Hardenability modeling

Modeliranje prekaljivosti

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Abstract: The paper presents the use of genetic programming and linear regression method for hardenability modeling for 51CrV4 spring steel. The experimental data on chemical composition, distance from the specimen face and Jominy test results of 74 batches were collected. On the basis of the experimental data set, a mathematical model for the Jominy test was developed by genetic programming and linear regression. The models were also tested on the basis of experimental data on 871 batches. The results show that the genetically developed model performs better and the results can be easily used also in practice.

Izvleček: V članku je predstavljena uporaba genetskega programiranja in linearne regresije pri modeliranju prekaljivosti vzmetnega jekla 51CrV4. Uporabljeni so podatki 74 šarž: kemična analiza, razdalja od čelne ploskve in rezultati Jominyjevega preizkusa. Na podlagi teh podatkov smo z genetskim programiranjem in linearno regresijo izdelali matematična modela za rezultate Jominyjevega preizkusa. Oba modela smo preverili z eksperimentalnimi podatki 871 šarž. Rezultati kažejo, da se genetsko dobljeni model vede bolje in da se lahko rezultati raziskave zlahka uporabijo v praksi.

Key words: hardenability, Jominy test, spring steel, modeling, genetic programming
Ključne besede: prekaljivost, Jominyjev preizkus, vzmetno jeklo, modeliranje, genetsko programiranje

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INTRODUCTION

Hardenability is a steel property which describes the depth to which the steel may be hardened during quenching. The Jominy test is a method for determining the hardenability of steel which involves heating a test piece from the steel (25 mm diameter and 100 mm long) to an austenitising temperature and quenching from one end with a controlled and standardised jet of water. After quenching the hardness profile is measured at intervals from the quenched end.

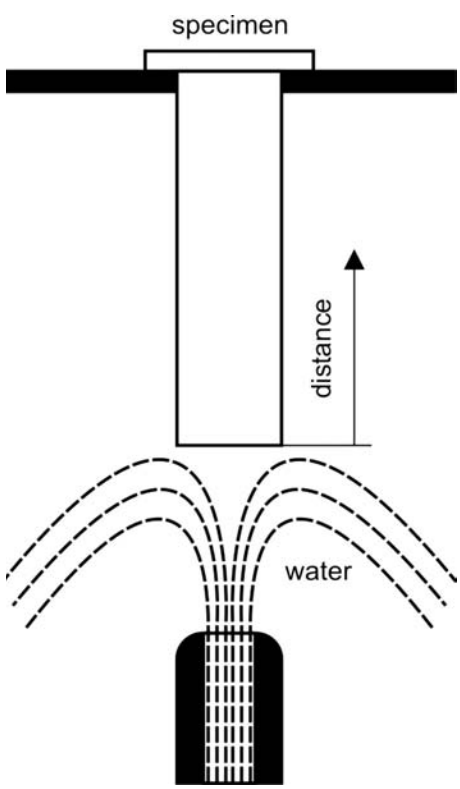

Figure 1. Jominy test

Several attempts for Jominy test modeling have been made[1–4] including the artificial intelligence approach. [3]

In this paper genetic modeling and linear regression method for a Jominy test modeling is proposed. Genetic programming has been successfully implemented into several manufacturing processes. [5, 6]

EXPERIMENTAL SETUP

The experiment was performed with 51CrV4 spring steel specimens collected in the period of October 2003 to September 2007 in the factory Štore Steel Ltd. [7] Distance from the specimen face (1.5 mm, 9 mm, 15 mm, 30 mm, 50 mm) and chemical composition (mass fractions of C, Si, Mn, P, S, Cr, Mo, Ni, Al, Cu, Ti, V, Sn, Ca, N) were used for mathematical modeling of the Jominy test (Table 1).

Training data set (74 batches) was used Jominy test results prediction, whereas the testing data set (871) was used for verifying the model. The average chemical composition of 51CrV4 spring steel used in the research is shown in table 2.

Table 1. Experimental data (mass fraction, *w*/%)

Batch #	Distance *D*/mm	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Ti	V	Sn	Ca	N	Jominy [HRC]
1	2	0.52	0.3	1.04	0.01	0.001	1.13	0.02	0.11	0.017	0.17	0.004	0.16	0.012	0.001	0.007	62
1	9	0.52	0.3	1.04	0.01	0.001	1.13	0.02	0.11	0.017	0.17	0.004	0.16	0.012	0.001	0.007	62
1	15	0.52	0.3	1.04	0.01	0.001	1.13	0.02	0.11	0.017	0.17	0.004	0.16	0.012	0.001	0.007	58
1	30	0.52	0.3	1.04	0.01	0.001	1.13	0.02	0.11	0.017	0.17	0.004	0.16	0.012	0.001	0.007	50
1	50	0.52	0.3	1.04	0.01	0.001	1.13	0.02	0.11	0.017	0.17	0.004	0.16	0.012	0.001	0.007	43
2	2	0.52	0.3	1.03	0.009	0.002	1.14	0.02	0.1	0.015	0.17	0.003	0.16	0.011	0.001	0.008	61
2	9	0.52	0.3	1.03	0.009	0.002	1.14	0.02	0.1	0.015	0.17	0.003	0.16	0.011	0.001	0.008	61
2	15	0.52	0.3	1.03	0.009	0.002	1.14	0.02	0.1	0.015	0.17	0.003	0.16	0.011	0.001	0.008	58
2	30	0.52	0.3	1.03	0.009	0.002	1.14	0.02	0.1	0.015	0.17	0.003	0.16	0.011	0.001	0.008	56
2	50	0.52	0.3	1.03	0.009	0.002	1.14	0.02	0.1	0.015	0.17	0.003	0.16	0.011	0.001	0.008	45
3	2	0.55	0.26	1.03	0.014	0.004	1.12	0.03	0.08	0.013	0.18	0.002	0.16	0.009	0.0011	0.008	62
3	9	0.55	0.26	1.03	0.014	0.004	1.12	0.03	0.08	0.013	0.18	0.002	0.16	0.009	0.0011	0.008	59
3	15	0.55	0.26	1.03	0.014	0.004	1.12	0.03	0.08	0.013	0.18	0.002	0.16	0.009	0.0011	0.008	57
3	30	0.55	0.26	1.03	0.014	0.004	1.12	0.03	0.08	0.013	0.18	0.002	0.16	0.009	0.0011	0.008	53
3	50	0.55	0.26	1.03	0.014	0.004	1.12	0.03	0.08	0.013	0.18	0.002	0.16	0.009	0.0011	0.008	45
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
945	2	0.52	0.3	1.09	0.015	0.01	1.16	0.02	0.08	0.013	0.14	0.003	0.11	0.013	0.0013	0.012	63
945	9	0.52	0.3	1.09	0.015	0.01	1.16	0.02	0.08	0.013	0.14	0.003	0.11	0.013	0.0013	0.012	59
945	15	0.52	0.3	1.09	0.015	0.01	1.16	0.02	0.08	0.013	0.14	0.003	0.11	0.013	0.0013	0.012	55
945	30	0.52	0.3	1.09	0.015	0.01	1.16	0.02	0.08	0.013	0.14	0.003	0.11	0.013	0.0013	0.012	51
945	50	0.52	0.3	1.09	0.015	0.01	1.16	0.02	0.08	0.013	0.14	0.003	0.11	0.013	0.0013	0.012	46

Table 2. The average chemical composition of 51CrV4 spring steel used in the research

Training data set	*w*/%	Average	St. dev	Testing data set	*w*/%	Average	St. dev
	C	0.524	0.012345		C	0.520875	0.011203
	Si	0.280667	0.03214		Si	0.276695	0.033691
	Mn	1.006267	0.060607		Mn	0.997613	0.064439
	P	0.012973	0.0022		P	0.012589	0.00226
	S	0.005133	0.003087		S	0.004957	0.002668
	Cr	1.104933	0.068353		Cr	1.103564	0.063644
	Mo	0.038533	0.020139		Mo	0.043035	0.023867
	Ni	0.102667	0.019982		Ni	0.10568	0.020528
	Al	0.016587	0.005825		Al	0.016961	0.005442
	Cu	0.160133	0.029319		Cu	0.161231	0.029322
	Ti	0.003493	0.003126		Ti	0.004577	0.005245
	V	0.139067	0.022609		V	0.141328	0.021955
	Sn	0.011093	0.001595		Sn	0.011248	0.001757
	Ca	0.001283	0.000365		Ca	0.001283	0.000374
	N	0.010587	0.001908		N	0.010857	0.002206

JOMINY TEST AND GENETIC PROGRAMMING

Genetic programming is probably the most general evolutionary optimization method. The organisms that undergo adaptation are in fact mathematical expressions (models) for Jominy test prediction consisting of the available function genes (i.e., square root and basic arithmetical functions) and terminal genes (i.e., independent input parameters, and random floating-point constants). In our case the models consist of: function genes of addition, subtraction, multiplication, division and square root operation, terminal genes of distance from specimen face *D* and chemical composition (mass fractions of C, Si, Mn, P, S, Cr, Mo, Ni, Al, Cu, Ti, V, Sn, Ca, N).

Random computer programs of various forms and lengths are generated by means of selected genes at the beginning of simulated evolution. Afterwards, the varying of computer programs during several iterations, known as generations, by means of genetic operations is performed. After completion of varying of computer programs a new generation is obtained that is also evaluated and compared with the experimental data. The process of changing and evaluating organisms is repeated until the termination criterion of the process is fulfilled. This was the prescribed maximum number of generations.

For the process of simulated evolutions the following evolutionary parameters were selected: size of population of organisms 500, the greatest number of generations 200, reproduction probability 0.4, crossover probability 0.6, the greatest permissible depth in creation of population 6, the greatest permissible depth after the operation of crossover of two organisms 10 and the smallest permissible depth of organisms in generating new organisms 2. Genetic operations of reproduction and crossover were used. For selection of organisms the tournament method with tournament size 7 was used.

We have developed 100 independent civilizations of mathematical models for prediction of the Jominy test.

To make the presentation more clear let us have a look at the development of one of the independent civilizations with previously mentioned genes.

The result of the blind random searching for mathematical models in the initial generation is bad. The best mathematical model for prediction of the Jominy test in generation 1 is:

$$\begin{aligned} &-35.15+118.66\cdot C+13.72\cdot Cr+9.25\cdot Cu+15.13\cdot Mn \\ &+20.71\cdot Mo-126.73\cdot N+12.73\cdot Ni+54.83\cdot P+10.55\cdot Si \end{aligned} \tag{1}$$

with average deviation (%) for training data (74 batches) 92.62 %.

A slightly better model has been developed in generation 50:

$$29.27+60.38\cdot C-0.00276\,(33.44\cdot Al+9.25\cdot Cu)\,D^2 \tag{2}$$

with average deviation for training data (74 batches) 13.06 %.

The best model occurred in generation 156:

$$\begin{aligned} &29.27+60.38\cdot C-D\cdot Si \\ &+Mo(Mo-Mn^2(60.38+60.38\cdot C+Mn)Mo+Si(120.76\cdot Si^2) \\ &+Si^2(60.38\cdot Si+120.76\cdot Si^2+Mn\cdot Si^7) \\ &+Si(120.76\cdot Si+362.28\cdot Si^2+Si(120.76\cdot Si+181.14\cdot Si^2))) \end{aligned} \tag{3}$$

with average deviation for training data (74 batches) 4.22 %.

Table 3. The linear regression results

		Unstandardized Coefficients		Standardized Coefficients	*t*	Sig.
Model		*B*	Std. Error	*Beta*		
1	(Constant)	63.462	8.019		7.914	0.000
	Distance	–0.284	0.009	–0.846	–30.985	0.000*
	C	3.875	16.277	0.008	0.238	0.812
	Si	–0.981	5.298	–0.005	–0.185	0.853
	Mn	1.845	4.886	0.019	0.378	0.706
	P	37.209	39.616	0.029	0.939	0.348
	S	1.445	38.137	0.001	0.038	0.970
	Cr	–2.365	4.697	–0.028	–0.503	0.615
	Mo	12.553	9.045	0.044	1.388	0.166
	Ni	–17.477	9.130	–0.060	–1.914	0.056
	Al	–33.779	28.771	–0.038	–1.174	0.241
	Cu	0.263	6.863	0.001	0.038	0.969
	Ti	18.319	68.077	0.012	0.269	0.788
	V	–10.336	8.404	–0.040	–1.230	0.220
	Sn	–47.154	108.512	–0.013	–0.435	0.664
	N	93.117	102.366	0.040	0.910	0.364

*Statistical significance ($p < 0.05$)

The linear regression model is:

$$\begin{aligned} &63.462 - 0.284 \cdot D + 3.875 \cdot C - 0.981 \cdot Si + 1.845 \cdot Mn + 37.209 \cdot P + 1.445 \cdot S \\ &- 2.365 \cdot Cr + 12.553 \cdot Mo - 17.477 \cdot \mathrm{Ni} - 33.779 \cdot Al + 0.263 \cdot Cu + 18.319 \cdot Ti \\ &- 10.336 \cdot V - 47.154 \cdot Sn + 93.117 \cdot N \end{aligned} \tag{4}$$

$W = w(\mathrm{W})$; W = C, Si, Mn, P, S, Cr, Mo, Ni, Al, Cu, Ti, V, Sn, N
with average deviation for training data (74 batches) 4.25 %.

The average mass fraction deviation of the best model for testing data (871 batches) is 14.92 %.

The only statistically influential parameter ($p < 0.05$) in the linear regression model is distance from the edge ($p = 0.000$).

The average deviation of the best model for testing data (871 batches) is 4.37 %.

As the models are developed by simulated evolution based on probability, there is no guarantee that the models will contain all available independent parameters. During previous studies it was established experimentally that genetic programming for building of models, usually uses only parameters leading to successful solutions, whereas parameters not having decisive influence on the output parameter(s) are on the average more frequently eliminated by simulated evolution. [5, 6] Thus in our case, by analyzing the parameters present (i.e., remaining) in the best model, the influence of an individual parameter on the Jominy test can be indirectly estimated.

From sixteen terminal genes - monitored parameters (distance from specimen face, mass fractions of C, Si, Mn, P, S, Cr, Mo, Ni, Al, Cu, Ti, V, Sn, Ca, N) only five were present in the best model for Jominy test prediction.

It is possible to conclude that the distance from specimen face, mass fractions of C, Si, Mn and Mo are the most influential parameters for 51CrV4 spring steel hardenability.

Jominy test and linear regression

The results of linear regression modeling results are presented in the next table (Table 3).

Conclusion

In this paper prediction of the Jominy test by genetic programming and linear regression was performed. Prediction models were developed on the basis of experimental data on the chemical composition and distance from the specimen face of the 51CrV4 spring steel.

A training data set (74 batches) was used for Jominy test results prediction, whereas the testing data set (871 batches) was used for verifying the model.

Genetic programming predicts the Jominy test with average deviation for training data (74 batches) 4.22 % and 4.37 % for testing data (871 batches). With the genetic programming method we can also assume that the influence of the mass fractions of P, S, Cr, Ni, Al, Cu, Ti, V, Sn, Ca and N on Jominy test results is relatively small.

Linear regression predicts the Jominy test with average deviation for training data (74 batches) 4.25 % and 14.92 % for testing data (871 batch-

es). The only statistically influential parameter ($p < 0.05$) in the linear regression model is distance from the edge ($p = 0.000$).

The results show that both approaches give pretty the same idea about influencing parameters and also the genetically developed model performs better. The results can be easily practically used for chemical composition optimization.

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