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Statistical Analysis of the Effects of Mn and Cr Contents on Mechanical Properties of Deformed Steel Bar

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***Abstract*—China's steel industry is trapped both at home and *abroad* nowadays. Steel companies need to improve their competitiveness in terms of cost control and product effectiveness. Based on this background, the effect of chemical elements on the mechanical properties of steel bars is studied in this paper. First, we use the correlation analysis theory to obtain the Pearson correlation coefficient, and analyze the main factors and secondary factors that affect the properties of deformed steel bar. Next, we adopt the stepwise regression method to model the influence rule between deformed steel bar properties and chemical elements. According to the law of influence obtained above and neural network simulation curve, we prejudge the properties of the deformed steel bar after adding Cr powder. Finally, the optimal formula of yield strength, tensile strength and percentage elongation after fracture is obtained. The optimization scheme can reduce the consumption of alloy material, reduce the cost and improve the competitiveness of the enterprise.**

Keywords—deformed steel bar; chemical composition; mechanical properties; composition optimization scheme

I. INTRODUCTION

At present, China's steel industry is trapped both at home and abroad[1]. China has entered the medium and later period of industrialization, and several biggest steel consumption industries run into the investment saturation and demand declination[2]. The past development of steel industry driven by investment, export and consumption is accompanied by the problems of heavy pollution, high energy and resources consumption, low technical content and low additional value, which lies essentially in the over capacity of low and middle-end products and the under-supply of high-end products[3]. Along with the high-end orientation of the global industry competition mode and the increasing pressure form resources and environment, the existed growth pattern of steel industry has severely encumbered the harmonious and sustainable development of economy and society[4]. Meanwhile, the fatigued global economy, trade protectionism trend, and geopolitical factors also contribute to the shrinking of China's steel export[5]. Therefore, the harsh reality pushes China's steel industry to seek for a more sensible development path. This paper studies the influence of chemical element on properties of deformed steel bar to present a new component optimization scheme for enterprises,

Deformed steel bar is mainly used for skeleton of reinforced concrete component and it requires certain mechanical strength, bending and deformation properties, fabrication weldability in use. Most deformed steel bar adopts microalloying method, that is to add expensive microelement (such as Mn alloy material, V alloy material, etc.) into steel, adjust the composition proportion and to improve structure property[6].

A good composition design can guarantee the properties and control the production cost effectively at the same time. The element Cr in steel can significantly increase the strength, hardness and wear resistance. When the company uses mine rich in Cr, the Cr content in liquid iron will significantly increase[7]. It is valuable to research the reduction of alloy material like Mn and V in allowance range of deformed steel bar properties by Cr content increase, present the content modification scope of Mn, V, etc, and design composition optimization scheme[8]. By optimizing the components, the enterprise can reduce the cost of alloy materials and reduce the cost, thus improving the competitiveness.

We break through the linear model in the traditional research, and studies the nonlinear model of the performance and composition of the deformed steel bar. This paper is organized as follows. Section II presents a correlation analysis model to reveal the main factors, secondary factors that influence properties of deformed steel bar. Section III presents the linear regression model to study the influence rule between deformed steel bar properties and chemical elements. Section IV establishes the principal component analysis model to obtain the regression model. In Section V, we research the reduction of alloy material in allowance range of deformed steel bar properties by Cr content increase, present the content modification scope of Mn, V, etc, and design composition optimization scheme. Concluding remarks are provided in Section VI.

II. CORRELATION ANALYSIS MODEL

We want to represent the relationship between two different data types to analyze the main factors, secondary factors that influence properties of deformed steel bar.

A. Introduction of Pearson Correlation Coefficient

Pearson correlation coefficient is used to measure whether the two sets of data is in a line. It is used to measure the linear relationship between the fixed distance variables. When two variables are normal and continuous, and when they are linearly related[9], we use the Pearson product-moment correlation coefficient to show the correlation between these two variables. We've got tens of thousands of data, so the influence of sampling error is going to be very small.

B. Explain the Level Range

The greater the absolute value of the correlation coefficient γ, the stronger correlation coefficient is. When the correlation coefficient is close to 1 or -1, the correlation is stronger. When the correlation coefficient is close to 0, the correlation is weaker.

The correlation strength of variables is usually judged by the following values[10]:

Correlation coefficient 0.8-1.0: extremely strong correlation, 0.6-0.8: strong correlation, 0.4-0.6: medium degree correlation, 0.2-0.4: weak correlation, 0.0-0.2: extremely weak correlation or not related.

C. Calculation of Pearson Correlation Coefficient[11]

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(Y_i - \bar{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}} \quad (1)$$

Take the relationship between the yield strength of the steel and the manganese as an example:

x_i : Content of Mn in column i .

$\bar{x}$: Average content of Mn

Y_i : The yield strength of deformed steel bar in column i

$\bar{Y}$: Average yield strength of deformed steel bar

The Pearson correlation coefficients of each element to the yield strength of the deformed steel bar are shown in Table I:

TABLE I. PEARSON CORRELATION COEFFICIENT OF THE CHEMICAL ELEMENT TO THE YIELD STRENGTH OF THE DEFORMED STEEL BAR

Chemical Element	**C**	**Mn**	**S**	**P**	**Si**	**V**
Correlation Coefficient	0.74	0.63	0.21	0.09	0.81	0.35
Chemical Element	**Cr**	**Ni**	**Cu**	**Mo**	**Alt**	
Correlation Coefficient	0.48	0.22	0.56	0.37	0.48	

This reflects that Si is the main factor affecting yield strength, and C is a minor factor. Under the same content of C and Mn, the yield strength can be controlled by increasing or decreasing Si content.

The Pearson correlation coefficients of each element to the tensile strength of the deformed steel bar are shown in the Table II:

TABLE II. PEARSON CORRELATION COEFFICIENT OF THE CHEMICAL ELEMENT TO THE TENSILE STRENGTH OF THE DEFORMED STEEL BAR

Chemical Element	**C**	**Mn**	**S**	**P**	**Si**	**V**
Correlation Coefficient	0.62	0.72	0.13	0.14	0.67	0.08
Chemical Element	**Cr**	**Ni**	**Cu**	**Mo**	**Alt**	
Correlation Coefficient	0.24	0.47	0.45	0.52	0.18	

It can be known form the above table that Mn is the main factor for the tensile strength of the deformed steel bar, Si content is secondary factor, and the C content is the third factor.

The Pearson correlation coefficients of each element to the percentage elongation after fracture of the deformed steel bar are shown in the Table III:

TABLE III. PEARSON CORRELATION COEFFICIENT OF THE CHEMICAL ELEMENTS TO THE PERCENTAGE ELONGATION AFTER FRACTURE OF THE DEFORMED STEEL BAR

Chemical Element	**C**	**Mn**	**S**	**P**	**Si**	**V**
Correlation Coefficient	0.71	0.53	-0.59	0.48	0.67	0.14
Chemical Element	**Cr**	**Ni**	**Cu**	**Mo**	**Alt**	
Correlation Coefficient	0.27	-0.15	0.43	0.32	0.14	

This reflects that C element can increase the strength of steel and reduce plasticity. From the extent of the impact, C element is in the first place. P element is the secondary factor affecting the percentage elongation after fracture. The percentage elongation after fracture increases with the increase of the S content, but the degree of the influence is relatively small. Mn element is fourth. We know that Mn is a endure element in carbon steel, which can improve the strength of carbon steel. With the increase of Mn content, the percentage elongation after fracture of the steel will be increased.

III. Linear Regression Model

A. Yield Strength of Deformed Steel Bar

The corresponding independent variables of each chemical element are shown in the Table Ⅳ:

TABLE IV. THE CORRESPONDING INDEPENDENT VARIABLES OF EACH CHEMICAL ELEMENT

Chemical Element	**C**	**Mn**	**S**	**P**	**Si**	**V**
Corresponding Variable	x_1	x_2	x_3	x_4	x_5	x_6
Chemical Element	**Cr**	**Ni**	**Cu**	**Mo**	**Alt**	
Corresponding Variable	x_7	x_8	x_9	x_{10}	x_{11}	

Define the following equation:

$$\begin{aligned} y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6 \\ + b_7x_7 + b_8x_8 + b_9x_9 + b_{10}x_{10} + b_{11}x_{11}, \end{aligned} \quad (2)$$

where a is the constant term and b is the regression coefficient.

By using the least square method to calculate the known data, the regression coefficient is obtained, and the multiple linear equation between the yield strength and the chemical composition is established. The regression coefficients and statistical values F are calculated by using the multiple regression method. The regression equation of the type 1 deformed steel bar and the type 2 are calculated in MATLAB:

$$y = 472.4985 + 87.6948x_1 - 19.6597x_2 + 60.0866x_5$$

$$y = 469.5467 + 55.9428x_1 - 16.3831x_2 + 65.8164x_5$$

$$F_{g1} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 49.3385$$

$$F_{g2} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 36.6860$$

$F_g >> F_{form}^{0.01}$, which shows that the regression equation is significant at level $\alpha=0.01$.

The correlation coefficient $R = \sqrt{\frac{S_{\mathrm{back}}}{L_{yy}}} = 1.343$

The R value is close to 1, which indicates that the linear correlation of the regression equation is closely related.

F_2 and F_3 are significant on level $\alpha=0.01$. F_1 is not significant on the level $\alpha=0.05$, indicating that the sum of squares of partial regression of x_2 and x_3 is significantly better, and the x_1 is second.

The value of F indicates that the content of Si in steel is the main factor affecting yield strength, and the content of Mn is the secondary factor, and the C content is the third factor.

By the above regression equation, when the content of C and Mn is constant, the yield strength value can be determined, and the content of Si can be calculated. So we can know that Si content can adjust the yield strength of deformed steel bar.

B. Tensile Strength of Screw Thread Steel

Using MATLAB to calculate the regression equation of the tensile strength of two kinds of thread steel:

$$y = 651.6856 + 143.7464x_1 - 23.2608x_2 + 73.6760x_5$$

$$y = 642.0468 + 140.6546x_1 - 13.1522x_2 + 57.4988x_5$$

$$F_{g1} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 68.1654$$

$$F_{g2} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 33.0164$$

$F_g >> F_{\mathrm{form}}^{0.01}$, which shows that the regression equation is significant at level $\alpha=0.01$.

Coefficient of correlation $R = \sqrt{\frac{S_{\mathrm{back}}}{L_{yy}}} = 1.233$

The R value is close to 1, which indicates that the linear correlation of the regression equation is closely related.

Through the above analysis, we can know that: The main factor which influences the tensile strength of the steel bar is Mn, Si content is the secondary factor, and the C content is the third factor.

C. Percentage Elongation after Fracture of Deformed Steel Bar

Using MATLAB to calculate the regression equation of the percentage elongation after fracture of two kinds of deformed steel bar:

$$y = 26.0600 + 1.3565x_1 - 1.7400x_2 + 1.6256x_3 + 13.0646x_4$$

$$y = 25.5632 + 3.9702x_1 - 2.4722x_2 + 1.9387x_3 + 21.2698x_4$$

$$F_{g1} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 6.2561$$

$$F_{g2} = \frac{U \div m}{Q \div (n-m-1)} = \frac{U}{S^2} = 13.1916$$

$F_g >> F_{\mathrm{form}}^{0.01}$, which shows that the regression equation is significant at level $\alpha=0.01$.

Coefficient of correlation $R = \sqrt{\frac{S_{\mathrm{back}}}{L_{yy}}} = 1.343$

The R value is close to 1, which indicates that the linear correlation of the regression equation is closely related.

From what has been discussed above, Carbon in steel is to enhance the strength, reduce the plastic element. From the degree of the influence, C element is in the first place. Phosphorus is second significant factors influence the percentage elongation after fracture. The percentage elongation after fracture increases with the increase of the content of sulfur, but the influence is relatively small. Mn element is fourth. We know that manganese is endure element in carbon steel, which can improve the strength of carbon steel to. With the increase of manganese content, the percentage elongation after fracture can be slightly improved. Therefore, the results of the regression analysis are consistent with the theory[12-13]. Si is the least significant factor.

D. Stepwise Regression Model

The basic idea of stepwise regression is to introduce variables into models one by one. Each time we introduce an explanation variable, we need to run an F test, and we did a t-check on the variables selected one by one. When the previously introduced explanatory variable is no longer significant due to the introduction of the later explanatory variable, we remove it to ensure that only significant variables are included in the regression equation before each new variable is introduced. This is an iterative process, until there is no significant explanatory variable we can add to the regression equation, and not significant variable that we need to remove form the regression equation to ensure that the final set of explanatory variables is optimal.

According to the above idea, we can use stepwise regression to remove the variables which cause multicollinearity. The specific steps are as follows. First we use explained variable to make a simple regression for each considered explanatory variable. Then, we base on the regression equation corresponding to explanatory variable, which has the largest contribution to explained variable, and gradually introduce the remaining explanatory variable. After stepwise regression, it is possible to ensure that the explanatory variables retained in the model are both important and not seriously multilinear.

When using the general linear regression method, we find that the regression coefficient of some elements cannot pass the correlation test. Chemical elements should be gradually added for regression analysis.

TABLE V. STANDARDIZED DATA SHEET

Model		Non standardized coefficient		Standard coefficient	t	Sig.	Co linear statistic	
		B	Standard error				Tolerance	VIF
1	(Constant)	.000	.004		-.054	.957		
	Zscore(V)	.359	.004	.359	84.699	.000	1.000	1.000
2	(Constant)	.000	.004		-.053	.958		
	Zscore(V)	.351	.004	.351	83.260	.000	.995	1.005
	Zscore(Si)	.113	.004	.113	26.842	.000	.995	1.005
…	……	……	……	……	……	……	……	……
8	(Constant)	.000	.004		-.052	.958		
	Zscore(V)	.350	.004	.350	82.046	.000	.963	1.038
	Zscore(Si)	.114	.005	.114	21.366	.000	.621	1.609
	Zscore(C)	.055	.004	.055	12.810	.000	.935	1.070
	Zscore(Cr)	-.056	.006	-.056	-9.717	.000	.519	1.926
	Zscore(MN)	-.047	.005	-.047	-9.525	.000	.709	1.411
	Zscore(P)	.028	.004	.028	6.335	.000	.921	1.085
	Zscore(Ni)	.021	.005	.021	3.905	.000	.629	1.589
	Zscore(S)	.014	.004	.014	3.254	.001	.979	1.022

The results are as follows, taking the yield strength model as an example:

We remove Cu, ALT after standardizing. The result of the stepwise regression:

$$y = 0.349V + 0.131Si + 0.054C - 0.067Cr - 0.047Mn + 0.026P - 0.024Mo + 0.029Ni + 0.017S$$

Then we remove Mo element after standardizing. The result of the stepwise regression is as follows:

$$y = 0.39V + 0.117Si + 0.053C - 0.057Cr - 0.044Mn + 0.025P + 0.023Ni + 0.017S$$

At last we remove Mo, Cu, ALT element after standardizing. The final result:

$$y = 0.39V + 0.117Si + 0.053C - 0.057Cr - 0.044Mn + 0.025P + 0.023Ni + 0.017S$$

IV. PRINCIPAL COMPONENT ANALYSIS MODEL

After the stepwise regression model, we perform the principal component analysis and get the regression model.

Through MATLAB analysis, it is found that the relationship between the tensile strength of different steel bars and chemical element is different:

The regression equation of type 1 deformed steel bar:

$$y = 584.62 + 83.764C + 28.079Mn + 223.435S - 452.493P - 6.877Si - 930.487V + 244.354Cr - 81.327Ni + 247.553Cu + 812.473Mo - 88.334ALT$$

The regression equation of type 2 deformed steel bar:

$$y = 586.343 + 69.754C - 7.338Mn + 34.987S + 3.873P + 35.965Si + 232.032V - 78.457Cr + 755.137Ni + 124.432Cu + 147.336Mo - 17.327ALT$$

V. NEURAL NETWORK MODEL

A. Neural Network Simulation(Taking Cr and Type 1 Deformed Steel Bar as an Example)

According to the actual collected data, Through the BP neural network simulation[14-15], we obtain the tensile strength simulation diagram of the Cr element on the type 1 deformed steel bar as shown below:

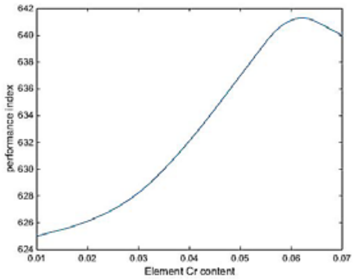

FIGURE I. EFFECT OF CR ELEMENT ON TENSILE STRENGTH.

B. *Composition Optimization Scheme*

The increase value of yield strength, tensile strength, and percentage elongation after fracture in the range which Cr can be added can be achieved. Then we take these values into the curves of Mn, V, and get the reduced content of elements Mn, V. Finally, the composition optimization scheme is as follows:

Optimization formula of tensile strength:

$$Y=624.84+0.0295Mn+0.00511Cr$$

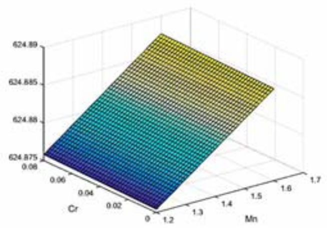

FIGURE II. OPTIMIZATION SCHEME OF TENSILE STRENGTH.

Optimization formula of yield strength:

$$Y=458.203+0.00285Mn+0.00284Cr$$

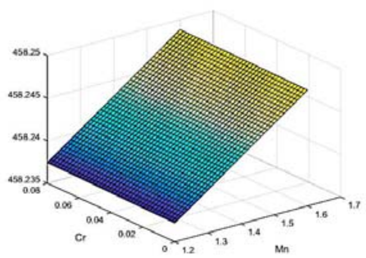

FIGURE III. OPTIMIZATION SCHEME OF YIELD STRENGTH.

Optimization formula of percentage elongation after fracture:

$$Y=25.594+0.000213Mn-0.000392Cr$$

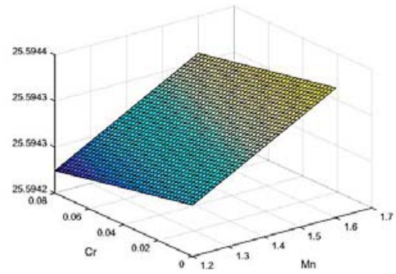

FIGURE IV. OPTIMIZATION SCHEME OF PERCENTAGE ELONGATION AFTER FRACTURE

VI. CONCLUSION

Steel companies in China need to improve their competitiveness in terms of cost control and product effectiveness immediately. Data analysis method provides a new idea for composition optimization. This paper innovatively proposes a method of using stepwise regression in the traditional regression analysis method to research the relationship between the chemical element and mechanical property of deformed steel bar. We find that there are multiple linear relations between the yield strength, tensile strength and percentage elongation after fracture of the deformed steel bar. Through the neural network simulation, we prejudge the properties of the deformed steel bar after adding Cr powder and finally obtain the optimal formula. The optimization scheme can reduce the consumption of alloy material, reduce the cost and improve the competitiveness of the enterprise, providing a new solution for the sustainable development of the steel industry.

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