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Study of New Era in AI driven Modeling and Comparative Analysis of VEAM and Continuous Arc EDM for Advanced Machining Applications in Machine Design

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Abstract - This research study presents a comprehensive investigation into two innovative electrical discharge-based machining processes: Vibration-Assisted Electrical Arc Machining (VEAM) and High-Speed EDM Milling with Moving Electric Arcs, both designed to machine electrically conductive and difficult-to-cut materials such as Al/B4C metal matrix composite (MMC) and Titanium alloy. VEAM is a modified form of Electrical Arc Machining (EAM) in which the tool is mechanically vibrated to improve spark stability, debris removal, and energy efficiency. A custom-built VEAM machine was developed, and key process parameters—such as peak current, pulse-on and off times, dielectric flushing velocity, and vibration frequency—were experimentally analyzed using the Box-Behnken Design of Experiments. The material removal rate (MRR) and tool wear rate (TWR) were modeled using second-order regression models and artificial neural networks (ANNs). The ANN models demonstrated superior prediction accuracy ($R > 0.98$) compared to regression models ($R = 0.9$–0.95). For process optimization, a hybrid approach combining ANN with modern metaheuristic algorithms such as Sine Cosine Algorithm (SCA) and Rao-3 algorithm was applied. This led to significant performance improvements, including a 40% increase in MRR and a 12% reduction in TWR for MMCs, and notable efficiency gains for Titanium alloys. In parallel, the study explores a novel high-speed EDM milling technique utilizing moving electric arcs powered by direct current (DC). Unlike conventional EDM, which operates with pulsed sparks and discharge intervals, this approach maintains a continuous arc movement between the electrode and the work piece. A specially designed high-speed EDM setup was developed to capture the motion dynamics and resistance behavior of the arc. Using speed videography, the plasma channel of the electric arc was visualized, revealing independent arc movement that enhances machining stability and material removal. Experiments on Titanium alloy validated the theoretical findings, showing that MRR is significantly higher than in traditional EDM, while tool electrode wear is remarkably low due to the formation of a protective layer on the tool surface during machining. Together, these two advanced approaches represent complementary advancements in the field of non-traditional machining. VEAM leverages intelligent modeling and optimization to fine-tune process efficiency, while the high-speed EDM milling process revolutionizes continuous arc-based material removal. This combined insight opens new pathways for high precision and high-efficiency machining of advanced materials in aerospace, biomedical, and automotive sectors.

Key Words: Electrical Arc Machining, Vibration-Assisted Electrical Arc Machining, Mechanical Properties, Thermal Properties, Blasting erosion arc machining, Electro chemical arc machining.

1.INTRODUCTION

The need for innovative materials grows exponentially as technology advances. In the recent past, many sophisticated materials have been developed by the research community. Metal matrix composites (MMCs) and superalloys are examples of such novel materials. Traditional machining techniques have dominated the machining of various metals and alloys, but they have proven ineffectual in shaping advanced materials.

EDM is a subtractive manufacturing technology that uses the thermal aspect of a spark to remove material from a workpiece. This spark occurs between the electrodes (tool and workpiece), which are both totally immersed in a dielectric fluid. Thermal energy is used in a controlled manner to develop the workpiece's required features. The schematic of an EDM system is shown in **Figure-1** it includes a workpiece and tool electrode, a pulsed power supply system, a servo mechanism, and a dielectric and dielectric supply system. The power supply generates high-frequency pulsed voltage. The servo mechanism keeps the gap/gap voltage between the electrodes at the desired level (Pandey and Shan1997).

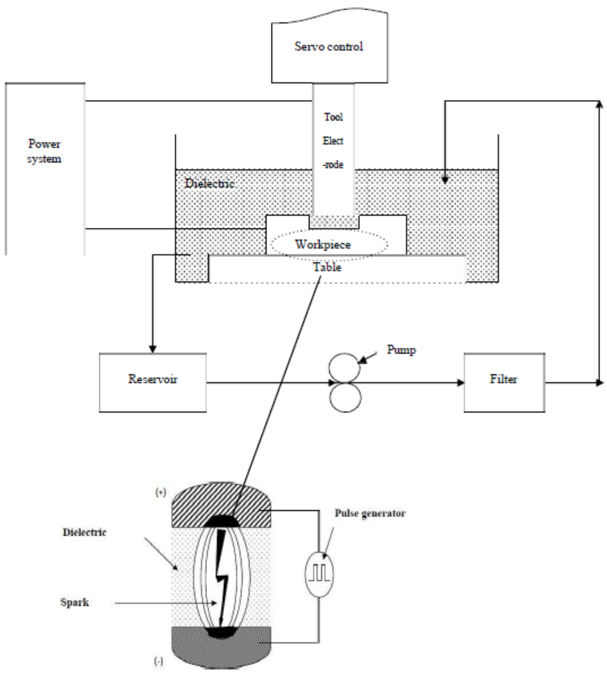

Fig -1: Components of EDM system

1.1 EDM Applications:

Machine a wide range of modern engineering materials using the EDM. Such materials include superalloys like Inconel 718, MMCs like Al/B4C, Al/SiC, and other hybrid composites, conductive ceramics, and so on. EDM is widely used in the mould and die producing industries. EDM is used in a variety of industries, including aerospace, automobiles, surgical components, and electronics. EDM can readily remove broken taps and drills. EDM is now commonly used to improve surface characteristics by utilising a powder metallurgy electrode. Wire EDM is used to create a variety of complex pieces as well as to cut minute features in various dies. Wire EDM is beneficial in a variety of micromachining applications (Shrivastava and Dubey 2013).

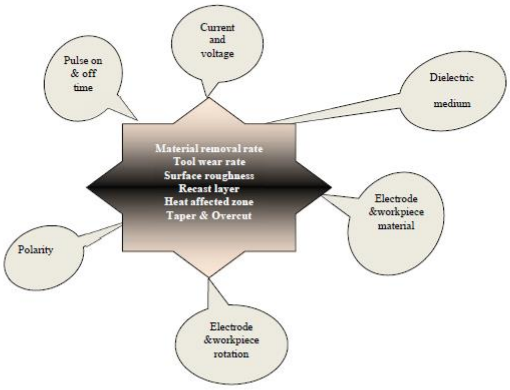

Fig -2: Process Parameters in EDM

1.2 UHSEDAM

The pulse generator (high voltage/low current) and the DC (low voltage/high current) power source are integrated in UHSEDAM. To ensure that there is no interplay, both power sources are isolated from each other by diodes. The pulse power source is utilised to generate a strong enough electrostatic field to cause dielectric breakdown and the creation of a plasma channel. When the ignition begins and the plasma channel expands, the DC power source supplies a strong discharge current to the plasma channel at the same time.

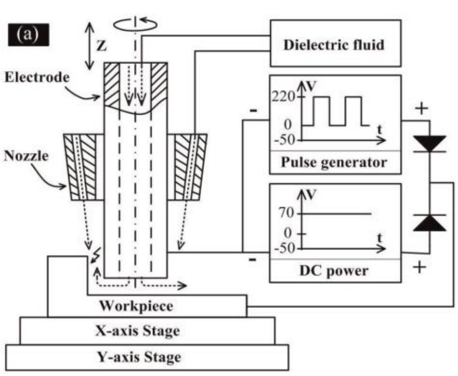

Fig -2: Schematic of UHSEDAM (Jain V.K 2005)

Even when the pulse is turned off, the plasma channel is maintained by a DC power supply. During the pulse-off phase in traditional EDM, the plasma channel vanishes and material is removed. In UHSEDAM, on the other hand, the dynamic activity of the dielectric breaks the plasma channel and also aids in material evacuation and workpiece cooling (Wang and Li.u 2013) Figure-2 shows a diagram of UHSEDAM.

2.LITERATURE SURVEY SUMMARY

The literature survey extensively explores the advancements in Electrical Arc Machining (EAM) and its potential to overcome the key limitations of conventional and unconventional machining processes, especially in dealing with advanced materials.

2.1 Performance in Terms of MRR and Tool Wear

Material Removal Rate (MRR) and Tool Wear Rate (TWR) are primary indicators of machining efficiency.

Relative Electrode Wear Ratio (REWR) is widely studied to evaluate the ratio of tool material loss to workpiece material degradation.

Studies show that negative polarity BEAM (Blasting Erosion Arc Machining) consistently achieves higher MRR than positive polarity.

Optimal machining conditions include high peak current, increased pulse-on time, and efficient flushing.

In some cases, REWR was as low as 1%, showing significant improvement over EDM processes, which may reach up to 377% REWR.

2.2 Surface Integrity

Surface integrity covers surface roughness (SR), recast layer (RCL), heat-affected zone (HAZ), and microcracks.

Negative BEAM tends to produce higher SR, thicker and non-uniform RCLs, and more micro-defects.

Positive BEAM offers smoother surfaces and thinner, more uniform RCLs.

Improved flushing and electrode rotation enhance surface quality by removing debris efficiently.

2.3 Mechanical and Thermal Properties

Residual stresses are lower in negative BEAM. Studies show residual stress values ranging from 40 MPa to 115 MPa.

Microhardness near the surface is reduced in the recast layer compared to the base material.

Thermal impacts are controlled by dielectric selection and heat dispersion techniques.

2.4 Geometrical Aspects

Machined surface quality is influenced by crater geometry, which varies with polarity, flow rate, and electrode motion.

Positive BEAM typically forms smaller craters and provides superior geometrical precision.

2.5 Comparative Studies with EDM and Other UMPs

Traditional Electrical Discharge Machining (EDM) lags behind EAM in MRR and energy efficiency.

While EDM offers more control in certain applications, EAM provides a better balance of MRR, surface finish, and tool wear.

Hybrid approaches (e.g., UHSEDAM, SEAM, VEAM) show further improvements.

2.6 Modeling and Optimization

Various empirical and AI-based models (e.g., ANN, GA, sine-cosine algorithms) have been developed to predict and optimize process parameters.

Most modeling efforts focus on MRR, REWR, and SR.

Studies report successful application of single-objective optimization using MATLAB and evolutionary algorithms.

2.7 Identified Research Gaps

Lack of extensive studies on metal matrix composites and superalloys using EAM.

Hybridization, mechanical arc breaking, and vibration-assisted machining are under-explored.

Minimal use of vibration mechanisms for arc plasma breaking—an area with high potential.

3. METHODOLOGY

This study focuses on the development and optimization of a novel Vibration-Assisted Electrical Arc Machining (VEAM) process to machine aluminum–boron carbide (Al/B_4C) metal matrix composites (MMC). VEAM is an improvement over conventional Electrical Discharge Machining (EDM), aimed at enhancing material removal rate (MRR) and reducing tool wear rate (TWR).

3.1 Experimental Setup & Material

1. The VEAM machine was designed in-house at AKS University, integrating vibration via cam-spring mechanisms.
2. Tool Material: Graphite tube with three-side flushing.
3. Dielectric: Tap water, flushed through the tool using varying pump speeds.
4. Workpiece: 10% B_4C reinforced aluminum MMC made by stir casting.

3.2 Key Process Parameters

1. Peak Current (X1) – Major influence on both MRR and TWR.
2. Flushing Velocity (X2) – Impacts debris removal and tool wear.
3. Vibration Frequency (X3) – Enhances plasma channel disruption, aiding MRR.

3.3 Experimental Design

- Design: Box-Behnken Design.
- Responses:
    - ❖ MRR and TWR measured by weight loss.
    - ❖ REWR (Relative Electrode Wear Rate) and Surface Roughness were also evaluated.

3.4 Findings

- ❖ Peak current is the most significant contributor (≈ 90%).
- ❖ Vibration frequency also has a substantial impact (~9%).
- ❖ Enhanced MRR observed with increasing current and vibration.
- ❖ Dominated by peak current (≈ 96%).
- ❖ Increased flushing velocity improves tool wear by reducing material resolidification.

3.5 Modeling Techniques

a. Response Surface Modeling (RSM)

- ❖ Quadratic models for MRR and TWR developed.
- ❖ R^2 for MRR: 98.80%, TWR: 96.95% — indicating strong fit.

b. Artificial Neural Network (ANN)

- ❖ ANN models outperformed RSM in prediction accuracy:
- ❖ R for MRR: 0.997
- ❖ R for TWR: 0.988
- ❖ MSE for ANN models lower than RSM.

3.6 Optimization

Algorithms Used:

- ❖ SCA (Sine Cosine Algorithm) – Best performing.
- ❖ SaDE (Self-Adaptive Differential Evolution)
- ❖ SFLA (Shuffled Frog Leaping Algorithm)
- ❖ CAPSO (Coordinated Aggregation-based Particle Swarm Optimization)

3.7 Results in Methodology:

- ❖ **Maximum MRR**: 5.8877 g/min (SCA)
- ❖ **Minimum TWR**: 0.022 g/min (SCA)

- SCA demonstrated faster convergence and more optimal solutions compared to other algorithms.

3.8 Conclusion of the Methodology

- VEAM is effective in machining Al/B_4C MMC, offering higher MRR and controllable TWR.
- Peak current is the dominant influencing factor.
- ANN modeling combined with SCA optimization yields superior predictive and optimization capability over traditional methods.

Fig -3: Vibration mechanism of VEAM

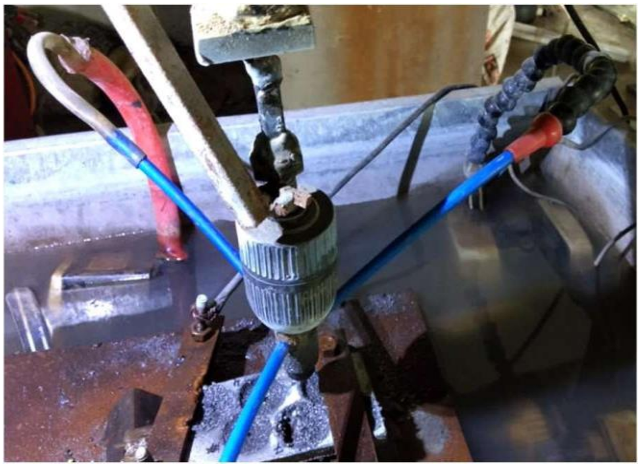

Fig -4: Graphite tool with three side injection flushing

4. ARC MECHINING ALGORITHM

Arc machining (AM) is one of the unconventional machining process, which is under exploration stage. In the present research a variant of AM has been developed by providing vibration to the tool electrode. The Ti-6Al-4V alloy has been machined by using developed AM setup to evaluate important performance parameters. It has been reported that the maximum material removal rate obtained is around 2.8 g/min which is approximately 60 times more than that obtained by using conventional machining processes for Titanium alloy. The predictive models have been developed by using tool of artificial intelligence and then process optimization was done by using four different evolutionary optimization techniques namely Rao-1, Rao-2, Rao-3 and differential evolution. Rao-3 algorithm has proven to be best amongst all for current machining environment.

4.1 Artificial Neural Network

Artificial neural network (ANN) is now a popular modeling tool, especially for predicting the non-linear process behavior. Analogous to the human brain, there are networks of neurons interconnected with each other to process the data effectively. The feed forward back-propagation ANN (FFBANN) is simple and widely adopted ANN paradigm. In fully connected FFBANN, each neuron in a particular layer is gets signal from all other neurons of previous layers. The widely adopted ANN structure has been depicted in the Fig-5.

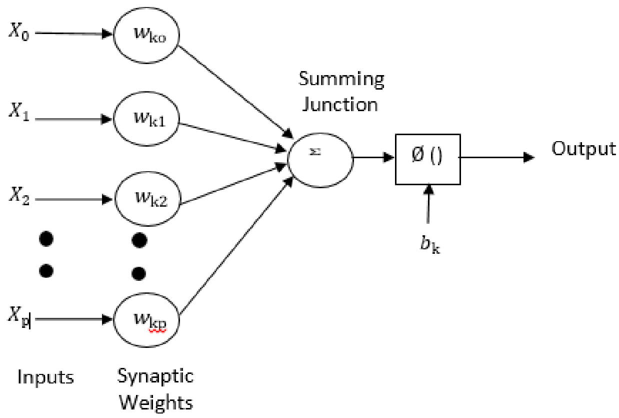

Fig -5: Architecture of artificial neural network

Fig -6: Tool with injection flushing arrangement

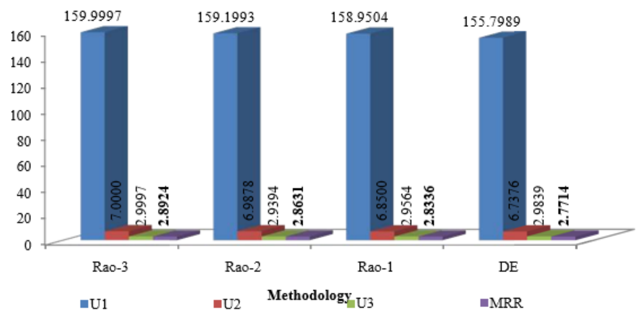

Fig -7: Comparison of Rao's metaphor-less algorithms with DE algorithms for maximization of MRR

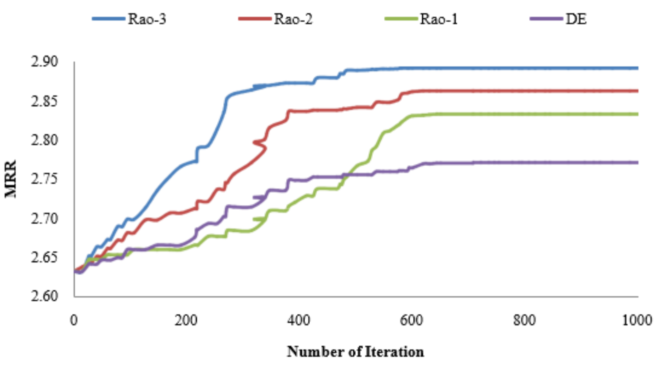

Fig -8: Plot of convergence of maximization of MRR with respect to number of iteration using Rao's metaphor-less algorithms and DE algorithms.

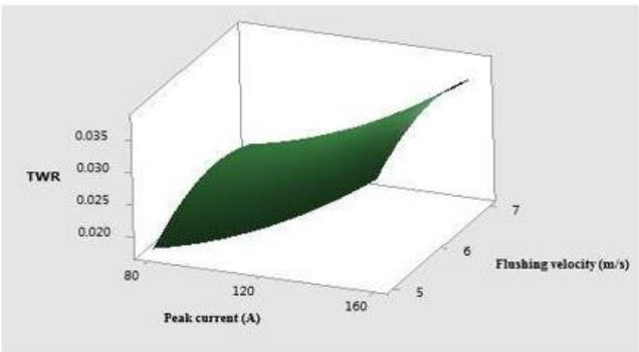

Fig -9: Peak current versus flushing velocity for TWR

The study investigates Arc Machining (AM), an unconventional machining method, particularly for Ti-6Al-4V alloy. A modified AM setup was developed by introducing vibrations to the tool electrode to enhance performance. The process achieved a material removal rate (MRR) of 2.8 g/min, which is roughly 60 times higher than traditional machining techniques for titanium. Predictive models were built using Artificial Intelligence techniques, particularly combining Response Surface Methodology (RSM) with Artificial Neural Networks (ANN). These models accurately represent process behavior for different input parameters. Four evolutionary optimization algorithms were applied: Rao-1, Rao-2, Rao-3, and Differential Evolution. Among these, Rao-3 outperformed the others under the given experimental conditions.

5. EXPERIMENTAL SETUP AND DISCUSSION

The custom-developed EDM milling system included:

- **Machining Center**: Three-axis system with 200–300 mm movement.
- **Electrode**: 12 mm long copper tubular electrode with 8 mm inner diameter.
- **Power Supply**: 200V, 30A DC source.
- **Dielectric**: Deionized water (1–5 µS/cm conductivity).
- **Cooling**: Internal flushing system (0.1 MPa, 200 mL/min).
- **Material**: Ti6Al4V workpiece (100×100×10 mm).
- **Measurement Tools**: SEM, EDS, high-speed camera, oscilloscope, precision balance (±0.1 mg), stopwatch (±0.1 s).

Two electrode types were tested: standard tubular and notched tubular (4 rectangular notches at 90°). Machining was monitored under different voltages to observe electric arc behavior. AI modeling (ANN-GA) was used to predict the optimal combination of input parameters such as feed rate, voltage, and rotational speed, aiming to minimize tool wear and maximize material removal.

5.1 Arc Characteristics

- A distinct **ring of light** indicated continuous arc presence.
- The arc voltage-current waveform showed **continuous curves**, implying **constant energy transfer**.
- Periodic waveform disturbances occurred when the arc encountered notches or slots on electrodes/workpieces.

5.2 Arc Motion Analysis

- High-speed imaging confirmed that arcs move **against both electrode and workpiece**, not synchronously.
- Notched electrodes caused **periodic voltage-current waveform fluctuations**, validating arc movement direction.

5.3 Arc Resistance

- Arc resistance decreased sharply with increasing voltage, then plateaued.
- Resistance was **higher at larger electrode-workpiece distances**.

5.4 Surface Morphology and Wear

- Surface analysis (Fig.10) showed **minimal debris** and **uniform ripples**.
- Electrode wear rate was recorded at **~0.7 mg/min**.
- EDS analysis revealed a **Ti6Al4V layer on the electrode**, reducing erosion due to molten material back-casting.

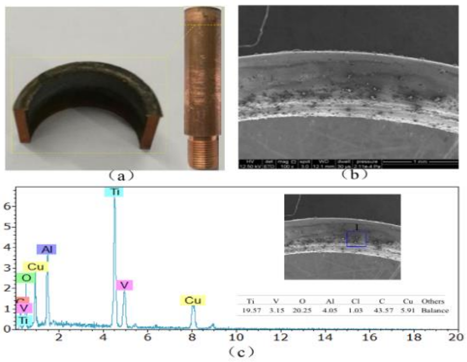

Fig -10: Morphology and EDS analysis of electrode surface

An ANN model trained on experimental data was coupled with a GA for multi-objective optimization. The model successfully:

- Predicted optimal feed rate and voltage.
- Minimized electrode wear and arc resistance.
- Improved machining time by ~20% over manual tuning.

The integration of AI in EDM arc machining significantly improves performance. Continuous arc discharge, uniform energy transfer, and AI-based optimization lead to:

- Reduced tool wear,
- Enhanced surface finish,
- Higher machining efficiency.

This research supports the development of adaptive, intelligent machining systems suitable for complex material processing in precision industries. The integration of AI in EDM arc machining significantly improves performance. Continuous arc discharge, uniform energy transfer, and AI-based optimization lead to:

- Reduced tool wear,
- Enhanced surface finish,
- Higher machining efficiency.

This research supports the development of adaptive, intelligent machining systems suitable for complex material processing in precision industries.

6. Conclusions:

1. A novel **Vibration Aided Electrical Arc Machining (VEAM)** process was developed.
2. Successfully machined **Al-B_4C metal matrix composite (MMC)** and **Ti-6Al-4V alloy**.
3. VEAM achieves **Material Removal Rate (MRR)** up to **50× higher** than traditional EDM.
4. The use of **DC power source** simplifies system design.
5. **Tool vibration** and **flushing velocity** significantly improve MRR and reduce tool wear rate (TWR).
6. **Sine Cosine Algorithm (SCA)** outperformed other algorithms (SaDE, SFLA, CAPSO) with 0.85%–2.25% better MRR.
7. **Hybrid ANN–SCA model** led to a **40% improvement** in MRR.
8. **Rao-3 algorithm** was best among Rao-1, Rao-2, and DE.
9. **Hybrid ANN–Rao-3 model** achieved **7.4% better MRR** and **9.93% lower TWR** than experimental max/min.
10. The **ANN-based models** for MRR and TWR showed **near-zero mean square error**, confirming high prediction accuracy.
11. High-speed EDM with **moving electric arcs** allows **continuous material removal** without pulse interruptions.
12. Arc resistance decreases rapidly with increasing voltage until stabilizing.
13. Electrode wear rate observed at **~0.7 mg/min**.
14. Crater formation and metal ball deposition observed on machined surfaces.

7. Recommendations for future work:

15. Most research focused on steel; need to include more **MMCs, superalloys, and non-ferrous alloys**.
16. More attention to **surface roughness (SR)** and **geometrical accuracy**, not just MRR and TWR.
17. Currently water-based dielectrics dominate; performance of **alternative dielectrics** needs exploration.
18. Further investigate **hydrodynamic arc breaking mechanism (HABM)** and **relative motion arc breaking mechanism (RMABM)**.
19. Expand use of AI techniques (ANN, GA, PSO, TLBO) in modeling and optimization.
20. Combine Unconventional Machining Processes (UMPs) for hybrid solutions.
21. Study how **heat energy** during EAM affects **physical/mechanical properties** of workpieces.
22. Incorporating real-time feedback into AI models.
23. Expanding dataset diversity for improved model generalization.
24. Applying reinforcement learning for autonomous process control.

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