С.Сейфуллин атындағы Қазақ агротехникалық университетінің **Ғылым жаршысы(пәнаралық) = Вестник науки** Казахского агротехнического университета им. С.Сейфуллина **(междисциплинарный).** - 2020. - №3 (106). - P.261-269

ANALYSIS OF REGRESSION MODELS OF STRENGTH AND PLASTIC PROPERTIES OF DEFORMATION-THERMALLY HARDENED REINFORCING PROFILE

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Annotation

Numerous studies have shown that the processes of structure formation as a result of the combined effect of plastic deformation and phase transformations on the alloy are different from the formation of the structure during conventional heat treatment and provide a high set of mechanical properties that cannot be achieved by conventional methods of heat treatment or complex alloying.

Currently, in the production of rod reinforcement for reinforced concrete structures, technologies of combined deformation and thermal hardening are increasingly used. When hot rolling is combined with subsequent heat treatment, intensive and controlled cooling of hotly deformed austenite is performed directly at the exit from the finishing stand of the rolling mill, which leads to a strong grinding of the structure, and, consequently, provides high mechanical properties of the material than when cooling in air, as was the case at many existing rolling mills.

Analytical review of the literature on the problem of combining hot deformation with heat treatment shows that the efficiency of deformation and heat treatment depends on the temperature of rolling, the total degree of fragmentation and deformation, the degree of a single strain, time interval from the end of hot rolling to the beginning of accelerated cooling, duration of intensive cooling defines the temperature smoothback, like the original steel (cast or rolled), and finally, the chemical composition of the processed steel [1].

Key words: reinforcement profiles, mathematical model, deformation – thermal strength, dispersion, Fischer criterion, student criterion, rolling.

Introduction

In relation to the reinforcing profile with a diameter of 12-14 mm, the development of a mathematical model of the final mechanical properties of the rolled, finished rolling on a small-grade machine of the production of rolling varieties was carried out taking into account the following features of the existing technology:

1) the deformation, speed and temperature modes of hot rolling of the reinforcement profile are given with a certain strict restriction of their change in accordance with the accepted calibration of the shafts with the possibility of existing technological equipment;

2) the ultimate goal of the production of deformation-heat-hardened rolling at the station is to make hot-rolled reinforcing profiles of class 35GS of low-strength alloy steel a-111 hardened carbon steel St.It is a replacement for strength equal to 5, which provides significant savings in ferroalloys and facilitates the technology of melting and rolling.

Research materials and methodology

Taking these features into account, 12 mm reinforcing profiles made of Steel were selected as the object of research. Various factors are perceived as: the temperature of the end of rolling, the duration of the break from the end of deformation to the beginning of intensive cooling, the duration of intensive cooling, which provides different levels of self-discharge temperature. At the same time, the influence of various cooling methods and the type of primary billet (casting or rolling billet) are taken into account.

Main results of research and development

The study was conducted using the traditional method of active experimentation [2], for which a complete factor experiment plan was selected when there were three variable factors at two levels. The strength limit σv (MPA) and relative elongation δ5 (%) were adopted as optimization parameters when tested.

Conversion factors are:

1) the temperature of the metal during rolling is τ, °c (x_1), which is measured by an optical pyrometer when rolling the metal;

2) intense cooling τ, C (X_2), which is determined by a stopwatch from the moment the metal comes out of the roll to pause, is measured with an accuracy of 0.25 c; intense cooling duration τ, c (X_3).

Table 1 presents the planning Matrix and the results of the experiment in thermal hardening of the reinforcing profile No. 12 of steel.

Cooling was carried out in the nozzle with the opposite movement of the flow, when quenching, the water pressure relative to the direction of movement of the metal is 0.15 MPA (15 ATM.).

Experiments were conducted taking into account randomization.

Model coefficients were calculated using the Formula [3]:

$$b_i = \sum(x_{i-u} \times \qquad (1)$$

where: I is the factor number, u is the experiment number, n is the number of experiments in the planning atrice; x_{i-u} is the value of the factor in the U-experiment; y_u is the value of the optimization parameters in the same experiment.

The coefficient of Model b_0 for the strength limit was calculated as follows:

b_0=(1510+1480+1530+1520+1210+1500+1370+1410)/8=1441,25,

for relative elongation:

b_0=(8,3+17,4+8,0+18,0+6,0+3,2+1,5+9,4)/8=8,98.

The values of the remaining coefficients are given at the end of the table (lines 13 and 14).

To determine the $(S_y)^2$dispersion, a series was set at the main level, based on the results of $(S_y)^2$ out of 5 experiments: for the strength limit $(S_y)^2$= 391.7, and for the relative elongation $(S_y)^2$=2.42, respectively, the standard error:

$$\sum S_в = \pm\sqrt{(S_y)^2} = \pm\sqrt{391.7} = \pm 19.79;\ S\delta_5=\pm\sqrt{(S_y)^2}=\pm 2.42 = 1.55.$$

Table 1 - planning Matrix and experimental results, reinforcement profile No. 12, St.5sp

Response factors and functions	emper ature, t, °C	elay,	Dura tion and intense cooling,	Interaction of factors				Optimi zation parameter	
				*			*	olidity, $\sigma_в$, MПa	elativ e elong ation, δ_5 %
code	1	2	x_3	$_1x_2$	$_1x_3$	$_1x_3$	$_1x_2x_3$		
1. Basic level (0) 2. Change interval (1) 3. Upper level (+1) 4. Lower level (-1)	030 0 090 70	0 0	3 1 4 2						
5. 8 series of experiments on a full-factor experiment plan 2 . 3 4 . 5 6 . 7 8 . 0. 1. 2.			+ + - - - -					510 480 210 500 370 410	,3 7,4 ,0 ,2 ,5 ,4
13. coefficients b_i for $\sigma_в$	36,25	6,25	68.75	28,75	6,25	,250	3,75		

14. coefficients δ_5 for b_i	3,03	0,25	3.95	,45	,75	,175	1,23		

Regression models of strength and relative elongation δ5 for thermal hardening:

$$\sigma_{\text{в}} = 1441{,}25 - 36{,}25_{x_1} - 16{,}25_{x_2} + 68{,}75_{x_3} - 28{,}75_{x_1x_2} + 46{,}25_{x_1x_3} + 5_{x_2x_3} + \\ +33{,}75_{x_1x_2x_3} \qquad (2)$$

$$\delta_5 = 8{,}98 - 3{,}03_{x_1} - 0{,}25_{x_2} + 3{,}95_{x_3} + 1{,}45_{x_1x_2} - 1{,}75_{x_1x_3} + 0{,}175_{x_2x_3} - 1{,}23_{x_1x_2x_3} \qquad (3)$$

Checking the significance of regression coefficients was performed according to the Steudent criterion, according to which the confidence interval for the strength was equal to -$\Delta b_i = \pm 22{,}26$, for the relative elongation -$\Delta b_i = \pm 1{,}75$ [4].

Comparison of absolute values of regression coefficients with a reliable interval and comparison of coefficients below the value of the confidence interval (statistically insignificant coefficients) we get the following regression equations:

$$\sigma_{\text{в}} = 1441{,}25 - 36{,}25_{x_1} - 16{,}25_{x_2} + 68{,}75_{x_3} - 28{,}75_{x_1x_2} + 46{,}25_{x_1x_3} + 1{,}25_{x_2x_3} + \\ +33{,}75_{x_1x_2x_3} \qquad (2')$$

$$\delta_5 = 8{,}98 - 3{,}03_{x_1} + 3{,}95_{x_3} - 1{,}75_{x_1x_3} \qquad (3')$$

In these equations, the value of factors (Table 1) is calculated on a scale encoded by formulas, and the corresponding values on a natural scale are calculated using the formula:

$$x_1 = \{[\tau, {}^\circ C] - 1030\}/60,$$
$$x_2 = \{[\Delta\tau, c] - 10\}/10,$$
$$x_3 = \{[\tau, c] - 3\}/1,$$

If, for example, it is necessary to determine the strength of rolling at a temperature of 1050°C, the delay is $\Delta\tau = 15c$ and the cooling duration is 2.5 c, then we put the values in the equation (2').

$$x_1 = \frac{1050 - 1030}{60} = \frac{20}{60} = 0{,}33;$$

$$x_2 = \frac{15 - 10}{10} = 0{,}5;$$

$$x_3 = \frac{2{,}5 - 3}{1} = -0{,}5$$

Accordingly, these modes must have a strength limit after thermal hardening

$$\sigma_{\text{В}} = 1441{,}25 - 36{,}25 * 0{,}33 + 68{,}75 * (-0{,}5) - 28{,}75 * 0{,}33 * 0{,}5 + 46{,}25 * 0{,}33 * (-0{,}5) + 33{,}75 * 0{,}33 * 0{,}5 * (-0{,}5) = 1375 \text{ МПа}.$$

However, before applying the Equations (2') and (3'), it is necessary to test the hypothesis of their sufficiency.

Checking the model for compliance. The scheme for calculating the nonconformity variance for the strength model is given in Table 2.

Calculated values $\sigma_{\text{В}}$ are determined from the Rasch regression equation. For example, the conditions of the third experiment were as follows (Table 1):

$$x_1 = +1;\ x_2 = -1;\ x_3 = +1;\ x_1x_2 = -1;\ x_1x_3 = +1;\ x_1x_2x_3 = -1,$$

$$(_{\sigma_{\text{В}}})^{\text{расч}} = 1441{,}25 - 36{,}25(+1) + 68{,}75(+1) - 28{,}75(-1) + 46{,}25(+1) \\ + 33{,}75(-1) = 1515.$$

Nonconformity variance by Formula:

$$(S_{\text{неад}})^2 = \frac{\sum[(\sigma_{\text{в}})^{\text{расч}} - (\sigma_{\text{в}})^{\text{экс}}]^2}{n - k'} = \frac{2125}{8-6} = 1062{,}5, \qquad (4)$$

where k' is the number of significant coefficients in the equation (2').

The calculated value of the Fischer criterion, which allows us to test the hypothesis of compliance of the model with experimental data, was determined by the equation:

$$(F_{ff})^{\text{расч}} = \frac{(S_{\text{неад}})^2}{(S_y)^2} = \frac{1062{,}5}{391{,}7}; \qquad (5)$$

where $(S_y)^2$ f1 =4 experiment variance defined by the number of degrees of Freedom 2.

At the level of 5% significance, F is the tabular value of the criterion: $(F_{2.4})^{\text{табл}}=6{,}94$.

$F_{\text{расч}} < F_{\text{табл}}$ since the equation sufficiency hypothesis (2') is rejected and can be used to predict mechanical properties when thermo-hardening steel reinforcing profiles with a diameter of 12 mm.

Checking the adequacy of the calculated nonconformity criterion Equation (3'):

$S^2_{\text{неадек.}} = \frac{29{,}57}{8-4} = \frac{29{,}57}{4} =$and Fischer's calculation criterion:

$F_{4.4} = \frac{(S^2_{\text{неадек.}})}{(S_y)^2} = \frac{7{,}39}{2{,}42} =$ and comparison of $F_{\text{табл}}$ with table size $F_{\text{расч}}$ at the significance level ($\alpha=0{,}05$, ($F_{2.4} = 6{,}94$), $F_{\text{расч}} < F_{\text{табл.}}$ it was shown that.

This means that the equation sufficiency hypothesis (3') is rejected and can be used to predict mechanical properties during thermal hardening of reinforcing profile steel with a diameter of 12 mm [5].

and δ_5, the equations obtained to determine are used as a working hypothesis for preliminary calculation of the expected mechanical properties of the finished reinforcement rolling after thermal hardening at the given levels of various factors: temperature, latency and duration of intensive cooling.

Since laboratory experiments were carried out depending on the conditions of the final processing stage of 280 light-section Mills, 280, in the resulting models, we actually understand the Rolling temperature with the final rolling temperature [6].

According to 5sp GOST 380-98, the vibrations of these elements in real melts do not significantly affect the results of determining the final properties within the limits allowed under the conditions of this GOST.

Table 2-scheme for calculating the variance of the model mismatch for the strength limit

№	$(\sigma_{\text{в}})^{\text{экс}}$	$(\sigma_{\text{в}})^{\text{расч}}$	$\Delta\sigma_{\text{в}}=(\sigma_{\text{в}})^{\text{экс}}-(\sigma_{\text{в}})^{\text{расч}}$	$(\Delta\sigma_{\text{в}})^2$

1.	1510	1525,0	15,0	225,00
2.	1480	1495,0	15,0	225,00
3.	1530	1515,0	15,0	225,00
4.	1520	1505,0	15,0	225,00
5.	1210	1227,0	17,5	306,25
6.	1500	1517,0	17,5	306,25
7.	1370	1352,5	17,5	306,25
8.	1410	1392,5	17,5	306,25
				$\sum(\Delta\ \sigma_{\text{в}})^2=2125$

No.12 regression equation for the strength limit of a deformation-thermally hardened reinforcing profile:

$$\sigma_{\text{в}} = 1441{,}25 - 36{,}25_{x_1} + 68{,}75_{x_3} - 28{,}75_{x_1x_2} + 46{,}25_{x_1x_3} + 33{,}75_{x_1x_2x_3} \qquad (6)$$

The values of the model coefficients indicate the force of influence of factors. As you know, the greater the numerical value of the coefficient, the more this factor affects the strength limit. Therefore, comparing the coefficients of the model, we can conclude that the strength limit is affected by the duration of intense cooling (x_3) (1), the maximum impact factor of which is 68.75 (of course, at the selected change intervals); an increase in the duration of intense cooling leads to an increase in the strength limit, which indicates the coefficient sign $(b_3 = +68{,}75)$ [7].

The temperature of the Rolling end at the selected variation intervals (x_1) has a negative regression coefficient $b_1 = 36{,}25$, that is, when the Rolling end temperature decreases, the strength limit decreases. The second factor (x_2), the break from the end of rolling to the beginning of intensive cooling, has a weak effect on the strength limit at the selected change intervals ($\Delta\tau = 0$ sec to $\tau=20$ sec), the effect of which was statistically small, $b_2 = -16{,}25$, that is, less than the confidence interval in determining these coefficients. This suggests that $0<\tau < 20$ seconds will have little effect on the formation of the final mechanical properties of the metal to be processed at a break from the end of the hot roll to the beginning of intensive cooling.

As can be seen from the given regression equation, the effect of pair interaction $b_{12} = -28{,}75$ and $b_{13} = +46{,}25$ also significantly affects the value of the strength limit; from the sign and value of these coefficients, the joint effect of the final temperature of rolling and break to the beginning of intensive cooling at the selected intervals of their change reduces the strength limit, and the joint effect of the temperature of the end of rolling and the duration of intensive cooling, on the contrary, increases the strength limit [8].

The joint effect of the break $(b_{23} = +1{,}25)$ on the onset of intense cooling from the end of rolling and the duration of the most intense cooling practically does not affect the change in the strength limit, that is, it is statistically insignificant. The share of the combined effect of all three factors was significant $(b_{123} = +33{,}75)$. This coefficient reflects the force of action of one of the factors, depending on the level of the other two factors [9].

Regression model of relative elongation.

No.12 the regression equation obtained to predict the levels of an important elasticity indicator, such as the relative elongation of a deformation-thermally hardened reinforcing profile, has a significantly smaller number of members of the equation than the similar regression equation for the strength limit.

$$\delta_5 = 8{,}98 - 3{,}03_{x_1} + 3{,}95_{x_3} - 1 \qquad (3')$$

At the same time,at the selected deviation interval, the delay factor x_2 does not affect the relative elongation rate from the end of the hot roll to the beginning of intensive cooling: $(-0$.

The greatest effect on the relative elongation value is the duration of intensive cooling, for which the regression coefficient was equal to $b_3 =$ at the same time, an increase in the cooling duration leads to an increase in the optimal relative elongation (within the selected deviation). Further, according to the degree of influence on the elongation value, the temperature of the Rolling tip is $b_1 =$, while increasing the temperature of the Rolling tip reduces the relative elongation, which indicates a minus sign in the regression equation [10].

Discussion and conclusion of the received information

Thus, the value of the strength limit at the selected deviation intervals (by the degree of their significance) is affected – the duration of intensive cooling (b_3), the effect of pair interaction (b_{13}), the end temperature of rolling (b_1), the effect of pair interaction (b_{12}) and the effect of triple interaction (b_{123}).

The relative elongation is reduced by a simultaneous increase in the level of the end temperature of rolling and the duration of intensive cooling, which is reflected in the value and sign of the effect of the pair interaction $(b_{13} = -1{,}75)$, other effects, in particular: from the beginning to the end of an intense hot remdawg hypothermia $(b_{12} = +1{,}45)$, prior to intensive exposure and hypothermia before the end of the length with a quick remdawg hot $(b_{23} = +0{,}175)$ to the temperature of the pair interaction and the interaction of the Troika – before the end of the intensive cooling and intensive cooling with hot remdawg duration until the beginning of $(b_{123} = -1{,}23)$, selected when relatively little effect on the magnitude of the temperature deviation for the interval sarudi remdawg complete.

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ДЕФОРМАЦИЯЛЫҚ-ТЕРМИЯЛЫҚ БЕРІКТЕНДІРІЛГЕН АРМАТУРАЛЫҚ ПРОФИЛЬДІҢ БЕРІКТІК ЖӘНЕ ПЛАСТИКАЛЫҚ ҚАСИЕТТЕРІНІҢ РЕГРЕССИЯЛЫҚ МОДЕЛЬДЕРІН ТАЛДАУ

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Түйіндеме

Термиялық беріктендірудің тиімділігіне байланысты негізгі параметрлер: деформацияның басталу және аяқталу температурасы, жалпы дәреже, бөлшек және деформация дәрежесі, өту арасындағы үзілістердің ұзақтығы, деформация аяқталған сәттен бастап қарқынды салқындату басталғанға дейінгі уақыт аралығы, өздігінен іске қосу температурасына дейін жеделдетілген салқындату ұзақтығы және өңделетін болаттың химиялық құрамы.

Накты прокат пішіні технологиялық процестер технологиялық параметрлердің өзгеру ауқымының алуан түрлілігімен сипатталады, олардың әр түрлі комбинациясы тіпті бір болат маркасы үшін де, илектелген профильдің бір түрі мен өлшемі үшін де мүлдем басқа түпкілікті механикалық қасиеттерге әкелуі мүмкін, бұл өте қиын, көбінесе әр түрлі профильдер мен прокат сорттарының түрлері үшін дайын илектің соңғы механикалық қасиеттерін болжаудың бірыңғай математикалық модельдерін әзірлеудің практикалық мүмкін еместігі. Сондықтан технологиялық параметрлердің өзгеру ерекшеліктерін ескере отырып, пішіні, профиль өлшемдерінің және болат маркаларының белгілі бір түрлері үшін соңғы механикалық қасиеттерді болжаудың математикалық модельдерін жасауға тырысудың ең қолайлы нұсқасы.

Кілттік сөздер: арматуралық профильдер, математикалық модель, деформациялық – термиялық беріктілік, дисперсия, Фишер критерийі, студент критерийі, илемдеу.

АНАЛИЗ РЕГРЕССИОННЫХ МОДЕЛЕЙ ПРОЧНОСТНЫХ И ПЛАСТИЧЕСКИХ СВОЙСТВ ДЕФОРМАЦИОННО – ТЕРМИЧЕСКИ УПРОЧНЕННОГО АРМАТУРНОГО ПРОФИЛЯ

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Резюме

Основными параметрами, от которых зависит эффективность термического упрочнения являются: температура начала и конца деформации, суммарная степень, дробность и степень деформации, длительность пауз между проходами, интервал времени с момента окончания деформации до начала интенсивного охлаждения, продолжительность ускоренного охлаждения до температуры самоотпуска и, наконец, химический состав обрабатываемой стали.

Реально существующие технологические процессы на конкретных прокатных станах характеризуются большим разнообразием диапазона изменения указанных технологических параметров, различные сочетания которых могут привести к совершенно различным конечным механическим свойствам даже для одной и той же марки стали и для одного и того же вида и размера прокатываемого профиля, что обуславливает чрезвычайную трудность, часто и практическую невозможность разработки единых математических моделей прогнозирования конечных механических свойств готового проката для различных профилей и типов прокатных сортовых станов. Поэтому наиболее приемлемым вариантом попытки создания математических моделей прогнозирования конечных механических свойств для конкретных типов станов, профилеразмеров и марок сталей с учетом особенностей изменения технологических параметров.

Ключевые слова: арматурные профили, математическая модель, деформационно – термическое упрочнение, дисперсия, критерий Фишера, критерий Стьюдента, прокатка.

ANALYSIS OF REGRESSION MODELS OF STRENGTH AND PLASTIC PROPERTIES OF DEFORMATION-THERMALLY HARDENED REINFORCING PROFILE

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Summary

The main parameters that determine the effectiveness of thermal hardening are: the temperature of the beginning and end of deformation, the total degree, fraction and degree of deformation, the duration of pauses between passes, the time interval from the end of deformation to the beginning of intensive cooling, the duration of accelerated cooling to the self-release temperature, and, finally, the chemical composition of the processed steel.

Actual technological processes at specific rolling mills are characterized by a wide variety of the range of changes in the specified technological parameters, different combinations of which can lead to completely different final mechanical properties even for the same steel grade and for the same type and size of the rolled profile, which causes extreme difficulty, it is often also practically impossible to develop unified mathematical models for predicting the final mechanical properties of finished products for various profiles and types of rolling mills. Therefore, the most acceptable option is to create mathematical models for predicting the final mechanical properties for specific types of mills, profile sizes and steel grades, taking into account the peculiarities of changing technological parameters.

Key words: reinforcement profiles, mathematical model, deformation – thermal strength, dispersion, Fischer criterion, student criterion, rolling.