Original Research

Study on the Wear of Hardened Opener Shares of the Grain-Fertilizer-Grass Seeder

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Abstract
The importance of this study lies in the fact that the wear of the working bodies of seeding machines leads to an increase in fuel consumption, which results in increased costs and a deterioration in the quality of seeding, thus leading to a decrease in yield. This paper aims at studying the state of hardened working bodies of a grain-fertilizer-grass seeder. Based on the results of existing information and the possibility of further implementation of shared hardening technologies, the following methods of improving wear resistance were adopted – (i) electric arc surfacing with hard-alloy electrodes and Sormayt®, and (ii) hardening share by high-frequency heat treatment. To carry out this study, samples of the opener shares of a grain-fertilizer-grass seeder, made of the structural spring steel 65Mn, were used. An ultrasonic flaw detector was used to study the condition of the worn-out surface layer of the opener shares. These studies allowed us to establish that the strengthened samples increase the hardness of the material. On the basis of experiments with rotatable central composite design, the optimal parameters for achieving maximum hardness of the grain-fertilizer-grass seeder's opener share were determined the material composition; a soaking time and a resistivity. Under these conditions, the hardness of the steel reached 94.46 HRC. Based on these results, it is recommended to replace the standard factory heat treatment with surfacing of the entire working part of the seeder openers with T590 electrodes to achieve the best shares of hardening for use in agricultural enterprises.

Keywords - Abrasion, Coatings, Hardness, Surface treatments, Tribological systems, Wear.

INTRODUCTION

It is known that one of the factors influencing the high yield of agricultural crops is the quality of sowing operations, as it creates favorable conditions for germination of seeds in the soil. It should be noted that the working bodies of the sowing equipment, with the share of furrow openers, exert forces on the soil during seeding (Petukhov et al., 2013). Therefore, during operation, with the increase in the operating time of grain-fertilizer-grass seeders, the detrimental effect caused by abrasion, wear and corrosion increases, leading to a decrease in the physical, mechanical and operational properties of the material.

Research analysis shows that more than 30 factors affect the wear nature of the working bodies of tillage machines. The main factors of wear in arid and wind-eroded areas are the depth of seeding, the intensity of the impact of the opener share on the soil, the properties of the material from which the working bodies are manufactured, and the method of their hardening.

The outcome of laboratory and field studies conducted by [2-22] on the working bodies of seeders and other tillage machines showed that the degree of wear of the protective surface layer of the opener shares that were hardened by various methods depends on the properties of the steel, the mode of operation, mechanical properties of the soil, etc. However, these studies did not investigate the condition of the worn surfaces due to the presence of defects (the presence of porosity and microcracks in the deposited layers, their delamination, unsatisfactory roughness, places of corrosion, etc.), and provide a rational method of surface hardening of the working bodies of the seeder.

The aim of this study was to improve the wear resistance of opener shares of the grain-fertilizer-grass seeder by demonstrating a rational method for their surface hardening.

The analysis of the wear factors allowed us to select three main factors for further study: (i) the material composition was selected from the structural factors, including the influence of the presence of the chemical element chromium (Cr) on the material strength and wear of 65Mn steel (AISI SAE 1065), (ii) the material resistivity was selected from the exploitation factors, and (iii) the soaking temperature during hardening was selected from the technological factors.

MATERIALS AND METHODS

To carry out this research, samples of the opener shares of the grain-fertilizer-grass seeder were used, made of structural spring steel 65Mn, which is most commonly used in fast-wearing working bodies and can be obtained with a less rough surface and less decarburization during hot processing compared to other steels. 65Mn Steel has higher strength, toughness and wear resistance, high resistance to small plastic deformations and relaxation resistance, fairly high hardenability, and relatively low cost [23].

Typically, at the factory, shares are quenched in an oil medium (heating up to 800 - 830°C) and tempered (at 300 - 350°C) with air cooling.

Based on the review of existing information and the possibility of further implementation of shared hardening technologies prevalent in agricultural enterprises in Kazakhstan, the following methods of improving wear resistance were adopted: electric arc surfacing with hard-alloy electrodes T 590 (Mn 1.0-1.5%, Si 2.0-2.5%, C 2.9 - 3.5%, P ≤ 0.04, S ≤ 0.035, Cr 22.0-27.0, B 0.5-1.5) and CS-1 (Sormayt® No. 1) with a diameter of 5.0 mm; high-frequency heat treatment-heating of shares for quenching.

Heat treatment of mass-produced shares was carried out in an electric furnace (model SNOL 12/12-V) and the working surfaces of the experimental share samples were treated with an inverter welding power source (model-Flex Tec 500P).

HFC-hardening of opener-shared samples was carried out in the temperature range of 800 - 820°C in quenching medium oil. Surfacing processing of T590 and CS-1 electrodes (Sormayt® No. 1) was performed in the optimal mode: surfacing current I = 250 - 300 A (constant reverse polarity), voltage U = 50 - 70 V.

Microstructural analysis of the samples of the opener working body was carried out. Microspecimens were made in several stages: experimental samples were cut to minimum dimensions of 12x10 mm, 10x10 mm and ground on abrasive paper P240, P320, P600, P1200, P2000. The surface layer was polished until the traces from the previous paper were removed and the grinding direction was changed by 90°. The surface of the sample was polished on a polishing wheel using a cloth in a metallographic grinding machine. After polishing, the samples were washed with water, degreased with alcohol swabs and dried on filter paper. To reveal the microstructure, the microspecimens were etched with aqua regia in the proportion of 3 parts hydrochloric acid to 1-part nitric acid, and subsequently aged for 20-30 h prior to use.

Metallographic analysis shows that in the initial state, the surface of 65Mn steel consists of ferrite and lamellar pearlite, as well as cementite (Fig. 1). Fig. 2 shows the microstructure of the diffusion layer of 65Mn steel samples after heat treatment, from which it can be seen that the dark etch-hardened layer has a martensitic structure and a layer of thermally-affected surface in the cross-sectional structure after surface quenching. After heat treatment, the formation of martensite grains was observed, with small particles of carbides of alloying elements distributed along their boundaries.

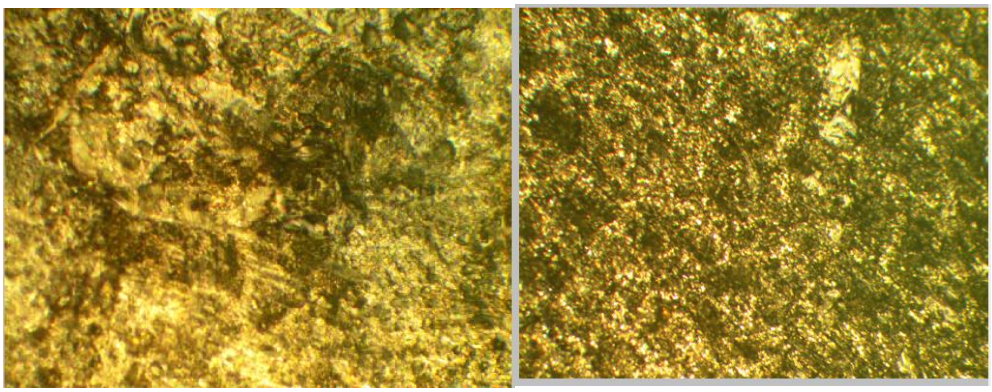


FIGURE 1
INITIAL MICROSTRUCTURE OF THE DIFFUSION LAYER OF 65MN STEEL SAMPLES

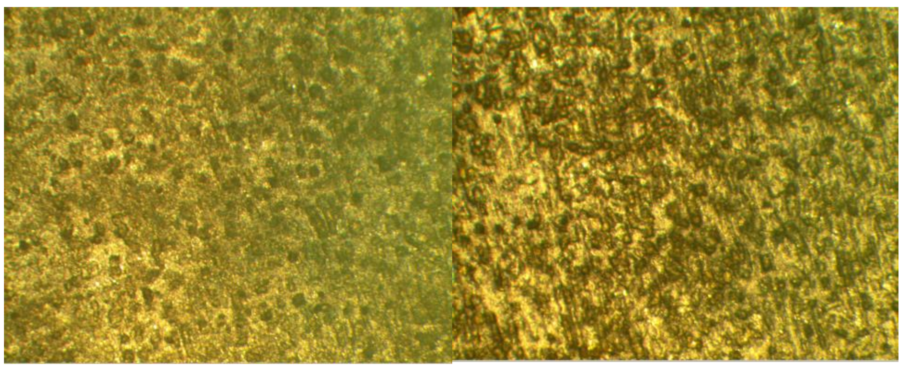
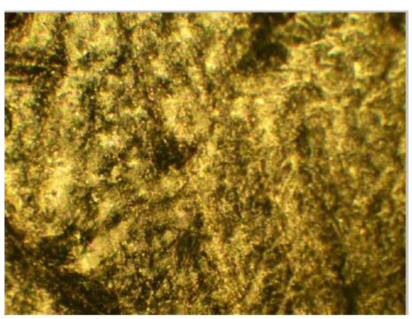
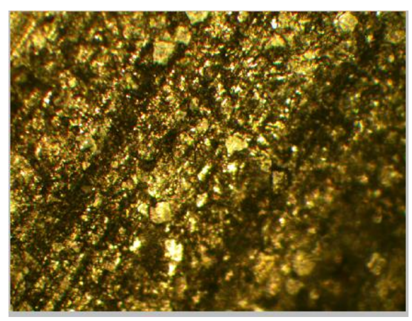


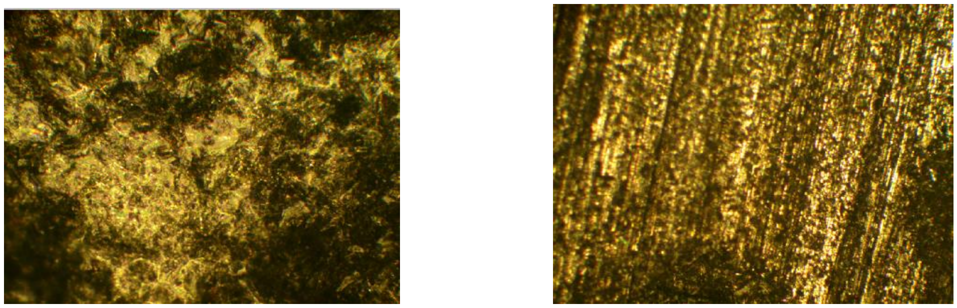
FIGURE 2
MICROSTRUCTURE OF THE DIFFUSION LAYER OF 65MN STEEL SAMPLES AFTER HEAT TREATMENT





a b

FIGURE 3
MICROSTRUCTURE OF THE DIFFUSION LAYER OF 65MN STEEL SAMPLES: (A) INITIAL MICROSTRUCTURE, AND (B) AFTER HARDENING WITH T590 WIRE



a b

FIGURE 4
MICROSTRUCTURE OF THE DIFFUSION LAYER OF 65MN STEEL SAMPLES: (A) INITIAL MICROSTRUCTURE, (B) AFTER HARDENING WITH SORMAYT®

The initial microstructure of the samples before hardening was coarse-grained pearlite surrounded by ferrite (Fig. 3). After hardening with T590 electrode wire and Sormayt®, a significant structural refinement was observed. The size of martensite needles was reduced in the case of Sormayt®, and on the surface hardened with T590 wire. Due to the presence of secondary cementite and pearlite cementite in the structure, a finer acicular martensite was formed in the diffusion layer, as shown in Fig. 4.

The mass-produced and hardened samples of the opener share (Fig. 5) were retrofitted onto the grain-fertilizer-grass seeder and field tests were conducted during the spring sowing campaign of 2019 under soil and climatic conditions of the Akmola region of Kazakhstan in ordinary black humus soil (chernozem) (moisture 25 - 45%, soil contamination with stones of average diameter of 50 mm being 0.6 - 1.5 pcs/m2) when a class 2 tractor was used for sowing vetch (spring), creeping clover, and alfalfa.

Opener-ripper Seeder used for sowing

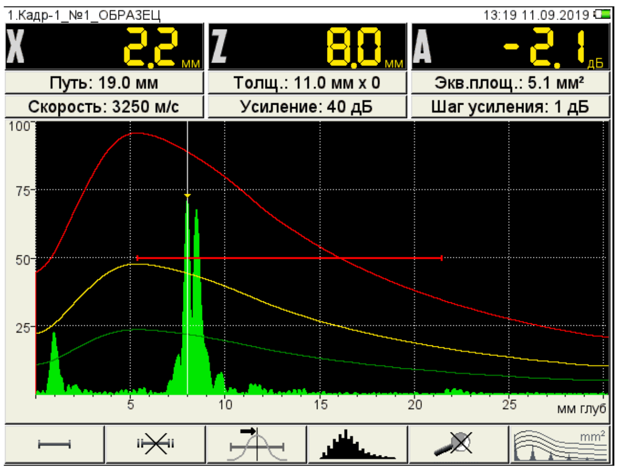
FIGURE 5
PHOTOGRAPH OF THE GRAIN-FERTILIZER-GRASS SEEDER (PHOTOGRAPHER: D. KOSSATBEKOVA)

The condition of the worn surface layers of the opener shares in the presence of defects (microcracks on the hardened surfaces, porosity, continuity, and internal stratification of the deposited layers, corrosion centers) was studied with an ultrasonic flaw detector, model A1212 MASTER (Fig. 6e). This device makes it possible to implement standard and specialized methods of ultrasonic testing with high productivity and measurement accuracy.

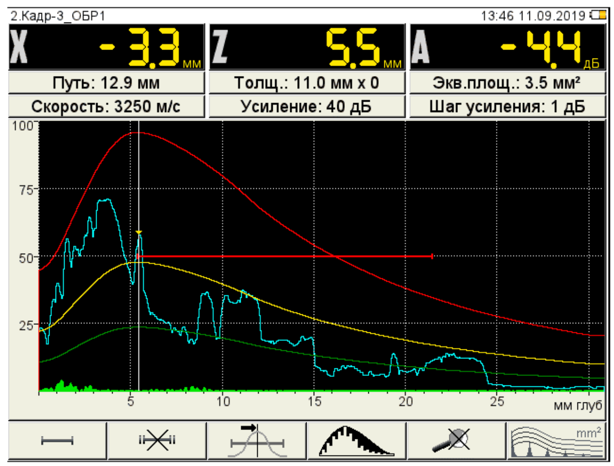
The “Distance Gain Size” diagrams (DGS diagrams), shown in Fig. 6a and b and obtained during the course of this study using the S5182 sensor (Fig. 6c) of the A1212 MASTER flaw detector, allowed us to determine the three levels of control (rejection, control, and search) from the curves displayed on the screen. The calculation of the equivalent area of the studied reflector was performed automatically.

The maximum hardness will be determined experimentally by the method of a rotatable central composite experiment. The following variables are taken as input factors: composition of the material (effect of chromium content on hardness), soaking during processing, and material resistance of the hardened material.

The statistical analysis of the experimental data points was conducted by SAS software.

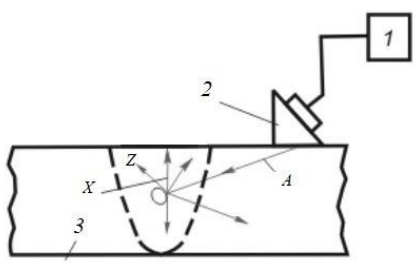


a



b

c



d

e

FIGURE 6
RESULTS OF THE STUDY OF WORN SURFACES OF THE OPENER SHARE USING AN ULTRASONIC FLAW DETECTOR: (A AND B) DGS DIAGRAMS; (C) THE PROCESS OF MEASURING THE WORKING SURFACE OF THE SAMPLE BY THE FLAW DETECTOR SENSOR; (D) THE PRINCIPLE OF OPERATION OF THE DEVICE; (E) ULTRASONIC FLAW DETECTOR MODEL A1212 MASTER: 1 - FLAW DETECTOR ELECTRONIC UNIT; 2 - PIEZO TRANSDUCER; 3 - CONTROLLED OBJECT

RESEARCH RESULTS AND DISCUSSION

I. Results of the flaw detection

Figure 6 shows the flaw detector frames (a and b) and the measurement process (c) for sample number 1 (65Mn steel, hardened with T590 surfacing wire on the front and back sides). The DGS diagram shows (Fig. 6a) that the signal is caught by a direct beam. This is evidenced by the "number 0" after the multiplication sign in the window with the thickness of the object. The signal amplitude is 2.1 dB below the rejection level and the equivalent area is 5.1 mm^2. The reflection was obtained at a depth of 8 mm. We continue to probe the area along the coordinate X = 2.2 mm. At a distance X = -3.3 mm, a signal is found (Fig. 6b). In this area, when the signal changes, the amplitude is 4.4 dB below the rejection level, with a equivalent area of 3.5 mm^2. The display depth is 5.5 mm.

The same measurements were performed on samples No. 2 – No. 9. The results of studying the worn surfaces of the experimental samples of the opener share by an ultrasonic flaw detector are shown in Table I.

In this experiment, samples of mass-produced shares (No. 4, No. 5, No. 7, No. 8, and No. 9) were used with the same parameters. Among the selected samples, the highest and lowest values of amplitude data, display depth, and equivalent rejection area was found based on the experimental results.

TABLE I
RESULTS OF THE STUDY OF WORN-OUT SURFACES OF THE OPENER SHARES WITH A THICKNESS OF 11 MM

Sample number	Repetition of the experiment	Material	Defect parameters coordinates			Path (mm)	Equiv. area (mm^2)	Average arithmetic eq. squares (mm^2)
			X (mm)	Z (mm)	A (dB)			
1	1	65Mn steel + T590 (front and back sides)	1.8	7.8	-5.7	18.5	3	3.25
	2		-3.3	5.5	-4.4	12.9	3.5	
2	1	65Mn steel + T590 (full working part)	-3.5	5.4	-6.9	12.7	2.5	2.85
	2		-2.1	6	-5.1	14.2	3.2	
3	1	65Mn steel (HFC hardening)	17.6	6.8	-4.9	36	3.7	2.8
	2		-3.5	5.4	-8.8	12.7	1.9	
4	1	65Mn steel (factory-supplied technology)	10.9	9.9	-6.6	28.6	2.8	3.5
	2		11.7	9.6	-3.6	29.4	4.2	
5	1	65Mn steel (factory-supplied technology)	0.2	7.1	-5.6	16.8	3	3.45
	2		-2.9	5.6	-3.8	13.3	3.9	
6	1	65Mn steel +CS-1 (Sormayt® No. 1) standard	-3.5	5.4	-4.2	12.7	3.6	3.55
	2		-3.5	5.4	-4.5	12.7	3.5	
7	1	65Mn steel (factory-supplied technology)	1.2	7.6	-2.5	17.9	4.8	4.8
	2		3.1	8.4	-0.8	17.9	4.8	
8	1	65Mn steel (factory-supplied technology)	5.5	9.6	-2.2	22.6	5.1	4.6
	2		-1.3	6.4	-3.5	15.1	4.1	
9	1	65Mn steel (factory-supplied technology)	-1.7	6.2	-11.1	14.7	1.5	4.1

The economic costs of the heat treatment hardening process were determined (hardening on a universal laboratory muffle electric furnace SNOL 12/12V for 175 min at a temperature of 800-830°C (±20°C), maintaining the temperature for 40 min, followed by tempering the sample with aging in oil for 5 min and cooling) and the process of surfacing with T590 electrodes (E320Ch25S2GR) (Chernyak et al., 2000) was calculated according to the following index method. The selected samples had identical masses and dimensions before hardening. The output is shown in Table II.

TABLE II
TECHNO-ECONOMIC INDICATORS OF HEAT TREATMENT AND SURFACING PROCESS WITH T590 ELECTRODES

The name of indicators	Surfacing with T590 electrodes	Heat treatment
The cost of work under the piece-rate system (wages per unit of parts) in US dollar	1.5	7.06
Cost of materials per unit (consumables) in US dollars	0.29	4.5
Electricity cost (US dollars)	0.02	0.13
Workshop unit cost (US dollars)	1.8	11.7
Full processing time (h)	0.1013	4.1
Piece-calculation time (h)	0.0297	4.07
Number of workers	1 welder	1 thermist

Analysis of the techno-economic indicators of the high-frequency heat treatment of the working bodies (sample No. 3) and the process of surfacing with T590 electrodes (sample No. 2) (Table II) shows that the cost of surfacing is about 4.6 times lower than that of heat treatment.

II. Determination of maximum hardness by the rotatable central composite experiment method

The shapes and wear properties of the shares hardened by different methods are sufficiently determined by the appearance of the individual working bodies. The characteristic wear of the shares can be seen from the photographs shown in Fig. 7.
It is very difficult to establish the analytical dependence of the maximum hardness on the surface hardening method.
The experiment was carried out on the basis of the second-order rotatable central composite experiment (Spiridonov, 1981).
The levels and intervals of variation of the factors used in the study are shown in Table III.

TABLE III
MATRIX FOR PLANNING SECOND-ORDER ROTATABLE CENTRAL COMPOSITE EXPERIMENT

Factors				Optimization parameter
Natural designation	Material composition Cr (%)	Soaking τ (h)	Material resistivity R (μΩ·m)	Material hardness HRC
Coded	x_1	x_2	x_3	y
Upper level	25	3	0.55	-
Main level	13.25	2	0.40	-
Lower level	0.25	1	0.25	-
Variation interval	12.25	1	0.15	-


a


b


c


d

e

f

g

h

k

FIGURE 7
PHOTOS OF WORN SURFACES OF GRAIN-FERTILIZER-GRASS SEEDER SHARES HARDENED BY VARIOUS METHODS (PHOTOGRAPHER: D. KOSSATBEKOVA)
A - SAMPLE WITH A HARDENED WORKING SURFACE BY SURFACING OF A T590 ELECTRODE (FRONT AND BACK SIDES); B - SAMPLE WITH A HARDENED WORKING SURFACE BY SURFACING OF A T590 ELECTRODE (COMPLETE WORKING PART); C - SAMPLE WITH A HARDENED WORKING SURFACE BY HIGH-FREQUENCY HEAT TREATMENT; D, E, G, H, K - SAMPLES WITH A THERMALLY PROCESSED WORKING SURFACE ACCORDING TO FACTORY TECHNOLOGY; F - SAMPLE WITH A HARDENED WORKING SURFACE BY SURFACING A CS-1 GRADE (GRADE NO. 1) (STANDARD) ELECTRODE.

We decided to approximate the dependence of T590 electrode surface hardened opener share hardness, HRC, as a function of the percentage of alloying element (chromium) in the electrode composition, soaking time, and material resistivity of surfacing [i.e., f(Cr, τ , R)], using a second degree polynomial. The levels and intervals of variation of factors implemented in the study are shown in Table IV.
A full second order response surface model for the hardness of the material is given by:

$$y = b_o + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 \quad (1)$$

TABLE IV
DESIGN MATRIX AND RESULTS OF EXPERIMENTS

Experiment number	x_1	x_2	x_3	**y**
1	1	1	1	61.8
2	-1	1	1	60.1
3	1	-1	1	25.90

4	-1	-1	1	16.40
5	1	1	-1	14.40
6	-1	1	-1	54.90
7	1	-1	-1	18.50
8	-1	-1	-1	22.40
9	0	0	1.682	19.9
10	0	0	-1.682	15.3
11	0	1.682	0	14.9
12	0	-1.682	0	46.3
13	1.682	0	0	16.8
14	-1.682	0	0	18.3
15	0	0	0	19.6
16	0	0	0	17
17	0	0	0	27.9
18	0	0	0	27.4
19	0	0	0	19.6
20	0	0	0	21

The planning matrix and experimental results are shown in Table IV. Fig. 8 shows the results of the full quadratic model analyzed by Statistical Analysis Software (SAS) (SAS Institute, Cary, NC 27513, USA). Overall, the results show that the model, as well as all variables in the model, are insignificant, with the coefficient of multiple determination, R^2 of only 0.44, and a negative adjusted R^2.

A closer examination of the residuals showed that data point number 11, shown in Table IV, was an outlier. This data point was removed and the data was reanalyzed. The results are presented in Fig. 9. Removing data point number 11 would not cause any multicollinearity issues because all values of variance inflation factors shown in Fig. 10 are close to 1 (almost no variance inflation issues). The model was highly significant ($p = 0.0006$) with a very high R^2 value of 0.92 and an adjusted R^2 value of 0.84. All variables in the model, except for X_1, X_1^2, and X_3^2, were significant. Fig. 10 shows a plot of the observed vales versus the predicted values given by the model. When the non-significant variables were removed from the model and the regression analysis was repeated, the model did not change. This is because there were no multicollinearity issues between the independent variables, as indicated by the values of the variance inflation factor.

Full Quadratic Model

The REG Procedure
Model: Linear_Regression_Model
Dependent Variable: y

Number of Observations Read	20
Number of Observations Used	20

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	2017.79251	224.19917	0.87	0.5754
Error	10	2565.29949	256.52995		
Corrected Total	19	4583.09200			

Root MSE	16.01655	R-Square	0.4403
Dependent Mean	26.92000	Adj R-Sq	-0.0635
Coeff Var	59.49685		

Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	1	21.68448	6.53237	3.32	0.0078	0
X1	1	-2.61549	4.33383	-0.60	0.5596	1.00000
X2	1	4.04043	4.33383	0.93	0.3731	1.00000
X3	1	4.52014	4.33383	1.04	0.3215	1.00000
X1X2	1	-5.55000	5.66271	-0.98	0.3502	1.00000
X1X3	1	6.95000	5.66271	1.23	0.2478	1.00000
X2X3	1	6.40000	5.66271	1.13	0.2848	1.00000
X1sq	1	1.02967	4.21844	0.24	0.8121	1.01830
X2sq	1	5.62493	4.21844	1.33	0.2120	1.01830
X3sq	1	1.01200	4.21844	0.24	0.8153	1.01830

FIGURE 8
THE FULL QUADRATIC MODEL DATA ANALYZED BY SAS SOFTWARE (COURTESY OF DR. S.K. UPADHYAYA, UNIVERSITY OF CALIFORNIA DAVIS, CA, USA)

Full Model without Outlier

The REG Procedure
Model: Linear_Regression_Model
Dependent Variable: y

Number of Observations Read	20
Number of Observations Used	19
Number of Observations with Missing Values	1

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	4081.05474	453.45053	11.66	0.0006
Error	9	349.95262	38.88362		
Corrected Total	18	4431.00737			

Root MSE	6.23567	R-Square	0.9210
Dependent Mean	27.55263	Adj R-Sq	0.8420
Coeff Var	22.63186		

Parameter Estimates						
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	1	22.11172	2.54386	8.69	<.0001	0
X1	1	-2.61549	1.68728	-1.55	0.1555	1.00000
X2	1	13.29056	2.08536	6.37	0.0001	1.19447
X3	1	4.52014	1.68728	2.68	0.0252	1.00000
X1X2	1	-5.55000	2.20464	-2.52	0.0329	1.00000
X1X3	1	6.95000	2.20464	3.15	0.0117	1.00000
X2X3	1	6.40000	2.20464	2.90	0.0175	1.00000
X1sq	1	-1.77088	1.68374	-1.05	0.3203	1.03448
X2sq	1	16.09997	2.15017	7.49	<.0001	1.16893
X3sq	1	-1.78855	1.68374	-1.06	0.3158	1.03448

FIG.URE 9
THE FULL QUADRATIC MODEL ANALYZED WITHOUT THE OUTLIER (COURTESY OF DR. S.K. UPADHYAYA, UNIVERSITY OF CALIFORNIA DAVIS, CA, USA)

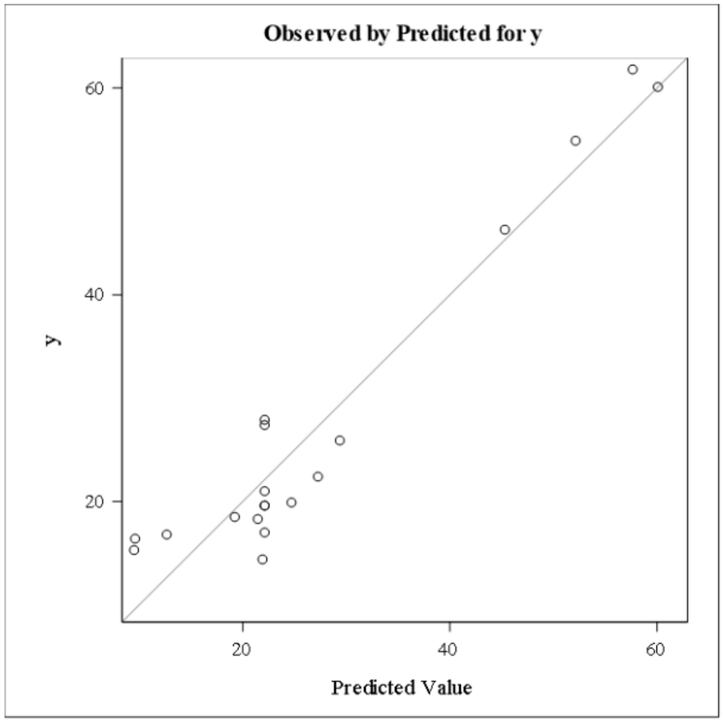


FIGURE 10
OBSERVED VERSUS PREDICTED VALUES FOR THE FINAL SELECTED MODEL (COURTESY OF DR. S.K. UPADHYAYA, UNIVERSITY OF CALIFORNIA DAVIS, CA, USA)

The final form of the prediction equation is given by the following equation:

$$y = b_o + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{22}x_2^2 \tag{2}$$

Equation (8) was used to determine the optimum values of x_1, x_2, and x_3 as follows:

$$\begin{aligned} \frac{dy}{dx_1} &= b_{12}x_2 + b_{13}x_3 = 0 \\ \frac{dy}{dx_2} &= b_2 + b_{12}x_1 + b_{23}x_3 + 2b_{22}x_2 = 0 \\ \frac{dy}{dx_3} &= b_3 + b_{13}x_1 + b_{23}x_2 = 0 \end{aligned} \tag{3}$$

Equation (3) was solved to obtain optimum values of the parameters. The optimal values of these factors were found to be: composition Cr = 13.61% in the material; soaking τ = 2.108 h and material resistivity R = 0.41 μΩ·m. Based on these factor values, the hardness of the steel is 94.46 HRC.

When strengthening 65Mn spring steel opener shares, the optimum point of equation (3) can be used to establish rational values for technological (soaking), structural (percentage of alloying elements - chromium), and operational (material resistivity) indicators.

CONCLUSIONS

Analyzing the photos of worn surfaces of the opener shares, the data in Tables I-II, the information on the hardening method, and the materials used, the following conclusions can be drawn:

1. According to the results of the microstructural analysis of the hardened specimens, it was found that hardened samples from surfacing with T590 electrodes and Sormayt®, as well as heat-treated specimens had secondary cementite and pearlite cementite in the final structure, which increased the hardness of the material.
2. The samples hardened by heat treatment and surfaced with T590 electrodes had the smallest equivalent rejection area (samples 2 and 3, Fig. 6b and c) and the highest hardness, while the cost of surfacing was approximately 4.6 times lower than heat treatment.
3. Based on the response surface methodology, the optimal parameters for achieving the hardness of the opener share of a grain-fertilizer-grass seeder were determined as - composition Cr = 13.61% in the material; soaking $\tau = 2.108$ h and material resistivity $R = 0.41$ μΩ·m. The corresponding maximum hardness of the steel is expected to be 94.46 HRC.
4. As the most rational way to harden the shares for production and agricultural enterprises, it is recommended that the standard factory-supplied soil-engaging part of the opener of seeders be replaced with T590 electrode treated units.

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