Research on Automotive Mechanical Manufacturing Processes and Precision Machining Technology

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Abstract: As the automotive industry advances toward electrification, lightweight design, and intelligent features, the requirements for component machining accuracy, surface quality, and material utilization have increased significantly. Traditional rough machining processes can no longer meet the demands of modern vehicles for high-performance engines, chassis components, and lightweight aluminum parts. This paper first reviews the application characteristics and optimization strategies of casting and forging processes in the manufacture of key automotive components such as engine blocks and transmission housings, and it explains the roles and synergy of sheet metal forming and welding technologies in body panels and modular chassis production. Next, this study delves into key CNC machining technologies—multi-axis kinematic machining, high-speed cutting, and tool-parameter optimization—as well as the applications of micro-machining and surface treatment for small-feature components like electronic sensor housings and fuel-system microchannels. By combining the concepts of flexible manufacturing systems and digital workshops, and through case analysis and experimental validation, a scheme is proposed for linking casting/forging rough machining to precision CNC machining. Utilizing digital twin technology and online monitoring, the process is visualized and optimized in a closed loop. Experimental results show that, by reasonably planning tool paths, optimizing cutting parameters, and introducing automated assembly units, part dimensional accuracy can be improved to within ±0.005 mm, surface roughness reduced to Ra 0.4 μm, production cycles shortened by 15 %–20 %, and yield rates increased by 12 %. Finally, with the lightweight and high-performance requirements of new energy vehicles in mind, future directions are projected: intelligent tool-path planning, online quality inspection, and green manufacturing technologies. This work provides both theoretical guidance and practical reference for building an efficient, low-consumption, and sustainable automotive mechanical manufacturing and precision machining system.

1. Introduction

Driven by global energy-saving policies and consumer demand for higher-quality vehicles, the automotive industry is rapidly shifting toward electrification, lightweight design, and intelligent features. These trends place unprecedented demands on component machining accuracy, surface finish, and material efficiency. Traditional casting and forging—valued for low cost and high

productivity—still produce critical parts like engine blocks and transmission housings, but issues such as porosity, shrinkage defects, and excessive forging allowances no longer meet modern precision and performance requirements. Meanwhile, thin-sheet designs using high-strength steel and aluminum alloys introduce challenges in sheet-metal forming and welding. Precision machining—CNC, multi-axis kinematics, and high-speed cutting—helps overcome these limitations but requires optimized tooling, cutting parameters, and thermal control. Micromachining and advanced surface treatments create small, high-aspect-ratio features, boosting wear resistance and fatigue life. Flexible manufacturing and automated assembly support multi-model, small-batch, and customized production, yet linking casting/forging, sheet-metal/welding, and precision machining into a cohesive workflow remains a challenge. Globally, Germany, Japan, and the US lead in CNC, digital twins, and intelligent manufacturing, achieving full-process control from design to assembly. Although Chinese manufacturers have advanced in casting, forging, CNC adoption, and simulation, gaps remain in mold design, defect detection, micromachining, online quality monitoring, and thermal-deformation control. Most have yet to build mature digital workshops or intelligent manufacturing systems, resulting in limited integration, flexibility, and traceability. To meet electric vehicle requirements, a fully coordinated process chain—from casting and forging through sheet-metal forming, welding, precision machining, and intelligent assembly—must be established, leveraging digital twins, big data, and artificial intelligence for closed-loop optimization and online quality control throughout the product life cycle.

2. Overview of Automotive Mechanical Manufacturing Processes

2.1. Casting and Forging Process Technology

Casting remains a fundamental process in automotive manufacturing for producing complex, load-bearing parts like engine blocks, transmission housings, and wheels. Molten metal or alloy is poured into sand or metal molds, yielding intricate features—internal passages, ribs—in one step, which improves material use and reduces machining stress. Common techniques include sand casting, investment (lost-wax) casting, and precision casting. Sand casting is cost-effective but prone to porosity and dimensional deviation, whereas investment and precision casting—using wax patterns and shell molds—offer superior surface finish and accuracy at higher mold-making cost. Recent innovations such as chill-core casting, vacuum low-pressure pouring, and ultrasonic-vibration casting further reduce gas entrapment and shrinkage defects[1]. By simulating mold filling and solidification during design, and optimizing gating and riser placement, stress concentrations are minimized, increasing yield and consistency in subsequent machining.Forging is preferred for high-strength parts—crankshafts, connecting rods, camshafts, and axle housings—because it refines grain structure, increases density, and enhances mechanical performance. Methods include open-die forging, drop-hammer forging, and closed-die (precision) forging, the latter producing near-net shapes with uniform properties. Forged parts exhibit excellent fatigue strength and impact resistance, but die costs and forging forces are substantial. To address these challenges, manufacturers increasingly use high-strength aluminum and titanium alloys for lightweighting and apply finite-element modeling to optimize forging parameters—temperature, pressure, strain rate, and deformation—to reduce defects and ensure uniform stress. Techniques such as stepped allowances, die venting channels, and isothermal forging further decrease internal stresses and surface roughness, resulting in stable blanks for downstream CNC machining. By integrating casting and forging based on load requirements and optimizing material selection and die design, lightweight, high-performance components can be produced while balancing cost and cycle time[2].

2.2. Sheet-Metal Forming and Welding Process Technology

Sheet-metal forming is essential for producing body panels, doors, roof panels, and chassis structures, contributing to lightweight construction, high strength, and a consistent appearance. Typical forming methods include stamping, shearing, bending, stretching, and deep drawing, each applying controlled forces to shape the sheet within its plastic deformation limits. Die design directly influences dimensional accuracy and forming quality, while sheet properties—yield strength, thickness consistency—and lubrication affect residual stress and springback. To minimize warping and cracking, manufacturers use finite-element simulation to analyze material flow and die loads, optimizing parameters such as stamping speed, die clearance, and lubricant type, as well as die geometry features like rib reinforcements and fillet radii. The increasing use of high-strength steel, ultra-high-strength steel, and aluminum alloys for lightweight vehicles heightens the need to control springback and maintain bending stiffness and ductility, achieving thin-sheet formability without sacrificing material performance.Welding complements sheet-metal forming by assembling separate panels into a unified body structure with overall stiffness and strength[3]. Common methods include spot welding, arc welding, laser welding, and friction welding. Spot welding—known for speed and precision—is widely used for body panels, while arc welding typically joins chassis frames and suspension parts. Laser welding, favored for its narrow heat-affected zone and fine weld bead, is increasingly applied to ultra-high-strength steel and aluminum alloy sheets. Welding heat input generates localized thermal stresses and distortion, which can compromise dimensional accuracy. To mitigate these effects, production lines integrate online monitoring and position-control systems to maintain jig and fixture alignment. Simulating weld sequencing and optimizing parameters—current, voltage, welding speed, and focus—helps reduce cracking and misalignment. For dissimilar-material joints (e.g., aluminum to high-strength steel), transition layers or hybrid filler wires are used, and laser settings are carefully controlled to ensure uniform penetration and joint integrity.Coordinating forming and welding is critical for lightweight, high-precision assembly. Proper tolerance matching and well-sequenced welding reduce dimensional stack-up in multi-part assemblies[4]. Digital simulation and virtual assembly in the planning stage uncover potential issues, allowing design or process adjustments. For instance, meeting door-to-side-body gap requirements may involve leaving allowances during stamping and employing localized preheating or staggered welding to limit distortion. In summary, sheet-metal forming and welding are vital for shaping components and assembling the complete vehicle structure. Their combined effectiveness directly impacts vehicle performance, appearance, and safety and underpins flexible production and large-scale customization[5].

3. Precision Machining Technology

3.1. CNC Machining Technology

CNC (Computer Numerical Control) machining is the core of automotive precision manufacturing and is widely used for components such as engine crankshafts, camshafts, and gears. By using computer programs to control tool paths, feed rates, and cutting depths in real time, multi-axis machining centers (e.g., three-axis, four-axis, and five-axis) can perform precision milling on multiple faces in a single setup, effectively reducing setup errors and achieving dimensional and geometric tolerances at the micron level. For different workpiece materials—such as ductile iron, quenched and tempered steel, aluminum alloys, and magnesium alloys—it is essential to select the appropriate tool substrate and coating and to adjust spindle speed, feed rate, and cutting depth according to material hardness and thermal conductivity. For example, aluminum alloys favor high spindle speeds, large feed rates, and shallow depths of cut, whereas ductile iron

requires lower spindle speeds, deeper cuts, and higher-rigidity tooling. Through numerical simulation and compensation algorithms, tool trajectories can be corrected to eliminate thermal deformation and cutting vibrations[6]. High-speed machining combined with minimum-quantity lubrication or dry cutting helps to reduce the influence of cutting heat on workpiece dimensions and surface finish, while extending tool life. To meet lightweight and complex-surface design requirements, three-dimensional modeling and tool-path optimization can be carried out in a CAD/CAM system, ensuring a constant cutting angle and a surface roughness below Ra 0.4 μm. Multi-axis machines allow multiple faces to be machined in one setup, avoiding cumulative errors from repeated repositioning and saving time that would otherwise be spent changing fixtures. By employing simulation modules for collision detection and stock-removal simulation, machining dead zones can be detected in advance and programs optimized accordingly. In the future, CNC machining will be deeply integrated with intelligent technologies: machine tools will be equipped with accelerometers, force sensors, and temperature sensors; edge computing and big-data analytics will enable online monitoring and predictive compensation for cutting vibrations, tool wear, and workpiece deformation—automatically adjusting cutting parameters or replacing tools to guarantee consistent quality. When combined with digital-twin technology, the machining process can be simulated in a virtual environment and compared with real-world data, achieving a closed-loop of virtual and physical control. This intelligent, digital workflow not only improves quality and consistency but also reduces trial-machining iterations and setup time, resulting in an efficient, flexible, and fully traceable precision-machining system[7].

3.2. Micromachining and Surface Treatment Technology

Micromachining techniques are primarily used for high-aspect-ratio or complex micro-feature components—such as fuel-injector microchannels, sensor housings, and small gears. Common methods include micro-milling, micro-drilling, laser micromachining, and ultrasonic machining. Micro-milling employs tools with diameters between 0.1 mm and 1 mm on CNC machines to achieve fine curved-surface machining, but places extremely high demands on tool rigidity, spindle dynamic balance, and vibration control. Micro-drilling is suitable for machining channels with diameters from 0.2 mm to 0.5 mm and high length-to-diameter ratios; it requires the use of wear-resistant carbide micro-drills and optimized parameters—such as spindle speed and feed rate—to ensure hole-diameter accuracy within ±0.005 mm and hole-wall roughness of Ra ≤ 0.2 μm. Laser micromachining uses ultrashort pulsed laser beams to vaporize material layer by layer; it offers noncontact processing, high speed, and a very small heat-affected zone, but requires strict control of laser power and scan path. Ultrasonic machining employs high-frequency vibration to create microcracks and remove material, making it especially advantageous for precision finishing of small holes in hard or brittle materials; however, its processing efficiency is relatively low, so it is usually reserved for special-function components. Overall, micromachining must consider material properties, tool coatings, cooling-lubrication strategies, and machine-tool stiffness—continuously optimizing via simulation and experimentation to ensure micro-feature accuracy and consistency[8].

Surface treatment technologies aim to enhance component wear resistance, fatigue performance, and bonding strength with coatings or adhesives. Ultrasonic peening uses ultrasonic energy to assist micro-shot impact, injecting compressive stress into the surface and producing nanoscale grains, which significantly improves fatigue strength. Micro-shot peening uses high-velocity ceramic or steel beads to uniformly bombard the surface, achieving controlled roughness (Ra 0.2 μm–0.4 μm) and introducing a compressive stress layer to enhance fatigue resistance under high-cycle loading. Chemical plating deposits a uniform thin film on complex geometry parts—commonly used for

sensor housings and fuel-line components—without requiring an external electric field. Electroplating involves pre-treatment steps and strict control of current density and temperature to achieve dense coatings with minimal pinholes. For dissimilar-material joints—such as aluminum alloy to high-strength steel—chemical pre-treatments combined with functional coatings can be used to enhance adhesion and prevent coating delamination or corrosion under high-temperature, high-pressure conditions[9]. By choosing appropriate treatment methods and parameters, and combining them with post-treatment processes, one can optimize surface hardness, wear resistance, and residual stress, thereby significantly improving the durability and reliability of critical automotive components[10].

4. Integrated Application of Manufacturing Processes and Precision Machining

4.1. Flexible Manufacturing and Automated Assembly

Under multi-model, small-batch, and frequently changing production requirements, traditional dedicated production lines struggle to balance efficiency and flexibility. Flexible Manufacturing Systems (FMS) address this by combining CNC machining centers, automated loading/unloading robots, storage racks, and automated guided vehicles (AGVs) within the same workshop or production cell to seamlessly transition cast or forged blanks into precision-machined components. Once a casting or forging has undergone preliminary processing, an automated conveyor system transports the blank to a multi-station CNC machining center, where roughing, semi-finishing, and finishing are orchestrated in a single, integrated workflow. Each machining station uses standardized interfaces and flexible fixtures, enabling rapid changeovers to accommodate different part dimensions and geometries—thus avoiding lengthy downtime associated with frequent die changes or equipment reconfigurations. A centralized monitoring system collects real-time data on machining status and production metrics at each station; by simulating line layout and machining paths in a digital workshop platform, bottlenecks can be identified and station sequences optimized, minimizing material transport time and in-process inventory, and maximizing overall equipment utilization. For lightweight materials (such as aluminum and magnesium alloys) and complex curved surfaces, FMS can further incorporate intelligent tool path compensation and online monitoring: multi-axis tool paths are dynamically adjusted to ensure consistent dimensional accuracy and surface finish. Automated assembly, as the downstream link in precision manufacturing, is tightly integrated with FMS to form a closed-loop process chain from blank machining to final vehicle assembly. In modular production of chassis subassemblies, axles, and engines, robotic arms and vision-guided systems handle automatic loading, positioning, fastening, and inspection of components. For example, after precision machining and surface treatment of an engine block and cylinder head, final assembly of the valve train and oil-passage components is performed by multi-joint robots that can apply high bolting torque and insert lifters with high accuracy, while vision or laser displacement sensors detect part geometry deviations in real time to provide automatic compensation. On the chassis line, robots and AGVs cooperate to transport axle housings, suspension modules, and bearings to the precise assembly station; force-control technology enables flexible press-fits, ensuring that assembly gaps meet design specifications. To reduce cumulative assembly errors, key stations feature online measurement cells that capture geometric dimensions, torque data, and tolerances immediately after assembly. These results are fed back to upstream flexible machining stations via the MES, allowing adjustment of subsequent machining parameters or jig positions and establishing a full-process quality closed loop.By organically combining flexible manufacturing and automated assembly, production lines can switch efficiently and maintain stable operations while guaranteeing machining accuracy and assembly quality—especially in a multi-model, small-batch production environment. This integrated process

design not only improves resource utilization but also allows a rapid response to market demands without substantially increasing labor costs, thereby supporting automotive manufacturers in their pursuit of lightweight, high-performance, and customized vehicles.

4.2. Intelligent Manufacturing and the Digital Workshop

As the Industry 4.0 concept advances, intelligent manufacturing and digital workshops have become key to enhancing competitiveness in the automotive sector. A digital workshop interconnects equipment, sensors, and information systems—such as machine tools, robots, fixtures, and inspection devices—via an Industrial Internet of Things (IIoT) platform, and integrates data collection with MES, ERP, and PLM systems to enable real-time monitoring and closed-loop control of production status and quality metrics. For example, when a CNC machine's tool-wear sensor detects abnormal vibration, the MES automatically issues an alert and logs the affected part lot, facilitating timely tool replacement and process improvement. Digital-twin technology creates virtual models of critical workshop equipment that mirror actual machining conditions, mechanical loads, and thermal deformation in real time. Engineers can then validate tool paths, fixture designs, and assembly workflows on the simulation platform—identifying potential collisions and process bottlenecks in advance—and also optimize line layouts and material-handling flows to minimize retrofit costs. Empowered by big-data analytics and AI algorithms, a digital workshop is not limited to data collection and visualization; it also moves toward active decision-making and adaptive optimization. By mining historical process parameters, machine responses, and quality inspection data, machine-learning or deep-learning models can be trained to predict tool life, forecast quality anomalies, and recognize production bottlenecks—helping factories quickly pinpoint root causes and implement corrective actions. For instance, in gear-grinding operations, one can analyze the relationship between dimensional deviations and grinding parameters across successive batches to train a compensation model; once a deviation trend is detected, the system automatically adjusts wheel feed paths or rotational speeds in real time. Meanwhile, AI-based vision inspection systems are widely applied in digital workshops to autonomously identify and classify weld-seam flaws, surface cracks, and coating uniformity—raising inspection accuracy and throughput while reducing human error. In summary, intelligent manufacturing and digital workshops build a highly collaborative production ecosystem through real-time data acquisition, digital-twin simulation, intelligent analysis, and closed-loop control. This approach not only elevates the visibility and controllability of manufacturing resources but also uses data-driven process optimization and predictive maintenance to lower production costs and improve quality stability—laying a solid foundation for deeply integrating automotive mechanical manufacturing processes with precision machining technologies and for steering the industry toward a greener, more flexible, and highly efficient future.

5. Experimental Research and Application Case Studies

In the experimental research phase, this study took the engine crankshaft and transmission gear as demonstration parts to design and validate optimized precision-machining processes. For the 42CrMo quenched-and-tempered steel crankshaft, the blank was first formed by hot forging, then consecutively machined on a CNC center in a "roughing → semi-finishing → finishing" sequence. Using finite-element cutting simulation, spindle speed (3,000 – 3,500 rpm), feed rate (0.08 – 0.12 mm/rev), and cutting depth (0.5 – 1.0 mm) were optimized to keep cutting vibrations and temperature rise under control, with tool life exceeding 25 parts per tool. Coordinate-measuring machine inspection showed that, after finishing, the crankshaft's critical dimension tolerances were within ±0.005 mm and roundness within 0.003 mm; X-ray residual stress measurement indicated a

peak surface compressive stress of approximately –280 MPa, and fatigue testing revealed an 18 % increase in fatigue life compared to a conventionally machined crankshaft. For the powder-metallurgy transmission gear, an "isothermal hot forging → low-speed roughing → precision CNC grinding" process was adopted. Infrared thermography monitored the thermal field during grinding, keeping local temperatures below 250 ℃ to avoid heat-check cracks. Gear measurement results showed a pitch error ≤ 0.005 mm, profile error ≤ 0.003 mm, and surface roughness Ra 0.2 μm; contact fatigue testing exhibited a 22 % increase in fatigue life.

In a real production-line case at a large domestic automaker, the precision machining line for engine blocks and crankshafts was studied. First, digital simulation optimized the layout of five primary workstations—blank feeding, roughing, semi-finishing, finishing, and online measurement—reducing queue times between the roughing and semi-finishing stations and increasing overall throughput by roughly 12 %. By installing vibration and force sensors on the five-axis machining center and the grinder, cutting-force and vibration data were streamed to the MES for edge computing. Whenever tool-wear indices exceeded preset thresholds, the system issued an automatic alert to prompt tool replacement, reducing downtime due to tool wear by about 28 % and saving approximately 18 hours per month in trial cuts and adjustments. After each grinding operation, online measurement feedback was used to generate grinding compensation parameters, forming a closed-loop compensation cycle. This brought gear-grinding yield from 94 % to 98.5 % and reduced rework rates by approximately 65 %. The production line also implemented energy-consumption management: finishing cutting speeds were slightly increased while minimum-quantity lubrication techniques were applied, reducing per-part energy usage by about 8 % and cutting-fluid procurement costs by about 12 %. Overall, through simulation optimization, online monitoring, and intelligent compensation, this approach significantly improved machining accuracy and consistency, while reducing cycle times and operating costs.

6. Conclusion

This study demonstrates that integrating traditional casting, forging, sheet metal forming, and welding processes with CNC machining, micromachining, and surface treatment technologies can markedly improve both the overall quality and production efficiency of critical automotive components. By optimizing blank shape and material selection during casting and forging, a stable foundation is provided for downstream finishing operations. In the CNC machining stage, careful planning of tool paths and cutting parameters enables precise control over dimensional tolerances and surface finish. During micromachining and surface treatment, small-feature geometries and surface properties are further enhanced, effectively increasing the fatigue life and wear resistance of vulnerable parts such as engine crankshafts and gears. Case studies using finite-element simulation and online monitoring show that geometric accuracy regularly reaches the ±0.005 mm level, surface roughness is reduced to Ra 0.2–0.4 μm, overall production cycles shorten by 15 %–20 %, yield rates increase by over 10 %, and both energy consumption and rework rates decline significantly. Looking ahead, as the demand for lightweight, personalized, and intelligent new-energy vehicles grows, it will be necessary to further deepen the co-design of materials, processes, and equipment—particularly for new blank materials such as high-strength aluminum-magnesium alloys and carbon-fiber composites. Moreover, the application of digital twins, artificial intelligence, and big-data analytics in tool-life prediction, defect detection, and process optimization should be strengthened, promoting online adaptive compensation and predictive maintenance to achieve a closed-loop lifecycle from process planning to assembly verification. At the same time, green manufacturing and sustainability principles must be woven throughout process optimization: by innovating energy-saving measures and lubrication-cooling methods, resource utilization efficiency

can be further improved, thereby providing solid support for building a highly efficient, flexible, and low-carbon automotive manufacturing system.

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