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Two Different Aspects of Non-Conventional Manufacturing Processes for the High End Applications

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ABSTRACT: The modern manufacturing industry often faces challenges in machining hard-to-cut materials due to their high strength and brittleness. With the increasing demand for precision, efficiency, and the ability to process complex materials, non-conventional manufacturing processes have become indispensable. Traditional machining methods struggle with issues such as excessive tool wear, poor surface finish, and machining limitations.

This paper explores various nonconventional manufacturing processes that have revolutionized manufacturing, including ultrasonic machining (USM), electrical discharge machining (EDM), laser beam machining (LBM), Laser additive manufacturing (LAM), abrasive water jet machining (AWJM), Chemical forming and hybrid machining techniques. It highlights key advancements, material compatibility, and industrial applications of these processes.

I. INTRODUCTION

Modern industries demand components with micro-scale features and intricate details, especially in medical implants, semiconductor devices, and optical systems. Non-conventional processes allow for better dimensional control, enabling the production of complex geometries with minimal surface defects. Non-conventional techniques leverage principles of thermal, electrochemical, and mechanical energy conversion to remove material with minimal tool wear and reduced mechanical stress, thereby improving efficiency and extending tool life.

Another critical factor necessitating non-conventional manufacturing processes is sustainability. Traditional methods often generate significant material waste, require extensive use of cutting fluids, and consume high energy. Techniques like powder-mixed EDM, electrochemically assisted microturning, and hybrid machining minimize environmental impact by optimizing energy use and reducing waste generation. As industries strive toward eco-friendly manufacturing, integrating non-conventional methods contributes to resource conservation and improved process efficiency.

Modern manufacturing processes have evolved significantly over the years, driven by advancements in technology, automation, and materials science. These processes aim to enhance efficiency, reduce waste, and improve product quality while meeting the demands of mass production and customization. Manufacturing today integrates traditional methods with cutting-edge technologies to optimize production. The primary categories of modern manufacturing processes include subtractive, additive, forming, and joining techniques.

1.1 Subtractive Manufacturing

Subtractive manufacturing, such as **machining**, involves removing material from a workpiece to achieve the desired shape. Processes like turning, milling, drilling, and grinding are widely used, especially in industries that require high precision, such as aerospace and medical device manufacturing.

Classification of non-conventional machining processes are shown in fig.1

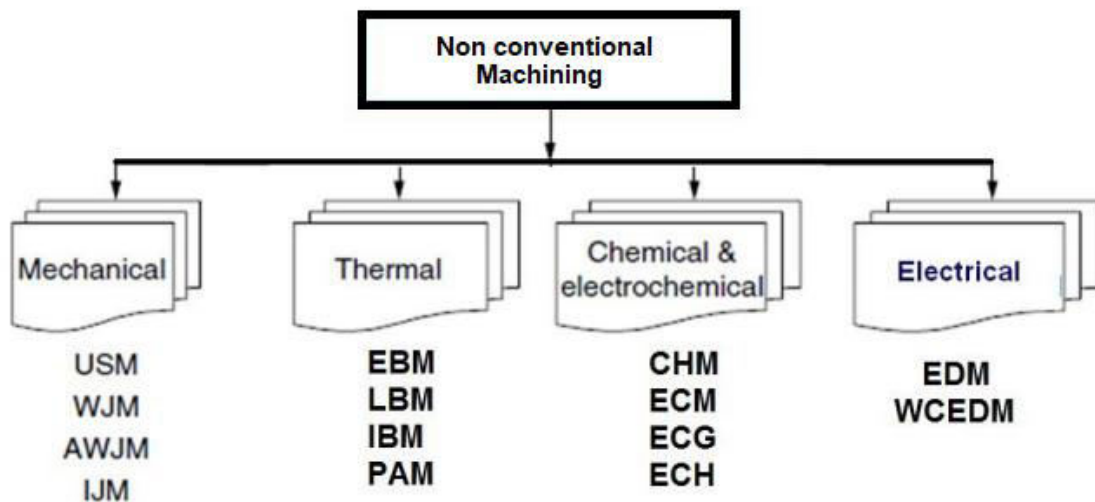


Fig. 1: Classification of nonconventional machining processes [1]

Comparison of different types non-conventional machining processes are given in the table: 1

Table: 1 Process Configuration

Table: 1					
Process	MRR	Surface finish (μ) CLA	Tolerance (μ)	Depth of surface damage	Power required
PAM	75000	Very Rough (In mm)	125	500	50000
Conventional machining	50000	0.5-5	50	25	3000
ECM	15000	0.1 -2.5	50	5	100000
EDM	800	0.2-1.2	15	125	2700
USM	300	0.2-0.5	7.5	25	2400
CHM	15	0.5-2.5	50	50	-----
EBM	1.6	0.5-2.5	25	250	150(avg) 2000(peak)
AJM	0.8	0.5-1.2	50	2.5	250
LBM	0.1	0.5-1.2	25	125	2 (avg)

Here we discuss of some of the advance non-conventional processes, their mechanism, material compatibility, and industrial applications.

1.1.1 Powder mixed electrical discharge machining (PMEDM)

Powder Mixed EDM (PMEDM) is an advanced EDM technology in which fine abrasive electrically conductive powder is added in the dielectric. Suspended metallic powders in dielectric decrease its insulating strength and consequently increases the inter-electrode gap conditions, which improves EDM performance and delivers superior surface finish compared to conventional EDM. The working principle of the PMEDM process states that upon application of appropriate voltage an electric field is generated which gives rise to positive and negative charges on the powdered particles. These energized powder particles get accelerated and start moving in a zigzag manner which leads to improving the spark gap between electrodes. In the direction of currentflow particles, interlocking takes place. This

chain helps in bridging the discharge gap between electrodes and thereby insulating strength of the dielectric fluid decreases and the spark gap increases. Figures 3 and 4 illustrate the Principle of Powder Mixed EDM and Mechanism of PMEDM respectively. [3]

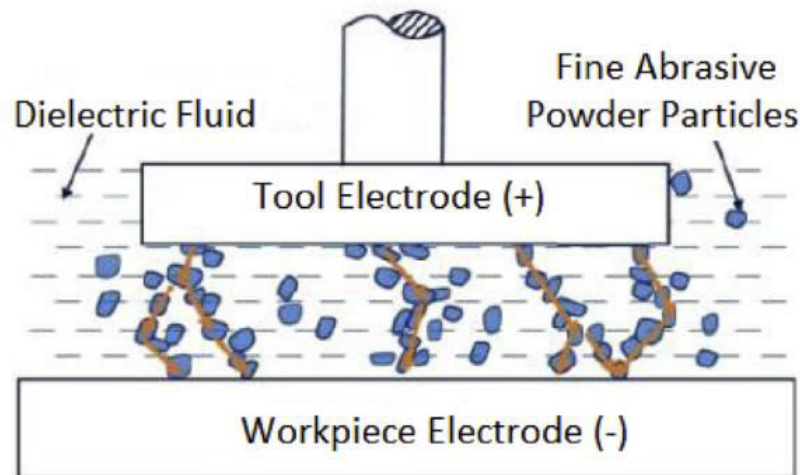


Fig. 2: Principle of PMEDM

1.1.1 Mechanism of Material removal of PMEDM

In PMEDM, an electrical field of intensity 105–107 V/m is generated when a voltage of 80–320 V is applied across the electrodes because of which Positive and Negative charges accumulate at the top and bottom of the powder particles respectively. Foremost discharge breakdown occurs where the electric field density is the utmost (between 'a' and 'b' in Figure 5). This breakdown may be between powder particles or between powder particles and tool or workpiece electrode. After the first discharge relocation of electric charges takes place which then gathers at point 'c' and 'd'. Depending upon the electric field density series of sparks keeps on occurring further Interlocking between different powder particles forms a chain that causes easy short-circuiting and leads to an early explosion in the gap. The combined effect of particle bridging and suspended additive particles modifies the plasma channel reduces the discharge power density and pulse explosive gas pressure.

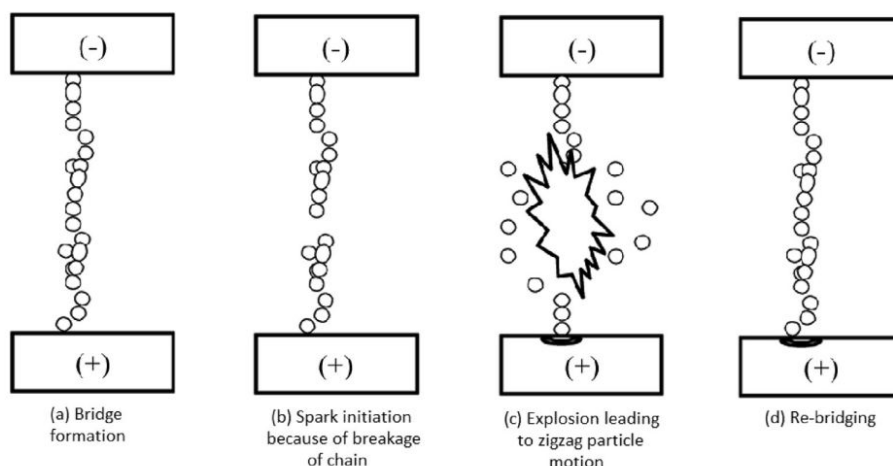


Fig.3 : Basic mechanism of powder mixed electro discharge machining.

1.1.3 Process Parameters of PMEDM

PMEDM is governed by several process parameters which influence machining efficiency and surface finish. These parameters are categorized into electrical, non-electrical, electrode-based, and powder-based factors:

1.1.3.1 Electrical Parameters

- **Peak Current (Ip):** Higher peak current increases MRR but may degrade surface quality.
- **Discharge Voltage (V):** Determines spark energy and affects gap stability.
- **Pulse-On Time (Ton):** Affects crater depth and recast layer thickness.
- **Pulse-Off Time (Toff):** Essential for dielectric deionization and debris flushing.
- **Duty Cycle (t):** Optimizing duty cycle improves machining rate.
- **Polarity:** Determines material removal direction.
- **Electrode Gap:** Affects gap stability and process efficiency.
- **Gap Voltage:** Controls the breakdown strength of dielectric.

1.1.3.2 Non-Electrical Parameters

- **Dielectric Fluid Selection:** Oils like kerosene, mineral oil, silicon oil or deionized water influence machining efficiency.
- **Flushing Mechanism:** Controls debris removal and improves spark efficiency.
- **Electrode Rotation:** Enhances spark stability and flushing effectiveness.
- **Workpiece Rotation:** Ensures better cooling and machining accuracy.

1.1.3.3 Electrode-Based Parameters

- **Electrode Material:** Copper, graphite, brass, tungsten, and their alloys are commonly used.
- **Electrode Size and Shape:** Determines cavity geometry and machining precision.

1.1.3.4 Powder-Based Parameters

- **Powder Type:** Aluminum, silicon carbide (SiC), titanium, tungsten, boron carbide, and carbon nanotubes (CNTs) are widely studied.
- **Powder Size:** Influences spark gap and surface roughness.
- **Powder Conductivity:** Higher conductivity improves MRR.
- **Powder Concentration:** Optimizing powder density prevents arcing while improving performance.
- **Powder Density:** Affects suspension stability and machining consistency.

1.1.3.5 Performance Parameters of PMEDM

PMEDM enhances machining performance metrics, which include:

- **Material Removal Rate (MRR):** Volume of removed material per unit time.
- **Tool Wear Rate (TWR):** Electrode erosion per unit time.
- **Wear Ratio (WR):** Ratio of TWR to MRR, influencing machining economics.
- **Surface Roughness (SR):** Determines micro-smoothness of machined surfaces.
- **Surface Quality:** Involves recast layer thickness, heat-affected zone, and microcracks.

1.1.4 Applications of PMEDM

PMEDM has widespread applications in automotive, aerospace, medical implants, surgical tools, and micro-manufacturing industries. **Key benefits include:**

- Mirror-like reflective surfaces.
- Improved microhardness and corrosion resistance.
- Machining of intricate profiles, complex 3D shapes, and fragile components.
- Nano-powder mixed PMEDM for biomedical implant manufacturing.
- Processing of advanced materials like metal matrix composites (MMCs).

1.1.5 Comparison of different parameters of PMEDM with conventional machining.

Table 2: Different parameters of PMEDM

Process	MRR mm ³ /min	Surface finish (μ) CLA	Tolerance (μ)	Depth of surface damage	Power required
PMEDM	200-300	8-20	10	40(1/3 times of Normal EDM)	50000
Conventional machining	50000	0.5-5	50	25	3000

II. ADDITIVE MANUFACTURING (3D PRINTING)

Additive manufacturing (AM) has transformed manufacturing by enabling rapid prototyping and complex geometries that are difficult to achieve using traditional methods. Laser additive manufacturing is a layer-by-layer process that offers flexibility in manufacturing complex shapes without dedicated tools. It is also used for repairing high-cost parts, making it attractive to various industries.

Additive manufacturing (AM) is a promising technological family that has revolutionized the manufacturing horizon for producing complex parts. These technologies are widely used in various industries such as aerospace, medical, molding, and tooling because of the freedom to design complex geometries in a single process with minimum waste material, without using dedicated tools, and in a reduced CAD-to-part time. Among a wide variety of methods, laser based technologies are mostly relevant when dealing with metal parts, namely Powder Bed Fusion and Directed Energy Deposition, both working with powder materials. Of these methods, Directed Energy Deposition Particularly Laser metal deposition is a popular method among the molding and tooling industries for adding to the free form capability, the ability to work with complex shaped parts and superalloys. While this method offers less potential accuracy and geometry complexity freedom compared to Powder Bed Fusion, it is compatible with larger parts and has a lower processing cost. Further, it is highly compatible with conventional processes, such as machining, allowing a hybrid manufacturing processes.[4].Fig.4(a) and 4(b) shows the schematic and actual setup of laser additive manufacturing.

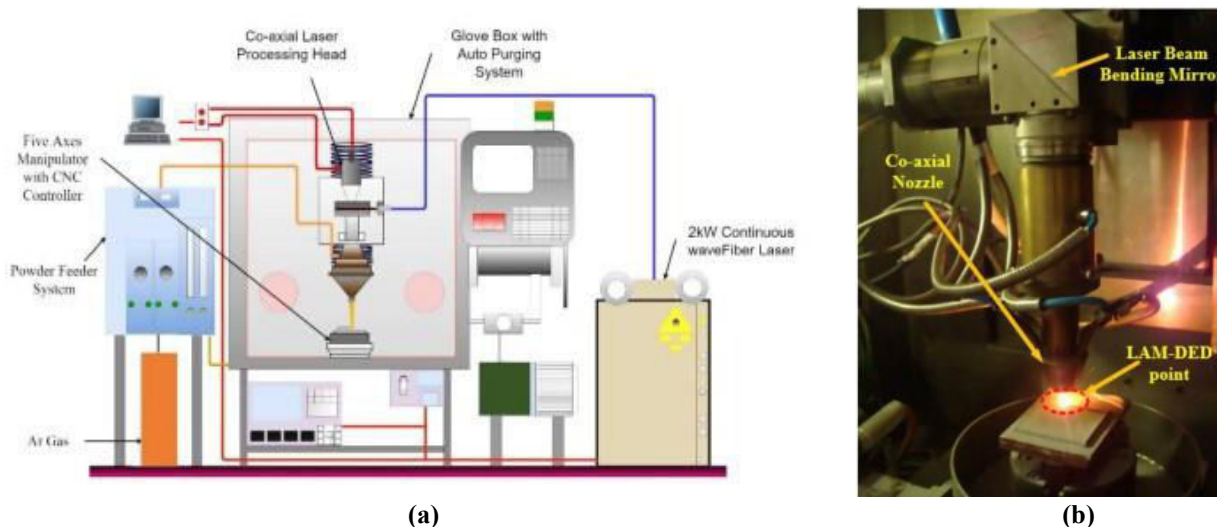


Fig:4 Schematic diagram of Laser additive manufacturing setup(a)
and LAM photograph during process (b)

2.1 Mechanism of Material deposition in LAM:

2.1.1 Powder Bed Fusion:

Powder Bed Fusion (PBF) is an additive manufacturing process where a heat source, like a laser, selectively fuses powder particles together, layer by layer, to create a solid 3D object. This technique is also known as Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM), depending on the specific type of powder and heat source used. It is very useful for the manufacturing of objects of plastics, ceramics metal etc. We can see the powder bed fusion in fig:5 [5]

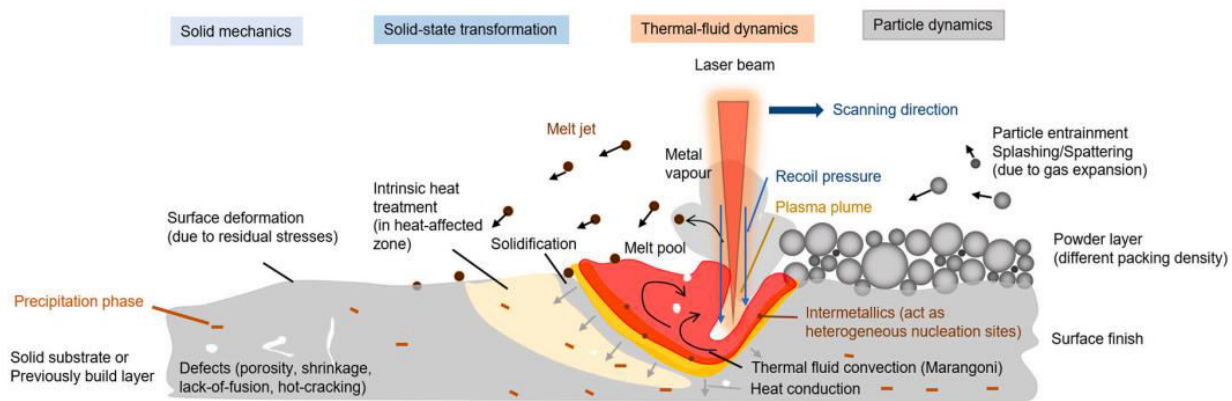


Fig:5 Powder Bed Fusion method

2.1.1.1 Working: In Powder bed fusion method of additive manufacturing a powder delivery system with a integrated roller is used to spread a layer of metal material powder of desired thickness and then a heat source may be Laser or Electron beam or plasma arc source melts the powder in the desired shape. Molten metals solidifies and form a layer and further an another layer of powder is spread by the roller (spreader) and melted by the heat source. The process repeats itself and a layer by layer a solid structure formed. After completion of the printing of the object the remaining un melted powder is removed and can be reused after screening. Fig 6 shows the L-PBF AM setup.

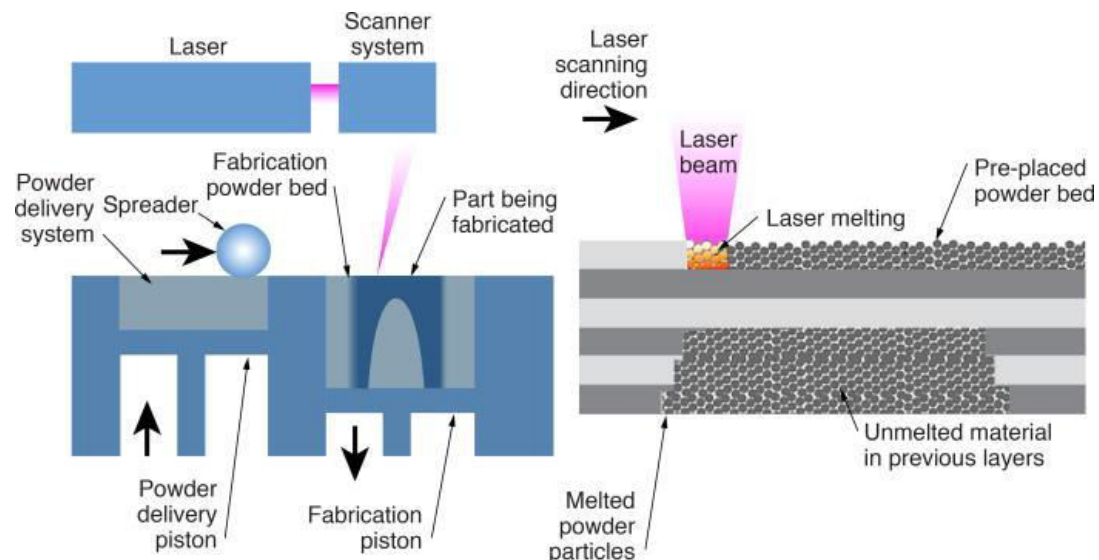


Fig. 6: Powder bed fusion laser additive manufacturig setup

2.1.2 Directed Energy Deposition

Using this intricate printing method called **directed energy deposition**, old components can often be repaired or given a material boost. The structure can be managed greatly during energy deposition, producing high-quality objects. Although the nozzle isn't locked to one axis and can travel in several directions, the focused energy deposition and material extrusion mechanism are comparable. Although this process can be used with polymers and ceramics, it is commonly used with metals. The deposition of laser and laser-engineered net shaping (LENS) illustrates this technology. It is possible to create or repair parts that range in size from millimeters to meters using the new technology known as laser deposition. Laser deposition technology is being more widely used in its manufacturing, transportation, aerospace, oil, and gas industries because it provides scalability and a variety of abilities in a single system.[6]

2.1.2.1 Working: In direct energy deposition method of additive manufacturing the material is fed in wire form or powder form to and melted on substrate simultaneously by a heat source LASER or Electron beam. The molten material forms a bond with surface of substrate and solidifies creating a solid structure. This process is repeated layer by layer, following a digital design, to build the desired 3D object. The nozzle or table of machine can move in x, y and z simultaneously to create a 3D model. We can see the process in figure 7.

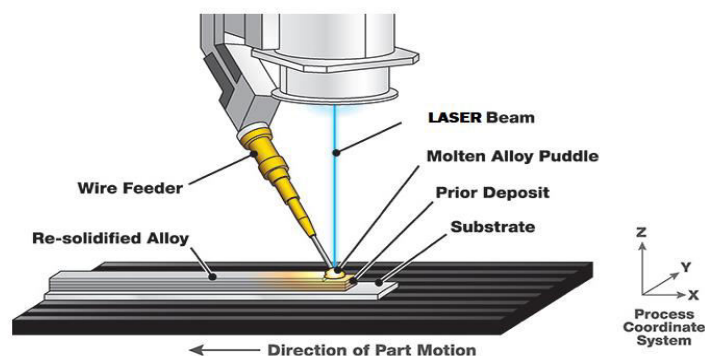


Fig. 7: Laser Direct energy deposition additive process

2.2 Comparison between Powder Bed Fusion and Directed Energy Deposition methods:

Feature	Powder Bed Fusion (PBF)	Directed Energy Deposition (DED)
Process	Layer-by-layer from powder bed	Deposit on existing part
Build Time	Slower	Faster
Cost	Higher	Lower
Surface Finish	Higher	Lower
Accuracy	Higher	Lower
Part Size	Typically smaller	Can be larger
Applications	Final parts, complex geometries	Repair, coating, large parts

2.3 Mechanical properties of the processed Object:

In a study two type of sample of Fe-Co alloy made by L-PBF and L-DED and tensile test has been carried out. Due to the fundamentally different manufacturing approaches, each set of tensile samples had different mechanical properties. **Fig. 8** shows a comparison of the 0.2% offset yield strength and total strain values for conventional, L-PBF, and L-DED processed binary Fe-Co. The conventional material, which represented hot-extruded ingots, had yield strength and ductility values of 200–400 MPa and 0–4%, respectively, depending upon post heat treatment quenching conditions. Similarly, L-DED material exhibited a yield strength range of 250–460 MPa with ductility of 0–2.7%. Fundamentally different was the L-PBF processed material, which exhibited notably higher yield strength ranging from 450 to 560 MPa with ductility of 5% to 32%; the high strength and ductility corresponding to specimens processed with removable heat sinks. The performance for L-PBF Fe-Co is notable when compared to conventional and L-DED material, showing evidence of a 300% increase in strength and an order-of-magnitude improvement in ductility.[7]

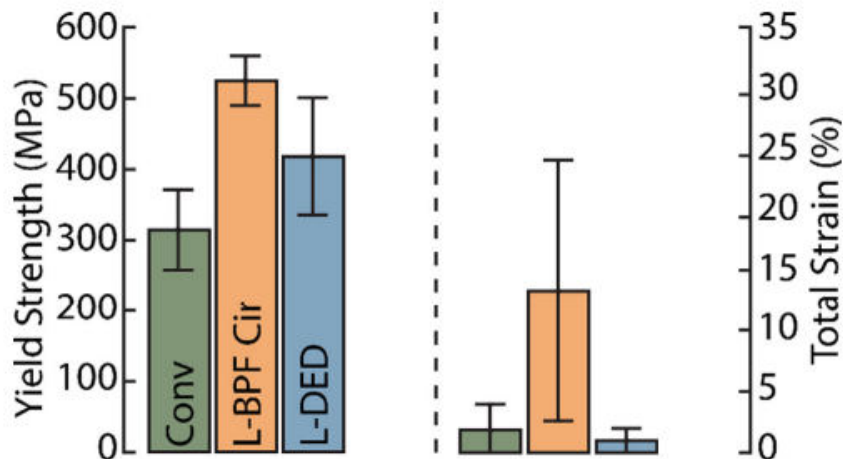


Fig.8: Comparison of mechanical properties for conventional, L-PBF and L-DED processed Fe-Co alloys

2.4 Application of Laser additive manufacturing

- Prototyping and Rapid Tooling: Additive manufacturing allows for quick creation of physical prototypes, enabling faster design iteration and testing. It is used for producing rapid tooling, including molds for injection-molded parts, reducing lead times and development costs.
- Aerospace and Defense: Additive manufacturing is used to produce lightweight and complex parts for aircraft and spacecraft, improving fuel efficiency and performance.
- Automotive: Additive manufacturing enables the production of lightweight and customized engine parts. It's used in the production of complex engine parts and for prototyping new designs.
- Medical and Healthcare: Additive manufacturing is used to create custom implants, prosthetics, and surgical tools. It's used for bioprinting tissues and organs, and for creating realistic functional prototypes for medical applications. Additive manufacturing also aids in drug discovery and testing by creating models of human cells and tissues.
- Construction and Architecture: Additive manufacturing is being used to print building structures and components, enabling faster construction and custom designs.
- Consumer Goods and Customization: Additive manufacturing enables the production of personalized products like eyewear, jewellery, and even customized food items.
- Energy Sector: Additive manufacturing is used to create lightweight and efficient components for power generation equipment. It is used for manufacturing components for solar panels and wind turbines.
- Other Industries: Additive manufacturing is also used in the fashion, education, and food industries for creating custom designs and products. It is used in the electronics industry for producing complex and miniaturized components.

III. SUSTAINABLE MANUFACTURING

Environmental concerns have pushed manufacturers toward sustainable practices. **Green manufacturing** emphasizes reducing waste, improving energy efficiency, and utilizing biodegradable or recyclable materials. **Advance nonconventional manufacturing processes** with other innovative approaches help minimize environmental impact by optimizing resource consumption.

IV. FUTURE TRENDS

Looking ahead, advancements in **nanomanufacturing**, **quantum computing applications in manufacturing**, and **biofabrication** will further transform production methods. The integration of **robotics**, **AI-driven quality control**, and **human-machine collaboration** will continue shaping the next generation of manufacturing.

V. CONCLUSION

Modern manufacturing is now integrated with **Industry 4.0**, leveraging automation, artificial intelligence (AI), and the Internet of Things (IoT). **Cyber-physical systems**, **digital twins**, and **machine learning** optimize production efficiency and predictive maintenance. **Smart factories** use real-time data to enhance decision-making, reducing downtime and increasing productivity. Modern manufacturing processes blend efficiency, sustainability, and innovation. By leveraging automation, precision machining, and smart technologies, industries achieve high-quality products while adapting to evolving consumer and environmental demands.

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