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THE RELIABILITY OF THE BRAKE METALLIC ELEMENTS SUBJECTED TO TRIBO-THERMAL FATIGUE WEAR

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Summary

The paper presents a methodology for estimating the reliability of the metallic structures, which are in the composition of the mechanical brakes. Reliability estimation of these structures presumes the taking into consideration of many factors, which can have contrary influences on the tribo-thermal fatigue durability. Reliability evaluation of the metallic material is done on the basis of its characteristics (chemical composition and hardness), and of the main parameters of dry friction regime (contact pressure and sliding speed). The calculus relations which are presented in the paper are based on the experimental results obtained in the tribo-thermal fatigue wear tests done in accordance with the real stresses of the mechanical brakes. The relations presented in the paper can be used to the design of the metallic elements of the dry friction couples from the mechanical brakes.

Key words: *Tribo-thermal fatigue wear, Brake metallic elements, Reliability*

1. INTRODUCTION

Tribo-thermal fatigue is a kind of wear, which characterizes the metallic elements friction surface. During the braking processes, in every mechanical brake, it appears the heat elimination. The biggest part of the heat quantity (over 90%) is taken by the metallic element of the braking couples. Due to this fact, the metallic element friction surface grows hot. In this case, the maximum temperature on the friction surface can reach values in the range of 300–800 °C. For the heavy-duty mechanical brakes the temperature values are frequently situated at the superior part of this range [1].

Taking into account of the above considerations, it is necessary to estimate the reliability of these elements for a better braking couple design. The tribo-thermal fatigue wear of the braking couples metallic elements is influenced by many factors which generally have contrary effects and usually it is evaluated with the number of cycles until the first crack appearance on the friction surface. Thus, they can be enumerated: the maximum temperature value which characterize the thermal cycle, the hardness of the metallic element friction surface, the chemical composition of the metallic elements material, the nominal contact pressure, the sliding speed and so others.

Usually, for a technical system, the reliability is defined as the good working probability for a period of time under specified conditions of operating. For the metallic elements of the mecha-nical braking couples, the reliability estimation must take into account at least the above-enumerated influence factors [2].

The thermal stresses and strains which appear in the friction surface adjacent zone have high values which are in the range of 100 – 800 MPa for the stresses, respectively of 0.2 – 1.0 % for the relative strains, so, much more than the yield limits of the metallic materials used at the braking couples construction. Because the heatings produced by braking have a variable or almost cyclic character, the thermal stresses and strains effects are similar to that which characterize the low cycle fatigue [1, 2]. These effects consist in the cracks appearance on the friction surface. In time, the number and the size of these cracks increase, and the result is the reach of the fatigue fracture state.

The initiation and the development of the cracks are also favored by the microstructural transformations that appear as a consequence of the high temperature values reached in the metallic structure. When the braking couple metallic elements are made from low and middle alloy steels, these transformations have a specific character because of the heating rates that are situated in the range of 40 – 80 °C/s. One of the main effects of these transformations is the structure hardening [1]. The structure hardness depends of the temperature value and the number of thermal stress cycles. Therefore, the hardness level can be an indicator of the reliability of the metallic structure.

Taking into account of the above statements, the paper aim is to develop a methodology, which can be used at the estimation of the reliability of the braking couples metallic elements. This methodology is based on the researches concerning the operating behavior of the mechanical band brakes, which equip the drilling drawworkses.

2. EXPERIMENTAL CONDITIONS

The experiments were done on a testing stand built for tribo-thermal fatigue studies of the braking couples metallic elements. This testing stand is equipped with a friction couple cylinder-plan like. The test piece has a special form, being tubular inside in order to permit the cooling of the frontal wall trough a cooling tube. The temperature value on the friction surface is indirectly determined, using the temperature value measured on the exterior surface of the test piece (cylindrical part) with a thermocouple, put from the frontal face (the friction surface) at different distances. It was preferred this possibility because the thermocouple assembly by enclosure in an orifice put under the friction surface can create stress concentrators which quickens its cracking process [1, 2].

The friction couple materials were for the metallic element the middle alloy steels and for the non-metallic element, a friction composed material ferrodo like. The chemical composition of the tested steels is presented in Table 1 and the mechanical characteristics in Table 2.

Table 1: *Chemical composition of the tested steels*

Alloying Elements	Composition, % wt
C	0.32 … 0.42
Mn	0.43 … 1.46
Cr	0.24 … 1.01
Ni	0.09 … 0.63
Mo	0.04 … 0.21
Si	0.25 … 0.52

Table 2: *Mechanical characteristics of the studied steels*

Mechanical characteristic	Values
Tensile strength	540 … 930 MPa
Yield limit	295 … 735 MPa
Elongation	12 … 16 %
Reduction of area	25 … 50 %
Hardness	170 … 225 HV

The initial structure of the tested steel was pearlitic-ferrite, typical for the dead-full annealing treatment.

The experimental regime parameters values were the contact pressure in the range of 0 – 2.5 MPa; the sliding speed in the range of 0 – 8 m/s; the temperature on the friction surface in the range of 100-800 °C. These regime parameters values were established according with the real values which were used in the band brake exploitation.

The metallic test pieces were subjected at heating cycles between two temperature limits (t_{min}, t_{max}) and the heat was generated by friction. The heating rates were in the range of 40 – 80 °C/s and the cooling rate in the range of 5 – 10 °C/s. The thermocycles were done without keeping at the maximum temperature of the cycle [1, 2].

The tribo-thermal fatigue durability was estimated using as criterion the first crack appearance on the friction surface. Also, there were determined the hardnesses on the friction surface at the beginning and respectively at the end of each test [4].

3. THE CHEMICAL COMPOSITION INFLUENCE ON THE TRIBO-THERMAL FATIGUE DURABILITY

One of the important factors, which influence the tribo-thermal fatigue durability, is the chemical composition, which at its side determines the structure of the steel and its metallurgical transfor-mations.

In Figure 1, it is presented the dependence between the durability and the carbon content of the tested steels, for different specific caloric loading (pv) values (the specific caloric loading is defined like the product between the contact pressure p, and the sliding speed v), and for different maximum temperature value of the thermal cycle.

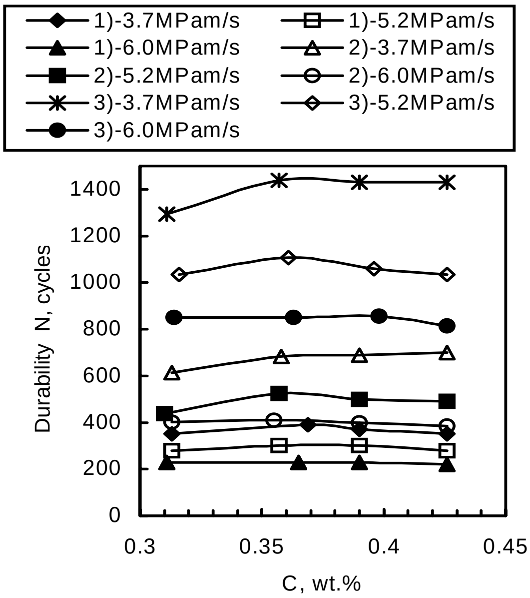

Figure 1: *The durability vs. carbon content for different specific caloric loading values, and for different maximum temperature values of the thermal cycle: 1) 800°C; 2) 700°C; 3)600°C.*

From Figure 1 it can be observed that the durability increases with the decrease of the specific caloric loading and maximum temperature for carbon contents lower than 0.35 wt.%. Over this value, generally the durability variation presents a small decrease.

Analyzing the influence of the others chemical-alloying elements it can be done the followings remarks [3]:

- the manganese and the silicon have the same influence on the microstructure and on the characteristics of the low and middle alloy tested steels;
- the chromium, the nickel and the molybdenum influence in the same manner the tribo-thermal fatigue durability of the tested steel.

Taking account of the above remarks there were represented the dependencies between the durability and these chemical alloying elements contents in Figure 2 and Figure 3.

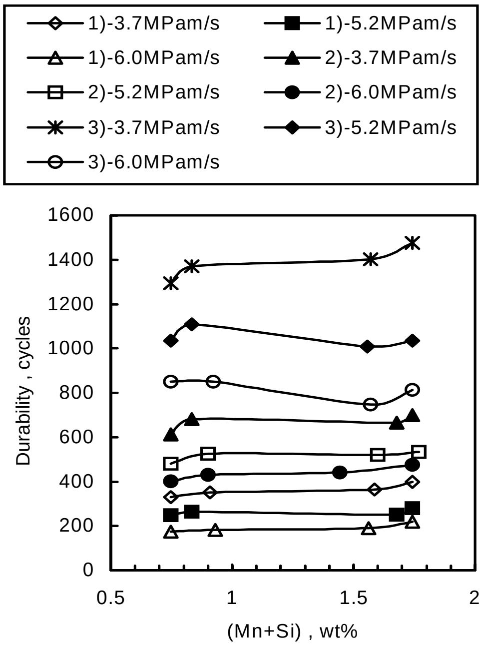

Figure 2: *The durability vs. manganese and silicon content for different specific caloric loading values, and for different maximum temperature values of the thermal cycle: 1) 800°C; 2) 700°C; 3)600°C.*

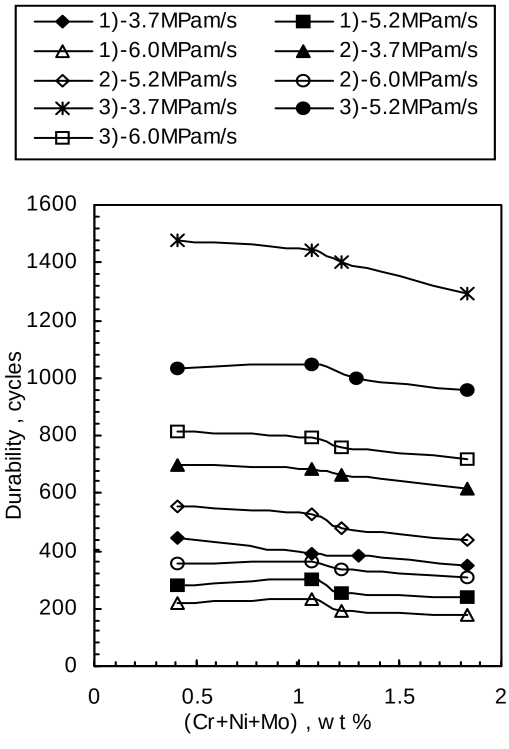

Figure 3: *The durability vs. the chromium, nickel and molybdenum content for different specific caloric loading values, and for different maximum temperature values of the thermal cycle: 1) 800°C; 2) 700°C; 3)600°C.*

From Figure 2 it can be observed that the increase of the Mn and Si content implies the durability decrease for the high values of the specific caloric loading and for the maximum temperature of 600°C. For maximum temperature values of 700°C and 800°C the increase of the Mn and Si content implies the increase tendency of the durability.

Regarding the influence of the Cr, Ni and Mo content, from Figure 3 it can be observed that the increase of their content implies the decrease of the durability especially for the high maximum temperature values of the cycle because these elements favor the carbides appearance.

4. THE TEMPERATURE AND FRICTION SURFACE HARDENING INFLUENCE ON THE TRIBO-THERMAL FATIGUE DURABILITY

The microstructural transformations due to the thermal stresses, repeated in the intercritic transformation range, had therefore, the tested materials granulation finishing. Therefore, for maximum temperature of 600 °C, the micro-structure is made in majority from fine bainite with preponderant ferritic zones. For maximum temperature of 800 °C, the microstructure is much finer, close to sorbite. Also, it appears as a consequence at granulation finishing, the increase of the hardness on the friction surface and in the same time the sagging of the globular carbides, especially on the intergranular limits [4].

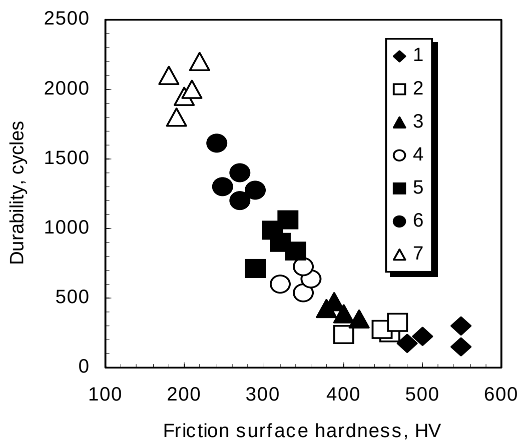

Figure 4: *The tribo-thermal fatigue durability vs. the friction surface hardness for different maximum temperature values of the thermal cycle on the friction surface: 1) 800 °C; 2) 750 °C; 3) 700 °C; 4) 650 °C; 5) 600 °C; 6) 600 °C; 7) 550 °C* [4].

From Figure 4 it can be observed that the durability decreases both with the increase of the maximum temperature value of the thermal cycle and with the increase of the hardness of the metallic material on the friction surface.

For temperature values until 600 °C the hardness is almost the same with this one which characterizes the initial state of the tested steel (see Table 2).

For quantitative estimation, in this case, it was done a multiple regression analysis, which has the form [4]:

$$N = A \cdot H^{b} \cdot t^{c} \qquad (1)$$

where: N is the tribo-thermal fatigue durability which is expressed like the number of stress thermal cycles until the first crack appearance on the friction surface; H is the hardness value which corresponds to the durability N, HV; t is the maximum temperature value of the thermal cycle, °C; A, b, c are the coefficients of the regression which have the values $A = 1.88\cdot10^{17}$, $b = 0.293$, $c = -5.424$.

Using the experimental data which are presented in Figure 4, with the help of a multiple regression analysis, it can be emphasized through a quantitative relation, the influence of the temperature and of the initial hardness of the metallic material on the final hardness which corresponds at the first crack appearance moment [4]:

$$H = K \cdot t^{d} \cdot h^{f} \qquad (2)$$

where: H is the final hardness corresponding at the first crack appearance on the friction surface, HV; t is the maximum temperature reached every cycle on the friction surface, °C; h is the initial hardness of the metallic material, HV; K, d, f are the regression constants which have the values $K = 0.012$, $d = 1.757$, $f = -0.209$.

An important conclusion which results from Figure 4, and also from eq. (1) and (2) is that the tribo-thermal fatigue durability can be associated with a maximum limit of the friction surface hardness which is specific for every maximum temperature value of the stress thermocycle.

Thus, it can be concluded that the equation (2) can be used for determination of a hardness limit value, which corresponds at the highest maximum temperature value, which characterizes the friction couple.

5. RELIABILITY MODELING OF THE METALLIC STRUCTURES SUBJECTED TO TRIBO-THERMAL FATIGUE WEAR

The reliability modeling of the metallic structures subjected to tribo-thermal fatigue wear in the mechanical brakes presumes to established a independent parameter which can be the time, the distance or better the durability expressed like the number of thermal cycles. Therefore in this case it has to be determined a relation which permits the estimation of a durability limit as a function of the main factors above presented. This relation was obtained after a regression analysis, and has the form:

$$N = -5424 - 120.227(pv) - 721.993(H/h) + \\ + 1.709\cdot10^4(C) + 213.467(Mn+Si) + \\ + 1.164\cdot10^3(Cr+Ni+Mo) \quad (3)$$

where: N is the limit durability, cycles; pv – the maximum limit value of specific caloric loading which can appears during the couple exploitation, MPa·m/s; H – the limit value of the friction surface hardness corresponding to durability N, HV; h – the initial hardness value of the friction surface, HV; C – the carbon content, wt.%; $(Mn+Si)$ – the manganese and silicon content, wt.%; $(Cr+Ni+Mo)$ – the chromium, nickel and molybdenum content, wt.%.

The characteristics of the regression analysis (3) are: the variation range for the durability N=150…1600 cycles; the variation range for specific caloric loading pv=1…9 MPa·m/s; the variation range for the limit hardness H=150…600 HV; the variation range for the initial hardness h=150…250 HV; the variation range for the maximum temperature of the thermocycle t=550…800 ^oC; the variation range for the carbon content C=0.3 – 0.45 wt.%; the variation range for manganese and silicon content (Mn+Si)=0.5-2.0 wt.%; the variation range for chromium, nickel and molybdenum content (Cr+Ni+Mo)=0.2-2.0 wt.%; the determination coefficient value, $R^2 = 0.939$; the multiple correlation coefficient value, R= 0.969; the experimental data dispersion around the regression surface for a 95 % confidence interval, in the range of ± 40 cycles.

For the modeling of the survival processes, which are characteristics to tribo-thermal fatigue wear of the brake metallic elements, it was used the Weibull partition law with two parameters. The probability density of this law is:

$$f(x, \beta, \lambda) = \beta\lambda x^{\beta-1}\exp(-\lambda x^{\beta}) \quad (4)$$

where: x is the taken into account variable ($x>0$) which for the considered case is the durability; λ, β - the two law parameters ($\lambda>0$, $\beta>0$). The Weibull partition function with two parameters is:

$$F(x, \beta, \lambda) = 1 - \exp(-\lambda x^{\beta}) \quad (5)$$

The relation gives the reliability is:

$$R(x, \beta, \lambda) = 1 - F(x, \beta, \lambda) = \exp(-\lambda x^{\beta}) \quad (6)$$

and shows the well working probability in the variable range of $(0, x)$.

The relation (3) permits to calculate a limit durability, which corresponds to certain steel and to certain regime parameters. The durability value evaluated with relation (3) corresponds to the reliability value R=0. Also the durability value R=1 corresponds to a durability N=0cycles. In this case, it can be written:

$$R_{(N)} = \exp(-\lambda N^{\beta}) = 0 \quad (7)$$

$$R_{(N=0)} = \exp(-\lambda 0^{\beta}) = 1 \quad (8)$$

If relations (7) and (8) are considered like a system, than its solutions are the two Weibull partition law parameters λ and β. The parameter λ can be deduced from equation (8) and it has always the value $\lambda\cong 0.001$ being independent on the concrete factors, which were taken into account in eq.(3). In this case the β parameter is deduced from eq. (7) and it is dependent on the limit durability calculated with the eq. (3), and so, on the concrete factors. The β parameter can be calculated with the relation:

$$\beta = \frac{1}{lg\,N}\left\{lg\left[lg\left(\frac{1}{R_{(N)}}\right)\right] - lg(lg\,e) - lg\,\lambda\right\} \quad (9)$$

For example, if it is considered a middle alloy steel which has the chemical composition: 0.32C – 0.74(Mn+Si) – 1.84(Cr+Ni+Mo), than it can be calculated the β parameter values as a function of specific caloric loading and for different values of the *H/h* hardnesses ratio, where the hardness H was calculated with relation (2). The results are represented in Figure 5.

If it is considered a brake metallic element which is made from a certain steel, and this is stressed with a specific caloric loading (pv) value, than it can be calculated the limit durability N with relation (3) for a certain hardnesses ratio (H/h) value, and so, the parameter β. Knowing these factors it can be plotted the reliability variation curves, as it is exemplified in Figure 6 for a 0.32C – 0.74(Mn+Si) – 1.84(Cr+Ni+Mo) steel.

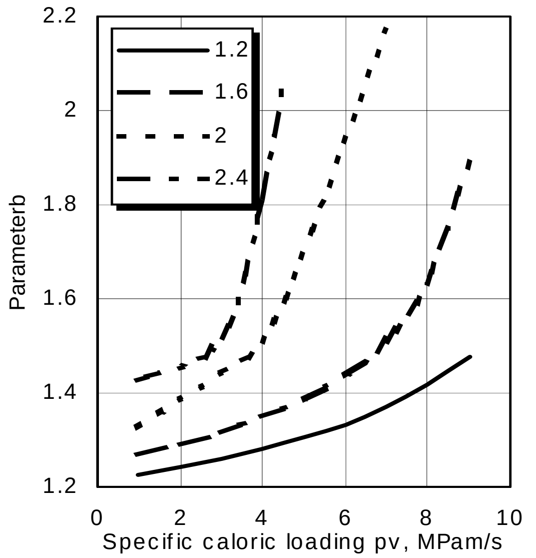

Figure 5: *The dependence between parameter β and the specific caloric loading for different value of the H/h hardnesses ratio and for a 0.32C-0.74(Mn+Si)-1.84(Cr+Ni+Mo) steel.*

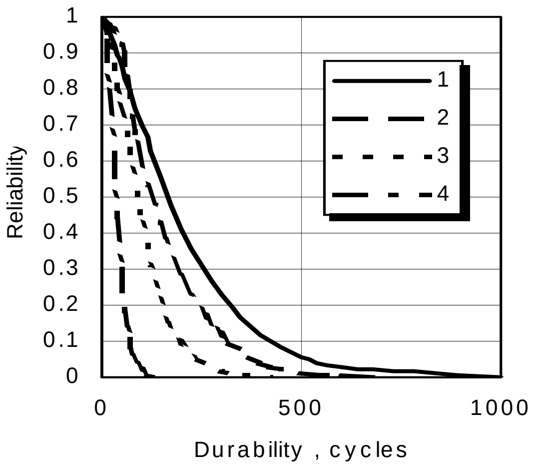

Figure 6: *The reliability vs. the durability for a 0.32C – 0.74(Mn+Si) – 1.84(Cr+Ni+Mo) steel, pv=4 MPam/s, and for different hardnesses ratio (H/h) values: 1-(H/h)=1.2; 2-(H/h)=1.6; 3-(H/h)=2; 4-(H/h)=2.4.*

6. CONCLUSIONS

The design of the brake metallic elements, which are made from low and middle alloy steels, has to take into account a lot of factors, which influence their reliability. Therefore, it has to estimate for every case the reliability as a function of the concrete working conditions. The main conclusions, which can be detached from this paper, are the followings:

- the paper results refer to the low and middle alloy steels which generally are used for the brake metallic elements construction and also for others dry friction couples metallic elements;
- the maximum hardness of the friction surface can be calculated with the relations (1) and (2) as a function of maximum temperature which can stress the metallic element;
- the relation (3) can be used for the limit durability evaluation and also for the determination of the Weibull law parameters;
- the presented results can be used both for design and for exploitation activities of the dry friction couples of the mechanical brakes.

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