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A. C. DRUMEANU, N. N. ANTONESCU

Tribo-Thermal Fatigue and Residual Carrying Capacity Estimation of the Braking Couples Metallic Elements

Wear by tribo-thermal fatigue of the metallic elements from the heavy duty mechanical brakes represents one of the main causes of premature cutting out of action of these, much more before their wear by abrasion to reach the limit value. Due to the variable character of the braking process, metallic materials degradation is produced by cracking, and it has a character similar to that characteristic to low cycle fatigue.

The paper presents an estimation methodology of the residual carrying capacity for the braking couples elements which are made from low and middle alloy steels. This methodology is based on the microstructural transformations that appear inside the metallic elements as a consequence of the temperature variation on the friction surface. This transformations implie the hardness increase of the friction surface ajacent zone. Therefore, the residual carriyng capacity can be estimated during the brake utilization comparing the hardness measurements on metallic elements friction surface with the hardness which characterizes its cutting out of action due to the cracks appearance. The paper results can be used both at the design and the exploitation of the heavy-duty mechanical brakes.

Keywords: *heavy-duty mechanical brakes, tribo-thermal fatige, residual carrying capacity*

1. INTRODUCTION

The starting point of the researches, which are presented in this paper, was the braking couples metallic elements cutting out of action due to the tribo-thermal fatigue.

Tribo-thermal fatigue is a kind of degradation 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].

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 matrials 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 final result is the reach of the fatigue fracture state.

The initiation and the development of the cracks are also favoured 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 [3].

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 carrying capacity of the metallic structure.

C. Drumeanu,
N. N. Antonescu
"Petroleum-Gas" University, Ploiesti, ROMANIA

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Taking into account of the above statements, the paper aim is to develope a methodology which can be used at the estimation of the residual carrying capacity of the braking couples metallic elements. This methodology is based on the researches concerning the operating behaviour of the mechanical band brakes which equip the drilling draw-workses.

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 [3].

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
Cu	0.08 … 0.24
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.

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 [3].

3. EXPERIMENTAL RESULTS

3.1. The regime parameters influence on the friction surface temperature

The temperature value on the friction surface is influenced by the regime parameters i.e. the nominal contact pressure and the sliding speed. It has to do the observation that the friction coefficient influences especially the heating time value.

In Figure 1 is presented the dependence between the temperature on the friction surface and the slidding speed for different contact pressure values [2].

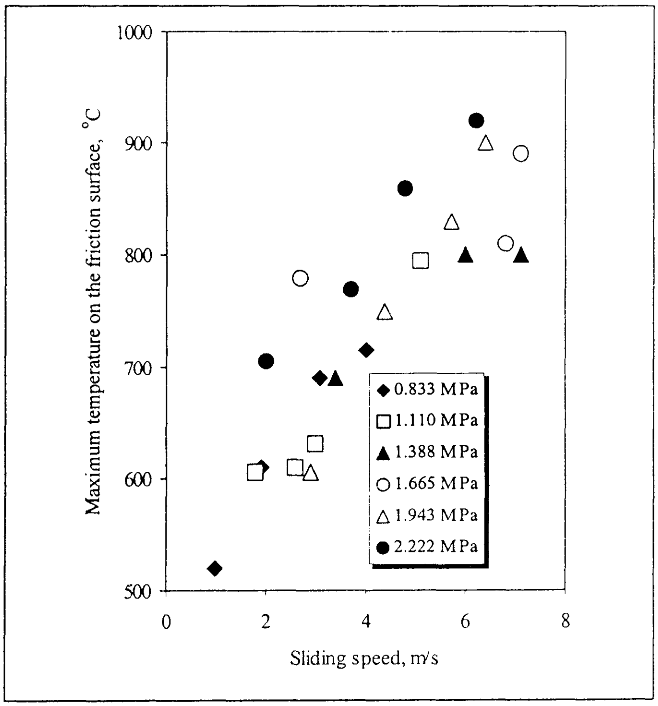

Figure 1. Maximum temperature on the friction surface vs. sliding speed for different contact pressure values

From Figure 1 it can be observed that the maximum temperature on the friction surface increases both with the increase of the sliding speed and of the contact pressure. To emphasize the quantitative influences of these parameters on the friction surface temperature it can be done a multiple regression analysis like [2]:

$$t = a_0 + a_1 \cdot p + a_2 \cdot v \qquad (1)$$

where: t is the temperature value reached on the friction surface, °C; p is the nominal contact presure, MPa; v is the sliding speed, m/s; a_0 , a_1 , a_2 are the coefficients of the regression equation, which charcterize the tested steels series, $a_0 = 419$, $a_1 = 82$, $a_2 = 49$.

The charcteristics of the regression analysis (1) are: the variation range for temperature values reached on the friction surface, t = 500 – 950 °C; the variation range for nominal contact pressure values, p=0.8-2.5 MPa; the variation range for sliding speed values v=0–8.0 m/s; the multiple correlation coefficient value, R = 0.935 ; determination coefficient value , R^2 = =0.874; the experimental data dispersion around the regression surface for a 95 % confidence interval, in the range of ±46 cycles.

About the results of the analysis regression (1), it is remarkably the good correlation between the variables taken into account. This fact proves that the contact pressure and sliding speed have the major weight over the temperature value reached on the friction surface.

3.2. The temperature and heating rate influence on the microstructural transformations and on the friction surface hardness

For the tested steels which were cyclic non-isothermal stressed in conditions as close as posible to those characteristic for the functioning of the band brakes, the heating rates were situated in the range of 40-80 °C/s and the cooling rates in the range of 5-10°C/s. Taking into account these stress conditions, at the analyse of the microstructural state it has to be considered the following aspects [4]:

test pieces heating was done in a quik state, case in which in the transformations that took place there appeared proper particularities;

the maximum temperatures of the stress thermal cycles were situated in the range of 500-800 °C, which included also the values that characterize, for all types of tested steels, the range of intercritic transformation;

the test pieces were submitted, during their heating and cooling, to temperature strains with values in the range of 0.2-1.0 %, and corresponding to thermal stresses in the range of 100-800 MPa.

The microstructural transformations due to the thermal stresses, repeated in the intercritic transformation range, had as a consequence, the tested materials granulation finishing. Therefore, for maximum temperature of 600 °C, the microstructure is made in majority from fine bainite with preponderant ferritic zones. For maximum temperature of 800 °C, the microstructure is much more fine, 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.

3.3. The temperature and friction surface hardening influence on the tribo-thermal fatigue durability

The temperature and friction surface hardening influence on the tribo-thermal fatigue durability are put in evidence in Figure 2.

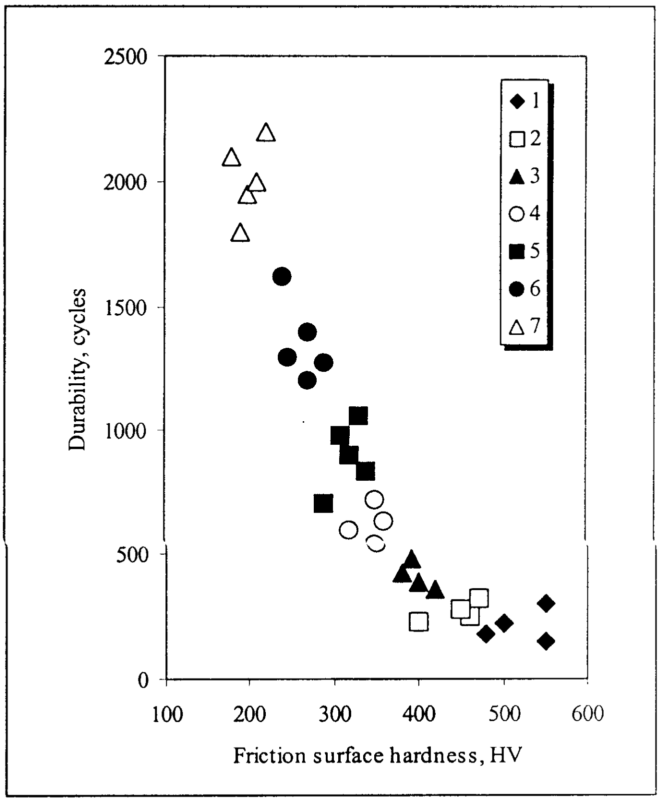

Figure 2. The tribo-thermal fatigue durability vs. the friction surface hardness for different maximum temperature values of the thermal cycle on the friction surface: 1) 800 °C; 2) 750 °C; 3) 700 °C; 4) 650 °C; 5) 600 °C; 6) 600 °C; 7) 550 °C.

From Figure 2 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 1).

For quantitative estimation, in this case, it was done a multiple regression analysis which had the form:

$$N = A \cdot H^b \cdot t^c \qquad (2)$$

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 $A = 1.88 \cdot 10^{17}$, $b = 0.293$, $c = -5.424$.

The characteristics of the regression analysis are: the variation range for durability N = 150-2500 cycles; the variation range for the hardness H = 150-600 HV; the variation range for the maximum temperature of the thermal cycle t = 550-800 °C; the determination coefficient value, $R^2 = 0.973$; the multiple correlation coefficient value, R = 0.986; the experimental data dispersion around the regression surface for a 95 % confidence interval, in the range of ± 70 cycles.

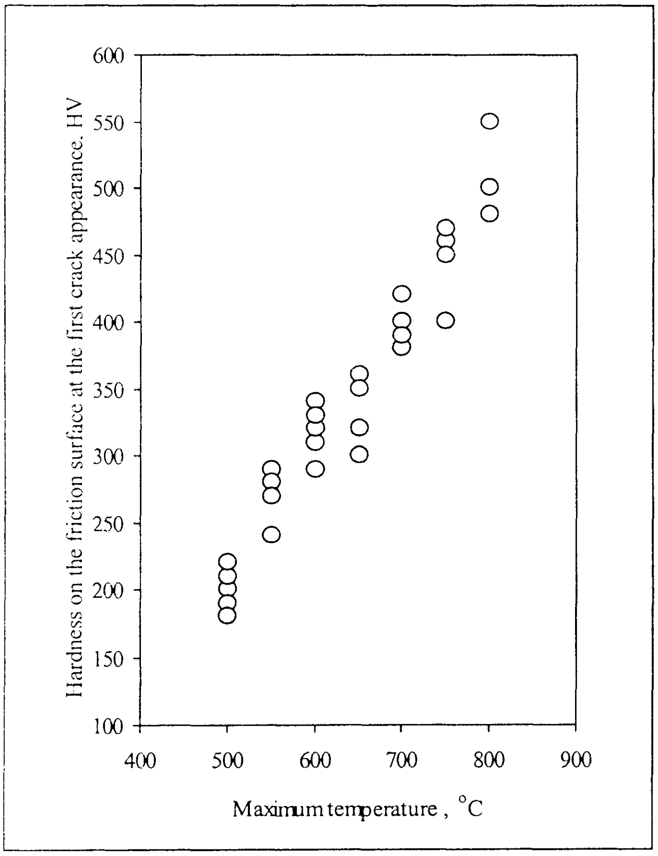

Figure 3. The hardness on the friction surface at the first crack appearance vs. the thermal cycle maximum temperature on the friction surface

The hardening level of the metallic structures which reached the crack degradation state was mainly influenced by the maximum temperature value of the thermal cycle and also by the initial hardness of the friction surface. This fact can be observed in Figure 3 and in Figure 4.

From Figure 3 it can be remarked that the increase of the thermal cycle maximum temperature implies the hardness increase. It has to be done the observation, that the hardness increase is also influenced by the thermal strains and stresses which at their turn for maximum temperature values in the range of 600 – 800 °C reach high values.

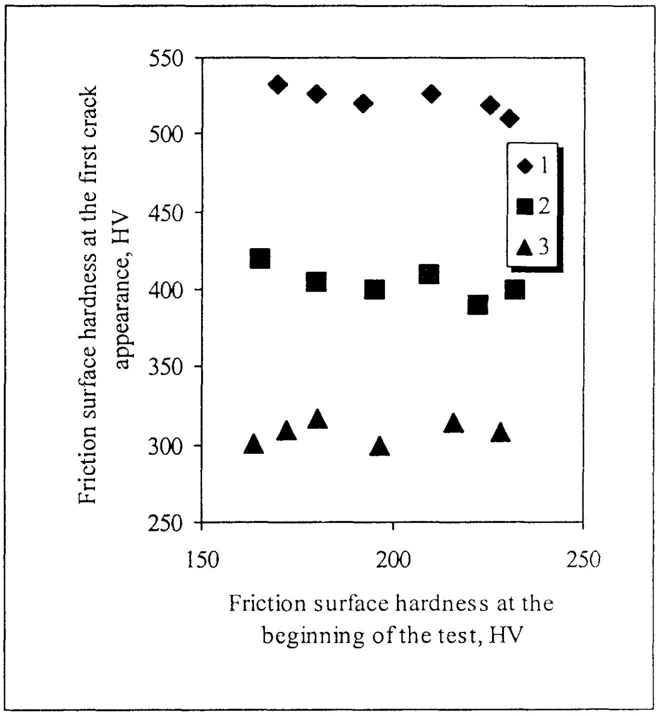

Figure 4: Friction surface hardness at the first crack appearance vs. the initial friction surface hardness and for different maximum temperature values of the thermal cycle: 1) t=800 °C; 2) t=700 °C; 3) t=600 °C.

Using the experimental data which are presented in Figure 3 and 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:

$$H = A \cdot t^b \cdot h^c \qquad (3)$$

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; A, b, c are the regression constants which have the values $A = 0.012$, $b = 1.757$, $c = -0.209$.

The characteristics of the regression analysis (3) are: the variation range for the hardness H = 150-600 HV; the variation range for the maximum temperature of the thermal cycle t = 550-800 °C; the variation range for the initial hardness h = 150 - 250 HV; the determination coefficient value, R^2 = 0.0.896; the multiple correlation coefficient value, R = 0.947; the experimental data dispersion around the regression surface for a 95 % confidence interval, in the range of ± 14 HV.

An important conclusion which results from Figures 3 and 4, and also from eq. (3) is that the tribo-thermal fatigue durability can be associated with a maximum limit of the friction suface hardness which is specific for every maximum temperature value of the stress thermocycle.

4. THE RESIDUAL CARRYING CAPACITY OF THE MIDDLE ALLOY STEELS SUBJECTED TO TRIBO-THERMAL FATIGUE

The carrying capacity of a technical system is the measure of its aptitude to support the prescribed stresses. In the case of its own fault appearance the carrying capacity decreases and is called "residual carrying capacity" (RCC) [5].

In the situation of cyclic non-isothermal stresses which characterize also the tribo-thermal fatigue, RCC can be determined using the hardness values that can be measured on the friction metallic element surface during the mechanical brakes exploitation. The effective safety coeeficient can be calculated with the relation:

$$c = H_d / H \tag{4}$$

where: H is the effective hardness value which characterizes the friction surface after an exploitation time; H_d is the limit hardness corresponding to a certain maximum temperature value of the cycles and to a limit durability of the metallic structure damaged by cracking, which is calculated with equation (3).

In the case of the mechanical brakes each thermal stress is characterized by a maximum temperature value which is different from a thermal cycle to another one. In this case RCC can be calculated with the next cumulation criterion of degradation:

$$RCC = \sum_{i=1}^{r} \frac{H_i}{H_{di}} = \frac{1}{c} \leq \frac{1}{c_a} \leq 1 \tag{5}$$

where: H_i is the partial hardness value which characterizes the friction surface after a number of thermal cycles which take place under maximum temperature $t_{max,i}$; H_{di} is the limit hardness corresponding to cyclic thermal stresses which take place at $t_{max,i}$; $i = 1,2,\ldots, r$ are the number of thermal stress collectives which are characterized by the maximum temperature value $t_{max,i}$; c_a is the admissible safety coefficient which usually in this case can be considered $c_a = 1$.

5. CONCLUSIONS

For mecanical brakes it is important to know the remaining life time of the metallic elements from the point of vue of tribo-thermal fatigue durability. Therefore this paper proposes a calculation methodology for RCC evaluation of this braking elements. This methodology is based on the friction surface hardness evaluation. The main steps which can be done for RCC evaluation are the following:

- for the braking couple metallic element it is determined the maximum temperature value which appears on the friction surface; this value can be directly measured or calculated with the help of the equation (1) when there are known the contact pressure and the sliding speed values;
- the maximum temperature value above determined is used with the initial hardness value at the evaluation, with the help of equqtion (3), of the final hardness which characterizes the cracking degradations of the friction surface;
- the above obtained results can be used at the RCC evaluation with the equation (5).

Another important conclusion is the fact that the metallic structures subjected to tribo-thermal fatigue behave like an "accumulator" of the thermal stresses and strains. Therefore, for the increase of the "accumulator capacity" and in this way, the tribo-thermal fatigue durability, it has to be used metallic materials which are characterized in the initial state by a low hardness.

The paper results refer to braking couple metallic elements which are made from middle alloy steels, and they can be used both in the exploitation and in the design of the heavy-duty mechanical brakes.

REFERENCES

[1.] Antonescu, N.N., Drumeanu, A.C., Nae, I., Some Aspects Concerning Wear by Thermal Fatigue of Some Steels Used to Dry Friction Couples Construction, 10th International Colloquium, 09-11 Jan.,1996, Esslingen: 899-908

[2.] Drumeanu, A.C., Antonescu, N.N., Wear by Thermal Fatigue of the Metallic Elements from the Mechanical Brakes, 11th International Colloquium, 13-15 Jan., 1998, Esslingen: 1927-1934

[3.] Drumeanu, A.C., Antonescu, N.N., Tribo-Thermal Fatigue Testing Device, 12th International Colloquium, 11-13 Jan., 2000, Esslingen: 2035-2044

[4.] Antonescu, N.N., Drumeanu, A.C., Nae, I., Temperature and hearing rate influence on microstructural transformations of some steels used to dry friction couplers construction, 2nd International Conference on Tribology, Balkantrib'96, 5-7 June, 1996, Thessaloniki, Greece: 273-280

[5.] Drumeanu, A.C., Antonescu, N.N., The Influence of Wear by Thermal Fatigue on the Safety in Operation of the Dry Friction Couplers, 11th International Colloquium, 13-15 Jan., 1998, Esslingen: 1899-1906.