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Study on Fracture Force Control and Tool Replacement Cycle of V-Groove in 13Cr11Ni2W2MoV Stainless Steel

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Abstract

Aiming at the unstable fracture force of V-groove components made of 13Cr11Ni2W2MoV stainless steel during batch processing, this study proposes a stability optimization method based on the control of tool machining frequency. Firstly, comparative experiments on machining times and tool wear are carried out, and a mathematical model describing the variation of tool corner wear with machining frequency is established. Secondly, sampling tests of fracture force are conducted with the measured V-groove diameter and tool machining times as variables, to explore the action mechanism of the two factors on the fracture force of components and clarify the evolution law of fracture force at different tool wear stages. Finally, based on the fracture force test data of V-groove components under various wear conditions, the influence of tool wear on mechanical properties is analyzed, and the threshold of the maximum allowable tool machining times that ensures qualified fracture force is determined. The results of small-batch trial production verify that the proposed method can effectively reduce the discrete deviation of component fracture force and significantly improve the quality stability of batch machining.

Keywords

Tool Wear, 13Cr11Ni2W2MoV Stainless Steel, V-Groove Machining, Fracture Force

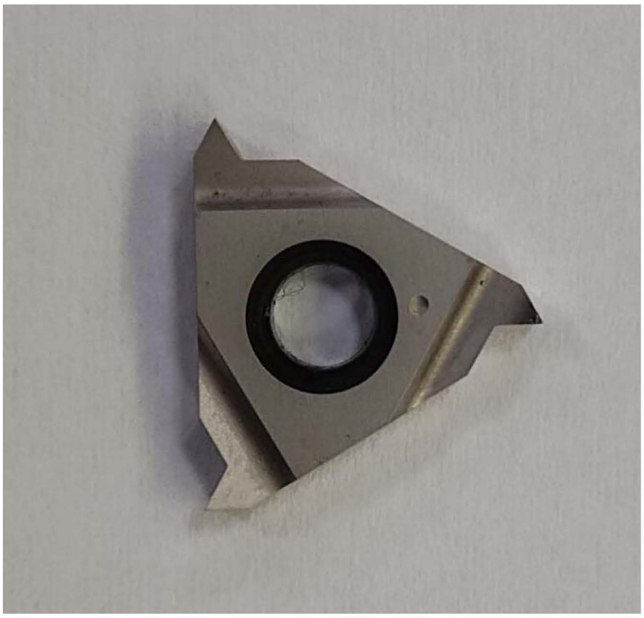
1. Introduction

13Cr11Ni2W2MoV is a martensitic heat-resistant stainless steel. Benefiting from its outstanding high-temperature mechanical properties and corrosion resistance, this alloy has been extensively adopted in aerospace and high-end equipment manufacturing industries [1]-[3]. For the machining of components made of this material, the V-groove tensile fracture separation structure [4]-[6] realizes directional fracture by fabricating V-grooves at pre-separation positions and applying axial tension, leveraging the stress concentration effect at groove roots. The V-groove of the workpiece investigated in this paper adopts a 60˚ included angle, with a reduced cross-section diameter of φd (the initial value of d is set as 2, adjustable according to material properties) within a tolerance of ±0.05. The required fracture load is 5175 N ± 350 N. No explicit dimensional tolerance is specified for the root fillet radius, which is controlled autonomously by the machining process. Nevertheless, the root fillet radius of machined V-grooves is inherently determined by the tool nose radius. As machining batches accumulate, progressive wear enlarges the tool nose radius continuously, generating dimensional deviations between the actual root fillet and the designed reduced diameter φd. Tool wear compensation via machining programs can guarantee the dimensional accuracy of φd, yet it fails to offset variations in tool nose radius. This leads to systematic fluctuations in the tensile fracture load of finished workpieces. Severe tool wear will drive the fracture load beyond the permissible design range and result in out-of-specification product performance. Accordingly, scientifically evaluating tool wear conditions and determining a permissible maximum number of machining cycles are critical prerequisites for stabilizing the fracture load performance of V-groove parts and ensuring consistent product quality.

Tool wear and service life prediction have long remained a prominent research focus in the field of cutting machining. Numerous scholars have established empirical formulas correlating cutting speed with tool life [7]-[11], proposed classical algorithms for stress concentration factor calculation, and analyzed the effects of V-groove geometric parameters on fracture load. Nevertheless, two prominent research gaps persist in existing literature. First, few studies have constructed a quantitative mapping relationship between tool wear and the tensile fracture load of V-grooves. Second, methodologies for determining the maximum allowable machining quantity constrained by qualified fracture load performance are rarely reported. To address the aforementioned engineering challenges, this work takes the V-groove tensile fracture process of 13Cr11Ni2W2MoV stainless steel as the research subject. The evolution law of tool nose radius wear and its action mechanism on workpiece fracture load are revealed herein. A quantitative correlation model between tool wear magnitude and tensile fracture performance is established, and the permissible service life threshold of cutting tools is defined. The research outcomes provide theoretical support and practical engineering references for suppressing batch-to-batch fluctuations in the fracture load of V-groove components, achieving steady-state process quality control, and formulating rational tool replacement criteria.

2. Establishment of Tool Nose Radius Wear Model

The test material adopted in this study is 13Cr11Ni2W2MoV stainless steel conforming to the national military standard GJB2294A-2014, whose specified hardness range for finished components is HRC 32-37. To fully characterize the tool wear behavior under the harshest working conditions, specimens with the maximum hardness of HRC 37 within the permissible range were selected for testing, guaranteeing that the derived conclusions possess universal applicability and sufficient safety margin for the full hardness spectrum of the alloy. The target component features a revolved part with a 60˚ V-groove, and all V-groove machining operations were implemented on a CNC lathe. 3ER A60 VM7 cemented carbide external threading inserts were utilized to machine the V-groove profiles, while separate cutting tools were deployed for rough turning, semi-finish turning and other structural features. Machining parameters were set in accordance with field production specifications and kept constant throughout the entire test: spindle speed of 1000 r/min, feed rate of 0.008 mm/r, and cutting depth of 0.75 mm. This setup eliminates interferences of variable cutting parameters on the evolution law of tool wear. A single brand-new cutting insert was used for continuous sequential machining starting from the 1st workpiece up to the 600th workpiece. The morphology of the machined tool is presented in **Figure 1(a)**. After processing 600 workpieces, severe dark discoloration was observed at the tool nose, accompanied by substantial blunting of the cutting edge. The tool was thereby judged to reach the failure criterion and withdrawn from further machining trials.



(a) Physical image of the first tool wear test (right tool tip)

(b) Physical image of the second tool wear test (right tool tip)

Figure 1. Physical image of wear condition at tool tip after test piece testing.

To establish a quantitative relationship between machining quantity and tool nose radius, inspection sampling points were randomly selected at intervals throughout the machining process. A toolmaker's microscope was utilized to measure and record the diameter of the tool nose radius. As shown in **Figure 2**, a cubic polynomial function was employed to fit the experimental data in this study. Let the machining quantity be defined as x (workpieces) and the tool nose radius diameter as y (μm). The fitted model is expressed as: $y = 1\times10^{-6}x^3 - 1.1\times10^{-3}x^2 + 3.598\times10^{-1}x + 4.8802\times10^{1}$. The coefficient of determination of the fitted curve is $R^2 = 0.7039$, which demonstrates that the proposed quadratic polynomial model can adequately characterize the variation trend of tool nose radius against machining quantity. Nevertheless, approximately 30% of the total variance remains unexplained by the model, indicating a moderate-upper fitting accuracy of the established mathematical model.

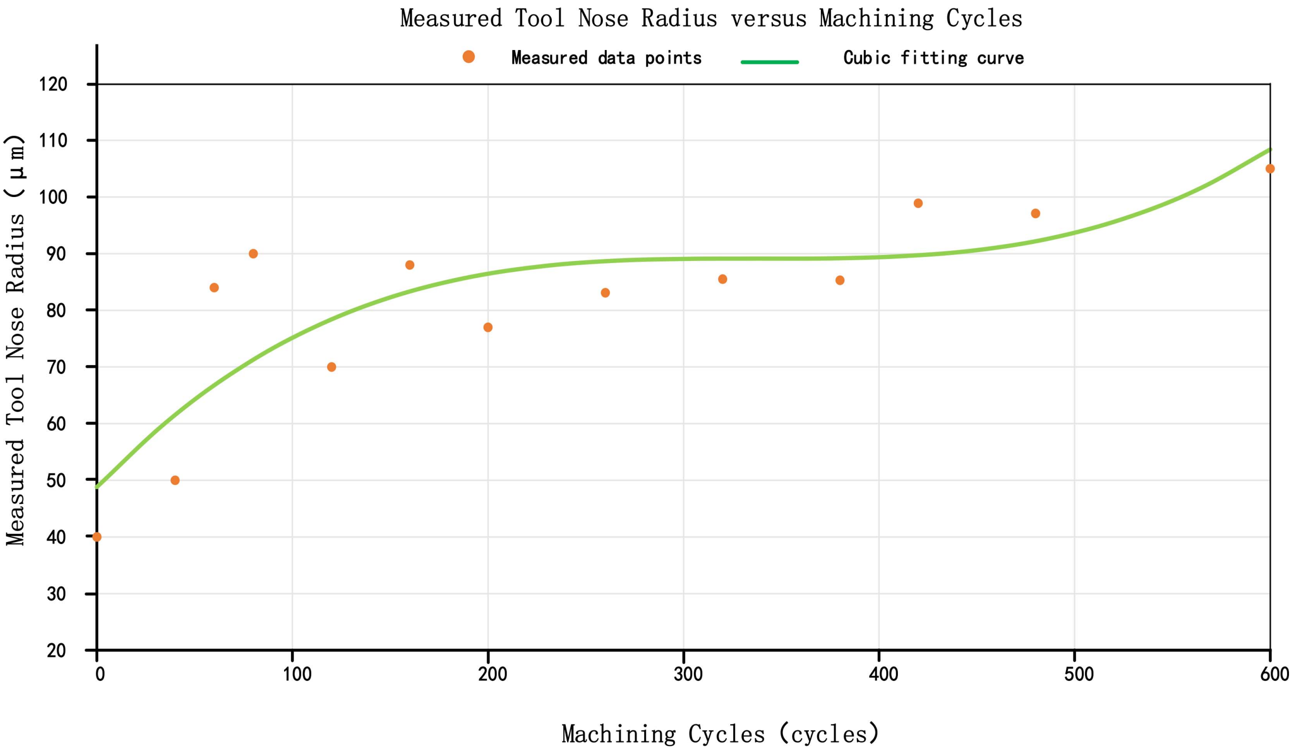


Figure 2. Fitting model between measured tool nose radius and machining times.

It can be observed from **Figure 2** that the tool nose radius exhibits a monotonically increasing trend with rising machining quantity. During the initial machining stage (0 - 200 workpieces), the tool nose radius increases rapidly at first with a gradually declining growth rate, which corresponds to the primary wear stage of the cutting tool, wherein the rounded tool nose expands drastically. As the machining quantity further rises (200 - 400 workpieces), the tool nose radius slowly decreases after reaching its peak; this interval represents the steady wear stage of the cutting tool, where the radius varies mildly and even slightly declines. In the late machining stage (400 - 600 workpieces), the tool nose radius climbs again following a brief drop, suggesting that the cutting tool may enter an accelerated severe wear stage.

3. Investigation on the Influence of Tool Wear on V-Groove Diameter and Breaking Force

To investigate the effects of tool wear on the V-groove diameter and product breaking force, V-groove machining was selected as the research subject in this work, and the target V-groove diameter φd was controlled within φ2 ± 0.05 mm (To improve test efficiency, the φd value is not adjusted according to material properties, leading to deviations of specimen tensile fracture force from the median value of 5175 N). Restricted by the geometric dimensions of tensile specimens and the length of raw material, the experiments were divided into a tool wear test group and a specimen preparation group, both of which adopted identical machining parameters and NC programs. In the specimen preparation group, tensile specimens were mass-produced from a single bar stock, with a maximum of 17 specimens machined from one raw material bar. This method effectively eliminates interference in breaking force test results induced by material property variations among different raw stocks. Brand-new cemented carbide external threading turning inserts were utilized in the wear test group. The cutting tools were first subjected to predetermined machining cycles to achieve pre-wear, followed by intermittent specimen machining to fabricate tensile specimens corresponding to different wear stages. According to the fitted model of tool nose arc wear, rapid tool nose wear and remarkable dimensional fluctuation occur within the first 200 machined workpieces. Therefore, customized sampling criteria were established for this experiment: one tensile specimen was fabricated every 20 cumulative workpieces when the total machining quantity was less than 200; after the machining quantity exceeded 200 workpieces, the sampling interval was adjusted to one specimen per 40 cumulative workpieces. The actual measured V-groove bore diameters were monitored in real time during machining, and tool wear compensation was implemented promptly based on dimensional deviations to guarantee that all machined dimensions complied with the specified design tolerances. After all specimens were machined, the worn cutting tool is displayed in Figure 1(b). Obvious darkening and severe passivation of the cutting edge can be observed on the worn tool nose. Breaking force tests were conducted uniformly on all 17 specimens, and the experimental test data are summarized in Table 1. All measured values of φd fell within the tolerance range of φ2 ± 0.05 mm.

Table 1. Measured data of tool wear test specimens and tool compensation values.

Serial No.	Number of Workpieces/piece	Measured Diameter φd/mm	Tool Offset/mm	Breaking Force/N
1	20	2.013	—	6155
2	40	1.995	−0.03	6054
3	60	1.983	—	6025
4	80	2.000	—	5953
5	100	1.998	—	6036

Continued

6	120	1.987	−0.02	5949
7	140	1.979	—	5943
8	160	1.980	—	5889
9	180	1.975	—	5962
10	200	1.982	—	5924
11	240	1.978	—	5944
12	280	1.959	−0.02	5934
13	320	1.961	—	5903
14	360	1.969	—	5790
15	400	1.961	—	5919
16	440	1.963	—	5862
17	480	1.964	—	5924

Figure 3 plots the evolution of measured V-groove diameter φd and theoretical diameter without tool compensation as a function of machining quantity. The following conclusions can be drawn from the curves: 1) As the machining quantity increases, the tool nose undergoes continuous wear and passivation, shortening the effective length of the cutting edge. Without tool compensation, the V-groove diameter φd shows an overall rising trend. 2) Unlike the upward tendency of the theoretical uncompensated φd, the measured φd decreases overall, and its reduction rate is greater than the growth rate of the theoretical diameter. 3) The shrinkage of groove diameter after tool compensation does not stem from tool wear; instead, it originates from the cumulative stepwise superposition of repeated compensation offsets. 4) The initial 20 workpieces correspond to the primary wear stage characterized by an excessive wear rate, where the corrective effect of tool compensation is neutralized by rapid tool abrasion. For the machining range of 80 - 200 workpieces, the measured φd fluctuates slightly around the median dimension, signifying the onset of the tool's steady wear stage. After 200 workpieces, the value of φd decreases markedly, and the tool enters the accelerated severe wear stage. After the last tool compensation at 280 workpieces, the φd dimension tends to be stable.

Figure 4 presents the variation of breaking force against machining quantity. The breaking force exhibits an overall downward trend, declining from an initial value of 6155 N to a final value of 5924 N, with a total reduction of 365 N. Similar to the evolutionary trend of φd, the breaking force also decreases continuously yet with more pronounced fluctuations. The minimum breaking force of 5790 N occurs at the 360th workpiece, representing a drop of 365 N relative to the initial value. This abnormally low value emerges during the stable stage after tool compensation, which can be attributed to deteriorated machined surface quality induced by accumulated tool wear within this stage. Furthermore, tool compensation exerts a weaker influence on breaking force compared with groove diameter.

No obvious recovery of breaking force is observed after three rounds of compensation operations. This finding indicates that tool compensation primarily improves dimensional accuracy while imposing limited enhancement on mechanical performance.

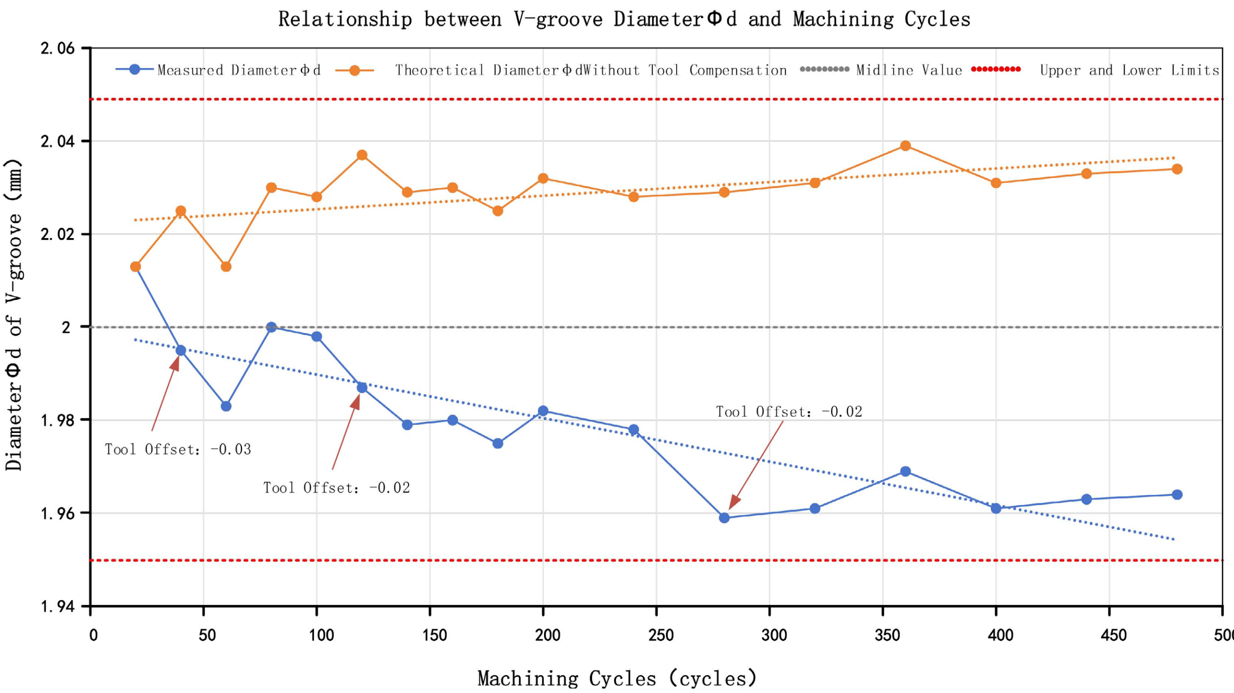


Figure 3. Trend curve of φd value of V-groove versus machining times.

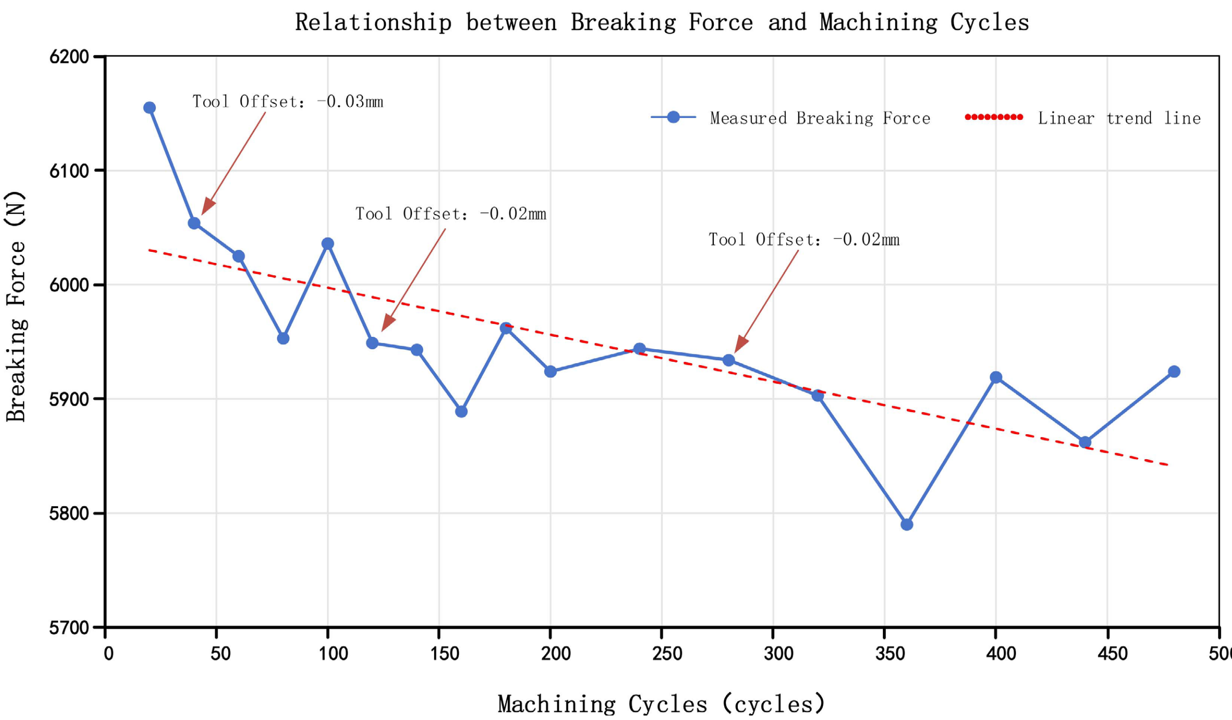


Figure 4. Trend chart of breaking force vs machining times.

Two rounds of segmented sampling experiments regarding tool wear were carried out in this study, and the primary research conclusions are summarized as follows: 1) The entire tool wear process can be distinctly divided into three stages: primary wear stage, steady wear stage, and accelerated wear stage. 2) Manual tool compensation can effectively slow down the decreasing trend of groove diameter, yet it has obvious limitations. The stable diameter value after each compensation decreases sequentially, the marginal benefit of repeated compensation diminishes continuously, and tool compensation cannot fully restore the original machining performance of the cutting tool. 3) During the primary wear stage (0 - 200 workpieces), the sharp tool nose suffers rapid abrasion. Despite relatively drastic variations in tool nose radius R and V-groove diameter φd, the breaking force of machined products remains within a narrow stable range. However, after 200 workpieces (covering the steady and accelerated wear stages), although tool compensation can constrain φd within the required dimensional tolerance, it fails to guarantee the machining quality of the V-grooves. Consequently, the breaking force of products cannot be stably controlled and exhibits severe fluctuations. In summary, based on the experimental findings of this work, the allowable machining quantity for V-groove feature machining using 3ER A60 VM7 cemented carbide external threading turning inserts is determined to be no more than 200 workpieces.

4. Verification Test with Small-Batch Production

To verify the effectiveness of the breaking force control strategy for V-groove products proposed in this work, two production batches (Group A and Group B) with 920 workpieces each were manufactured separately. After machining of each batch, 5% of the workpieces (46 specimens) were randomly selected for breaking force testing. For Group A, the machining quantity of each external threading turning insert was strictly limited to no more than 200 workpieces, and inserts were replaced immediately once the threshold was exceeded. For Group B, no restriction was imposed on the service life of each cutting insert, while all other machining procedures and process parameters were identical to those of Group A. The statistical acceptance results of breaking force for the two groups are listed in Table 2. Group A yielded an average breaking force of 5170.91 N, with a trivial deviation of −4.09 N from the target value and a standard deviation of 100.10 N. All sampled specimens satisfied the specification requirements, corresponding to a 100% qualification rate. By contrast, Group A exhibited an average breaking force of 5433.89 N with a positive deviation of +258.89 N and a standard deviation of 270.51 N. A total of 20 specimens exceeded the upper specification limit, leading to a low qualification rate of only 56.52%. The standard deviation of Group B was 2.70 times that of Group A, accompanied by an obvious upward shift of the mean value. Process capability analysis indicated that Group A had Cp = 1.166 and Cpk = 1.152, which represents acceptable process capability. In comparison, Group B presented Cp = 0.431 and Cpk = 0.112, values far below the acceptable lower threshold for stable production.

Table 2. Descriptive statistical results of breaking force in Group A and Group B.

Statistical Indicators	Group A (Machining Cycles ≤ 200 pieces)	Group B (Uncontrolled)
Sample Size	46	46
Mean Value/N	5170.91	5433.89
Standard Deviation/N	100.10	270.51
Cp	1.166	0.431
Cpk	1.152	0.112
Pass Rate/%	100.00	56.52

The following conclusions are obtained from the small-batch verification tests described in this chapter: 1) Restricting the allowable machining quantity of cutting tools remarkably improves the stability of breaking force. The standard deviation of Group A accounts for merely 37.0% of that of Group B. 2) Limiting the machining quantity enables the average breaking force to stay close to the target value. The deviation of Group A is −4.09N, while that of Group B reaches +258.89 N, showing an extremely significant discrepancy between the two groups. 3) The control strategy proposed in this work is effective and capable of confining the breaking force of products within the required specification range.

5. Conclusions

This work takes V-groove components made of 13Cr11Ni2W2MoV stainless steel as the research object. Systematic investigations were conducted targeting three core issues: the evolution law of tool nose radius wear, the performance control of component breaking force, and the determination of the allowable maximum machining quantity of cutting tools. Combined with theoretical modeling, performance tests and small-batch verification experiments, the major conclusions are summarized as follows: 1) During the V-groove machining of 13Cr11Ni2W2MoV stainless steel, a stable quantitative correlation exists between tool nose radius wear loss and machining quantity. The wear calculation formula derived in this paper can accurately predict the tool wear state under different machining batches and realize quantitative pre-judgment of tool wear severity. This study fills the research gap that no dedicated quantitative model is available to characterize tool wear in V-groove machining of this specific material. 2) Tool nose wear acts as the dominant factor deteriorating the stability of breaking force for V-groove components. Increasing tool wear loss readily triggers quality defects including breaking force deviation and excessive data fluctuation. Through correlation analysis between wear loss and breaking force performance, the maximum allowable machining quantity of 200 workpieces is identified to guarantee breaking force compliance with technical specifications. An integrated control framework covering tool wear, machining quantity and product mechanical performance is thereby established. 3) Small-batch production tests verify the feasibility and reliability of the proposed control strategy. Replacing cutting tools according to the determined maximum machining threshold effectively eliminates disqualification risks of product mechanical properties induced by excessive tool wear, and significantly improves the mass-production quality consistency and processing stability of V-groove components.

In conclusion, the research outcomes of this paper deliver effective guidance for precision mass machining of V-groove features on 13Cr11Ni2W2MoV stainless steel under given processing conditions, and provide crucial technical support for machining process optimization, precise tool life management and improvement of product quality stability for high-strength stainless steel components under identical working conditions. Furthermore, the research methodology adopted in this work can serve as a reference for machining quality control of precision structural parts fabricated from similar difficult-to-cut materials.

Author Contributions

Conceptualization, Xiaozhao SHI, Ying TANG and Yiwei LU; methodology, Xiaozhao SHI; software, Xiaozhao SHI; validation, Xiaozhao SHI, Ying TANG, Jingxin WENG, Li LI and Youcai QIU; formal analysis, Xiaozhao SHI and Jingxin WENG; investigation, Xiaozhao SHI and Jingxin WENG; resources, Xiaozhao SHI, Ying TANG and Yiwei LU; data curation, Xiaozhao SHI; writing—original draft preparation, Xiaozhao SHI; writing—review and editing, Xiaozhao SHI; visualization, Xiaozhao SHI; supervision, Yiwei LU; project administration, Xiaozhao SHI, Ying TANG and Yiwei LU; funding acquisition, Xiaozhao SHI and Yiwei LU. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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