OPTIMIZATION OF PARTIAL HIGH-FREQUENCY QUENCHING TECHNIQUE PARAMETERS OF ROTARY TILLING BLADES
/
旋耕刀局部高频淬火工艺参数优化

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ABSTRACT
The high-frequency quenching technique can enhance the surface hardness of 65Mn rotary tilling blades, thereby improving their wear resistance. This approach addresses common issues found in conventional rotary tilling blades, such as severe wear failure, short service life, and reduced operational efficiency due to frequent replacements. The quenching position was determined through finite element simulation. Based on orthogonal rotation combination tests using ternary quadratic regression, quenching temperature, tempering temperature, and tempering time were identified as key test factors. Using blade hardness as the evaluation index, the optimal parameters were determined to be a quenching temperature of 852 °C, tempering temperature of 171 °C, and tempering time of 85 minutes. Under these conditions, the blade hardness reached 57.5 HRC, meeting the national standard. Blades treated with these optimal quenching parameters were tested under actual soil conditions over a total operating area of 67 hm². The results showed that the average wear of the quenched blades was 11.9 g, and their wear resistance was 3.13 times higher than that of blades treated with conventional heat treatment. This represents a significant improvement in abrasion resistance and provides a solid experimental foundation for the reliability assessment of rotary tilling blades.

摘要
针对目前市面上旋耕刀工作过程中磨损失效严重, 使用寿命低, 耕作时需要频繁更换刀具影响作业效率等问题。采用高频淬火技术, 对65Mn 旋耕刀表面进行强化处理从而提高其耐磨性. 通过有限元仿真确定淬火位置，基于三元二次回归正交旋转组合试验. 确定了淬火温度, 回火温度和回火时间为关键试验因素, 以旋耕刀的硬度为试验指标, 得出最优试验参数淬火温度为852℃, 回火温度为171℃, 回火时间为85min, 此条件下旋耕刀的硬度值为57.5HRC, 符合国家标准. 采用最优工艺参数对65Mn 旋耕刀进行高频淬火, 在实际土壤环境中进行田间试验, 总作业面积67hm². 结果表明: 经淬火处理后的旋耕刀平均磨损量为11.9g, 与传统热处理后的旋耕刀相比耐磨性提高了3.13 倍, 磨损程度得到极大改善, 为旋耕刀的可靠性研究提供了试验基础.

INTRODUCTION
With the rapid development of agricultural mechanization, the service life of the key parts of agricultural machinery and equipment is expected to get longer and longer *(Hao et al., 2021)*. Rotary tillers are essential agricultural machinery that significantly influence the quality and efficiency of soil tillage. Their supporting rotary tilling blades are responsible for critical operations such as ploughing, soil crushing, and land preparation, resulting in a flat and soft surface suitable for sowing *(Xiao et al., 2022)*. Therefore, the performance and service life of the blades directly affect the overall quality and effectiveness of the rotary tiller.

Most rotary tilling blades just operate in the open air, and interact with sand grains and crop stubble for a long time, resulting in serious wear and tear and a low service life, frequent failure and damage. According to incomplete statistics, more than 80% of the soil parts of agricultural machinery operation are scrapped due to the wear and failure of grinding particles, which not only increases the operation cost of agricultural machinery, but also seriously affects the operation quality and efficiency *(Yadav et al., 2020; Zhu et al., 2022; Zhao et al., 2024; Kaur et al., 2011; Temesgen et al., 2009; Valboa et al., 2015; Sun et al., 2022; Li, 2018).*

In recent years, how to effectively improve the wear resistance and corrosion resistance of rotary tillage blade surface, reduce the energy consumption and reduce the loss is an urgent problem to be solved for agricultural machinery *(Wang et al., 2013; Shen et al., 2022)*. In the past, to enhance the surface hardness of rotary tilling blades, many researchers both domestically and internationally have employed various coating preparation techniques to create wear-resistant layers on the blade surface, achieving significant research outcomes *(Xiao et al., 2013; Falalu et al., 2020; Wang et al., 2022; Xie et al., 2021; Dariusz et al., 2017; Huang et al., 2015; Lee et al., 2006; Satit et al., 2007)*. However, these methods often involve high equipment costs, complex procedures, and expensive materials, making them difficult to implement on a wide scale and limiting their practical applicability.

In order to reduce the cost, this study adopts partial high-frequency quenching technique, compared with the traditional heat treatment technique, which has the advantages of extremely fast heating speed, easy depth control of quenching layers, uniform heating and high production efficiency. Moreover, only the surface of a certain depth of the workpiece is reinforced, while the core parts basically maintain the organization and performance before treatment, so that the combination of high strength, high wear resistance and high toughness can be obtained. Because 65 Mn materials have better friction performance and better economy, the 65 Mn rotary tilling blades were selected to analyze the significance of the influence of each factor on the hardness of rotary tilling blades. Finally, the field test was carried out to verify the actual working effect of partial high frequency quenching, so as to provide a reference for improving the wear resistance of the surface of rotary blades.

MATERIALS AND METHODS

Partial high-frequency quenching technique of rotary tilling blades

High-frequency quenching is a rapid surface treatment technique characterized by controllable quenching depth and uniform heating. It selectively hardens the surface of the workpiece to a specific depth while preserving the original microstructure and mechanical properties of the core. As a result, it achieves an optimal combination of high strength, excellent wear resistance, and good toughness. Additionally, the method offers numerous advantages, including a high start-up success rate, high efficiency, precise control, smooth and continuous power adjustment (10–100% of rated power), reliable operation, advanced technological integration, and ease of operation.

The partial high-frequency quenching technique of rotary tilling blades is: first start the power supply, the machine begins to work; operate the partial high-frequency quenching device through the control panel of the equipment; hold the rotary tilling blades in the clamp device on the bench and clamp it; transfer the rotary tilling blades to the induction coil by the turntable automatically changing positions; heat the blade by moving the high-frequency induction coil to the blade position; use the infrared high-temperature sensor to collect the temperatures; and give feedback to the PLC control system. When heated to the set temperature range, the system automatically stops heating and returns to the original position; clamp the cylinder and loosen the blade; the return cylinder pushes the blade into the quenching fluid to cool it quickly; complete the quenching of a blade. Replace the rotary tilling blades in turn with the rotation of the turntable and repeat the high frequency quenching technique, as shown in Fig. 1.

Fig. 1 - Flow chart of high-frequency partial quenching technique of rotary tilling blades

<u>Test materials and equipment</u>

Type IT245 rotary tilling blade was selected, as shown in Fig. 2 below, the material is 65 Mn steel, and its chemical composition is shown in Table 1. According to the shape of the rotary tilling blade selected, the electromagnetic induction coil used was bent to a fixed shape, as shown in Fig. 3 below.

Table 1

65 Mn Steel Chemical Composition (wt.%)

C	Si	Mn	P	S	Cr	Ni	Cu
0.62~0.70	0.17~0.37	0.90~1.20	≤0.035	≤0.035	≤0.25	≤0.25	≤0.25

Fig. 2 - The rotary tilling blades of choice

Fig. 3 - Electromagnetic induction heating coils

The high frequency quenching device is used to quench the rotary tilling blade, and SX2-15-12 box resistance furnace to temper the blades, FLIR-T440 infrared thermal imager to measure the temperature, and HR-150A Roche hardness tester to measure the hardness.

The partial high-frequency quenching device is mainly composed of control system, cooling device, heating device, power supply, clamping device and working table, as is shown in Fig. 4.

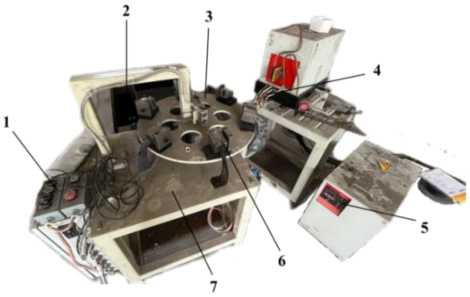


Fig. 4 - Rotary tilling blades high-frequency partial quenching device
1 – Control system; 2 – Cooling device; 3 – Rotating disk; 4 – Heating device;
5 – Power supply; 6 – Clamping device; 7 – Working table

<u>Experiment indicators and methods</u>

Each set of tests was conducted indoors with all doors and windows closed, maintaining a constant temperature of 15 °C. The rotary tilling blades underwent partial quenching. The quenching frequency was set to 20 kHz, resulting in an effective quenching depth of approximately 0.8–1.5 mm. After quenching, the blades were cooled using No. 20 mechanical oil at room temperature, then tempered in an SX2-15-12 box resistance furnace and allowed to cool to room temperature following tempering. The surface of each specimen was cleaned, and one side was polished using No. 800 corundum sander to remove the oxide layer. Hardness measurements were performed using an HR-150A Rockwell hardness tester. Each blade's surface hardness was measured three times, and the average was taken as its final hardness value. Each test level was repeated three times, and the average of these three repetitions was used as the final hardness value for that level.

Finite element simulation of rotary tilling blades

To determine the optimal partial quenching position of the rotary tilling blade, the blade was modeled in SolidWorks and analyzed using ANSYS Workbench. The test focused on the right-side machete blade of the IT245 rotary tiller. The 3D model was created in SolidWorks using operations such as stretching, bending, scanning and cutting, as illustrated in Fig. 5 and Fig. 6.

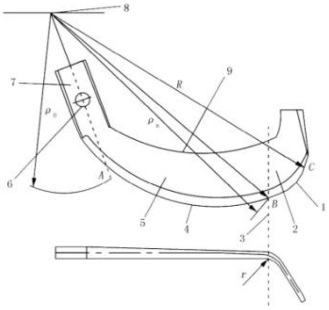


Fig. 5 - Schematic diagram of the structure of the rotary tilling blades
1 – Positive cutting edge; 2 – Front cutting section; 3 – Bend lines; 4 – Side cutting edges; 5 – Side cutting section;
6 – Mounting holes; 7 – Hilt; 8 – The center of rotation of the cutter roller; 9 – Back edge curve

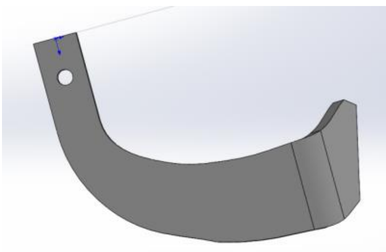


Fig. 6 - Geometric solid model

65 Mn is often adopted as the model material, and the main mechanical properties are shown in Table 2.

Table 2

65 Mn mechanical properties table

Material	Density / kg·m^{-3}	Elastic modulus / GPa	Poisson's ratio	Yield strength / MPa	Allowable stress / MPa
65Mn	7850	210	0.3	800	340

To improve the grid quality, the tetrahedral mesh was used to automatically divide the geometry, and the size of the grid was set to 6 mm to generate 2398 tetrahedral units, 10378 nodes, with a good grid quality of 0.7, as shown in Fig. 7.

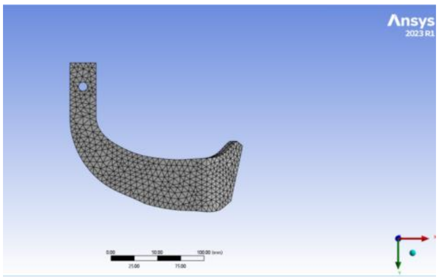


Fig. 7 - Meshing the model

Loads and boundary conditions were applied to the rotary tilling blades based on actual working conditions. Fixed constraints were assigned to the inner surfaces of the circular mounting holes. A force of 500 N, perpendicular to the surface, was applied to the side cutting edges, main cutting edges, and transition surface cutting edges for simulation and analysis.

Analysis of simulation results

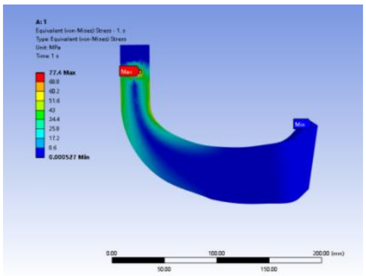


Fig. 8- Stress contour diagram

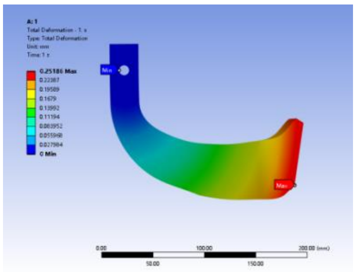


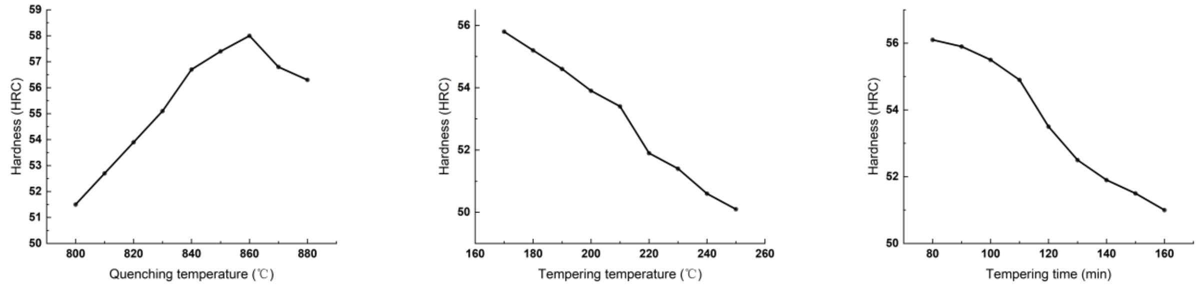
Fig. 9 - Total deformation contour diagram

Fig. 8 and Fig. 9 show the results of the static simulation analysis. The stress is concentrated at the mounting hole of the blade handle, as the rotary tilling blade acts as a single-degree-of-freedom rigid body. The section of the blade furthest from the constraint exhibits lower rigidity and greater deformation. Conversely, the area near the constraint, the handle, experiences the highest stress concentration due to the restriction at the tie point, with a maximum stress value of 77.4 MPa. The maximum displacement occurs at the main and side cutting edges and gradually decreases symmetrically toward both sides. The maximum total deformation is 0.25 mm, indicating that the simulation results meet the mechanical strength requirements for steel. Furthermore, the results are consistent with the actual fracture-prone areas observed in the field. Based on this analysis, the optimal quenching position is identified as the main cutting edge.

Analysis of influencing factors

Uni-variate test

The test aims to identify the factors that influence the wear resistance of the blade, specifically quenching temperature, tempering temperature, and tempering time. By varying one factor while keeping the others constant, the significance of each factor's impact on the test index can be assessed. If a factor has a significant effect, a reasonable value range is determined and later used as an input in the multi-factor optimization test. The quenching temperature is preset at 9 levels ranging from 800℃~880℃; the tempering temperature at 9 levels from 170℃~250℃; and the tempering time at 9 levels from 80 min~160 min.



(a) Quenching temperature (b) Tempering temperature (c) Tempering time

Fig.10 - Statistical graph of single factor examination results

With a tempering temperature of 210℃ and a tempering time of 120 minutes, the rotary tilling blades were subjected to quenching to investigate the influence of quenching temperature on hardness. The results indicate that quenching temperature significantly affects the hardness of the rotary tilling blade, making it a critical parameter in the quenching process. According to the test data, a clear relationship between quenching temperature and hardness is observed (as shown in Fig. 10a). Specifically, the hardness of the rotary tilling blade initially increases with rising quenching temperature, reaches a maximum at 840℃, and then gradually decreases. As quenching temperature increases, the dissolution of carbon and alloying elements in the 65Mn steel into the austenite phase becomes more pronounced, promoting the formation of martensite during cooling. Since the hardness of quenched steel is primarily determined by the martensite content, this leads to a peak in hardness at the optimal temperature. However, higher temperatures do not always yield better results. Due to the high sensitivity of 65Mn steel to overheating, temperatures exceeding 840℃ cause the austenite grains to coarsen, which diminishes the strength and toughness of the resulting martensite. This, in turn, leads to a reduction in quenching hardness and increased hardness loss during subsequent tempering.

The rotary blades were quenched at a quenching temperature of 840℃ and a tempering time of 120min. According to the test data, the tempering temperature and hardness relationship curves are shown in Fig. 10b. The hardness of rotary blades decreases with the increase of tempering temperature mainly because the tempering of 65 Mn steel is a diffusion and transition process from sub-stable martensite and residual austenite structure to ferrite and carbide. When the tempering temperature is low, the internal stress generated in the quenching process cannot be fully released, resulting in a slight hardness decrease. If the internal stress cannot be fully alleviated, cracking or deformation problems will arise. When the tempering temperature reaches 210℃, it is a more suitable tempering temperature for 65 Mn steel blades; within this temperature range, the internal stress can be effectively released and the hardness can be moderately reduced; customarily, a higher comprehensive hardness and toughness can be obtained, thus meeting the requirements of rotary blades. However, when the tempering temperature is too high, the martensite structure will be further decomposed (converting to bainite or ferrite). As a result, the hardness will be greatly reduced, which will also reduce the abrasive resistance and impact resistance of the blades.

The rotary blades were quenched at a quenching temperature of 840℃ and a tempering temperature of 210℃. According to the test data, the relationship curves of tempering time and hardness are shown in Fig.10c. The change trends and principles of hardness with the tempering time are consistent with those of the tempering temperature. When the tempering time is too short, the internal stress cannot be released. The residual stress will affect the service life and safety of the blades. The hardness decrease is small, and the ideal comprehensive performance cannot be obtained. When the tempering time reaches 120 min, it can fully release the internal stress and reduce the hardness appropriately, which can maintain a high hardness level, but also improve the toughness and impact resistance of the blades. When the tempering time is too long, the martensite structure will be further decomposed to the more stable bainite or ferrite transition, which will not only lead to a great decrease in hardness, but also reduce the wear resistance and blade retention ability.

Combination trail

Based on the effects of the three factors (quenching temperature, tempering temperature and tempering time) on the hardness of rotary tilling blades, the test adopts Box-Behnken response surface trial design. With the quenching temperature being x_1, tempering temperature being x_2, tempering time being x_3, the hardness response value being Y, the ternary quadratic regression orthogonal rotation combination test is carried out.

Regression analysis is conducted with Design-Expert 12.0 software, and significance verification test and variance analysis are performed on the basis of the test results. The levels of test factors and their coding are shown in Table 3.

Table 3

Test factor level table

Level	Parameter		
	Quenching temperature [℃]	**Tempering temperature [℃]**	**Tempering time [min]**
-1	820	170	80
0	840	210	120
1	860	250	160

RESULTS

Test scheme and results

Based on a ternary quadratic regression orthogonal rotation combination test, a total of 17 test groups were conducted. Using blade hardness as the response variable *Y*, and quenching temperature x_1, tempering temperature x_2, and tempering time x_3 as influencing factors, a multiple regression analysis was performed. The regression equation for hardness *Y* was derived from the test data using Design-Expert 12.0 software, and its statistical significance was subsequently evaluated. The experimental design and corresponding results are presented in Table 4.

Table 4

Combined test protocols and results

No.	Quenching temperature / [℃]	Tempering temperature / [℃]	Tempering time / [min]	Hardness / [HRC]
1	-1	-1	0	50.6
2	-1	1	1	57.6
3	1	0	1	47.4
4	-1	0	-1	53.1
5	0	1	-1	48.5
6	1	0	-1	56.9
7	0	0	0	48.7
8	1	0	-1	54.5
9	0	0	0	57.9
10	0	0	0	55.9
11	0	0	0	57.4
12	0	-1	1	52.3
13	0	0	0	55.5
14	-1	1	0	54.5
15	1	-1	0	54.7
16	0	0	0	54.5
17	0	1	1	54.1

The input data were analyzed using the Box-Behnken design in Design-Expert software to fit the regression model. Based on the results of the analysis of variance (ANOVA), a quadratic polynomial model was selected to best represent the relationship between the variables. The resulting regression equation describes the relationship between quenching temperature, tempering temperature, and tempering time with respect to blade hardness, and is given as follows:

$$\begin{aligned}\hat{Y} &= 54.66 + 3.36X_1 - 1.85X_2 - 0.7875X_3 - 0.325X_1X_2 \\ &- 0.65X_1X_3 - 0.775X_2X_3 - 3.11X_1^2 + 0.62X_2^2 + 0.595X_3^2\end{aligned} \tag{1}$$

The significance test of the coefficients in the regression equation obtained the ANOVA results as shown in Table 4; the significance test coefficient of the hardness *Y* regression model being p<0.0001, the equation can be deduced to be more significant. The regression equation can better reflect the practical problems. On account of p=0.4905>0.05 of the mismatch term (Lack of Fit), the model fitting loss is not significant and fits well with the actual situation, which can be used to analyze and predict the optimal process parameters of high frequency quenching *(Wang et al., 2024)*.

The coefficient of determination R^2 of the model was 0.9892, indicating that the model had high significance, while R^2_{Adj} = 0.9754 was able to explain 97.54% of the response value variation in the trial and was also close to the predicted correlation coefficient R^2_{pred}. Therefore, this model can better describe the relationship between hardness and each response factor, and this secondary regression model can be used to analyze and predict the optimal process parameters of high-frequency quenching.

As shown in Table 5, quenching temperature, tempering temperature, and tempering time (based on one-factor trials) all have significant effects on the hardness of the rotary tilling blade. The order of influence is as follows: quenching temperature > tempering temperature > tempering time. Regarding interaction effects between two factors, the following were found to significantly affect hardness: the interaction between quenching temperature and tempering time, tempering temperature and tempering time, as well as the quadratic terms of quenching temperature, tempering temperature, and tempering time. In contrast, the interaction between quenching temperature and tempering temperature did not show a significant effect on hardness.

Table 5

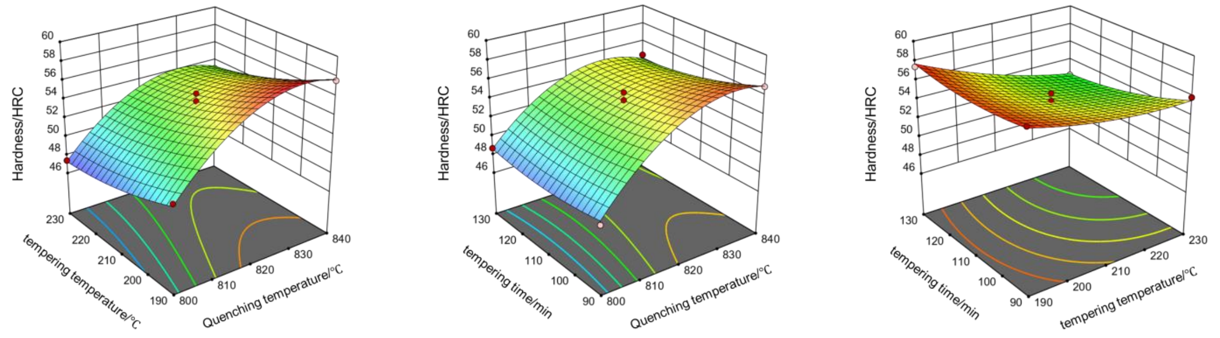
Analysis of variance of hardness

Source of variation	Sum of square	Degree of freedom	Mean square	*F* value	*P* value	Significance
Model	169.67	9	18.85	71.35	< 0.0001	**
X_1	90.45	1	90.45	342.34	< 0.0001	**
X_2	27.38	1	27.38	103.63	< 0.0001	**
X_3	4.96	1	4.96	18.78	0.0034	**
X_1X_2	0.4225	1	0.4225	1.6	0.2465	
X_1X_3	1.69	1	1.69	6.4	0.0393	*
X_2X_3	2.4	1	2.4	9.09	0.0195	*
X_1^2	40.59	1	40.59	153.64	< 0.0001	**
X_2^2	1.62	1	1.62	6.13	0.0425	*
X_3^2	1.49	1	1.49	5.64	0.0492	*
Residual	1.85	7	0.2642			
Lack of Fit	0.7775	3	0.2592	0.967	0.4905	
Pure Error	1.07	4	0.268			
Sum	171.52	16				

Note: $p \le 0.01$ means highly significant(**); $0.01 < p \le 0.05$ means significant (*); $p > 0.05$ means not significant.

Analysis and discussion of factor interaction

The images generated in the Model Graphs visually reflect the effects of each factor on the response value. The influence of each factor is clearly demonstrated through the changes in factor levels. To investigate whether the interaction between factors significantly affects the hardness of the rotary blades after quenching, response surface analysis was employed. This analysis involved fixing one factor and examining the interaction between the other two factors. Fig. 11 presents a three-dimensional graph of quenching temperature, tempering temperature, and tempering time, which provides a clear visual representation of how each factor influences the quenching performance of the rotary blades. It also demonstrates how these factors interact and jointly affect the evaluation indexes.



(a) Interaction effect of quenching temperature and tempering temperature on hardness

(b) Interaction effect of quenching temperature and tempering time on hardness

(c) Interaction effect of tempering temperature and tempering time on hardness

Fig. 11 - The effects of the interaction of various factors on the hardness of rotary tilling blades

Fig. 11a illustrates the response surface diagram showing the interaction effects between quenching temperature and tempering temperature on the hardness of rotary blades, with tempering time fixed at 120 minutes (0 level). The analysis reveals that when the quenching temperature is held constant at a low level, the change in hardness with increasing tempering temperature is minimal. However, at higher quenching temperatures, the hardness value decreases consistently as the tempering temperature increases. When the tempering temperature is held constant, the hardness response value increases within a certain range as the quenching temperature rises. However, once the quenching temperature reaches 840℃, any further increase leads to a gradual decline in the hardness of the rotary blades. This behavior is attributed to the growth of austenite grains: initially, the grains are fine, but as the quenching temperature increases, they begin to coarsen significantly. The higher the temperature, the more pronounced this grain growth becomes. In the case of 65Mn steel, excessive grain coarsening reduces the material's hardness, thereby diminishing the effectiveness of the heat treatment.

Fig. 11b presents the response surface diagram illustrating the interaction between quenching temperature and tempering time on the hardness of rotary blades, with tempering temperature fixed at 210℃ (0 level). The analysis shows that within the tested range, when the quenching temperature is held constant, the effect of tempering time on hardness is not significant at lower quenching temperatures. However, at higher quenching temperatures, the hardness gradually decreases with increasing tempering time. Conversely, when tempering time remains constant (regardless of whether it is at a high or low level) the hardness initially increases as the quenching temperature rises, but then slowly goes down when the quenching temperature reaches 840℃. This is because the tempering process is a diffusion and transition process from sub-stable martensite and martensite and residual austenite tissues to ferrite and carbide. As tempering time extends, internal stresses are gradually relieved, leading to a moderate reduction in hardness.

Fig. 11c illustrates the response surface diagram showing the interaction effects between tempering temperature and tempering time on the hardness of rotary blades, with the quenching temperature fixed at 840℃ (0 level). The analysis indicates that within the tested range, when the tempering temperature is held constant, the change in hardness with increasing tempering time is minimal at lower tempering temperatures. However, at higher tempering temperatures, the hardness gradually decreases as tempering time increases. Similarly, when tempering time is held constant (regardless of whether it is at a high or low level) the hardness decreases with increasing tempering temperature, with the decline being more pronounced at higher levels. This trend results from the interaction between tempering temperature and tempering time: during tempering, the transformation of martensite and retained austenite into ferrite and carbide occurs. The atomic diffusion along grain boundaries promotes grain growth, which increases the material's fracture toughness. However, this grain coarsening simultaneously leads to a reduction in hardness.

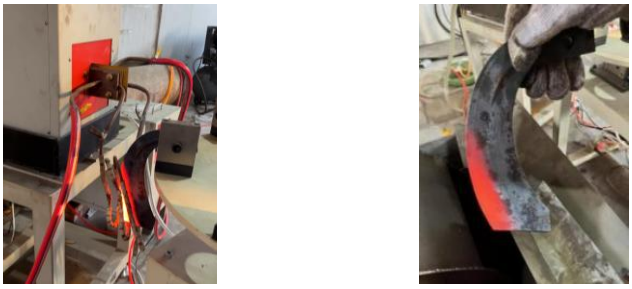
Parameter optimization and validation tests

The optimal combination of quenching process parameters was determined by analyzing the experimental data and optimizing the influencing factors. Based on the quenching performance requirements of rotary tilling blades and the boundary conditions of the key parameters, an optimization model was established. Using quenching temperature X_1, tempering temperature X_2, and tempering time X_3 as constraint variables, and hardness Y as the optimization target, a mathematical model for the rotary blade quenching process was developed. The computational method for this model is described in Equation (2) *(Wang et al., 2023)*.

$$\begin{cases} maxY \\ 820 \le X_1 \le 860 \\ 170 \le X_2 \le 250 \\ 80 \le X_3 \le 160 \end{cases} \tag{2}$$

The target parameter was set to be maximized in the optimization module of Design-Expert 12.0 software. Each process variable was constrained within the ranges specified in Table 3. The optimized combination of process parameters was identified as follows: quenching temperature of 852.2℃, tempering temperature of 171.4℃, and tempering time of 84.7 min. Under this combination, the rotary tilling blade is predicted to achieve optimal quenching performance, with a hardness value of 57.9 HRC. To verify the reliability of the model, the optimized process parameters were tested under the same experimental conditions. The test specimens, both before and after quenching, are shown in Fig. 12.

For improved operability in practical applications, the optimized values were rounded to quenching temperature of 852℃, tempering temperature of 171℃, and tempering time of 85 min. Under these conditions, the measured average hardness was 57.5 HRC, with a relative error of only 0.81%, confirming the accuracy and credibility of the regression model and optimization analysis. It is worth noting that the optimized tempering temperature lies at the boundary of the test parameter range, indicating that low-temperature tempering effectively eliminates quenching stress while avoiding deformation or cracking. This ensures dimensional stability during operation and maintains the high hardness and wear resistance of the blade after heat treatment.



(a) Test site (b) Quenched samples

Fig. 12 - Test site and quenched rotary tilling blades samples

Field testing

When tilling with the rotary blades, the actual soil environment is often very complicated, as a result the soil tank test bench in the laboratory cannot fully simulate the field test conditions. In order to further verify the correctness of the above quenching test conclusions, the rotary blades are quenched under the above optimal process parameters to verify the wear resistance of the high-frequency quenching technique. Before the test, all the rotary blades were washed and dried, weighed with a balance with an accuracy of 0.1 g, and the original mass was recorded. The 10 rotary blades were quenched with the optimal parameter combination, and the other 10 were not treated, as shown in Fig.13.

(a) Unquenched rotary tilling blades (b) Quenched rotary tilling blades

Fig. 13 - Heat treatment before field trials

Then, the rotary blades quenched with the optimal combination parameters and the original blades without being quenched are installed on the shaft of the rotary blades alternately for a contrast test, as shown in Fig. 14. Field test site lies in the corn planting field of Yi County, Jinzhou City, Liaoning Province (Fig.15)： the soil was sand soil, the average moisture content of the test soil was 19.8%, and the total working area was 67 hm^2. After the tillage, all rotary blades were removed and the surface soil was wiped off the friction loss was weighed and measured. The quality changes of rotary tilling blades before and after the field test are shown in Table 6.

Fig. 14 - Schematic diagram of rotary tilling blades installation

Fig. 15 - Field trials

Table 6

The amount of wear and tear of the rotary tilling blades

Title	Test blade number									
	1	2	3	4	5	6	7	8	9	10
The amount of wear on the rotary tilling blades after quenching/(g)	11.3	12.5	11.7	10.9	12.6	12.8	11.4	11.7	11.4	13.1
The amount of wear on the rotary tilling blades after not quenching/(g)	37.6	38.1	36.9	36.7	36.8	37.9	37.6	35.9	36.8	37.4

Discussion

From the table data, the average abrasion of 10 quenched blades is only 11.9 g, while the average abrasion of the other 10 without being quenched is as high as 37.2 g. In contrast, the wear resistance of the blades after being quenched increase by 3.13 times, which demonstrates that the high frequency quenching can effectively improve the wear resistance of the blades.

In order to improve the wear resistance of rotary tilling blades, many scholars at home and abroad used various coating preparation techniques to prepare wear resistance layer on the surfaces of rotary tilling blades. *Amardeep et al (2012)* compared three different kinds of explosive spraying coatings on high strength steel rotary tillers, namely WC-Co-Cr, Cr_3C_2NiCr and Stellite-21, and the following field tests showed that the three coated rotary blades show excellent wear resistance, helping to extend the service life of rotary tillers. *Zhan (2022)* prepared Fe/WC/CeO_2 stack welding layer on Q235 matrix by using plasma stack welding technology. In the field comparison test, it was found that the grinding crack of the cutting edge of the 65 Mn rotary tillers was dense and the abrasion was obvious, while the Fe/WC/CeO_2 stack welding layer carried no obvious wear marks, and the stack welding layer did not fall off, and the wear quality was reduced by about 65%. *Long et al (2022)* took 65 Mn rotary tillage blades as the matrix, selected BNi-2 brazing material and the carbide as the brazing coating material, studied the influence of heat treatment process after brazing coating on the tissue evolution and hardness of nickel base alloy, and the results showed that the hardness of the coating was high in the state of brazing coating. However, through comprehensive comparison, it is evident that although thermal spraying, plasma stack welding, and brazing coating technologies can enhance the microstructure of materials and improve the wear resistance of rotary tilling blades, these methods are associated with complex processes, high costs, and technical challenges. If not precisely controlled, the desired improvement in wear resistance may not be achieved, making these methods less practical for widespread application in agricultural settings. Compared with these surface strengthening processes, the high-frequency quenching technology adopted in this paper has the advantages of uniform heating, rapid heating-up and simple processing. The induction heating principle only heats the surface of the material to achieve the effect of hard outside and tough inside, which just meets the needs of rotary tilling blades.

CONCLUSIONS

In this study, 65 Mn steel, a commonly used material of rotary blades was selected, and based on the existing heat treatment research and combined with the characteristics of agricultural production, a partial high-frequency quenching technique with low cost and excellent performance was adopted to solve the wear and failure problem of 65 Mn rotary blades. In the quenching test, the hardness of rotary blades was taken as the technical index of partial high frequency quenching, and the appropriate parameter range of high frequency quenching was explored under the preliminary quantitative condition. Then, the following conclusions were drawn:

(1) The finite element static solution result shows that the maximum total deformation of rotary blades is 0.25 mm, located at the positive cutting edge position, and the maximum stress of rotary blades is 77.4 MPa, located at the upper half of the back edge curve. The solution result is in line with the actual situation, and the quenching position is determined. Single factor test preliminarily determined the value range of the parameters as follows: the quenching temperature is 820℃ ~860℃, the tempering temperature is 170℃ ~250℃, and the tempering time is 80min~160min; under these conditions, the hardness of the rotary blades is above 48, and the quenching effect is good.

(2) A regression model expressing the hardness of rotary blades was established by ternary quadratic regression orthogonal rotation combination test, and the influence pattern of each parameter was analyzed by using Design-Expert 12.0 software, and the fitting and significance tests were performed by ANOVA.

The effects of each factor on the hardness of rotary blades is as follows: quenching temperature>tempering temperature>tempering time. The interaction between quenching temperature and tempering time, between tempering temperature and tempering time both have a more significant effect. The optimized parameters bring about the best quenching conditions: quenching temperature 852℃, tempering temperature 171℃, and tempering time 85min, when the hardness of rotary blades is 57.5 HRC, which not only meets the national standard, has good wear resistance and corrosion resistance, but also provides a test basis for the study of high-frequency quenching technique and supporting equipment design.

(3) Through comparative analysis between the 10 blades quenched using the optimal quenching parameter combination and the 10 unquenched original blades, the average wear of the quenched blades was found to be only 11.9 g, whereas the unquenched blades exhibited an average wear of 37.2 g. This indicates that the wear resistance of the blades improved by 3.11 times after high-frequency quenching, thereby confirming the effectiveness and feasibility of the high-frequency quenching technique for enhancing the durability of rotary tilling blades.

(4) High-frequency quenching, as an emerging surface treatment technology, effectively enhances the surface wear resistance of metal components and offers considerable economic benefits. This study presents a preliminary investigation into the application of high-frequency quenching on 65Mn rotary tilling blades, demonstrating a notable improvement in their wear resistance. However, to further facilitate the adoption of this technique in agricultural production, more in-depth and systematic research is required. Importantly, the high-frequency quenching method is not limited to 65Mn steel; it holds promise for optimizing the surface treatment of other soil-contact parts in agricultural machinery. To expand its applicability, a comprehensive database of quenching parameters for various metal materials should be established, providing a valuable reference for enhancing the wear resistance of metallic components. It is worth noting that this study focused primarily on surface hardness and wear performance. To gain a more comprehensive understanding of the material behavior post-quenching, future research will explore the internal microstructural changes of the treated materials, thereby enabling more accurate and reliable evaluations of the high-frequency quenching process.

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