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Advancements in Non-Conventional Manufacturing: Process Optimization and Applications

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1. INTRODUCTION TO NON-CONVENTIONAL MANUFACTURING

1.1 Definition and Scope

Non-conventional manufacturing encompasses a broad range of techniques that transcend traditional subtractive machining processes such as milling, turning, and drilling. These methods often include additive manufacturing (AM), also known as 3D printing, and non-traditional machining techniques like wire electrical discharge machining (WEDM). The key characteristic that sets non-conventional methods apart is their reliance on novel physical principles—thermal, chemical, electrical, or mechanical—that allow the material removal or addition without conventional cutting mechanics. This expanded scope permits the processing of advanced and difficult-to-machine materials, including shape memory alloys and multi-material composites, which are challenging or impossible to treat effectively with conventional methods. Non-conventional manufacturing is essential in contemporary industries focused on lightweight, complex, or functionally graded components because it offers enhanced design freedom, improved resource efficiency, and adaptability to novel materials, meeting the escalating demands of sectors such as aerospace, automotive, energy, and biomedical engineering.

In particular, additive manufacturing techniques such as Wire Arc Additive Manufacturing (WAAM) have gained prominence as they enable the direct fabrication of large metal components by depositing material in successive layers. Similarly, non-traditional subtractive methods like WEDM have evolved to address the machining of smart materials by enabling precise material removal independent of mechanical properties. Overall, the non-conventional manufacturing landscape includes a suite of technologies that emphasize innovation in both process principles and applications, reflecting an essential part of the fourth industrial revolution's technological arsenal [1].

1.2 Historical Evolution and Recent Trends

The transition from conventional to non-conventional manufacturing has been driven by the limitations of traditional machining regarding material diversity, geometric complexity, and sustainability. Historically, subtractive manufacturing dominated due to its maturity and ease of automation; however, the rise of digitally controlled equipment, process innovation, and growing environmental concerns have accelerated the adoption of advanced manufacturing strategies. Over the last two decades, digitization and the integration of smart sensors have significantly propelled the evolution of additive and non-traditional machining processes by enabling real-time monitoring and adaptive control. This paradigm shift facilitates the fabrication of components with complex internal geometries and tailored properties that were previously unachievable.

Concurrently, sustainability has become a leading factor influencing technological adoption. Non-conventional methods often reduce material wastage by depositing or removing only the necessary material, enhancing resource efficiency. The adoption of WAAM exemplifies this trend, where its high deposition rates and minimal raw material usage are beneficial for the aerospace and automotive industries striving for lighter and more efficient parts. Similarly, advanced WEDM techniques enable precise machining of smart materials that support emerging applications in biomedical and aerospace fields, where traditional machining would typically cause damage or excessive tool wear. The escalating interest and widespread industrial uptake reflect these methods' capacities to deliver performance, sustainability, and innovation simultaneously [2].

1.3 Industrial Relevance and Applications

Non-conventional manufacturing techniques have gained significant traction across multiple high-value industrial sectors. For example, WAAM is notably applied in aerospace for manufacturing structural components and repairing high-cost alloy parts, in automotive for producing customized tooling and lightweight parts, and in nuclear industries where large metal structures with critical safety requirements are fabricated with enhanced precision and integrity. The molds and dies industry also benefits from these processes by shortening lead times and enabling complex tooling geometries tailored for rapid prototyping and small batch production.

From a broader industrial competitiveness perspective, non-conventional methods contribute to faster innovation cycles, improved product performance, and cost reductions through material and energy conservation. Integrated within Industry 4.0 frameworks, these methods facilitate smart manufacturing through digital twins, process monitoring, and data-driven optimization. As such, they help achieve stringent quality and performance standards while adapting flexibly to changing design and production demands. The application breadth and forward-looking adaptability of non-conventional manufacturing continue to position it as a strategic driver of manufacturing competitiveness and product innovation across critical sectors [1].

2. WIRE ARC ADDITIVE MANUFACTURING (WAAM): PROCESS AND OPTIMIZATION

2.1 Fundamental Principles and Equipment

Wire Arc Additive Manufacturing (WAAM) is a highly promising metal additive manufacturing technique that utilizes the energy from an electric arc to melt wire feedstock and deposit material in a layer-wise fashion to build components. Unlike powder-based AM methods, WAAM relies on wire electrodes as the raw material, offering higher deposition rates and lower material costs. The process can be classified under the broader category of directed energy deposition-arc (DED-arc) methods, which employ concentrated thermal energy sources such as an electric arc to provide the fusion necessary for layer formation. The electric arc serves both to melt the wire electrode and partially melt the substrate or previous layers, achieving metallurgical bonding that is crucial for component integrity.

The equipment for WAAM typically includes a power source for arc generation, wire feed mechanisms, robotic arms or gantry systems for precise movement, and shielding gas supplies to prevent oxidation during deposition. Compared to conventional additive manufacturing methods, which often use laser or electron beam energy sources with powder feedstocks, WAAM is distinguished by its simplicity and scalability, especially for large-scale or thick components. Its fusion-based process shares similarities with welding but differs in its layer sequencing and path planning to build up three-dimensional geometries, blending traditional welding expertise with modern digital manufacturing principles [1].

2.2 Process Parameter Control and Optimization

Achieving optimal results in WAAM requires precise control over multiple process parameters that influence the thermal history, melt pool dynamics, and final microstructure of the deposited metal. Critical parameters include welding current, voltage, wire feed rate, travel speed, and shielding gas flow. These parameters directly affect heat input, which controls layer adhesion, dilution, residual stresses, and distortion. Excessive heat can lead to grain coarsening, increased porosity, and cracking, while insufficient energy input may cause lack of fusion defects and poor mechanical performance.

Parametric optimization in WAAM involves balancing these inputs to enhance mechanical properties such as tensile strength, ductility, and hardness while minimizing defects. Advanced studies have demonstrated that systematic control and optimization of parameters can significantly improve deposition quality, reduce residual stresses, and control metallurgical phases. Strategies include feedback-based control systems using thermal and geometric sensors, computational modeling to predict optimal settings, and iterative experimental design approaches. Importantly, the optimization extends beyond single parameters to multi-variable interactions, considering the coupled effects on microstructural evolution and mechanical behavior, facilitating the tailoring of properties specific to industrial applications [1].

2.3 Industrial Applications and Performance Metrics

WAAM has found growing acceptance in industries demanding large-scale metallic components with high structural integrity. The aerospace industry uses WAAM for creating structural parts like brackets and frames due to its ability to fabricate complex geometries with reduced lead times and costs. In automotive, WAAM enables rapid tooling and customized lightweight parts that contribute to enhanced fuel efficiency and performance. The nuclear sector leverages WAAM's capability to manufacture and repair thick-walled components critical for safety.

The performance advantages of WAAM include exceptionally high deposition rates compared to powder-based AM techniques, which directly translate into shorter production times. The process also reduces raw material wastage since wire feedstock is fully utilized with minimal scrap. Further benefits relate to energy efficiency: WAAM consumes less energy than conventional joining and manufacturing processes largely due to its focused heat input and consolidation method. Performance metrics typically employed to assess WAAM components include tensile strength, surface finish, dimensional accuracy, and microstructural uniformity, with several studies demonstrating that under optimized conditions, the mechanical properties rival or surpass those of conventionally manufactured counterparts [1].

3. WIRE ELECTRICAL DISCHARGE MACHINING (WEDM) AND PROCESS ENHANCEMENTS

3.1 WEDM of Smart Materials: Challenges and Opportunities

Wire Electrical Discharge Machining (WEDM) is among the most widely used non-traditional machining technologies for electrically conductive materials, featuring a spark erosion mechanism that allows precise machining regardless of the mechanical properties of the workpiece. This capability is particularly valuable for smart materials such as shape memory alloys (e.g., Ni55.8Ti), which exhibit unique phase transformation behaviors, making conventional machining challenging due to high work hardening, elastic recovery, and thermal sensitivity.

WEDM is uniquely suited for shape memory alloys because it eliminates mechanical stresses and provides controlled heat input to avoid phase transformation alteration beyond the machining zone. However, machining such alloys demands process adjustments to balance efficient material removal while maintaining surface integrity and functional properties. The inherent challenges stem from the need for accurate dimensional control, minimized surface roughness, and avoidance of heat-affected zone degradation. Thus, advancing WEDM capabilities tailored to smart materials represents a critical opportunity for manufacturing components used in biomedical devices, actuators, and aerospace systems [2].

3.2 Influence of Nano-Material Mixed Dielectric Fluids

One of the recent process innovations to enhance WEDM performance is the incorporation of nano-materials, such as nano-graphene powders, into the dielectric fluids used during machining. The addition of nano-particles alters the dielectric properties, electrical conductivity, and discharge gap conditions, resulting in modified spark behavior and heat transfer characteristics. Experimentally, studies have shown that nano-graphene mixed dielectric fluids improve key machining outcomes including material removal rate (MRR) and surface roughness (SR).

These nano-additives facilitate higher MRR by enhancing the energy density of the electrical discharges while simultaneously decreasing SR through finer and more uniform spark erosion. The presence of graphene nanoparticles improves thermal conductivity and debris removal, leading to a more stable machining process and reduced surface defects. Such improvements are particularly valuable for machining NiTi shape memory alloys where surface quality directly affects functional properties. Optimization of the nano-powder concentration along with electrical parameters is essential to maximize the benefits without inducing unstable spark discharges or wire breakage [2].

3.3 Parametric Optimization Techniques

To manage the complexity of process parameters affecting WEDM outcomes, statistical and computational optimization techniques are widely applied. The Taguchi methodology, using orthogonal arrays such as L16, enables systematic experimentation while reducing the number of tests required to explore parameter spaces. In the context of WEDM for NiTi alloys with nano-graphene dielectric fluids, factors such as current, pulse-on time, pulse-off time, and nano-powder concentration are varied to assess their influence on MRR and SR.

Computational heuristic algorithms like the Heat Transfer Search (HTS) algorithm have been utilized in conjunction with Taguchi designs to identify optimal parameter settings. HTS supports the discovery of parameter combinations that maximize MRR or minimize SR, and the simultaneous consideration of both objectives facilitates efficient trade-off analysis through Pareto optimal solutions. These multi-objective optimizations are critical for balancing productivity and quality, enabling tailored process configurations for machining smart materials where surface integrity is vital for subsequent functional behavior [2].

4. DIRECTED ENERGY DEPOSITION (DED) IN ADDITIVE MANUFACTURING

4.1 Overview of DED Technologies

Directed Energy Deposition (DED) is a prominent additive manufacturing technique wherein focused energy sources—such as lasers, electron beams, or electric arcs—are used to melt feedstock material simultaneously with its deposition onto a substrate. DED encompasses diverse modalities including powder-fed and wire-fed systems, with operational variants tailored to the specific energy source and feedstock form. Laser- and powder-based DED methods, for instance, support precision fabrication with fine feature resolution, whereas wire-fed systems like WAAM excel in high deposition rate applications.

The fundamental principle involves creating a melt pool on the substrate surface as material is delivered, resulting in metallurgical bonding and layer growth. International standards from ISO and ASTM classify these processes, providing terminology and test methods conducive to industrial adoption. This standardization facilitates comparability and quality assurance across DED platforms while highlighting the technological diversity within the category. DED's versatility makes it suitable for repair, hybrid manufacturing, and functionally graded components, enabling industry-specific customization [3].

4.2 Defect Formation Mechanisms and Analysis

Defect formation in DED processes remains a critical challenge impacting the structural integrity and performance of fabricated parts. The rapid melting and solidification inherent to the process induce complex thermal gradients, leading to various defect types including porosity, cracking, lack of fusion, and residual stresses. Porosity can emerge from entrapped gases or insufficient overlapping of melt pools. Cracks often result from thermally induced stresses that exceed the material's fracture toughness, while lack of fusion appears from inadequate energy input or poor material feeding.

Process parameters such as energy density, powder feed rate, scanning speed, and shielding atmosphere greatly influence defect formation. The dynamic interactions between process variables and material properties necessitate thorough mechanistic understanding which informs defect mitigation strategies. Metallurgical phenomena such as dendritic solidification, grain boundary formation, and phase transformations occur on this microscopic level, demanding advanced characterization techniques to detect and quantify defects with precision. Consequently, defect analysis supports the refinement of process windows that optimize part quality within the constraints of manufacturing efficiency [3].

4.3 Quality Monitoring and Non-Destructive Testing (NDT)

Ensuring quality in DED-manufactured components requires robust monitoring and testing methodologies. In situ monitoring technologies capable of real-time detection of process anomalies and defect emergence are essential for reducing scrap and enabling adaptive control. Traditional NDT methods such as ultrasonic testing and radiography remain valuable but are often limited post-production and may lack sensitivity for early defect detection.

Advances in machine vision technologies have enabled automated geometric inspection during fabrication, capturing layer deformation and surface irregularities with high resolution. The integration of sensor data with multiphysics simulation models and data analytics is establishing the foundation for Digital Twins—virtual process replicas that mirror real-time manufacturing conditions. This integration allows predictive maintenance and dynamic process adjustments, significantly enhancing the accuracy and efficiency of DED systems.

Although these advancements offer promising pathways to superior quality assurance, gaps remain in fully realizing real-time defect prediction and control, necessitating ongoing research into sensor fusion, artificial intelligence algorithms, and multi-scale modeling frameworks [3].

5. PROCESS OPTIMIZATION TECHNIQUES IN NON-CONVENTIONAL MANUFACTURING

5.1 Experimental Design and Statistical Methods

Optimization in non-conventional manufacturing is underpinned by systematic experimental designs and robust statistical methodologies. Taguchi's orthogonal arrays constitute a widely used approach to design experiments that efficiently explore multiple process variables and their interactions with a minimal number of trials. This approach is effective in identifying significant factors influencing machining outputs and additive manufacturing quality.

Multi-objective optimization techniques and response surface methodologies further enable modeling of complex relationships between input parameters and performance metrics such as surface finish, mechanical strength, and productivity. Within WAAM and WEDM contexts, these methodologies have been applied to fine-tune energy inputs, feed rates, pulse characteristics, and environmental conditions, yielding optimized process windows for targeted material and product characteristics. The structured approach of DOE and statistical analysis facilitates reproducibility and improves process understanding necessary for industrial scalability [2].

5.2 Computational Algorithms and Heuristic Methods

Complementing statistical methods, heuristic and metaheuristic algorithms provide powerful tools for process parameter optimization in non-conventional manufacturing. The Heat Transfer Search (HTS) algorithm is an example utilized in WEDM optimization, emulating thermal energy transfer principles to efficiently search plausible parameter configurations that balance conflicting objectives like material removal rate and surface roughness.

Additionally, evolutionary algorithms and genetic algorithms have gained traction due to their ability to navigate multi-dimensional search spaces and handle nonlinear relationships commonly encountered in machining and additive manufacturing processes. These algorithms can be hybridized with physics-based models, merging data-driven insights with mechanistic understanding to accelerate optimization and robustness.

Such computational techniques augment experimental methods by narrowing practical parameter ranges and enabling adaptive optimization strategies that can respond dynamically to real-time data, advancing the precision and reliability of manufacturing outputs significantly [2].

5.3 Integration of Real-Time Monitoring and Feedback Control

The ultimate goal in process optimization is to achieve closed-loop control where real-time sensor data informs immediate adjustments to process parameters, ensuring consistent quality. In non-conventional manufacturing, coupling high-resolution sensors with advanced control algorithms allows adaptive modulation of energy input, deposition speed, or spark characteristics.

Machine learning models trained on historical and real-time data are capable of predicting defects and deviations before they materially impact the part, enabling preventative interventions. This integration is exemplified in DED systems employing Digital Twin frameworks, where sensor feedback tightens control over melt pool geometry and thermal profiles.

Industrial deployments of such systems demonstrate substantial improvements in part quality and process efficiency, although challenges related to sensor integration, data latency, and algorithm interpretability remain targets of ongoing research and development efforts [3].

6. MATERIAL CHARACTERIZATION AND MECHANICAL BEHAVIOR

6.1 Metallurgical Changes in Additively Manufactured Components

The metallurgical landscape of components produced through additive processes such as WAAM and DED differs substantially from conventional manufacturing due to rapid thermal cycles and layer-by-layer solidification. Microstructural evolution encompasses formation of columnar grains, texture variations, and non-equilibrium phases governed by localized cooling rates and thermal gradients. These features affect grain size distribution, phase morphology, and defect incorporation, directly influencing mechanical behavior.

Process parameters modulate thermal input, which in turn dictates grain refinement and transformation kinetics. Optimizing these conditions can reduce undesirable features like segregation or residual stresses, producing microstructures comparable or superior to traditional forged or cast materials. Advanced characterization techniques, including scanning electron microscopy and X-ray diffraction, provide insights into these transformations and guide process adjustments for targeted material properties [1].

6.2 Mechanical Properties and Performance Assessment

Mechanical testing of additively manufactured components assesses tensile strength, hardness, fatigue resistance, and impact toughness as critical indicators of performance reliability. WAAM and DED techniques, under properly controlled parameters, produce components with mechanical strengths meeting or exceeding those of wrought materials. However, the presence of process-induced defects such as porosity or micro-cracks can significantly degrade tensile and fatigue properties.

Post-processing treatments like heat treatment and surface finishing further enhance mechanical behavior by relieving residual stresses and refining surface roughness. Systematic performance assessment is crucial, especially for safety-critical applications in aerospace and nuclear industries. Hence, the characterization of mechanical behavior remains an integral part of process validation and certification protocols [1].

6.3 Composite and Multi-Material Structures

One of the exciting capabilities of WAAM is the simultaneous deposition or cladding of two different materials to fabricate composite structures tailored for specific functional requirements. This multi-material approach allows property gradients or enhanced interface characteristics otherwise unattainable through monolithic fabrication.

Challenges include controlling interfacial bonding, mitigating residual stresses from material incompatibility, and ensuring microstructural continuity. Research has focused on process parameter fine-tuning and intermediary layer strategies to optimize bonding strength and minimize defects. Such advancements support the development of functionally graded materials and novel component designs that meet diverse operational demands [1].

7. SUSTAINABLE AND EFFICIENT MANUFACTURING APPROACHES

7.1 Energy and Material Efficiency in Non-Conventional Processes

Non-conventional manufacturing processes contribute significantly towards sustainability goals by reducing raw material wastage and energy consumption. WAAM exemplifies efficient utilization of feedstock wire, with minimal leftover scrap compared to bulk casting or machining. Additionally, its high deposition rates lead to shorter production cycles, further minimizing energy consumption.

These efficiencies extend to non-traditional machining, where process innovations like nano-particle mixed dielectrics in WEDM reduce thermal damage and improve machining precision, allowing for fewer reworks and less material waste. Consequently, these technologies align with green manufacturing initiatives and circular economy principles aimed at minimizing environmental impact [1].

7.2 Advancements in Battery Manufacturing: Dry Electrode Technologies

Although distinct from metal fabrication, battery manufacturing benefits from innovations in non-conventional processes through the emergence of dry electrode technologies. Contrasted with traditional wet processes that involve solvent usage and high energy input for drying, dry electrode fabrication reduces environmental footprint significantly by eliminating solvent emissions and lowering energy consumption.

These advancements offer economic benefits by streamlining production and enabling higher energy density electrodes critical for energy storage applications. Research in this area highlights the synergy between material science and process engineering essential for sustainable manufacturing at scale, a paradigm transferable to metal AM and machining sectors as well [4].

7.3 Future Directions Toward Sustainable Industry

Looking forward, the sustainable manufacturing landscape increasingly intersects with non-conventional technologies that leverage process innovation and material advancements. Elevating technology readiness levels through continuous optimization, enhanced process control, and multi-material capabilities will promote widespread adoption.

Integration with circular economy frameworks—where material reuse, repair, and recycling are intrinsic—further supports sustainability. The collaborative evolution of manufacturing technology and environmental stewardship thus forms the foundation of future industry paradigms centered on efficiency, cost-effectiveness, and reduced ecological impact [4].

8. CHALLENGES AND LIMITATIONS IN NON-CONVENTIONAL MANUFACTURING

8.1 Process-Related Constraints

Despite significant advancements, non-conventional manufacturing processes face inherent limitations. In WAAM and broader DED methods, controlling heat input remains a critical challenge; excess thermal energy can introduce undesirable residual stresses and component distortion. Maintaining dimensional accuracy and superior surface finishes is complex due to thermal expansion and layer-wise deposition irregularities.

Defect formation, including porosity and cracking, continues to limit mechanical performance and process reliability. The mitigation of these issues demands sophisticated control systems and refined process parameter windows, which are still under optimization in many industrial contexts [1].

8.2 Material and Compatibility Issues

Non-conventional methods must also address material-specific challenges, especially when processing emerging alloys and composites. For example, the addition of nano-materials to dielectric fluids in WEDM may impact machining stability and spark behavior, requiring careful balancing to avoid adverse effects.

Multi-material WAAM depositions necessitate precise interface control to ensure bonding without compromising structural integrity. Achieving compatibility across diverse material systems calls for advanced process designs and understanding of metallurgical phenomena governing interdiffusion and residual stresses [2].

8.3 Technological and Industrial Barriers

From a broader perspective, the full potential of non-conventional manufacturing is tempered by industrial and technological barriers. Robust monitoring and quality assurance tools are essential but are currently limited by sensor capabilities and data integration challenges. Scalability and cost competitiveness also remain concerns relative to established conventional technologies.

Moreover, the lack of comprehensive standards and certification frameworks for new processes and materials slows adoption in regulated industries. Addressing these issues requires coordinated efforts in research, standardization, and industrial collaboration to translate laboratory successes into commercially viable solutions [3].

9. EMERGING TRENDS AND FUTURE RESEARCH DIRECTIONS

9.1 Digital Twins and Advanced Simulation Integration

Emerging trends emphasize the creation of Digital Twins, virtual replicas of manufacturing processes that integrate physics-based multiphysics simulations with real-time sensor data. This integration allows for predictive maintenance, early defect detection, and process parameter optimization, thereby significantly enhancing manufacturing accuracy and reducing waste.

Advanced simulation tools combine thermal, mechanical, and metallurgical models to forecast process outcomes over multiple scales, supported by data-driven algorithms that learn from historical and current production. This field is rapidly evolving and poised to revolutionize adaptive control and quality assurance in directed energy deposition and related processes [3].

9.2 Advanced Materials and Hybrid Manufacturing

Future research is progressing toward incorporating novel metal alloys with enhanced functionalities into additive manufacturing frameworks. WAAM and similar technologies are exploring composite materials and functionally graded structures to meet increasingly stringent performance requirements.

Hybrid manufacturing systems that combine additive and subtractive techniques in a single production line enable superior surface finishes and dimensional tolerances. Development of multi-material and multi-functional components through such hybridization opens avenues for innovative product designs and expanded application domains [1].

9.3 Intelligent Process Optimization and Automation

Artificial intelligence and machine learning continue to advance as integral components of process optimization. These technologies enable intelligent selection of process parameters, autonomous adjustments during manufacturing, and automated experimental designs that reduce trial-and-error approaches.

The trajectory toward fully autonomous manufacturing systems envisions real-time adaptive control loops that balance productivity, quality, and sustainability without human intervention. Progress in sensor technology, data analytics, and control theory underpins this transformation, marking a significant step in modern industrial manufacturing evolution [2].

10. CONCLUSION AND INDUSTRIAL IMPACT

10.1 Summary of Advances in Process Optimization and Applications

The last decade has witnessed profound improvements in non-conventional manufacturing technologies through advancements in Wire Arc Additive Manufacturing, Wire Electrical Discharge Machining, and Directed Energy Deposition methods. Progress in process parameter optimization, defect control, and quality assurance has brought these methods closer to wide industrial acceptance. Integration of experimental designs, heuristic computational algorithms, and real-time monitoring has elevated the efficiency, reliability, and mechanical performance of additively manufactured and non-traditionally machined components.

10.2 Industrial Adoption and Economic Considerations

Industries have begun reaping the benefits of these technologies in terms of enhanced component customization, reduced material costs, and shortened production cycles. However, challenges remain in scaling these systems economically while meeting stringent quality and regulatory standards. Addressing such barriers through innovation in monitoring, standardization, and materials processing will be critical for broader adoption.

10.3 Outlook for Future Manufacturing Paradigms

Looking ahead, the convergence of advanced material science, digital simulations, intelligent algorithms, and automation promises to transform global manufacturing paradigms profoundly. Non-conventional manufacturing techniques will form the backbone of this transformation, enabling sustainable, flexible, and efficient production ecosystems. Continued interdisciplinary research and industrial collaboration will be necessary to unlock the full potential of these cutting-edge manufacturing technologies [1].

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