhancing surface quality and diminishing roughness to sub-10 nm thresholds. The PeP process is driven by micro-plasma discharges within a vapor-gas envelope, guaranteeing regulated material removal with negligible structural impairment. Its compatibility with a wide range of metals and alloys, combined with the implementation of non-toxic electrolytes, makes it particularly suitable for applications where cleanliness, biocompatibility, and corrosion resistance are critically significant. PeP proven effectiveness in polishing medical implants and micro-components, aerospace parts, and optical devices. As the demand for high-performance and sustainable surface engineering solutions continue to rise, PeP stands out as a transformative field of precision finishing.

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Development, Manufacturing, Inspection, Testing and supply of Alloy 800 (UNS N08800) Steam Generator Tubes 700 MW(e) PHWRs under Fleet Mode

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Abstract

Alloy-800 (UNSN08800) grade Steam Generator (SG) tubes are selected for Indian PHWRs due to their inherent properties, including resistance to SCC & high temperature strength. These tubes are very well suited to for Condenser and Heat-exchanger applications. With the sanction of Fleet mode PHWRs (10 x 700 MWe) by the Government, requirement of SG tubes has grown multifold. These are 26 mtr long tubes, cold worked in finished condition to enhance Mechanical strength and subjected to rigorous quality tests including ECT, UT, IGC, SCC, Tensile Testing at room & elevated temperature, etc. Tubes qualified against these stringent tests are U bend into wide range of radii from 91 to 1014 mm CLR and further subjected to shot peening on external surface to improve resistance to SCC. NFC has developed complete in-house facilities for indigenous manufacturing of SG tubes. With the successful supply of over 32,000 tubes, NFC has established bulk production of these tubes for self reliance of the Indian Nuclear Power program under **'Atma Nirbhar Bharat'** Mission.

1.0 Introduction:

Alloy-800 (UNSN08800) grade U Bend tubes are used in Indian Pressurized Heavy Water Reactors (PHWRs) for Steam Generator (SG) application due to exceptional properties such as resistance to Stress Corrosion Cracking (SCC), general corrosion as well as good high temperature strength. Alloy-800 tubes are very well suited for Condenser and Heat-exchangers applications. This material is preferred over conventional Austenitic Stainless Steel (ASS) grades in Nuclear Power plants, since it is immune to SCC, unlike ASS and is well studied with respect to

Dr. Komal Kapoor, FNAE,
is the Chief Executive of Nuclear Fuel Complex (NFC) and Chairman of its Board. A distinguished Scientist and Metallurgical Engineer, he joined the 33rd BARC Training School batch in 1989 and has since served NFC for over three decades. He holds a Ph.D. in Metallurgical Engineering and Materials Science from IIT Bombay and is an Adjunct Professor at HBNI and Guest Faculty at the University of Hyderabad.

As Head of three nuclear fuel cycle facilities, Dr. Kapoor plays a key role in India's Nuclear Power Programme, including leading a major Greenfield project in Kota. He has significantly enhanced fuel quality, radiological safety, and the manufacture of critical nuclear materials and seamless tubes for strategic sectors.

With over 100 publications, he has fostered collaborations in nuclear engineering and earned numerous accolades, including the NMD Young Metallurgist Award. Dr. Kapoor serves on the Boards of Uranium Corporation of India Limited (UCIL) and the Indian Rare Earths Limited (IREL) and the Council Member of Atomic Minerals Directorate (AMD).

Dr. Kapoor is a Fellow of INAE and is Vice-President of The Indian Institute of Metals IIM, Vice-Chairman of The Indian Institute of Metals (IIM), Honorary Fellow of the Indian Society for Non-destructive Testing (ISNT), Past Chairman of ISNT Hyderabad Chapter, Vice-President of Society for Failure Analysis (SFA)-India, Life Member of Indian Nuclear Society (INS).

corrosion, mechanical and creep properties.

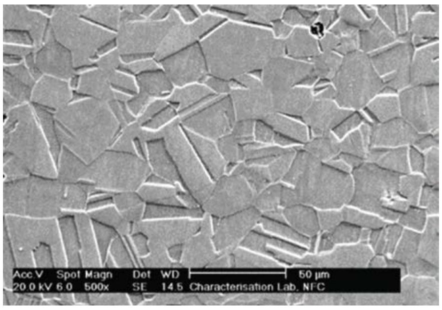


Fig-1: Microstructure of Alloy-800

Tubes for PHWR Steam Generators are in U bend form with shot peened external surface to improve resistance to SCC. Finished tubes are supplied in cold working conditions for increase in strength. Tube manufacturing starts with hot extrusion of mother blanks produced from forged and machined round billets and further reduced down to finished size through multi-pass cold working using combination of pilgering & drawing operations. Each cold working step, except final drawing is followed by mill-Annealing, typically consisting of charging the straight tubes through a continuous heat treatment furnace to recrystallize the material as seen in the microstructure (Fig-1) and dissolve all the carbides formed.

Chemical composition of Alloy-800 material used in SG tubes for Nuclear Power Plants is modified through controlled addition of Ti for stabilization (Table-1). As compared to standard ASTM grade, Nuclear Grade (NG) Alloy-800 has lower Carbon content to minimize sensitization, increased stabilization ratio (Ti/C: ≥12, Ti/(C+N): ≥ 8, N: ≥ 0.03) along with marginally increased Cr and Ni contents to achieve higher resistance to Pitting and Trans Granular Stress Corrosion Cracking (TGSCC). Nuclear Grade Alloy-800 also exhibits higher resistance to caustic induced SCC and almost immune to pure water SCC (PWSCC).

Element	Specification (%)
C	0.03 max
Si	0.3-0.7
Mn	0.40-1.0
P	0.015max
S	0.015max
Co	Aim for 0.015 max
Al	0.15 to 0.45
Ti	0.6 max
N	0.03 max
Cu	0.075 max
Cr	20-23
Ni	32-35
Fe	Remainder

Table 1. Chemical Composition

2.0 Indigenous development of SG tubes:

Alloy-800 SG tubes are one of the most critical tubular components used in the primary circuit of 700 MWe Indian PHWRs. These tubes of 19 mm OD & 1.1 mm wall thickness having length ranging from 21 to 26 m are used in U bend form in 72 different radii ranging from 91 to 1014 mm Centre Line Radius (CLR) with shot peened external surface. Specification requirements with respect to dimensions, chemical composition, mechanical, metallurgical, corrosion properties, residual stress, etc. are highly stringent to avoid any failure during service. Before NFC took up the manufacturing of SG tubes, these were imported for all the earlier PHWRs (220 & 500 MWe). The challenging task of indigenous development and supply of these critical tubes on par with international standards, was taken up at NFC, Hyderabad. Development commenced with a pilot order for supply of Alloy-800 U bend tubes for 700 MWe PHWRs, covering all 72 bend radii necessary for fabrication of the Steam Generator. Successful development and execution of the pilot order followed with bulk requirement i.e. 8 sets (20,000 tubes) from M/s. L&T, 3 sets (7500 tubes) from M/s. BHEL and 40 sets from M/s. NPCIL under Fleet mode (10x700 MWe PHWRs) which is currently under manufacturing.

Specifications for U bend tubes are stringent with respect to dimensional tolerances on bend radius, leg spacing (2R), ovality & out-of-roundness in the bend region. Further, the finished tubes after U-bending are subjected to Hydrostatic pressure testing (250 bar) and Glass bead peening over entire external surface i.e. bend region as well as both straight legs, to induce residual compressive stresses up to a depth of 0.12 mm (min) from the surface. Finished tubes with enhanced yield strength and high corrosion resistance are tested for Inter Granular Corrosion (IGC) as per ASTM G-28 and SCC as per G-36. Before taking up bending, finished tubes are subjected to Non-Destructive Testing (NDT) with stringent reference standards in Eddy Current Testing (ECT) from external side (OD) with 0.8 mm dia through holes, against ASTM specification of 1.5 mm, Ultrasonic Testing (UT) with 100µm depth, 1.5 mm length wedge shaped saw tooth notch with 60^{o} angle, Visual and Boroscopy examination, etc. SG tubes are specified with Signal to Noise Ratio (SNR) of 5 (min) in OD-ECT and also subjected to ID-ECT from internal side, as per reference standard as per Pre-Service Inspection (PSI) of Steam Generator at the fabrication stage.

3.0 Manufacturing process of Alloy-800 Steam Generator tubes:

Development of the manufacturing process was taken up in two stages. 1st stage was to manufacture straight tubes from forged & machined round billets to 27 m long finished tubes, meeting the stringent product specifications. The 2nd stage of development involved establishment of two new manufacturing processes namely 'U Bending' and 'Glass Bead Peening', since necessary facilities for carrying out these operations were not part of the manufacturing set up at NFC [1].

3.1 Manufacture of straight tubes:

Specifications for procurement of raw material i.e. forged, solution annealed & machined rounds were developed considering variables during thermo-mechanical processing and also final product specifications. Thermo-mechanical processing consists of hot extrusion followed by cold working which includes a combination of pilgering & drawing with intermediate and final annealing.

Alloy-800 possesses poor hot workability due to its low thermal conductivity, attributed to the presence of γ' precipitates such as Ni_3Al, $Ni_3(Ti, Al)$ and carbides precipitates such as TiC and $Cr_{23}C_6$. Presence of precipitates and relatively higher grain size in as received forged billet are responsible for its relatively higher elevated temperature strength and hence characteristically difficult to extrude. The forged rounds were sourced indigenously, conducting thorough checks for soundness, inclusion rating, carbide precipitation, grain size, chemical composition, etc. Hot Extrusion parameters including temperature, strain rate, lubrication, container preheating temperature, etc. were optimized to produce mother blanks with desired surface quality.

To meet the final stringent UT requirement, extruded blanks were subjected to extensive conditioning on internal as well as external surfaces. The internal surface was conditioned through honing and the external surface was machined and ground. Conditioned blanks were qualified Ultrasonically for soundness and taken up for further processing through three stages of cold pilgering up to pre-final size and after solution annealing were cold drawn with controlled cold work to meet the enhanced Yield Strength (YS) specifications. Intermediate cold work process parameters including area reduction, lubrication, tooling design and Annealing parameters i.e. soaking time, temperature, atmosphere both at intermediate and final stages were optimized in order to achieve consistent quality of tubes with respect to metallurgical properties, corrosion properties (IGC rate < 0.6mm/yr), resistance to SCC, closer control of dimensions, surface finish and qualification against stringent NDT. Final cold work was established through multiple experimental trials by varying cold reduction during drawing, to achieve specified mechanical properties.

3.2 Development of U bending process:

Finished tubes tested and accepted in all aspects viz. ECT UT, dimensions, ID Boroscopy, etc. having length up to 27 m are formed into 72 different bend radii ranging from 91 to 1014 mm CLR. This was initially performed over a Draw type bending machine using combination of ring dies for individual bend for lower range of radii (up to 260 mm CLR) and inverted truncated cone dies for multiple radii for higher range (above 273 mm CLR) with a feature to form required bend radius by altering position of bending plane over conical dies, resulting in lower tool inventory

Fig-2: Bending using Cone Dies

(Fig-2). Nevertheless, configuration of the machine, especially adjusting the bending plane w.r.t. die position was dependent on operator skill to obtain specific radius within tolerances which was a major limitation. Also, handling of tubes during bending operation was manual. To overcome the complexity and variability of operating the machine due to larger dependency on operator skill, a state of the art automated CNC based U

Fig-3: CNC Bending

Fig-4: CNC U Bending machine with handling system

Fig-5: Individual (72) Bending Dies

bending machine (Fig-3 & 4) with 72 independent ring dies (Fig-5), having 12 independent axes, with mechanized tube handling was indigenously developed, installed & commissioned. The machine was designed with CNC controlled mechanisms for tube loading, insertion, positioning, clamping and feeding with the help of pressure die over bending die having provision to rotate the bending arm up to 250° angle. The process parameters for bending viz. angle, radius of bend, pressure die motion, position, etc. were optimized to carry out bending of all 72 radii with close dimensional control viz. bend radius (±0.75 mm), ovality (<5%), out of roundness (<6%), wall thinning, etc. Die groove radius and profile were specially designed to limit distortion in the bend portion for meeting ovality & out of roundness specifications, avoiding usage of internal plug while bending majority of radii in the required range. 180° bending of the tube is one of the critical activities in the U bend fabrication for SG. The slenderness of the tube imposes challenges in the U-bending process to achieve the stringent quality requirements such as dimensional tolerances, ovality, wall thinning, residual stress, surface finish and other mechanical properties. A detailed benchmark simulation of metal forming behavior under tube bending was performed to design the dies [2]. The required forming parameters for the design of rotary draw bending dies for large centerline bend radius SG tube fabrication were derived from the simulation.

3.3 Development of Glass Bead peening process:

Post bending, tubes are subjected to Glass Bead peening to induce residual compressive stress on the external surface up to a depth of 0.12 mm (min) for improved resistance against SCC, while limiting the external surface finish within 3.3μRa as per the specifications. The process consists of blasting the external surface of U bend tubes with Glass Bead media (shots) using compressed air at optimum pressure to impart controlled cold work on the external

Fig-6: Glass Bead peening machine for U bend tubes

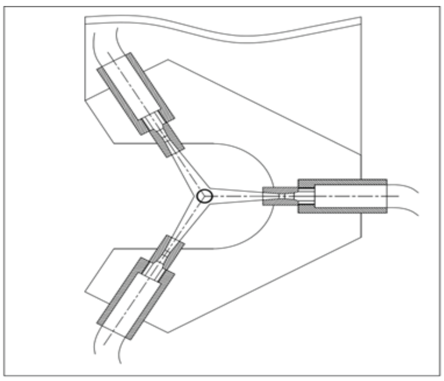


Fig-7: Nozzle configuration

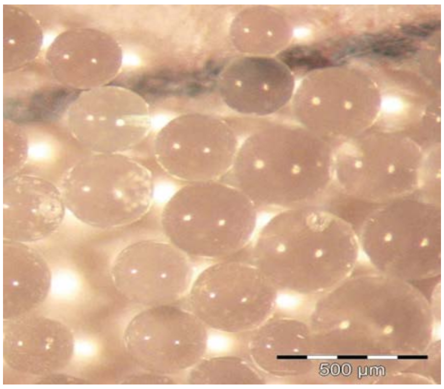


Fig-8: C Grade Glass

surface to induce residual compressive stresses. A special purpose automated Glass bead peening machine for U bend tubes (Fig-6) was developed indigenously, housing three sets of nozzle assemblies each carrying three convergent divergent nozzles placed at 120° apart (Fig-7) for uniform blasting of complete external surface of 19 mm OD tubes, covering bend region and both straight legs of U bend tubes of all 72 radii. The process parameters such as Glass bead particle size i.e. C-grade (Fig-8), blasting pressure, linear speed, etc. were optimized and established through extensive performance tests involving measurement of residual stress of shot peened tubes across sections with respect to operating parameters, using X-ray diffraction technique. With the optimized parameters, tubes of whole range of bend radii were shot peened, consistently meeting the specifications of residual compressive stress up to required depth and limiting the surface finish within the specified limits.

3.4 Inspection and Testing of tubes:

During the development of the process flow sheet, several experimental trials were conducted for meeting the quality requirement. While establishing the processes, an array of inspection and testing techniques were established, essential inspection and testing equipment were designed, developed and installed with capability to test the specified quality parameters and also to meet the testing capacities. Following is a brief summary of the inspection and testing carried out in meeting the stringent specifications.

a) UT of extruded & conditioned blanks

In order to improve the recovery during UT of the finished SG tubes, several experimental process studies were carried out. Typical defects encountered in the finished tubes were traced to those recorded in the extruded blanks. Standards for UT of extruded blanks after OD machining and ID honing stage were established. Periodic feed-back regarding material to be removed while conditioning of extruded blanks was given to Production through methodical analysis of defects intercepted during UT. This feed-back along with the extensive analysis of UT defects in the extruded blanks resulted in remarkable improvement of recovery in UT from 50% in the initial lots to over 85% in the subsequent lots after its successful implementation.

b) Ultrasonic & Eddy Current Testing of finished tubes:

A high-speed ultrasonic testing system with advanced testing features was essential for carrying out Ultrasonic testing in the final stage, in order to meet the testing rate required for fleet

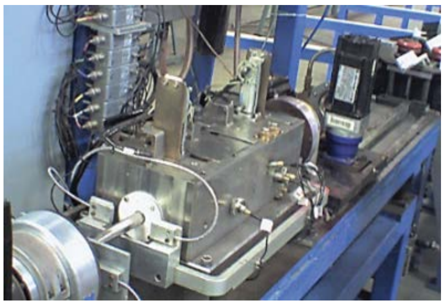


Fig-9: Tube rotating UT system

Fig-10: Probe rotating UT system

mode supplies. The existing testing unit with a rotating tube type system (Fig-9) for UT at NFC was capable of testing at relatively low speeds (4m/min), inadequate to meet the demand. To overcome the limitation, a high speed rotating probe type UT system (8m/min) was installed (Fig-10). In-house developed loading and unloading systems were integrated with the testing unit for handling 30 m long tubes. For OD side ECT a stringent reference standard of 0.8 mm dia. A through hole was specified, against the conventional standard of 1.5 mm dia (ASTM). Previously with the tube rotating UT system, ECT was carried out separately prior to UT, which required additional tube handling steps between ECT and UT. After successful induction of the probe rotating UT system, both ECT and UT are carried out simultaneously which has significantly contributed in enhancing productivity and reducing tube handling.

c) Pressure testing of U bend tubes

Fig-11: Pressure testing Unit

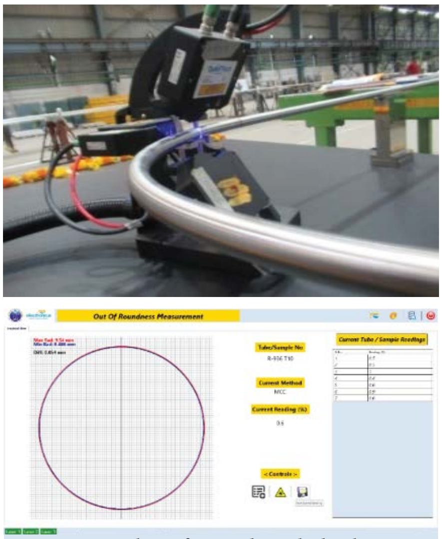
An automated Hydrostatic Pressure Testing system for U bend tubes was indigenously built and was commissioned (Fig-11) for testing of U bend tubes of whole range of bend radii (91 to 1014 mm CLR) at 250 bar pressure using De-mineralized water of low conductivity as per specifications.

d) Bending Process Qualification

Qualification of bending involves extensive testing of shortest bend radius formed over ring / cone dies including dimensional measurement i.e. bend radius, leg spacing (2R), flatness, outer diameter, wall thickness along with other tests Hydrostatic Pressure Testing (HPT), Liquid Penetrant Test (LPT), ball pass test, visual examination of internal surface, surface finish, wall thinning, ovality, out of roundness, optical illustration, hardness in the bend region, etc. Bulk production is commenced only after successful qualification of the Bending process as per specifications. Dimensional parameters including bend radius, leg spacing, ovality, and out of roundness are checked at regular intervals for each bend radii during Production, as a part of Process Control.

e) Special purpose out-of-roundness measuring unit

Measurement of Out-Of-Roundness (OOR) is one of the most critical dimensional parameters specified for U bend tubes. The measurement is to be carried out at 7 different locations



Screen shot of UI and result display

Fig-12: Laser based Non-contact out of roundness measurement

distributed along the bend portion. A custom built Laser based, non-destructive out of roundness measuring unit was developed (Fig-12).

f) Shot Bead Peening qualification

As per specification, compressive stresses are required to exist up to a depth of 0.12 mm (min) from tube outside surface, both in the straight as well as bent portions of the tube. Stress profiles of the shot peened samples blasted with a set of different operating parameters were analyzed at the OD (outside of the bend) and ID (inside of the bend) of the U bend region, as a function of depth. Optimum blasting pressure and linear speeds were established after multiple experimental trials, to consistently achieve required compressive stresses in the bend region as well as the straight legs.

g) Measurement of residual stress profiles

Establishing the depth of residual stress induced through shot peening required measurement of profile of

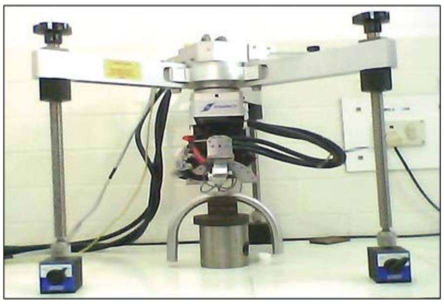


Fig-13: XRD stress measuring Unit

residual stress across the tube section. A new technique applying X-Ray diffraction (Fig-13) method was developed to evaluate the residual stresses across tube thickness. Profile of stress was plotted by measuring the stress after carrying out successive removal of surface layers from the OD using electro polishing technique [3]. This method was successfully implemented to qualify the shot peening process as well as for measurement of residual stress in production lots.

h) Dimensional inspection of U bend tubes using gauge block

A special purpose gauge block for measurement of dimensions of the U bend tubes including bend radius, leg spacing, leg length difference, etc. suitable for Inspecting complete set of bend radii ranging from 91 to 1014 mm CLR was designed, developed and installed.

i) Straightness check on surface plate (13m long)

Fig-14: Surface Plate Gauge Block

Straightness check is one of the critical requirements of the U bend tubes. This requires a very long surface plate with precise alignment along the length. A custom built surface plate (Fig-14) with 8 precisely machined and crafted granite blocks, aligned over 13 m length with an accuracy of 50μm over full length, was designed, developed and installed for checking and certifying straightness of U Bend tube.

j) Visual examination using boroscopy

Each SG tube with length of around 27 m is required to be examined

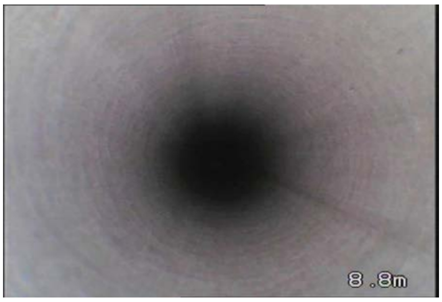


Fig-15: ID view with Boroscope

internally over full length. A special purpose long length ID videoscope was used to examine the ID surface of the tubes (Fig-15) at higher magnification (10X).

k) Mechanical, Metallurgical, Corrosion and Chemical tests

Stress corrosion testing in boiling $MgCl_2$ is one of the most rigorous corrosion tests to which the material is subjected. This test is performed on the U bend tube to certify resistance of the material against SCC. Product chemical analysis, metallography, Corrosion (IGC), elevated and room temperature tensile testing are carried out for these tubes as per specifications.

3.5 Storage, layout checking & packing of U-bend tubes

Packing of SG tubes is the final and crucial operation, as total 2489 U bend tubes covering 72 different bend radii for each set of SG are to be packed in 89 rows with alternate odd radii series configuration, divided into 13 boxes as per the sequence of tube

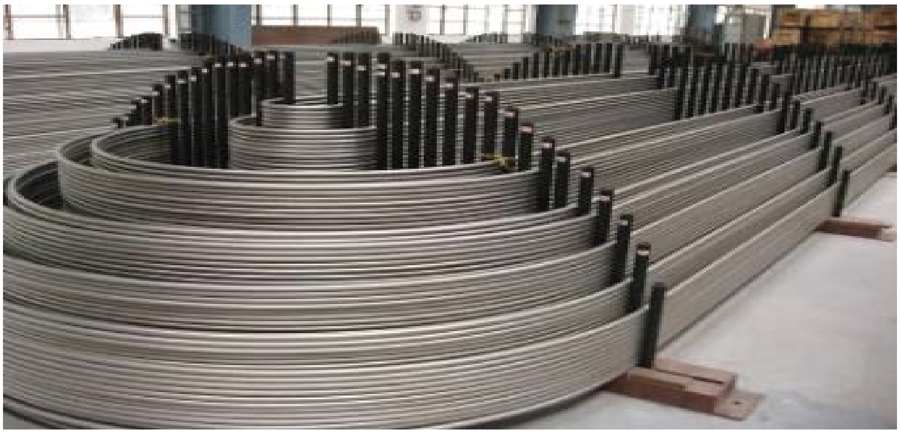


Fig-16: U Bend Storage Racks

Fig-17: Layout check fixture

insertion during fabrication of the Steam Generator assembly. Tubes are usually manufactured radius wise i.e. total quantity for each bend radius for a full set at a time. Tubes cleared in all respects i.e. Quality Assurance and Quality Surveillance, are stacked radius wise in custom built U bend storage racks (Fig-16). During packing, tubes of required radii from the storage racks are taken out row by

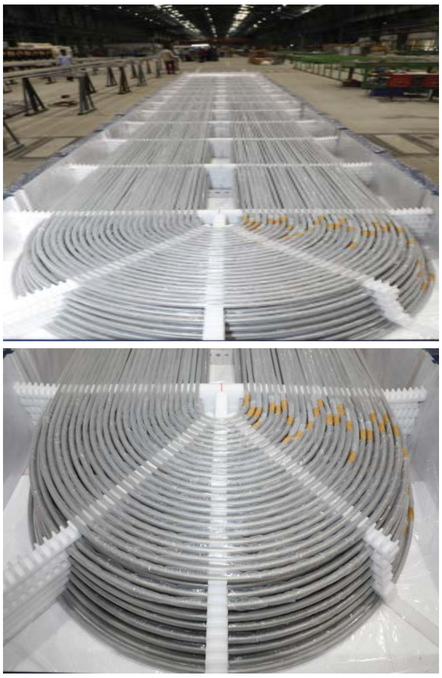


Fig-18: Even & Odd radii packed in reinforced plywood

row, thoroughly cleaned and placed on to layout checking fixture (Fig-17) with supports placed at specific locations (distance from bend portion) along the length for simulating grid baffle supports in the SG assembly during insertion. Each tube is internally sealed at two places from each end (100 and 300 mm from both ends) using special threaded halogen free plastic ID plugs. Both ends are closed with a halogen free plastic end cap. This is followed by polythene tube sleeving over full length and heat sealing at the ends. Sealed tubes are then placed in structurally reinforced plywood boxes in alternate even and odd radii layers (Fig-18) with grooved foam spacers between each layer at regular intervals along the length of the box. Finally, after obtaining QS clearance & Shipping Release, 2489 tubes for each SG set packed in 13 boxes along with a complete history docket are shipped to the SG manufacturer for further assembly [4].

4.0 Conclusion

With the above developmental works, NFC has established a complete set up for manufacturing of Steam Generator tubes for Nuclear applications and has successfully manufactured and delivered 45,000 U-Bend tubes required for 18 sets of Steam Generators. Manufacturing of 8th set against 40 set order for Fleet mode PHWRs is under progress. This has led NFC to become the fourth such facility in the world having capability to manufacture Steam Generator tubes for Nuclear application.

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Inkjet Printing: New Manufacturing Paradigm for Organic Light Emitting Diodes

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Abstract

Inkjet printing offers a promising, cost-effective alternative to traditional vacuum-based methods for manufacturing Organic Light Emitting Diodes (OLED). This digital, maskless technique enables high-resolution, additive deposition of functional layers, making it suitable for flexible, large-area, and customizable OLED displays. Researchers at IIT Kanpur have demonstrated multilayer OLED fabrication using inkjet printing for the anode, emissive layer, and dielectric patterning, eliminating the need for photolithography and indium tin oxide. Key challenges addressed include ink formulation, droplet control, interlayer compatibility, and achieving uniform film morphology. Using a Pixdro LP50 platform, the team successfully printed high-resolution patterns, flexible devices, and hybrid electrode structures, validating inkjet printing's scalability and design versatility. Applications range from wearable displays to smart signage. Ongoing optimization in material development and process integration is vital to fully realize inkjet printing's potential. Overall, this work establishes inkjet printing as a transformative technology for next-generation, low-cost, and environmentally sustainable OLED manufacturing.

Introduction

Organic Light Emitting Diodes (OLEDs) have become the leading technology for high-performance displays in smartphones, monitors, and televisions. However, current OLED manufacturing relies heavily on vacuum-based semiconductor processes, which significantly increase production costs. Solution-based techniques, particularly inkjet printing (IJP), offer a promising alternative by enabling cost-effective, additive, and high-resolution deposition over large areas. IJP stands out for its drop-on-demand precision, digital patternability, and compatibility with ambient processing, making it an attractive candidate for next-generation OLED fabrication. Nonetheless, several challenges remain before fully printed OLEDs can rival those made via vacuum deposition. These include the development of printable materials, strategies for multi-layer deposition without interlayer mixing, and high-resolution patterning to match display-grade standards. The overarching goal is to achieve OLEDs with high efficiency, luminance, and stability, while also enabling scalable, mask-free production. Continued advancements in material formulation, device architecture, and process integration are essential to unlock the full potential of inkjet-printed OLED displays. For past several years, we have been doing R&D to make printed OLEDs at the National Centre for Flexible Electronics, Indian Institute of Technology Kanpur. In this article, first we describe the OLED processing and inkjet printing. We are working with following objectives:

- Develop IJP process for the fabrication of printed OLED displays.
- Optimize the OLED device design and encapsulation to ensure high performance and long lifetime.
- Demonstrate the functionality of the printed OLED display in various applications.
- Develop a cost-effective and scalable manufacturing process for the production of printed OLED displays.

Inkjet-printed OLEDs offer a cost advantage of approximately 15–30% compared to traditional evaporated OLEDs, mainly due to higher material utilization (~95% vs. ~60%), elimination of expensive vacuum processes, and the absence of fine metal masks. Market analysts such as IHS Markit and TrendForce report 15–25% and ~25% cost savings, respectively, while JOLED, a pioneer in inkjet OLED production, claimed up to 30% savings.[1-4] These reductions make inkjet printing especially attractive for large-area and mid-size displays, positioning OLED technology as more competitive with LCDs and miniLEDs in terms of cost, while retaining superior contrast and design flexibility.

Organic Light-Emitting Diodes (OLEDs):

Organic light-emitting diodes (OLEDs) are composed of multilayered architectures, typically comprising an anode, hole transport/injection layers, an emissive layer, electron transport/injection layers, and a cathode. A representative structure anode/hole injection layer (HIL)/emission layer (EML)/electron injection layer (EIL)/cathode (Al) is illustrated in Figure 1, where each layer plays a specific electronic or optoelectronic role (see [5] for detailed material descriptions). While vacuum deposition is traditionally employed for several layers, recent

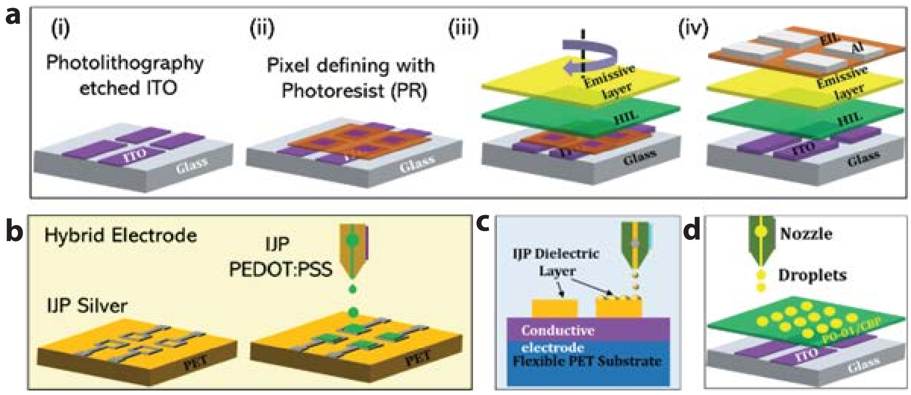


Figure 1. Inkjet-printed OLED device fabrication strategies. a) Schematic representation of a conventional OLED fabrication process: (i) photolithographic patterning of ITO on a glass substrate; (ii) pixel definition using a photoresist layer; (iii) sequential deposition of organic functional layers including the HIL and EML; and (iv) final device completion by deposition of an EIL and a top metal electrode (e.g., Al). b) Schematic of a fully inkjet-printed hybrid electrode architecture, wherein a patterned silver network is deposited onto a flexible PET substrate, followed by the inkjet printing of a high-conductivity PEDOT:PSS layer. This approach eliminates the need for transparent conductive oxides and vacuum-based patterning. c) Inkjet-printed dielectric patterning on flexible PET substrates, enabling lithography-free pixel isolation. The dielectric material is precisely deposited over the bottom electrodes to define the emissive areas. d) Direct inkjet deposition of a phosphorescent emitter (PO-01/CBP) onto the HIL-coated ITO/glass substrate, demonstrating additive and mask-free patterning of the EML for pixel definition. This methodology enables streamlined OLED fabrication with reduced material waste and enhanced patterning flexibility.

advances have enabled the use of solution-processable materials, particularly in conjunction with IJP techniques, for the deposition of active organic layers excluding the thermally evaporated top metal cathode.

Figure 1 illustrates our comprehensive approach toward the realization of fully or partially inkjet-printed OLEDs. Specifically, the emissive layer (TADF – Thermally Activated Delayed Fluorescent material) is shown to be inkjet-printed directly onto a PVK-TAPC (Poly(N-vinylcarbazole) - 1,1-Bis[4-[N,N-di(p-tolyl)amino]phenyl]cyclohexane) based hole transport layer stack.[5] In parallel, we demonstrate strategies to replace conventional ITO/PEDOT:PSS (Indium Tin Oxide/Poly (3,4-ethylenedioxythiophene)\:Poly (styrenesulfonate)) electrodes with hybrid inkjet-printed architectures,[6] comprising conductive silver patterns overlaid with high-conductivity PEDOT:PSS inks on flexible PET (Polyethylene Terephthalate) substrates. To further eliminate lithographic processing, we employed inkjet-printed dielectric materials (SU-8 photoresist) for precise pixel isolation,[7] enabling mask-free emissive area definition. The performance of these inkjet-integrated OLEDs was assessed through standard device characterization techniques including current density–voltage–luminance (J–V–L) measurements, current efficiency, and electroluminescence (EL) spectral analysis. These results collectively underscore the feasibility of scalable, additive OLED fabrication using inkjet printing, paving the way for cost-effective and flexible optoelectronic applications.

We encapsulated the devices using glass-to-glass encapsulation for rigid substrates, whereas for flexible PET substrates (PET), we used thin dielectric film (Al_2O_3), as reported in our prior study, which creates a great gas and moisture barrier.[8]

Inkjet Printing for OLED Fabrication:

Inkjet printing (IJP) has evolved from a mature technology in graphic industries into a highly promising tool for the fabrication of functional electronic materials and devices. Its digital, maskless, and additive nature, combined with scalability and cost-effectiveness, makes IJP an attractive alternative to conventional photolithography and vacuum-based deposition processes in thin-film

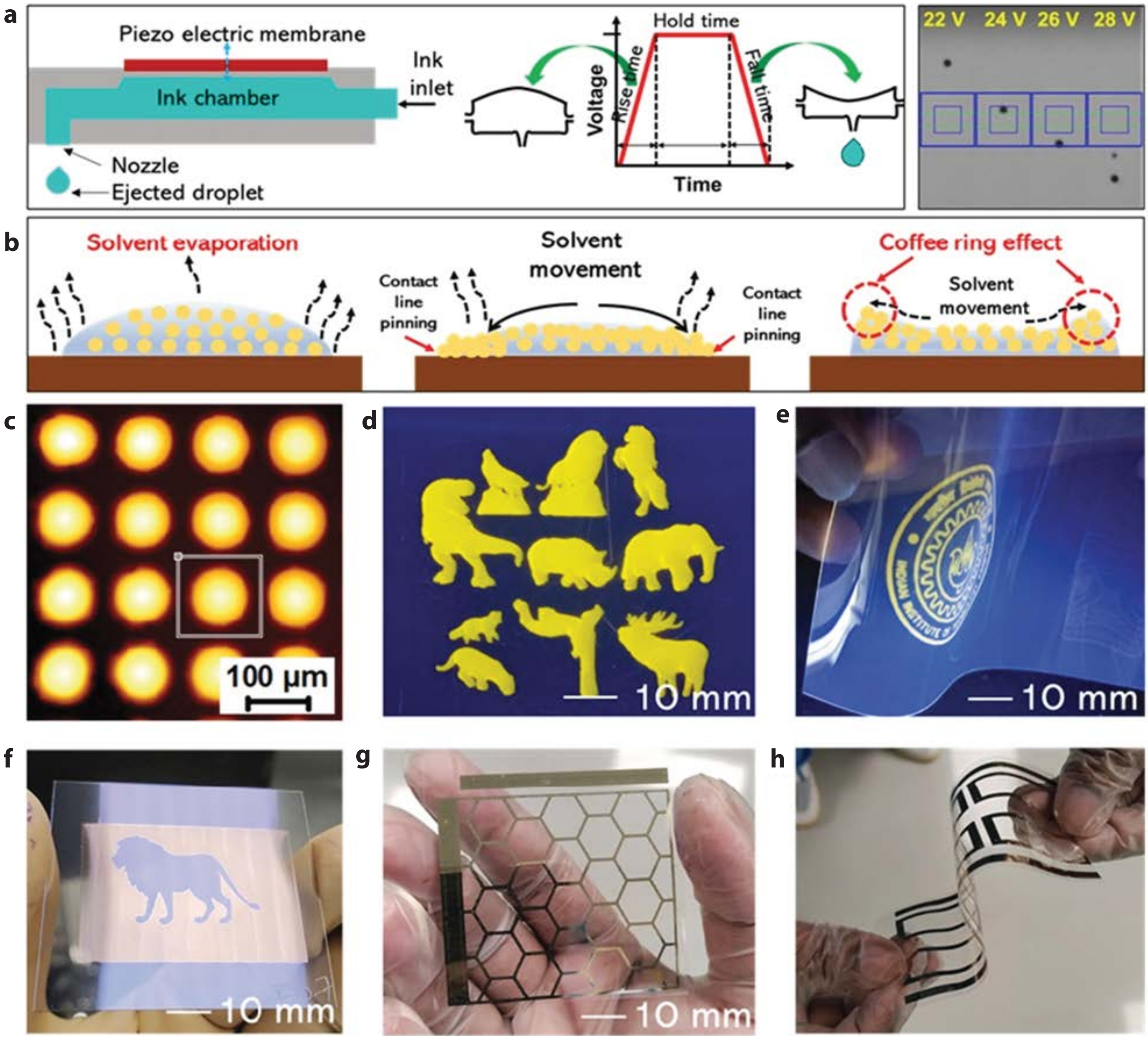


Figure 2. a) Schematic illustration of an inkjet printing mechanism showing droplet ejection driven by a piezoelectric membrane under a voltage pulse waveform. The inset (right) shows practical droplet ejection behavior at different applied voltages (22–28 V), indicating precise control over droplet formation. b) Depiction of the droplet-substrate interaction mechanism, highlighting solvent evaporation, internal flow, contact line pinning, and the formation of the coffee-ring effect. c) Optical image showing a uniform 2D array of circular droplets, printed under optimized inkjet parameters. d) Demonstration of complex pattern printing using inkjet technology, with various animal silhouettes printed to showcase design versatility and resolution. e) Inkjet-printed institutional (IIT Kanpur) logo on a flexible substrate, demonstrating the technique's applicability in flexible and wearable electronics. f) Inkjet-printed dielectric template using SU-8 epoxy material, shaped as a lion silhouette on a transparent substrate, emphasizing pattern fidelity. g) Large-area honeycomb pattern fabricated via inkjet printing for potential use in hybrid electrode structures. h) Flexible array of inkjet-printed silver strips (4 × 2 configuration), with each strip measuring 10 × 40 mm^2, suitable for applications in stretchable and printed flexible electronic devices.

electronics. As illustrated in Figure 2a, inkjet printing operates by ejecting picoliter-scale droplets from a printhead typically driven by a piezoelectric actuator under a programmed voltage pulse. This allows precise control over droplet size, volume, and deposition frequency. The inset in Figure 2a demonstrates experimentally the influence of applied voltage (22–28 V) on droplet formation, validating the controllability and reproducibility of the process.

One of the unique advantages of IJP is its material efficiency, with minimal waste and no need for subtractive etching, which offers both economic and environmental benefits. This technique has already been employed in the fabrication of various optoelectronic and electronic devices such as organic thin-film transistors (OTFTs), solar cells, memory devices, and sensors.[9,10] However, despite its promise, IJP must still address several critical challenges such as achieving uniform film formation over large areas, compatibility with a wide range of functional materials, process integration across multi-layer stacks, and long-term device stability. We have employed a Pixdro LP50 industrial inkjet printing platform, equipped with a piezoelectrically actuated 10 pL Dimatix cartridge comprising 16 nozzles (21 µm diameter each), to print functional

OLED layers and device components. Using this setup, we demonstrated high-resolution patterning capabilities and high-fidelity layer formation across a variety of flexible and rigid substrates.

Ink Formulation and Deposition Behavior:

A foundational requirement for successful inkjet-printed OLEDs is the formulation of stable, printable inks with optimized rheological properties. For consistent and defect-free droplet ejection, the ink must fall within a suitable range of viscosity (typically 8–12 cP) and surface tension (28–35 mN/m), dictated by the printer's fluidic system. As shown in Figure 2b, once the droplet is deposited, complex dynamics unfold at the droplet-substrate interface, including solvent evaporation, internal Marangoni flows, contact line pinning, and potentially, the formation of a coffee-ring effect all of which impact the final film morphology. To address these challenges, we formulate inks by tailoring solute concentration, solvent selection, and evaporation dynamics. Solvents such as 1,2-dichloroethane (DCE), chlorobenzene (CB), 1,2-dichlorobenzene (o-DCB), toluene, and methyl benzoate (MB) are used due to their compatibility with organic semiconductors and their physical properties suited for IJP processing. To suppress nozzle clogging and improve jetting stability, we often employ solvent blends, where the addition of a high-boiling-point component reduces premature drying and enhances film continuity. Once a stable ink is achieved, systematic optimization is carried out to ensure reproducible droplet placement, uniform film spreading, and minimal interfacial interaction with underlying layers.

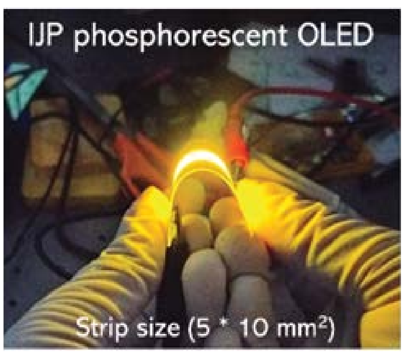
Surface wettability and roughness also affect ink spreading and droplet formation, with surface treatments (e.g., plasma, UV-ozone) often used to optimize rheological interactions between ink and substrate. Thus, balancing mechanical stability, thermal tolerance, and surface rheology is essential for reliable inkjet-printed OLED fabrication.

Figure 2c shows an optical micrograph of a highly uniform array of circular droplets, deposited using optimized parameters. In Figure 2d, we demonstrate the design flexibility and high resolution of IJP by printing a series of complex animal silhouettes, while Figure 2e highlights the successful printing of an institutional logo (IIT Kanpur) on a flexible substrate, underscoring the suitability of this method for conformable and wearable electronics. In addition to functional layers, inkjet printing can be used for structural patterning. Figure 2f depicts an inkjet-printed SU-8 dielectric template, patterned into a high-resolution lion silhouette. This further demonstrates the fidelity of the process in printing insulating materials essential for pixel isolation. We have also utilized IJP for large-area patterning, as shown in Figure 2g, where a honeycomb architecture was printed for use in hybrid electrode applications. Finally, Figure 2h presents an array of flexible, inkjet-printed silver strips (10 × 40 mm² each), arranged in a 4 × 2 configuration. These conductive patterns are compatible with stretchable substrates and can serve as interconnects or electrodes in flexible electronic platforms.

Demonstrations of Inkjet-Printed OLED Architectures:

To demonstrate the versatility and scalability of inkjet printing in OLED fabrication, multiple device configurations were developed and tested, as summarized in Figure 3. These examples highlight the potential of IJP for producing both flexible and large-area emissive

a



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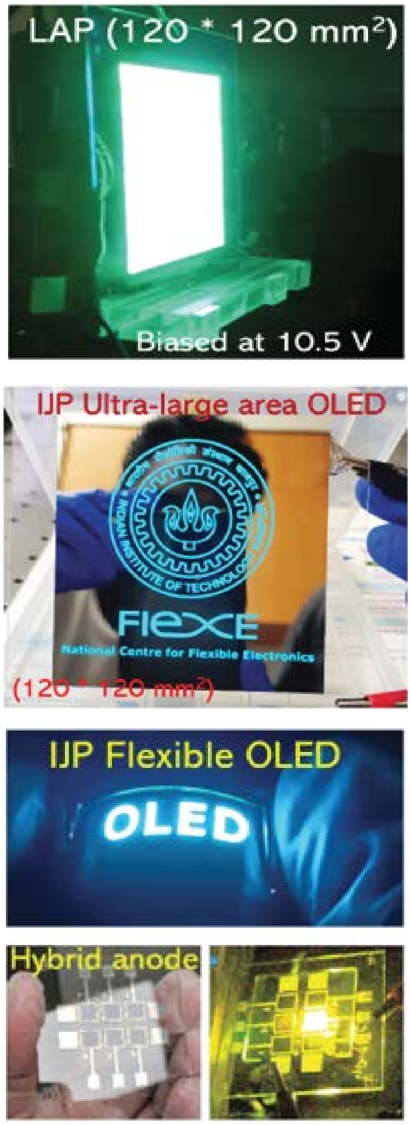

Figure 3. a) Inkjet-printed phosphorescent OLED using PO-01/CBP emitter on a flexible ITO substrate. The device, with dimensions of 5 × 10 mm², demonstrates bright emission on bending, highlighting its potential for wearable displays. b) Large-area (120 × 120 mm²) inkjet-printed OLED employing a TADF (thermally activated delayed fluorescence) emitter, operated at a bias of 10.5 V. c) Ultra-large-area OLED fabricated on an inkjet-printed dielectric template using SU-8 epoxy to pattern ITO electrodes. The printed pattern showcases institutional branding and precision. d) Flexible OLED device with inkjet-printed emissive text, illustrating the ability to integrate graphics and displays on flexible surfaces. e) Hybrid anode-based OLED. Left: Fabricated on a 50 × 50 mm² substrate using HC PEDOT:PSS as the transparent electrode, with inkjet-printed silver defining 4 × 4 mm² pixel areas for uniform charge distribution. Right: Illuminated OLED demonstrating successful operation without conventional ITO, enabling scalable, ITO-free display architectures.

devices using diverse functional materials and substrates. Figure 3a presents a flexible phosphorescent OLED fabricated by inkjet printing a PO-01/CBP emissive layer onto a flexible ITO-coated substrate.[11] The device, with compact dimensions of 5 × 10 mm², exhibits bright electroluminescence even under bending conditions. This confirms the mechanical robustness of the printed layers and underscores the applicability of IJP OLEDs for next-generation wearable and conformable display technologies. In Figure 3b, we demonstrate a large-area (120 × 120 mm²) OLED employing a thermally activated delayed fluorescence (TADF) emitter.[6] This device, fabricated entirely using inkjet-printable organic materials (excluding the cathode), is shown operating at a driving voltage of 10.5 V. The uniformity and luminance of the large-area emission validate the feasibility of scalable and homogeneous OLED fabrication via IJP. Figure 3c illustrates an ultra-large-area OLED, where the emissive pattern is defined by inkjet-printed SU-8 epoxy, used as a dielectric template to pattern ITO electrodes. This lithography-free approach enables precise definition of emission regions without vacuum-based or mask-based processing. The resulting display highlights an institutional (IIT Kanpur) logo, demonstrating not only the functional performance of the printed OLED but also the graphic versatility enabled by digital design integration.

In Figure 3d, a flexible OLED device is shown with inkjet-printed text ("OLED") embedded within the emissive layer. This highlights the ability to pattern custom graphics or alphanumeric information on bendable substrates, providing a highly adaptable platform for smart packaging, signage, and dynamic labels. Finally, Figure 3e showcases a hybrid anode-based OLED that entirely circumvents the use of ITO. The left panel shows the fabrication strategy: a 50 × 50 mm² PET substrate is coated with high-conductivity PEDOT:PSS as the primary transparent electrode, while inkjet-printed silver traces define discrete 4 × 4 mm² pixel areas to ensure uniform charge injection and distribution. The right panel shows a fully illuminated device, confirming successful operation and emission.[6] This architecture demonstrates the viability of ITO-free OLEDs, which are critical for low-cost, sustainable, and flexible display technologies. Together, these demonstrations establish inkjet printing as a powerful, maskless, and scalable approach for fabricating high-performance OLED devices on both rigid and flexible substrates. The integration of printable electrodes, dielectrics, and emissive materials enables rapid prototyping and customizable display designs for a broad spectrum of applications.

Summary

We have successfully demonstrated the fabrication of multilayer OLEDs using inkjet printing for the anode, emissive layer, and photoresist-based dielectric patterning. This approach eliminates the need for conventional lithography and vacuum deposition, offering a scalable and mask-free route to OLED manufacturing. Our results highlight the importance of understanding ink formulation, droplet dynamics, and film formation to ensure uniform layer deposition and reliable device performance. The ability to directly print functional and structural layers enables flexible, large-area, and customizable OLEDs. These developments position inkjet printing as a key enabler for next-generation display technologies, with strong potential for cost-effective, ITO-free, and fully printed OLED devices.

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