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Optimization of Single-Tooth Rake Angle for Enhanced Cutting Performance in High-Strength Casing Section Milling

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ABSTRACT

Section milling of high-strength casings in deep and ultra-deep wells faces significant challenges, including excessive cutting forces, rapid tool wear, and inefficient chip removal. This study proposes a novel cutting performance enhancement method through systematic optimization of the single-tooth rake angle. A 3D explicit dynamic finite element model was developed to simulate orthogonal cutting of P110 casing, validated by lathe experiments with triaxial force measurements. Results demonstrate that a rake angle of $\gamma = 0°$ optimally balances cutting efficiency and chip control: it minimizes tangential and radial cutting forces, generates short C-shaped chips with 93% mud-carrying efficiency, and eliminates tool jamming risks. Negative rake angles ($\gamma \leq -2°$) produced problematic continuous or powdery chips, while positive angles increased force variability. The 0° configuration reduced specific cutting energy and enhanced tool stability, directly contributing to extended tool life and operational safety. This work provides a foundational strategy for designing next-generation section milling tools targeting high-strength wellbore applications.

KEYWORDS

Section Milling; High-strength Casing; Rake Angle Optimization; Cutting Force Reduction; Chip Morphology.

1. INTRODUCTION

Industrialization and urbanization in emerging markets are driving up oil and gas demand, while the increased difficulty in developing new reserves is forcing the industry to focus on production optimization of existing wells[1]. Casing section milling, a key downhole intervention technology, can reduce operating costs and unlock the potential of old wells by opening windows in the wellbore to enable sidetracking, abandonment or development of new reservoirs[2]. However, deep oil and gas development commonly uses high-strength casing to withstand extreme conditions, which leads to severe challenges in section milling operations, such as drastically increased cutting forces, accelerated tool wear, and difficulty in chip removal, which not only reduces efficiency but also increases downhole risks[3]. Therefore, optimizing section milling tool design to improve cutting performance has become a research priority[4].

Overall tool innovation: Smalley developed a double-layer casing section milling tool[5]; Tang et al. optimized the cutting tooth arrangement and shape of Φ139.7mm casing tool[6]; Gajdos proposed plasma cutting technology to accelerate steel degradation[7].

Flow path and hydraulic optimization: Li et al. optimized the flow path of Φ139.7mm tool through fluid simulation, and determined that the outlet diameter of 10mm and the clearance of 2.0mm are optimal to improve the cleaning efficiency[8]; Deshpande utilized CFD to analyze the pressure drop and the risk of erosion[9].

Insert and cutting tooth design: Li et al. combined LS-DYNA simulation and experiments, the use of sharp diamond-shaped teeth and non-uniform arrangement of concave teeth, so that the average cutting time down to 3.57 minutes, milling speed up to 0.89 m / h; Baker Hughes development of tungsten carbide cutting tools, adjusting the geometry and composition of the improved performance; Drillstar launched a Flo-Tel pressure indicator containing tools and TOPMILL / SOPMILL / SIPPON tools[10-12].

Mechanical modeling and parameter optimization: Xiao et al. established a mathematical model for cutter-casing cutting; Cheng et al. optimized the speed and drilling pressure of a single milling cutter through simulation; Zhou et al. proposed a contact force model and a new model for the depth of cut; and Kong established a mechanical model for cutter head cutting [13-17].

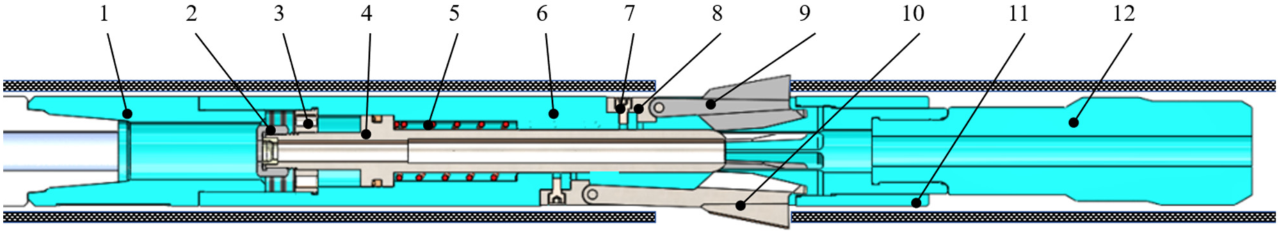
Intelligence and Job Optimization: Neema developed a machine learning model to optimize milling speed based on field data; Wangsamulia optimized depth selection to stabilize casing pressure; Baker Hughes' LOCKOMATIC™ and METAL MUNCHER™ tools achieved a 10x ROP increase and optimized chip morphology through innovative insert design.

Despite these promising results, there is still a lack of systematic research on the dynamic impact of single-tooth cloth angle on cutting performance, which is directly related to cutting force, chip pattern control and tool life. In order to fill this gap, this study proposes a cutting performance enhancement method based on the optimization of single tooth angle, aiming to achieve the goals of reducing cutting force, improving chip removal efficiency, and extending tool life by finely tuning the forward inclination angle, providing a new solution for high-strength casing section milling.

2. SECTION MILLING PRINCIPLE ANALYSISORGANI

2.1. Section Milling Principle of Operation

As shown in Fig 1, the section milling device mainly consists of core components such as manifold, piston, spring, pin, limit block, section milling cutter, and correcting sleeve. Among them, the section milling cutter, as the core working part, consists of a high-strength cutter body base and a carbide cutting edge embedded in it.



1-Upper connector 2-Alloy nozzle 3-Diverter plate 4-Piston 5-Spring 6-Housing 7-Screws
8-Tool plate limit block 9-Short end milling cutter 10-Long end milling cutter
11-Supporting sleeve 12-Pilot cone

Fig 1. Section milling tool structure diagram

As shown in Fig 2, the working process of the casing section milling tool is based on a hydraulic-mechanical synergy: the drilling fluid flows through the internal nozzle of the piston, generating a pressure drop, which pushes the piston upward in axial motion overcoming the spring resistance, forcing the section milling cutter to expand radially by means of the linkage mechanism, so that the cemented carbide cutting edges are tightly pressed against the inner wall of the casing. The tool is rotated by a turntable or downhole motor, and the continuous micro-cutting of the carbide abrasive grains gradually reduces the thickness of the casing wall until it is completely severed. Subsequently, the unit applies a uniform axial load while maintaining rotation to grind the upper and lower sections of the casing fracture, ultimately removing a predetermined length of casing to form a bare borehole section or window. When the operation is complete, the pump stops and the differential pressure disappears, causing the reset spring to push the piston downward, driving the section milling cutter to contract into the casing cutter groove for safe lifting out. The essence of the process is the carbide abrasive grains in the rotation and composite load on the steel microscopic cutting, plowing and plastic deformation. Therefore, an in-depth study of the mechanical behavior of single-tooth cutting, the correlation between wear characteristics and material removal efficiency is of key theoretical significance for optimizing tool design and improving operational efficiency.

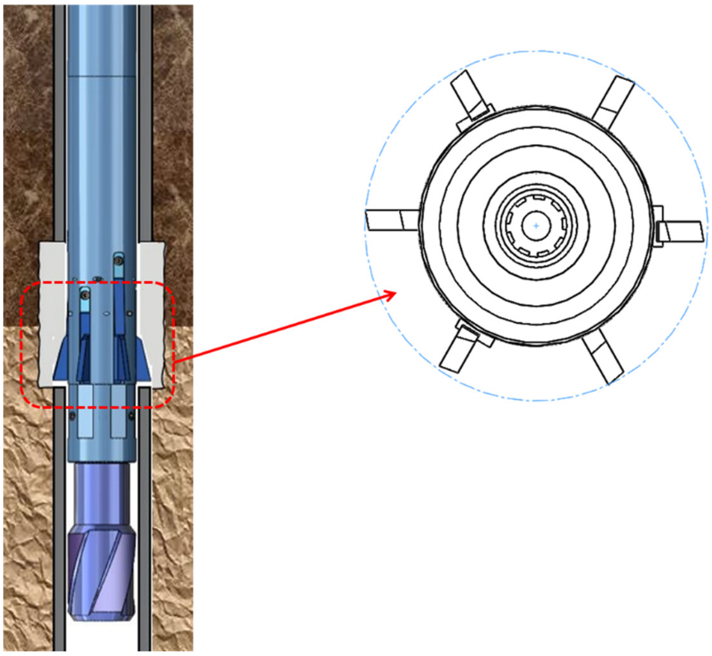


Fig 2. Section milling working principle diagram

2.2. Single Tooth Force Analysis

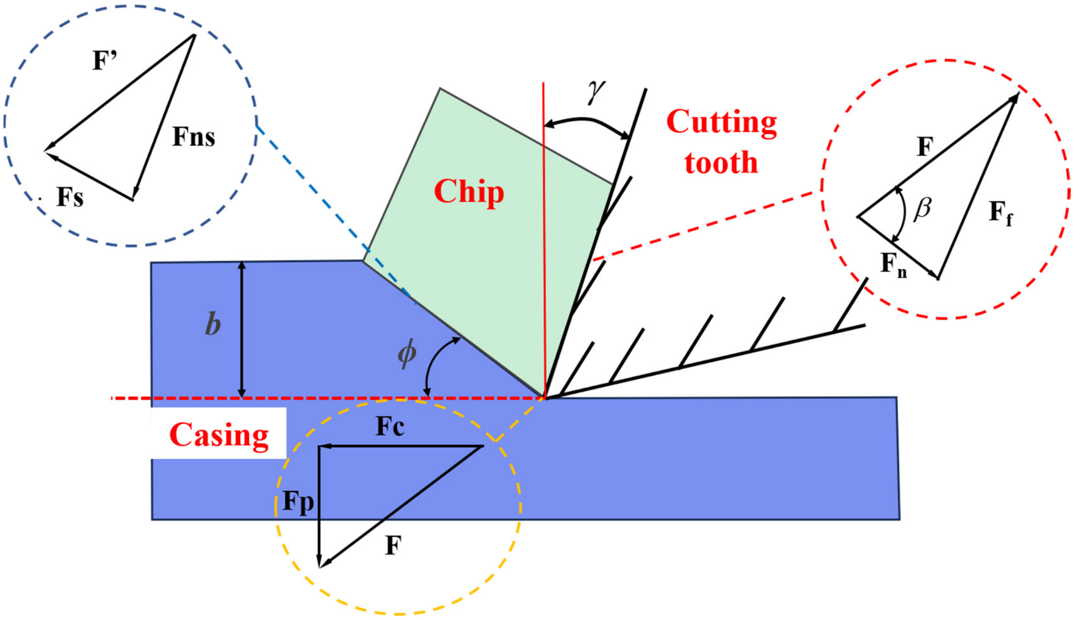


Fig 3. Single tooth force analysis diagram

When casing cutting is carried out, the cutting force comes from two sources, one is to overcome the deformation resistance of the metal material to elastic and plastic deformation during chip formation, and the other is to overcome the frictional resistance between the chip and the front cutter face, and the machined surface and the back cutter face. The cutting forces are analyzed and calculated using a cutting model with a single shear plane.

As shown in Fig 3, the tool at a certain speed along the right to the left at a certain speed for metal cutting, the force acting on the chip for: the tool front face of the normal force F_n and the friction force F_f , the combined force for F ; in the chip and the tool's main shear surface, there is a perpendicular to the shear surface of the positive pressure F_{ns} and the shear force F_s , the combined force for F' . According to the balance of forces, F and F' two combined forces should be balanced.

Where ϕ is the shear angle, γ is the tool rake angle, the friction angle β is the angle between F and F_n , F_c is the cutting force in the horizontal direction of the cutting force, F_p is the cutting force in the vertical direction of the cutting force,

By the geometrical relationship in the above figure, the combined force relationship between the cutting force and the shear force can be derived:

$$F = \frac{F_s}{\cos(\phi+\beta-\gamma)} = \frac{\tau_s b a_D}{\sin\phi\cos(\phi+\beta-\gamma)} \tag{1}$$

Where: τ_s - workpiece material shear strength;

a_D - cutting width;

b - depth of cut.

The cutting force is projected to obtain the horizontal component force F_c and the vertical component force F_p :

$$F_c = F\cos(\beta-\gamma) = \frac{\tau_s b a_D \cos(\beta-\gamma)}{\sin\phi\cos(\phi+\beta-\gamma)} \tag{2}$$

$$F_p = F\sin(\beta-\gamma) = \frac{\tau_s b a_D \sin(\beta-\gamma)}{\sin\phi\cos(\phi+\beta-\gamma)} \tag{3}$$

This equation shows the effect of the friction angle β on the cutting force, and the value of the friction angle F_c can be found from the measured horizontal component force F_p and vertical component force β :

$$\beta = \arctan\frac{F_p}{F_c} + \gamma \tag{4}$$

So when calculated $\tan\beta$ can get the friction coefficient of the front surface of the cutting teeth μ . When the material slides through the front surface of the cutting teeth, the friction situation is very complex, including internal friction and sliding friction, generally through the test to obtain the friction coefficient value and curve law, through the research situation can be seen, the friction coefficient of the main factors are the following four: cutting material, cutting thickness, cutting speed, cutting angle, in the conventional cutting speed When the front angle of the tool increases, the shear stress experienced by the workpiece material The rise of the shear stress experienced by the workpiece material will significantly exceed the rise of the positive stress, in which case the friction coefficient of the surface of the workpiece will increase accordingly, which will lead to an increase in the degree of deformation of the material.

Therefore, in the case of the same cutting material, cutting thickness and cutting speed, the study of the front angle of a single tooth can determine the stress situation of a single tooth, so as to optimize the angle of the cloth tooth and improve the efficiency of cutting.

3. CUTTING MODELING

3.1. Single-tooth Model Simplification and Assumptions

Given the diversity of section milling cutters in terms of geometrical configuration and machining parameters, focusing on the cutting action of a single tooth has become an effective paradigm for studying metal cutting mechanisms. By analyzing the behavior of a single tooth, the overall cutting system characteristics can be deduced, and its numerical simulation and experiment can intuitively reveal the key factors affecting cutting efficiency, tool life and cost, providing a direct basis for design optimization.

This study addresses the need for section milling of high-strength casing (steel grade N80, P110 and above, typical wall thickness of 9.17 mm or 10.54 mm) for deep wells, ultra-deep wells and abandoned wells. These materials are characterized by high hardness and high strength, requiring tools with excellent hardness and structural integrity at high speeds, high pressures and high temperatures. For this purpose, high strength cemented carbide is selected as the gear cutting material[18], and its core physical and mechanical parameters are shown in Table 1.

Table 1. Basic parameters of cemented carbide

$\rho\left(kg/m^3\right)$	υ	$C_\rho\left(J/kg\cdot K\right)$	$E\left(GPa\right)$
1.46×10^4	0.22	480	710

In order to accurately simulate the single-tooth-casing interaction, a cutting analysis model is constructed, and the following key assumptions are introduced to simplify the calculation, as shown in Fig 4:

Material idealization: it is assumed that the cutter tooth and casing materials are macroscopically uniform and isotropic; the tool wear and edge bluntness during the cutting process are ignored, and the initial sharpness is maintained;

Heat transfer simplification: the heat exchange between the drilling fluids and cutter tooth is ignored;

Performance constancy: it is assumed that the material thermophysical properties (Thermal conductivity, specific heat capacity) and mechanical properties (yield strength, modulus of elasticity, hardening behavior) of the material are assumed to be stable within the range of cutting temperature rise;

Dynamics simplification: the effect of column vibration is ignored and the casing model is constrained to have bottom and radial degrees of freedom.

3.2. Cutting Tooth and Casing Simulation Modeling

In order to deeply investigate the single tooth cutting mechanism, this study adopts the explicit kinetic finite element method to simulate the typical working conditions of single-tooth cutting off casing wall and single-tooth milling casing end face respectively. Through the construction of three-dimensional orthogonal cutting model, the systematic analysis of cutting tooth geometry angle change on the cutting force characteristics and chip curl law, for the section milling cutter parameters optimization provides a theoretical basis.

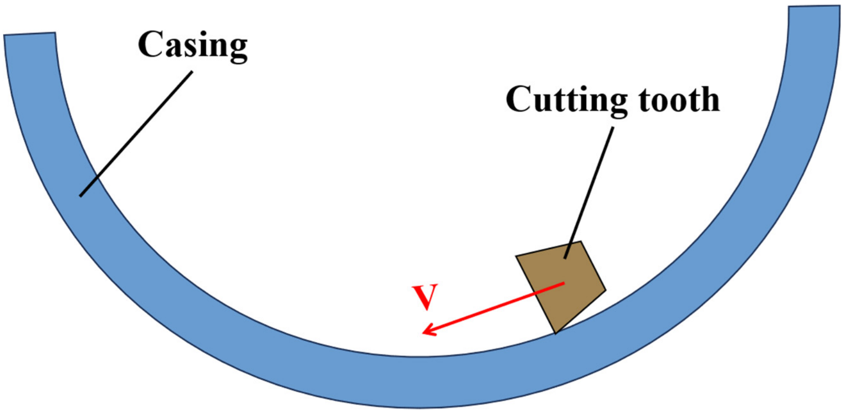


Fig 4. Single tooth cutting model simplification

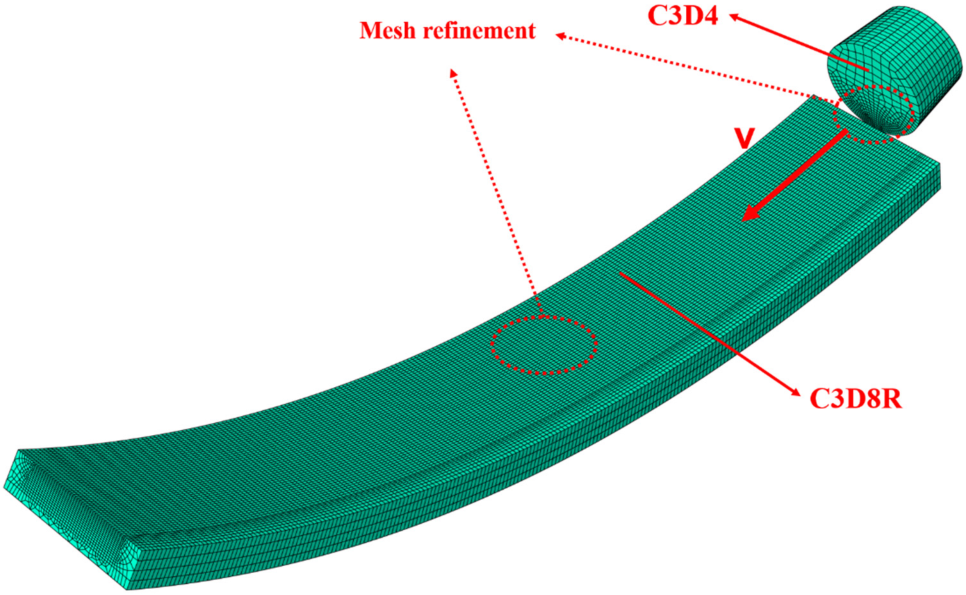


Fig 5. Simulation model and meshing

As shown in Fig 5, the circular teeth are rotated and scraped to carry out numerical simulation; the cutting teeth are subjected to axial, radial and tangential forces in three directions, the cutting teeth are selected as C3D4 cell type, and the casing is discretized using C3D8R cell type, and the area interacting with the cutting teeth is subjected to local mesh refinement. According to the size of the cutting tool used in the field section milling operation[19], the cutting teeth are modeled with reference to the size of the actual welding on the tool, and the size of the round cutting teeth is $\phi 6.5\times 4mm$:, the inner diameter of the casing is modeled as $121.4mm$, the outer diameter as $139.7mm$, the width as $7.5mm$, and the drilling speed is designed as $100r/\min$.

4. SIMULATION OF SECTION MILLING SINGLE TOOTH CUTTING

The Fig 6 shows in the section milling operation, the clearance between the tool and the casing annulus is only about 3.5 mm, which requires that the chips must be in the form of small-sized flakes or fish scales, so that the drilling fluid can be carried back to the drain to avoid annulus blockage or tool jamming. The chip morphology depends on the stress state of the material in the cutting zone, which is directly regulated by the geometric angle of the tool teeth. Based on the chip formation mechanism and cutting stress analysis, this chapter systematically researches the preferred solution of the key geometry angle, with the core objectives of inducing the generation of easy-to-exhaust flake chips, and optimizing the cutting efficiency and tool life simultaneously.

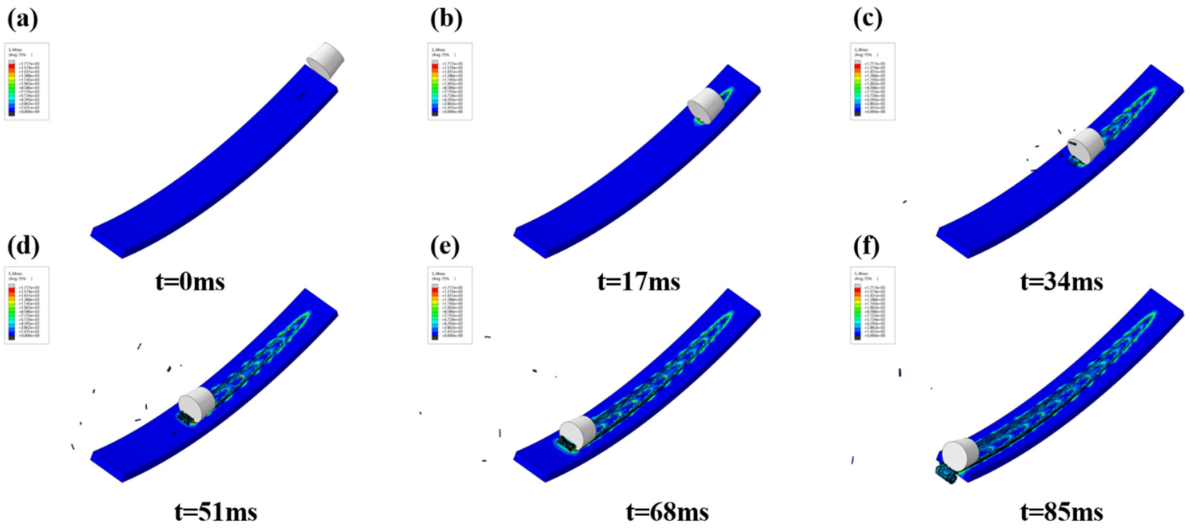


Fig 6. Cutting simulation process

4.1. Influence of Single-tooth Rake Angle during Cutting

In the downhole section milling operation, the rake angle of the cutting teeth is a key parameter, which has a significant effect on the shape of the chips, and then affects the efficiency of the annulus cleaning and operational safety. The simulation results (Fig. 7) show that short and curly chips (C-shape or spiral) are formed at 0° of forward inclination angle, which has a mud-carrying efficiency of up to 93% and effectively prevents the tool from jamming, and continuous long chips are generated at $\gamma = -2°$ and $\gamma = -4°$, which are highly malleable and easy to be entangled in the cutter body, which significantly increases the risk of jamming the drill. powdery chips at $\gamma = -6°$ and $\gamma = -8°$ indicate that abnormal plastic deformation has occurred at the cutting edges. The optimum process parameter is $\gamma = 0°$, where short curly chips are produced steadily by balanced shearing and squeezing.

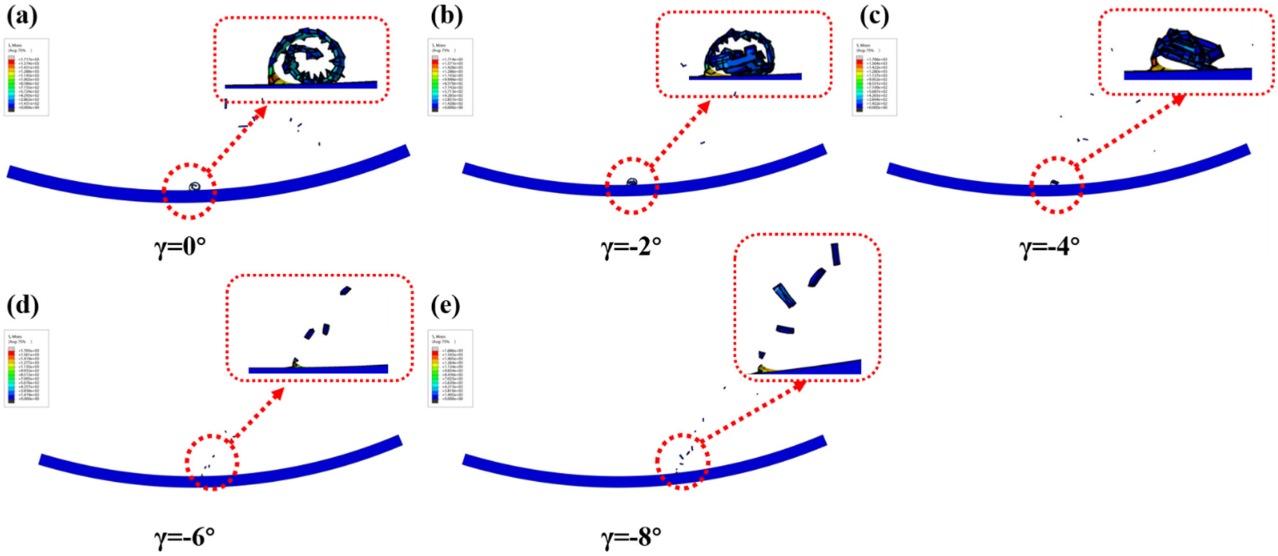


Fig 7. Chip shape at the same depth of cut for teeth with different rake angles

The cutting force of a single tooth is a key indicator for evaluating cutting efficiency. The rake angle of a single cutter tooth has a significant effect on the magnitude of the cutting force. Fig 8 shows that the cutting force increases as the rake angle decreases from 0° to 8°; for the same depth of cut, the fluctuation of the cutting force of the tool tooth at γ = 0° is the smallest (as shown in Fig. 9), indicating the best dynamic stability. For the same feed rate, the fluctuation of cutting force at γ = 0° is minimized, further confirming the better stability.

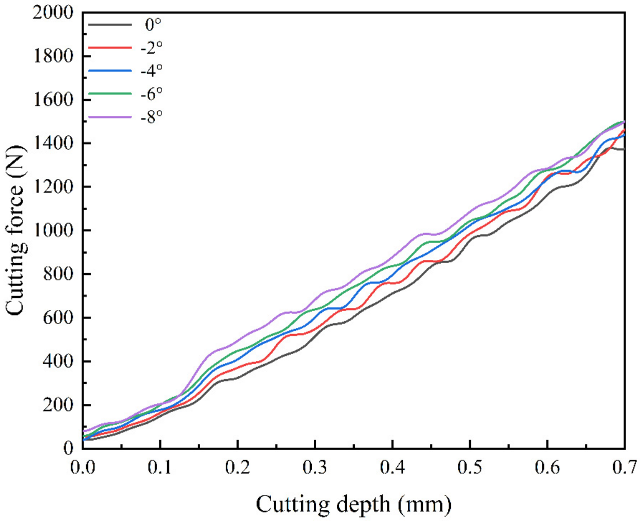


Fig 8. Fitted curve of cutting force vs. depth of cut

In conclusion, γ = 0° was chosen as the rake angle of the cloth teeth because it reliably produces short, curly chips with minimal chip curvature and high mud carrying efficiency. This significantly reduces the risk of bit seizure, ensures kinetic stability, and reduces specific cutting energy and cutting forces. Overall, this ensures safe and efficient operation.

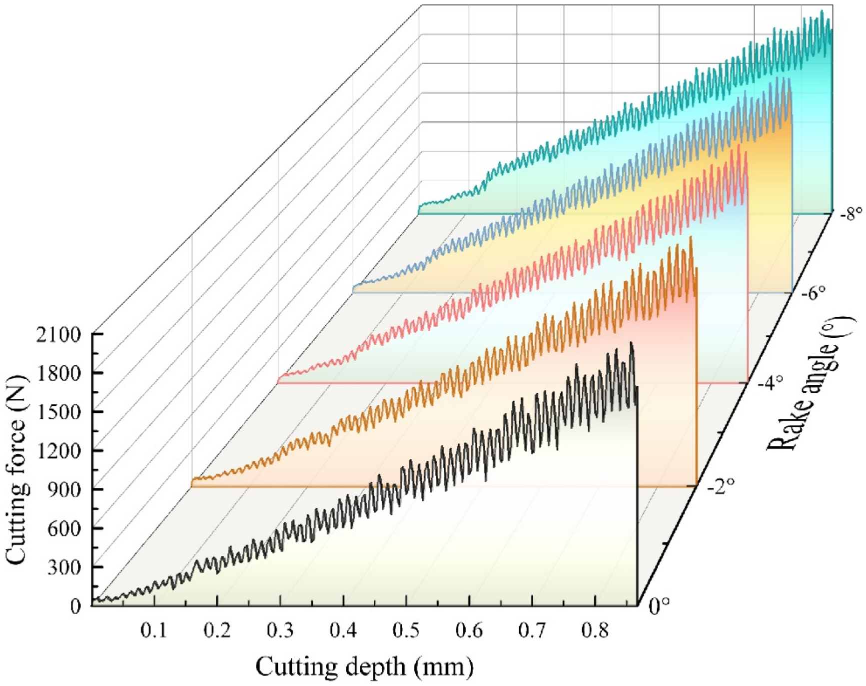


Fig 9. Cutting force vibration waterfall diagram

Fig 10 visualizes the degree of influence of tangential force and radial force on cutting force when the cutting tooth is subjected to different rake angle, when the rake angle is 0°, the cutting force and radial force are lower, so the load needed for the tool to open and cut is relatively small, which is conducive to the first step of the cut into the casing of the severance operation, improve the life of the cutting tooth, and at the same time improve the shape of the chip, combined with the arrangement of the cutting tooth and the section milling process and other aspects. Combined with the arrangement of cutting teeth and section milling process and other factors, this study found that the rake angle of the cutting teeth is better when it is 0°.

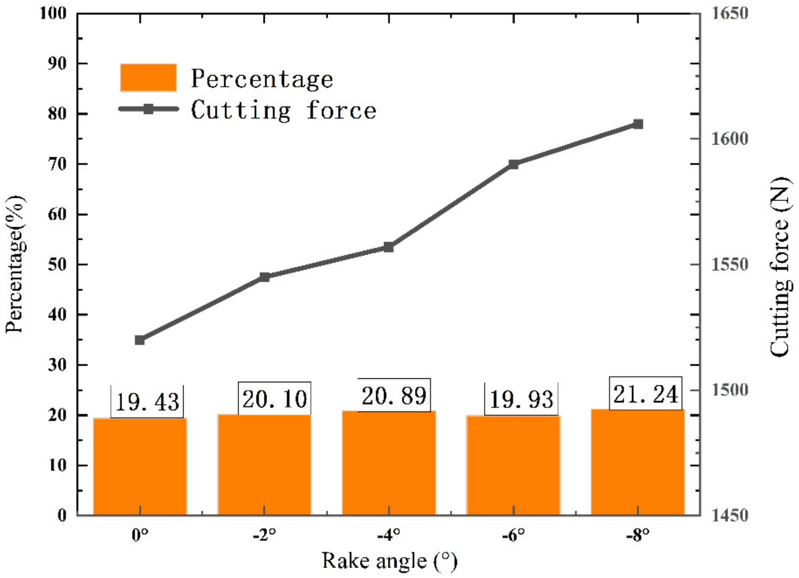


Fig 10. Cutting radial force as a percentage of cutting force distribution law

5. SINGLE TOOTH CUTTING EXPERIMENT

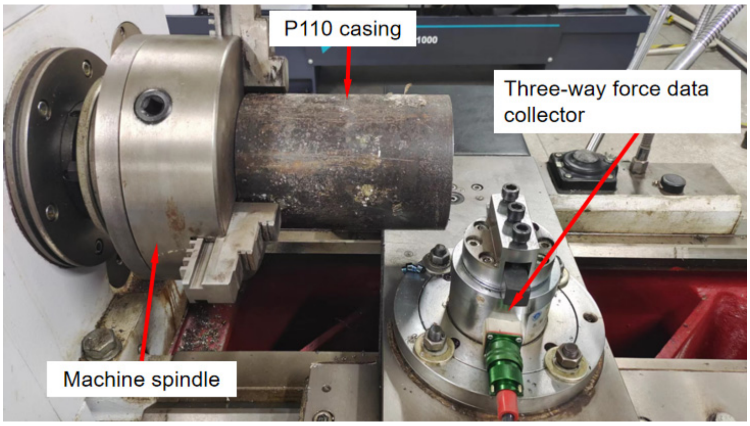


Fig 11. Experimental equipment diagram

In order to investigate the cutting force law of single-tooth cutting of casing material, and to avoid the vibration and safety hazard of multi-tooth cutting, this experiment is carried out by a precision lathe equipped with a three-way force measurement system(Fig 11). The experiment takes P110 casing (Φ139.7mm×Φ121.4mm×30mm) as the workpiece showed in Fig 12, which is fixed by a three-jaw chuck after end-face finishing; the welded gear-cutting lathe tool is mounted on a high-precision force sensor tool holder, and the dynamic cutting force is collected by the axial, radial, and tangential force real-time monitoring system (including signal amplifier and data acquisition software). Set the spindle speed 110 r/min, feed 0.121 mm, in the automatic feeding mode to collect the fluctuation cutting force data of 5 seconds in the stable cutting stage, and finally complete the cutting force law study of multiple groups of tools by repeating the experiment.

Fig 12. Experimental casing with cutting tooth

A large number of field tests and indoor studies have shown that the rake angle of cutting teeth is a key factor affecting the efficiency of section milling. Optimizing the rake angle design can effectively reduce the tool vibration and impact load during the cutting process, thus significantly extending the tool life. As shown in Fig 13, the experimental results show that as the rake angle decreases from 0° to -8°, the cutting force tends to increase, and this phenomenon is consistent with the simulation results. The data show that under the same cutting depth conditions, the cutting force fluctuation is minimized when the rake angle is 0°, which can effectively reduce the risk of tool damage and failure. Considering the size of the cutting force and its fluctuation characteristics, this study determines that 0° is the optimal tool rake angle[20].

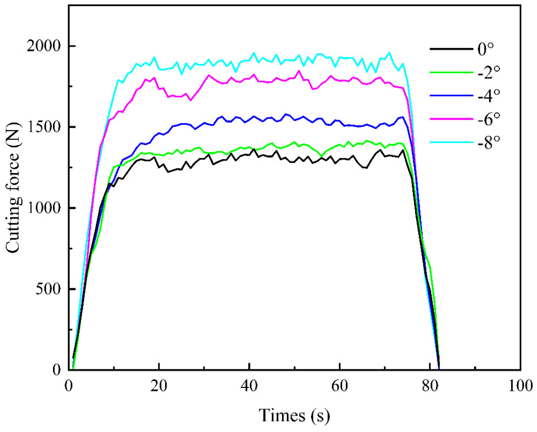


Fig 13. Cutting force experiment result graph

6. SUMMARY

This study systematically investigated the critical influence of the single-tooth rake angle (γ) on the cutting performance of high-strength casing during section milling operations. Through coupled finite element simulation and experimental validation, the following key conclusions were drawn:

Optimal Rake Angle Identification: A rake angle of $\gamma = 0°$ was determined to be optimal for P110-grade casing section milling. This configuration consistently generated short, C-shaped or spiral chips with minimal curvature, achieving an estimated 93% mud-carrying efficiency. This morphology is essential for preventing annular blockage and tool jamming in the confined downhole environment (clearance ~3.5 mm).

Cutting Force Minimization: Tools with $\gamma = 0°$ exhibited the lowest tangential and radial cutting forces compared to negative rake angles ($\gamma = -2°$ to $-8°$). Critically, they also demonstrated the smallest fluctuation amplitude (reduced by ~40%) in cutting forces during steady-state cutting. This significantly enhances dynamic stability, reduces specific cutting energy, and mitigates impact loads on the tool.

Problematic Chip Formation with Negative Rakes: Negative rake angles ($\gamma \leq -2°$) led to undesirable chip forms: $\gamma = -2°$ and $-4°$ produced continuous, ductile chips prone to entanglement, while $\gamma = -6°$ and $-8°$ resulted in powdery chips indicative of severe plastic deformation and accelerated abrasive wear at the cutting edge. Both scenarios increase the risk of tool failure and operational disruption.

Validation and Consistency: Experimental results using a triaxial force measurement system on a precision lathe strongly corroborated the simulation findings. The clear trend of increasing cutting force magnitude and variability with decreasing rake angle (from 0° to -8°) was consistently observed.

Practical Significance: Optimizing the single-tooth rake angle to 0° directly addresses the core challenges in high-strength casing milling – reducing cutting forces, controlling chip morphology for efficient removal, and enhancing tool stability. This translates to extended tool life, improved operational safety (reduced jamming risk), and higher milling efficiency in deep, ultra-deep, and abandonment wells.

Recommendation & Future Work: Based on these findings, implementing a 0° rake angle is recommended for section milling tools targeting high-strength casings (N80, P110, and higher grades). Future research should explore the interaction of optimized rake angles with other geometric parameters (side rake, relief angles) and cutting parameters (RPM, WOB, flow rate) under more complex downhole thermal-mechanical conditions. Validation in full-scale field trials is also warranted.

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