Critical inclusion size in spring steel and genetic programming

Kritična velikost vključka v vzmetnem jeklu in genetsko programiranje

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Received: October 9, 2009 **Accepted:** January 11, 2010

Abstract: In the paper the genetic programming method was used for critical inclusion size determination. At first the mathematical model according to dynamically testing results of the seven broken 51CrV4 springs has been obtained and after the optimization with the model was performed. For the modeling of the spring life the inclusion size of the inclusion found at the breakage surface and the distance of the inclusion from the spring tensile surface were used. The results show that the critical inclusion (the inclusion at the spring tensile surface) size in our case is 0.14 mm. The results of the proposed concept can be used in practice.

Izvleček: V članku je bila za določevanje kritične velikosti vključka uporabljena metoda genetskega programiranja. Najprej se je na podlagi eksperimentalnih podatkov sedmih prelomljenih vzmeti iz 51CrV4 izdelal matematični model, ki se je kasneje uporabil za optimizacijo. Za modeliranje trajnostne dobe vzmeti sta se uporabila velikost vključka, najdenega na prelomu, in njegova oddaljenost od natezne površine vzmeti. Rezultati kažejo, da je kritična velikost vključka (na natezni strani vzmeti) v našem primeru 0,14 mm. Rezultate predloženega koncepta lahko uporabimo v praksi.

Key words: spring steel, inclusions, modeling, genetic programming

Original scientific paper

Ključne besede: vzmetno jeklo, vključki, modeliranje, genetsko programiranje

Introduction

Spring life depends on steel and spring producers activities. Each producer part contribute to mechanical behavior of the produced spring.[1, 2]

The spring life is determined by dynamical testing. There are many different techniques for spring life determination.[1–4] In general the whole spring assembly or just a sample cutout is used for the spring life analysis. Šuštaršič et al. tried to determine the bend fatigue strength of selected spring steel with a resonant pulsator using standard Charpy V-notched specimens.[1–2] Murakami et al. tried to predict the upper and the lower limits of fatigue strength from the Vickers hardness of a matrix and the maximum size of inclusions defined by the square root of the projected area of an inclusion.[3] Murakami also introduces several spring steel quality determination techniques.[4]

In the present paper the dependence between inclusion size, inclusion location and spring life was discussed. The experimental data was collected after spring breakage between dynamic testing.

After the genetic programming method [5–7] was used to determine the correlation between spring tool life and inclusion size and inclusion location. With the genetically obtained mathematical model the critical inclusion size was determined.

The critical inclusion size information could be easily used for steel plant metallurgical processes design.

Spring life dynamic testing

We were using the three-point flexural testing device. The spring life dynamic testing is schematically presented in figure 1. The tested material was 51CrV4. The chemical composition of the tested material is colected in the table 1. Test frequency was 40 r/min, test force (F) between 3.3 kN and 50 kN,

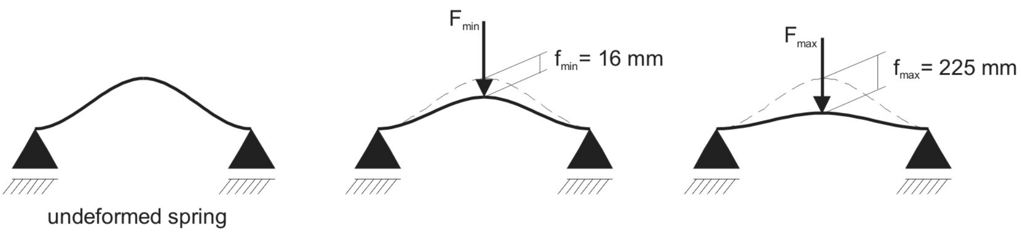

Figure 1. Spring life dynamic testing

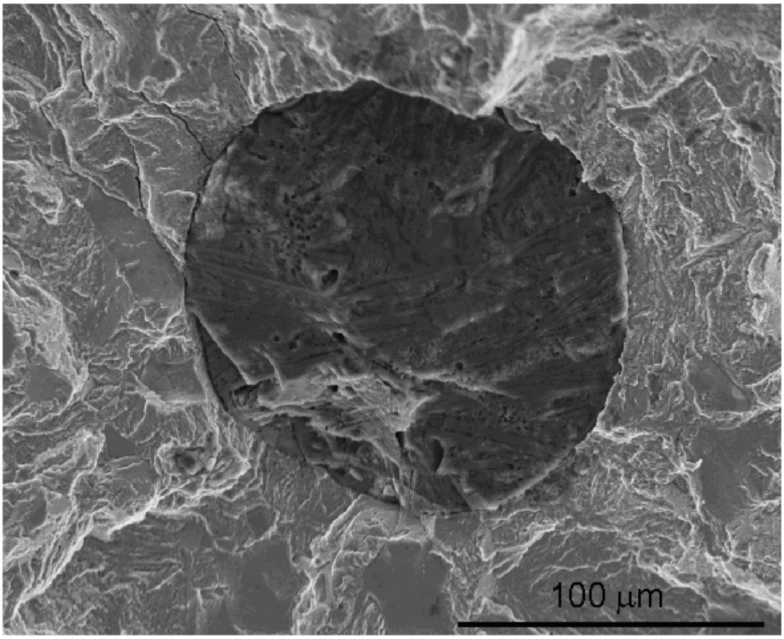

Figure 2. The inclusion found at the breakage surface of the spring number 2 (Table 3)

Table 1. 51CrV4 spring steel chemical composition (*w*/%)

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Nb	Ti	V	Sn	Ca	B
0,51	0,34	0,96	0,014	0,003	1,07	0,06	0,08	0,012	0,13	0,001	0,004	0,17	0,01	0,0009	0,0002

Table 2. The inclusion (spring number 2) chemical composition (*w*/%)

O	Mg	Al	Si	S	Ca	Ti	Fe	Zn
43,42	3,26	19,77	2,91	1,08	24,47	0,20	4,69	0,21

Table 3. The spring life dynamic testing data

Spring number	Inclusion size, *S*/mm	Inclusion depth, *D*/mm	Spring life [cycles, *r*]
1	0.33	3.75	53667
2	0.16	1.34	96484
3	0.22	0.91	60157
4	0.26	3.87	62437
5	0.44	3.71	57454
6	0.38	3.09	53200
7	0.2	1.19	53062

spring sink (*f*) from 16 mm to 225 mm. It is easily to conclude that the load was pulsative and the bottom and top surface were tensile and compressed, respectively.

After the spring breakage the inclusion size of and the depth of the inclusion found at the breakage surface (distance from the bottom spring surface) were measured. The inclusion and spring life data is collected in the table 3. The inclusion found at the spring number 2 breakage surface (Table 3) and its chemical composition is presented in the figure 2 and table 2, respectively.

Spring life modeling by genetic programming

Genetic programming is probably the most general evolutionary optimization method.[5–7] The organisms that undergo adaptation are in fact mathematical expressions (models) for spring life prediction consisting of the available function genes (i.e., 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 (*) and division (/), terminal genes of inclusion size (*S*) and inclusion depth (*D*).

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 evaluated and compared with the experimental data, too.

For spring life prediction the fitness measure was defined as:

$$\Delta = \frac{\sum_{i=1}^{n} \Delta_i}{n} \tag{1}$$

where n is the size of sample data, Δ_i is a percentage deviation of single sample data. The percentage deviation of single sample data, produced by individual organism, is:

$$\Delta_i = \frac{|E_i - G_i|}{E_i} \cdot 100~\% \tag{2}$$

where E_i and G_i are the actual spring life and the predicted spring life by a model, respectively. The smaller the values of equation (1), the better is adaptation of the model to the experimental data.

The process of changing and evaluating of 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 generation 100, 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 spring life prediction. Each civilization has the most succesfull organism – mathematical model for spring life prediction. The best most successfull organism from all of the civilizations is presented here:

$$\left(8.32555+8.40678(8.23089+D)+\frac{8.23089+D}{D}+\frac{D}{3.48269\cdot D-\frac{0.85092}{S}}\right)$$
$$\left(-\frac{8.55026}{8.32555-\frac{D}{S}}-\frac{\left(-29.777904+\frac{D}{8.32555-\frac{8.55026}{9.17647+\frac{8.23089+D}{D}}-\frac{D}{S}}+\frac{2}{S}\right)(6.66951+S)}{S}-\right.$$
$$\left.27.21465\cdot S\left(S+D+\frac{-8.55026+\frac{D}{S}+S}{1+\frac{1}{S\cdot D}}\right)+S\left(\frac{8.23089+D}{D}+S+\frac{-8.55026+2D+S}{8.32555-\frac{D}{S}}\right)+\frac{D+\frac{D}{S}+S}{3.48269\cdot D-\frac{0.85092}{S}}\right) \quad (3)$$

with fitness measure (average percentage deviation) 0.64 %.

The calculated spring life and percentage deviations from experimental data is presented in the next table (Table 4).

Table 4. The calculated spring life and percentage deviations from experimental data

Spring number	Inclusion size *S*/mm	Inclusion depth *D*/mm	Spring life [cycles] *r*	Predicted spring life [cycles] *r*	Deviation
1	0.33	3.75	53667	53673	0.01 %
2	0.16	1.34	96484	95829	0.68 %
3	0.22	0.91	60157	59715	0.73 %
4	0.26	3.87	62437	62788	0.56 %
5	0.44	3.71	57454	57969	0.90 %
6	0.38	3.09	53200	53187	0.02 %
7	0.2	1.19	53062	53890	1.56 %

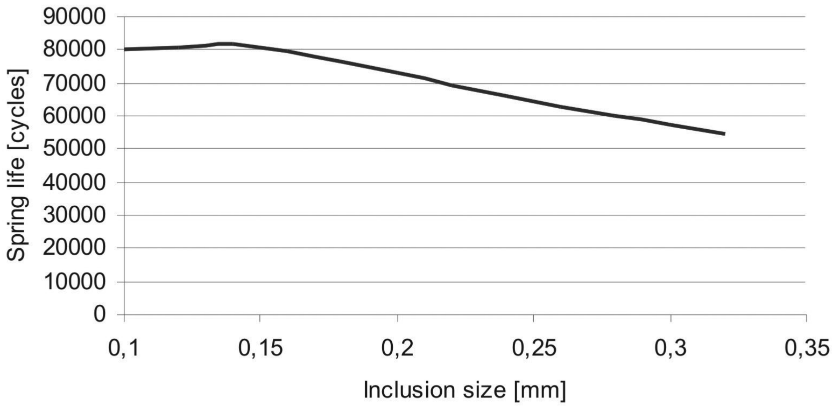

Figure 3. Spring life and inclusion size on the surface dependency

Critical inclusion size

According to the best genetically developed spring life model it is easily to calculate the critical size of inclusion on the spring surface. The spring life and inclusion size on the surface dependency is presented in the next figure (Figure 3).

The highest calculated spring value is at inclusion size 0.14 mm. After that value spring life rapidly decreases.

Conclusion

Spring life depends on many properties. One of the most important is inclusions size.

In the research 7 springs were dynamically tested on three-point flexural testing device. The tested material was 51CrV4. Test frequency was 40 r/min, test force between 3.3 kN and 50 kN, spring sink from 16 mm to 225 mm.

After the spring breakage the inclusion size and depth (distance from the bottom surface) were measured.

The genetic programming method was used to determine the correlation between spring tool life and inclusion size and inclusion location.

From the 100 runs (civilizations) the best predictive model for spring life was developed with average percentage deviation 0.64 %.

According to the best genetically developed spring life model it was easily to calculate the critical size of inclusion on the spring surface. The value is 0.14 mm.

With the help of genetic programming method the decision value was determined. According to known critical inclusion size value the right spring steel and steel plant technology could be easily selected. The results are compared with the similar more experimentaly-oriented research.[1]

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