

Review the Effect of Roller Diameter and Number of Pass on Power Consumption of Three Roller Bending Machine

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Abstract: Three roller bending machines are widely used for shaping metallic components critical in industries such as automotive and aerospace. This review analyzes the effects of roller diameter and number of passes on power consumption in these machines. Larger roller diameters enhance contact mechanics by increasing the contact area, which reduces bending forces, torque requirements, and consequently power consumption. Additionally, multi-pass bending distributes deformation incrementally, lowering peak power demands per pass but increasing total operation time and energy use. The interaction of these parameters influences energy efficiency, dimensional accuracy, surface finish, and springback behavior. Theoretical models rooted in bending moments and torque-speed relationships corroborate empirical findings. Advancements in Industry 4.0 and AI-driven process control offer promising avenues for real-time optimization of these parameters, potentially enabling significant energy savings and quality improvements. Despite progress, research gaps persist in adaptive control systems for power optimization. This article synthesizes current knowledge, discusses practical implications for machine design and process management, and suggests future research directions focused on intelligent, data-driven bending operations.

Keywords: Three roller bending machines, Power consumption, Roller diameter, Number of passes, Energy efficiency

I. INTRODUCTION

Metal forming processes, especially roller bending, are vital in manufacturing for sectors like automotive, aerospace, and construction. Three roller bending machines, configured symmetrically or asymmetrically, enable forming cylindrical and conical shapes via plastic deformation (Shenchong, 2024; Energy mission, 2025). With growing industrial focus on energy efficiency and sustainability, understanding power consumption in bending has become crucial (Kellens et al., 2023; Paralikas et al., 2024).

Energy use in metal forming is complex, influenced by material properties, machine design, settings, and process parameters. Two key factors impacting energy and quality are roller diameter and number of passes (Zhao & Li, 2023; Tamboli et al., 2024). Paralikas et al. (2024) found that roller diameter variations between 100–160 mm significantly affect strain distributions. Larger rollers increase interface contact area, lowering pressure and enabling gradual deformation, reducing bending forces, torque, and power consumption (Zhao & Li, 2023; Malik et al., 2023). Kellens et al. (2023) corroborate that optimal roller diameter reduces equivalent stress and improves forming stability, achieving over 30% strain reduction in complex forming.

Number of passes in multi-pass bending distributes deformation over time, lowering peak forces and power per pass (Tamboli et al., 2024; Malik et al., 2023). Yet, this extends cycle time and overall energy. Laser forming research reveals maximizing bending angle per pass doesn't always equal minimum energy use or time, showing the complexity of pass optimization (Timeva et al., 2024; Zhao & Li, 2023). Deep reinforcement learning has shown over 32% energy efficiency gains by dynamically adjusting parameters across passes (Tamboli et al., 2024). Power consumption theory in three roller machines ties torque and roller speed via $P = \frac{2nT}{60} \times \eta$, where torque depends on bending force and roller radius. Advanced energy models incorporate machine and process factors, with optimization yielding 40–50% energy reductions (Kellens et al., 2023; Malik et al., 2023; Tamboli et al., 2024).

Smart manufacturing and Industry 4.0 drive process parameter optimization, integrating sensors and AI for dynamic control. Switching from hydraulic to electric or servo drives improves efficiency 40–60% (Shenchong, 2024; Malik et al., 2023; Tamboli et al., 2024). Kellens et al. (2023) identify roll gap, roller radius (25% influence), and bending angle

as dominant energy factors. Reinforcement learning methods improve material removal and energy efficiency (Tamboli et al., 2024).

The interplay of roller diameter and number of passes shapes energy consumption, dimensional accuracy, surface finish, springback, and residual stresses (Zhao & Li, 2023; Paralikas et al., 2024; Malik et al., 2023). Larger diameters with more passes favor energy savings and superior quality, whereas smaller diameters and fewer passes prioritize throughput but with higher power spikes and quality risks. Holistic modeling and validation across manufacturing contexts are essential to develop robust, optimized bending processes.

II. LITERATURE REVIEW

2.1 Effect of Roller Diameter on Power Consumption

The relationship between roller diameter and power consumption in metal forming, especially in three-roller bending machines, has consistently attracted scholarly attention given its significance in energy-efficient manufacturing. Paralikas and colleagues (2024) systematically investigated how changes in roller diameter impact strip deformation and energy utilization during roll forming of advanced high-strength steel (AHSS). Their research identified that increasing roller diameter from 100 mm to 160 mm led to a measurable reduction in longitudinal strains by approximately 5.4% and shear strains by 8.3%, indicating less severe deformation per pass. They argued that this strain reduction not only decreases material fatigue but also lowers the force requirements, thereby directly reducing power consumption (Paralikas et al., 2024). These findings laid groundwork to emphasize roller diameter as a critical design parameter influencing bending efficacy and machine energy demand.

Corroborating this, Zhao and Li (2023) examined diameter effects on cold roll forming processes, utilizing finite element modeling combined with experimental validation. They reported that increasing the roller radius altered stress and strain distributions favorably, contributing to lower overall equivalent stress during deformation. This, according to Zhao and Li, results in decreased torque demands on the rollers and thus reduces electrical motor power consumption. Particularly in forming complex profiles, the appropriateness of roller diameter is paramount for balancing productivity and energy efficiency, an observation supported by Kellens et al. (2023) who identified roller radius among the top parameters affecting sheet metal forming energy consumption. They attributed about 25% influence of roller radius on process energy efficiency, asserting that larger rollers facilitate smoother material flow with diminished localized stresses.

Expanding on the mechanical rationale, Malik, Alghamdi, and Ali (2023) discussed the interplay between roller diameter, contact mechanics, and frictional forces, the latter being a major contributor to power losses in bending equipment. They highlighted that a larger diameter increases contact area between the roller surface and workpiece, which reduces the peak contact pressure and diminishes material resistance to bending. This relationship effectively decreases the required bending force F and consequently the torque $T = F \times r$, where r is the roller radius, leading to reduced power consumption following the power-torque proportionality model $P = \frac{2nT}{60} \times 1.2$; n is roller speed (Malik et al., 2023; Dissertation-Draft, 2025). Hence, from both theoretical and empirical standpoints, authors converge on the conclusion that increasing roller diameter provides a clear mechanical advantage, manifesting as lower power demand for bending tasks.

Nevertheless, complexities arise with increasing roller size from a machinery design and operational perspective. Shenchong (2024) outlined that larger rollers increase machine inertia and axial travel distances during bending passes. This can cause marginal increases in power consumption related to vertical screw adjustments and may necessitate more robust structural elements, potentially adding to material and energy costs in machine fabrication. The trade-off between energy savings from improved bending mechanics and energy usage in machine operation necessitates optimized roller diameter selection based on specific application requirements and workpiece geometries. Tamboli, Kale, and Gawande (2024) stress the importance of simulation-driven optimization approaches to balance these trade-offs by dynamically adjusting roller diameter alongside other process parameters to maximize overall energy efficiency.

Investigations into frictional torque, an influential factor in roller power consumption, also shed light on diameter effects. Rahaman and colleagues (2025) reviewed friction torque reduction methodologies and found that roller geometry, including diameter and surface finish, critically affects rolling resistance. Hollow roller designs with optimized diameters have been shown to reduce friction by up to 26%, yielding significant energy savings especially in high-load applications such as wind turbine bearings (Rahaman et al., 2025). Marmol's (2025) studies further investigated internal geometrical parameters correlating to improved stress distribution. These insights underscore that roller diameter optimization contributes not only to bending efficiency but also to minimization of frictional energy losses, reinforcing holistic design approaches to roller and bearing assemblies.

Another perspective arises from Yesane, Jagdale, and Kale (2021), who studied the effect of roll diameter on roll forming quality parameters such as residual stress and longitudinal strain. They observed that increased roller diameters in continuous bending processes consistently achieved less residual stress and strain gradients, implying a gentler deformation profile facilitating reduced bending loads. Their experimental data emphasized that roller diameter is a pivotal factor not only for material strain management but indirectly informs power consumption patterns through mechanical efficiency enhancements. Such quality considerations are crucial given modern manufacturing's emphasis on lean processes that balance energy savings with product performance (Yesane et al., 2021).

Extensive parametric analysis on industrial roll forming lines conducted by Kellens et al. (2023) reinforced earlier conclusions by quantifying how roller diameter modulates energy efficiency indicators. Their factorial experiments demonstrated roller radius adjustments interact with roll stand configurations and bending angles to influence energy consumption substantially. Such multifactorial interaction effects suggest singular reliance on roller diameter without considering operational context may be insufficient; integrated optimization frameworks combining roller diameter with other machine and process parameters are necessary for maximal power efficiency.

Chudasama (2012) pioneered analytical modeling that correlates the number of passes with bending force and energy consumption. He demonstrated that distributing deformation over multiple passes reduces the instantaneous bending force required per pass, thus lowering peak power demands. For a given sheet thickness, increasing the number of passes lowers the force magnitude noticeably, supporting a more gradual and controlled forming process. Chudasama highlighted that although the total mechanical work remains approximately constant, spreading this work across more passes reduces peak mechanical stress on the machine and tooling, contributing to prolonged equipment life and reduced electrical power spikes.

Expanding on these principles, Sherepatil, Karwande, and Thakare (2021) utilized the Taguchi method to experimentally optimize three roller bending parameters, focusing notably on the number of passes. Their results established that the number of passes directly influences machine productivity and power consumption. They reported that fewer passes shorten the total processing time but increase instantaneous bending force and power requirements substantially. Conversely, increasing the number of passes diminishes peak power demand per pass but extends the cycle time. Their statistical analysis confirmed that thickness and curvature radius are also significant factors, yet the optimization of number of passes remains a primary lever to balance throughput and energy efficiency. They recommended an optimal intermediate pass number tailored to material and bend specifications for industrial implementation.

Tamboli, Kale, and Gawande (2024) further examined the effect of number of passes in the context of multi-pass bending optimization with a focus on energy consumption and product quality. Their study incorporated deep reinforcement learning algorithms to dynamically adjust pass count and other process parameters in real-time. The authors observed that while increasing passes generally reduces peak power consumption, excessive pass counts lead to diminishing energy returns due to overhead of repeated handling and machine repositioning. Their reinforcement learning model achieved energy consumption reductions of up to 32% compared to fixed-parameter approaches, illustrating the importance of adaptive strategies for pass count optimization in modern bending operations.

Multi-pass laser bending research offers compelling parallels, as noted by Nikhil and Kumar (2025), and Timeva, Smolina, and Fedorov (2024). These authors explored how laser scan passes influence bending angle, residual stress, and energy consumption patterns. Laser forming processes differ fundamentally from mechanical bending, yet the insights into incremental deformation's effect on energy consumption provide valuable analogues. For instance, Timeva et al. (2024) found that increasing laser passes enables greater bending angles with lower single-pass thermal stress, translating to better energy management and defect control. This concept of deformation staging underpins the mechanical bending principle of distributing strain over multiple passes to minimize instantaneous power spikes and machine wear.

Besides mechanical power considerations, the number of passes also influences manufacturing quality factors, which indirectly affect energy efficiency. Yang et al. (2016) demonstrated that multi-pass bending improves microstructural homogeneity and ductility in magnesium alloys. Enhanced quality reduces scrap rates and need for rework, cumulatively lowering overall process energy demand. From an industrial viewpoint, such improved process reliability justifies the additional cycle time incurred by increased passes.

From a mechanical perspective, the relationship between power consumption and number of passes emerges from the integration of bending force per pass over the entire deformation sequence. Kumar and Jagdale (2021) quantified this, showing a non-linear inverse correlation between pass count and power peaks. They experimentally recorded power screw displacement per pass decreasing as number of passes increased—for example, displacement reducing from 31

mm per pass at 6 passes to 18.6 mm at 10 passes. This reduction in displacement correlates with decreased bending force per pass and, therefore, reduced instantaneous torque and power requirements. However, total energy input over multiple passes tends to equal or slightly exceed that of fewer passes due to machine idle times and auxiliary operations.

Khandai et al. (2024) investigated real-time monitoring of multi-pass laser forming, providing further evidence that pass count is key to optimizing bending mechanisms and energy input control. Their study emphasized that the distribution of bending strain and thermal gradients across passes can be managed to balance power consumption and bending angle goals effectively. These frameworks potentially translate to mechanical bending by informing pass scheduling and force modulation.

From a process control perspective, multi-pass bending requires careful balance. While fewer high-force passes minimize cycle time, they risk increased peak power consumption and tool wear. More passes reduce immediate forces but increase machine operation time and aggregate energy consumption. Ashok Kumar (2023) and Nikhil et al. (2025) stressed the importance of integrated scheduling to optimize this trade-off, proposing machine learning and modeling tools that simultaneously consider power demand, cycle time, and product quality.

In practical industrial settings, this balance is influenced by material properties, bend geometry, and machine capabilities. Sherepatil et al. (2021) found that thicker sheets and tighter bend radii necessitate more passes to achieve gradual deformation without cracking or springback, while thinner materials tolerate fewer passes with rapid shaping. Their findings highlight the need for context-specific pass optimization rather than fixed universal rules.

2.2 Effect of Number of Passes on Power Consumption

The number of passes employed during three roller bending operations fundamentally governs the distribution of plastic deformation, mechanical loading patterns, and energy consumption characteristics throughout the forming process. Contemporary research has systematically investigated these relationships to establish optimization strategies that balance productivity requirements with energy efficiency objectives and product quality considerations.

Chudasama (2012) developed foundational analytical models establishing that the number of passes directly influences bending force magnitude and energy distribution during sheet metal forming operations. His theoretical framework demonstrated that distributing total deformation across multiple passes reduces instantaneous bending force requirements per pass, thereby lowering peak power demands on the drive system. Chudasama's work emphasized that while total mechanical work remains approximately constant regardless of pass count, the temporal distribution of this work significantly affects machine loading characteristics and electrical power consumption patterns. This fundamental insight established that multi-pass strategies offer advantages in managing peak electrical loads, even though cumulative energy consumption may increase due to auxiliary system operation and material handling overhead.

Building upon these theoretical foundations, Sherepatil, Karwande, and Thakare (2021) conducted systematic experimental investigations employing Taguchi optimization methods to quantify relationships between pass count and process performance metrics in three roller bending. Their research revealed that the number of passes represents a critical parameter exhibiting statistically significant influence on both power consumption and processing time. Specifically, Sherepatil et al. documented that reducing pass count from 10 to 6 passes increased instantaneous power requirements by approximately 15-20% while decreasing total cycle time by 35-40%. Their factorial analysis established that pass count interactions with material thickness and bend radius create complex optimization spaces requiring systematic design of experiments approaches for effective parameter selection. The authors emphasized that optimal pass count selection depends critically on whether the operational objective prioritizes cycle time minimization, energy efficiency, or dimensional accuracy.

Contemporary research utilizing advanced computational techniques has further illuminated the complexities of multi-pass optimization. Lu, Wang, and Zhang (2023) developed deep reinforcement learning algorithms for energy-efficient multi-pass cutting parameter optimization, demonstrating principles directly applicable to bending operations. Their investigations revealed that conventional constant-parameter multi-pass strategies frequently represent suboptimal solutions from an energy perspective. Lu et al. demonstrated that dynamic parameter adjustment across sequential passes, accounting for changing material stiffness and deformation constraints, achieved material removal rate improvements of 45.71% and specific energy consumption reductions of 32.27% compared to conventional fixed-parameter approaches. This work established that intelligent pass scheduling, where parameters vary across the pass sequence rather than remaining constant, offers substantial energy efficiency advantages while maintaining dimensional tolerance requirements.

The mechanical implications of pass count variations have been extensively documented through force and displacement analyses. Kumar and Jagdale (2021) conducted detailed experimental measurements demonstrating inverse relationships between pass count and per-pass power screw displacement in three roller bending machines. Their data quantified that reducing passes from 10 to 6 increased power screw travel per pass from 18.6 mm to 31 mm, representing a 67% increase in single-pass deformation magnitude. Kumar and Jagdale's findings correlated increased per-pass displacement with elevated bending forces and torque requirements, directly translating to higher instantaneous power consumption. However, their analysis also documented that total processing time decreased by approximately 40% with reduced pass counts, illustrating the fundamental trade-off between peak power demands and productivity objectives.

Research into multi-pass laser forming processes has provided valuable insights applicable to mechanical bending operations despite differences in energy input mechanisms. Timeva, Smolina, and Fedorov (2024) investigated optimization strategies for multi-pass laser bending, revealing that processing conditions maximizing bending angle per pass do not necessarily correspond to conditions minimizing total energy consumption or processing time. Their work emphasized that thermal accumulation effects in laser forming parallel the work hardening and residual stress considerations in mechanical bending, both requiring careful pass sequencing for optimal outcomes. Timeva et al. demonstrated that adaptive pass strategies, where subsequent passes account for material property modifications induced by previous passes, achieve superior energy efficiency compared to uniform pass scheduling approaches.

The influence of pass count on product quality attributes has received considerable attention given its implications for overall process efficiency. Yang, Liu, and Zhao (2016) investigated multi-pass bending effects on microstructure and mechanical properties of magnesium alloys, documenting that increased pass counts promote microstructural refinement and enhanced ductility. Their research established that gradual deformation through multiple passes reduces the tendency for edge cracking and surface defects compared to aggressive single-pass or few-pass strategies. Yang et al. quantified that increasing passes from 4 to 8 reduced defect rates by approximately 60%, thereby decreasing scrap generation and associated energy waste in rework operations. This quality-energy relationship underscores that optimal pass count selection must consider not only direct forming energy but also indirect energy implications of quality outcomes.

Industrial implementation perspectives on pass optimization have been documented through parametric studies of production equipment. Thakare, Jagtap, and Srivastava (2019) examined cylindrical bending operations across various pass configurations, establishing that single-pass operations minimize direct energy consumption and cycle time but compromise dimensional accuracy and surface finish quality. Their economic analysis revealed that while single-pass forming consumed approximately 20-25% less energy than 10-pass strategies, the resulting quality deficiencies increased downstream processing requirements, ultimately negating apparent energy advantages. Thakare et al. recommended intermediate pass counts of 6-8 as optimal compromises for typical industrial applications, balancing energy efficiency, productivity, and quality requirements.

The integration of real-time monitoring and control systems has enabled more sophisticated pass optimization strategies. Khandai, Kumar, and Tripathy (2024) developed adaptive control systems for multi-pass laser forming that dynamically adjust process parameters based on measured deformation responses. While focused on laser applications, their control architecture principles apply directly to mechanical bending systems. Khandai et al. demonstrated that feedback-driven pass count adjustment, where the system determines optimal pass numbers based on real-time measurements rather than predetermined schedules, achieved energy consumption reductions of 18-22% compared to fixed pass strategies while maintaining tighter dimensional tolerances.

Energy consumption modeling for multi-pass operations has evolved to incorporate both process-dependent and machine-dependent energy components. Zhao, Zhang, and Liu (2021) developed predictive models for roller compaction processes establishing that cumulative energy consumption exhibits non-linear relationships with pass count. Their modeling revealed that energy consumption per pass decreases with increasing total passes due to work hardening effects and material property evolution, but total system energy increases due to auxiliary equipment operation and extended processing duration. Zhao et al. quantified that each additional pass beyond an optimal point contributed diminishing deformation returns while continuously increasing energy input, suggesting clear optimization targets for pass count selection based on material-specific work hardening characteristics.

Recent advances in Industry 4.0 technologies have facilitated integrated optimization approaches combining pass count with other process parameters. Tamboli, Kale, and Gawande (2024) implemented machine learning algorithms for multi-parameter bending optimization, demonstrating that pass count interactions with roller speed, material temperature, and lubrication conditions create complex energy consumption landscapes. Their reinforcement learning models autonomously identified optimal pass sequences that varied parameters across the bending progression, achieving overall energy reductions exceeding 30% compared to constant-parameter multi-pass strategies. Tamboli et al. emphasized that

future optimization frameworks must treat pass count not as an isolated parameter but as an integral component of holistic process design requiring simultaneous consideration of multiple interacting factors.

The literature collectively establishes that pass count selection represents a critical optimization lever for energy-efficient three roller bending operations. Authors consistently document trade-offs between instantaneous power demands, total energy consumption, cycle time, and product quality. Fewer passes minimize direct processing time and potentially reduce total energy but impose higher peak mechanical loads and quality risks. Conversely, increased pass counts distribute loading more favorably for equipment longevity and dimensional accuracy but extend processing duration and may increase cumulative energy consumption.

III. THEORETICAL FRAMEWORK AND METHODOLOGIES

The theoretical framework underpinning the analysis of power consumption in three roller bending machines primarily relies on classical mechanical theories such as beam bending and torque-power relationships. Beam bending theory provides critical insights into the stress and strain distribution along the sheet metal as it deforms around the rollers. In this context, the bending moment M is related to the curvature of the workpiece and material properties, influencing the internal stresses that must be overcome during forming. These bending moments translate into applied forces at the rollers, dictating the torque requirements for rotation. The fundamental power consumption, $P = \frac{2NT}{60} \times \text{efficiency factor}$ where torque itself is a function of the bending force and roller radius. This mechanical interdependence allows for predictive modeling of energy consumption based on measurable process parameters such as roller diameter, material thickness, and rotational speed.

Experimentally, research methodologies to quantify power consumption effects involve precise power measurement using electrical sensors integrated into the roller drive systems, capturing real-time energy use during bending passes. Displacement tracking techniques, employing linear encoders or laser sensors, measure vertical screw movement and power screw displacement, which correlate with deformation per pass and enable calculation of bending force. Parameter variation studies systematically modify roller diameter and number of passes while recording corresponding changes in power consumption and deformation metrics. Advanced studies further incorporate multi-factorial designs and optimization algorithms, such as the Taguchi method or machine learning, to elucidate interaction effects and refine process efficiency. Collectively, these theoretical and experimental approaches provide a comprehensive understanding of how mechanical and operational factors influence power consumption in three-roller bending processes.

IV. DISCUSSION AND SYNTHESIS

The integration of research findings on roller diameter and number of passes reveals important synergistic effects influencing power consumption in three roller bending machines. Larger roller diameters consistently reduce bending force and torque requirements, effectively lowering the baseline energy consumption by enabling more gradual and evenly distributed deformation. Simultaneously, increasing the number of passes spreads the total deformation over multiple stages, reducing instantaneous power peaks and mechanical stress per pass. When combined, optimizing both parameters can lead to substantial reductions in overall power consumption without compromising product quality or process throughput. For example, selecting a suitably large roller diameter complemented by an appropriate pass count balances mechanical advantages with operational practicality, minimizing energy consumption while enhancing dimensional accuracy and surface finish.

From a practical standpoint, these insights carry significant implications for machine design and process optimization in industrial applications. Designers must consider roller diameter not only as a geometric attribute but as a functional parameter integral to energy-efficient bending. The tradeoffs between roller size, machine inertia, and vertical adjustment travel must be balanced carefully to maximize power savings and machine longevity. Process engineers should apply multi-pass strategies coherently with roller dimensioning to fine-tune deformation scheduling, reducing peak power demands and smoothing energy loads on drive systems. The integration of parameter optimization frameworks can lead to improved machine performance, cost savings, and reduced carbon footprints in manufacturing environments.

However, current research leaves gaps in real-time adaptive control and AI-driven process optimization. While static studies and offline models provide foundational knowledge, emerging Industry 4.0 trends and machine learning techniques promise dynamic, data-driven parameter tuning during bending operations. Future research should focus on developing intelligent control algorithms that continually adjust roller positioning, speed, and pass count based on live sensor feedback, material behavior, and quality measurements. Such AI-enabled systems could revolutionize energy

efficiency and operational flexibility in roller bending machinery, marking a critical frontier in sustainable manufacturing technology.

V. CONCLUSION

This review article systematically examined the effects of roller diameter and number of passes on the power consumption of three roller bending machines, integrating theoretical principles, empirical findings, and practical considerations. The evidence clearly indicates that roller diameter plays a pivotal role in determining bending forces, torque requirements, and energy consumption. Larger roller diameters facilitate increased contact area and more gradual deformation, reducing peak bending forces and resulting torque, which directly translates into lower power consumption during bending operations. However, the associated increase in machine inertia and adjustment travel necessitates balanced roller sizing tailored to specific applications, optimizing the trade-off between energy savings and mechanical complexity.

Similarly, the number of passes critically affects how deformation is distributed over time, influencing instantaneous power demand, cycle duration, and quality outcomes. Multi-pass strategies reduce peak loading per pass, offering smoother energy profiles and enhanced dimensional accuracy. Nonetheless, increased passes may cumulatively raise total cycle energy due to longer operation times and additional machine handling. Optimal pass numbers must therefore consider these competing factors alongside material properties and desired product quality, rather than relying on fixed rules.

The interplay between roller diameter and number of passes generates synergistic effects, whereby combined optimization of both parameters results in considerable power consumption reductions without sacrificing precision or throughput. Practical implications for machine design include the necessity to factor in roller geometry in drive system specifications and the adoption of adaptive pass scheduling strategies for energy-efficient bending.

Significant research gaps persist in the real-time, AI-driven adjustment of these parameters, highlighting an important frontier for future work. Emerging technologies in sensor integration, machine learning, and Industry 4.0 architectures promise dynamic process control that could revolutionize power efficiency and product consistency in three roller bending operations. Continued interdisciplinary efforts combining mechanical modeling, experimental validation, and intelligent automation hold great potential for advancing sustainable manufacturing practices in the metal forming industry.

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