Study on the deterioration origin of thermomechanical contact fatigue

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Abstract. Thermomechanical wear is a complex phenomenon present in a number of industrial domains, such as rolling bearings, gears, friction wheels, rolling mill rollers. In this type of surface tribological deterioration, both fundamental and some peculiar wears are combined (abrasive, adhesive, corrosive wear and contact fatigue), with mechanical ant thermal causes. The present paper takes into account the contact fatigue type of deterioration, with both causes in mechanical variable load and the thermal tide action on the contact surface. There are some theories synthetically presented regarding the location of critical stresses in rolling contact fatigue. The Jacq thermal effect is briefly presented with some considerations concerning the temperature gradient in the metallic wall. The connection between the Jacq thermal anomaly and the thermomechanical contact fatigue is considered to be a new approach. Also, the same location for both mechanical and thermal critical stresses gives a strong support for the thermomechanical contact fatigue primary deterioration, according to the results obtained during the author's PhD research.

1. Introduction

Some industrial fields of activities have in common rolling contacts with or without lubrication. Under a normal mechanical load on the contact surface and after a significant number of solicitation cycles, the mechanical contact wear is present. Many applications in industrial activities are carried out with heat release.

In the rolling contacts, under thermal tide, the heat transfer from the warmer to the colder parts takes place during the technological process, which induces thermal stresses in or under the contact surfaces. When the two kinds of loads are present (mechanical and thermal) at the same time on a contact surface, a global thermomechanical contact wear will result, as a complex type of deterioration [1].

For the rolling linear contacts with a small slide, without an imposed lubrication (dry contact), under an important thermomechanical contact load, the decisive type of deterioration is thermomechanical wear. It's an atypical and complex competition of different types of wears (abrasive, adhesive, corrosive wears and contact fatigue), with mechanical and thermal causes, combined with some peculiar wears, resulting in the destruction of the corrugated contact layer [1].

Under certain work conditions [2], the decisive destruction phenomenon for the contact layer is thermomechanical fatigue. It's a complex mechanism of deterioration of the contact layer under a combined load, the two contact surfaces rolling with a small sliding one upon the other.

Thermomechanical fatigue has also a combined cause, as a result of mechanical load, rolling movement and thermal tide at the level of the contact surfaces.

The deterioration mechanism in thermomechanical contact fatigue is usually studied separately, determined by each cause in part.

2. The location of critical stresses in rolling contact mechanical fatigue

The technical literature concerning the rolling linear contact under mechanical load presents two different locations related to the contact surface for the decisive mechanical stresses in contact fatigue. In [3], different types of critical stresses are presented, which can be classified in two groups regarding their location; some are located on the contact surface and other in the contact subsurface, at different depth levels.

In a short presentation, the maximum normal stress is localized on the contact surface (σ_0, σ_{max}) by McKelvey, Mayer and Neifert, the maximum tangential stress (τ_{45D}), with two points of view, S.V. Pineghin with $\tau_{45(xy)sb}$ and Foord, Hingley, Cameron and Cioclov with $\tau_{45D(xy)sa}$, where "sa" and "sb" indexes indicate the position of the stresses on the contact ellipse; also, the traction normal stress σ_{yt} it's mentioned by Moyar, Morrow and Pineghin [3].

On a certain depth under the contact surface (z_0), the tangential orthogonal maxim stress (τ_0) can be observed, taken into account by Lundberg and Palmgren [3] as maximum for τ_{yz} localized under the contact surface at the depth of z_0 and the critical tangential stress (τ_c) are mentioned by Ollerton, Morey, Stullen and Cummings [3] as:

$$\tau_c = \tau_{yz} + k_c \cdot \sigma_n \text{ , with } \tau_{yz} = \tau_0 \qquad (1)$$

$$\sigma_n = max(\sigma_x, \sigma_y, \sigma_z) \qquad (2)$$

and k_c with values determined by number of load cycles.

In [4] Popinceanu, Diaconescu and Crețu developed an equivalent critical stress (σ_{ED}), located under the contact surface, by using in their approach an equivalent stress known as Huber-Misses-Heuckey, as follows:

$$\sigma_{E(\lambda)} = \frac{1}{2}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\lambda^2(\tau_{xy}^2 - \tau_{yz}^2) + 6\tau_{xy}^2\right]^{1/2} \qquad (3)$$

In (3) λ is the ratio value of different fatigue stress limits from the normative concerning the material's strength limits and according to the type of variable solicitation.

The equivalent critical stress (σ_{ED}) has the possibility to evaluate a complex load situation as the one that determines the thermomechanical contact fatigue with both thermal and mechanical originating cause components.

The hypothesis, that buy using as decisive stresses σ_0, τ_{45D} and σ_{yt}, with maximum values on the contact surface, gives no explanation for the origin of the destructions under the contact surface, fact that is fulfilled by the hypothesis with τ_0, τ_c and $\sigma_{ED(\lambda)}$. The equivalent stress $\sigma_{ED(\lambda)}$ have an enough high value also on the contact surface and give a global explanation for destruction origin points both on and under contact surface.

3. The influence of Jacq thermal anomaly on thermomechanical contact fatigue

At The Heat Transfer Congress in Paris in 1961, the French researcher J. Jacq presented some experimental tests regarding an anomaly in heat thermal conduction [5],[6]. The experimental results show that in a metal wall the thermal field is different than the theoretical thermal field given by the Fourier law for a certain λ conductivity equal in the entire structure of the metal wall (figures 1 and 2).

The temperature distribution within the structure of the metal wall is different in these two approaches; one of the consequences of this anomaly in heat thermal conduction is linked to the position of thermal fatigue origin point.

Taking into account the calculation equations for thermal stresses into a cylinder, as shown in figure 3, with two different temperature values on the inner and outer surfaces (T_1 and T_2), one may observe that the stresses value are in connection with $\Delta T = T_1 - T_2$ (see equations 4 and 5).
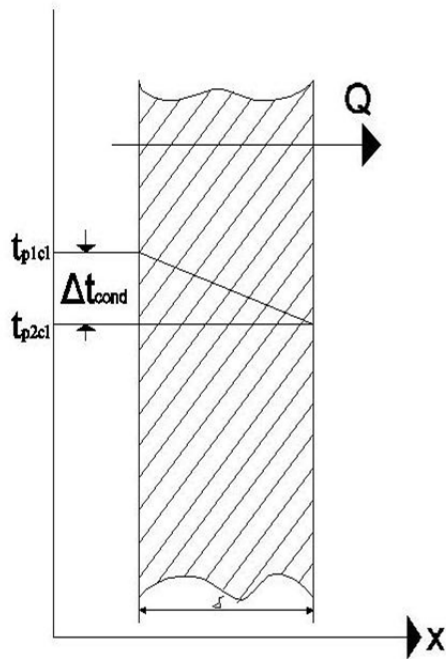

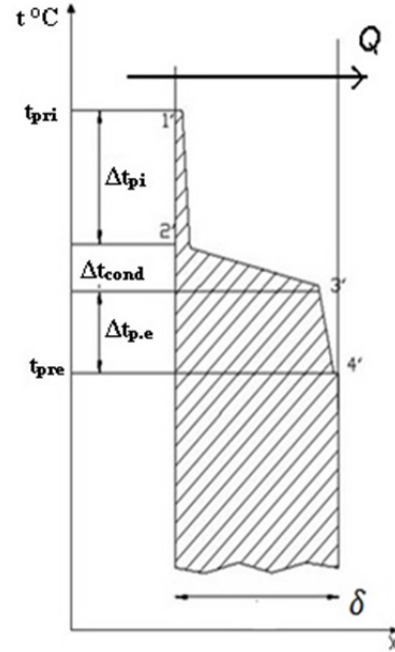**Figure 1**. Theoretical thermal field aspect through a metallic wall (classical theory).

Figure 2. Real thermal field aspect through a metallic wall in the case of Jacq thermal anomaly

In figures 1 and 2 [6] the notifications have the follow meanings:
- tpcl is the classic temperature for the wall after Fourier law;
- Δt_{cond} is the thermic fall in conduction transfer (classic).
- tpri is the real temperature distribution for the wall taking into account the Jacq thermal effect (enterance);
- tpre is the real temperature distribution for the wall taking into account the Jacq thermal effect (exit);
- Δt_{pi} is the thermic fall in the entrance wall, according to the Jacq effect;
- Δt_{pe} is the thermic fall in the exit wall, according to the Jacq effect;
- $\Delta t_j = t_{pi} + t_{pe}$, is the thermic fall after Jacq effect;

Consider a test cylinder with the inner radius R1 and outer radius R_2, with variable temperature only variable depending on radius and time T(r,t). At the beginning, the cylinder overall temperature equals zero and after the time t = 0, the cylinder gets introduced into two environments: outside the cylinder, with the temperature T_1 and inside the cylinder, with the temperature T_2 (figure 3 and equations 4 and 5).
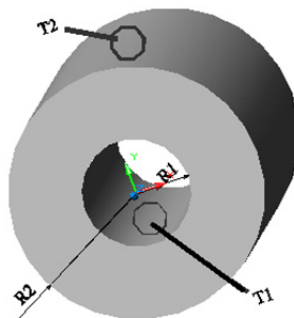

Figure 3. Test cylinder

$$\sigma_{rr} = \frac{E\alpha}{2(1-\mu)}\left(1 - \frac{R_1^2}{r^2}\right)[T(R_2, t) - T(r, t)] \tag{4}$$

$$\sigma_{\phi\phi} = \frac{E\alpha}{2(1-\mu)}\left(1 - \frac{R_1^2}{r^2}\right)\left[T(R_2, t) + \left(1 - \frac{R_1^2}{r^2}\right)T(r, t) - 2T(r, t)\right] \tag{5}$$

In (4) and (5), T(r,t) is the average cylinder temperature in regard to the radius r [1].

The considerable decrease of temperature in a very thin layer induces a significant stress value at that level. It's important to notice that the increase in the thermal stress value is located very near the surface at a certain depth, which can be the same as the z_0 value, as in the Lundberg and Palmgren tangential orthogonal maximum stress τ_0 [4].

This slope change for the temperature variation in a very thin layer under the contact surface, locates a higher value for the thermal stress; this takes place at an approximately same level of the decisive stress in mechanical contact fatigue.

This common position at the approximately same level for the two kinds of cylindrical stresses, with mechanical and thermal causes, determines an equivalent higher stress σ_{EDMT} [1] as the initial cause for very small cracks.

In this supplementary loaded position, located very near under the contact surface, conditions are created for the emergence of small dislocations in the overall structure, presented as small fractures or cracks that will eventually evolve to cover the entire surface.

According to Trozzi and Barbadillo [7], the initial deterioration and its progress in time of rolling mill rollers is illustrated in figure 4.
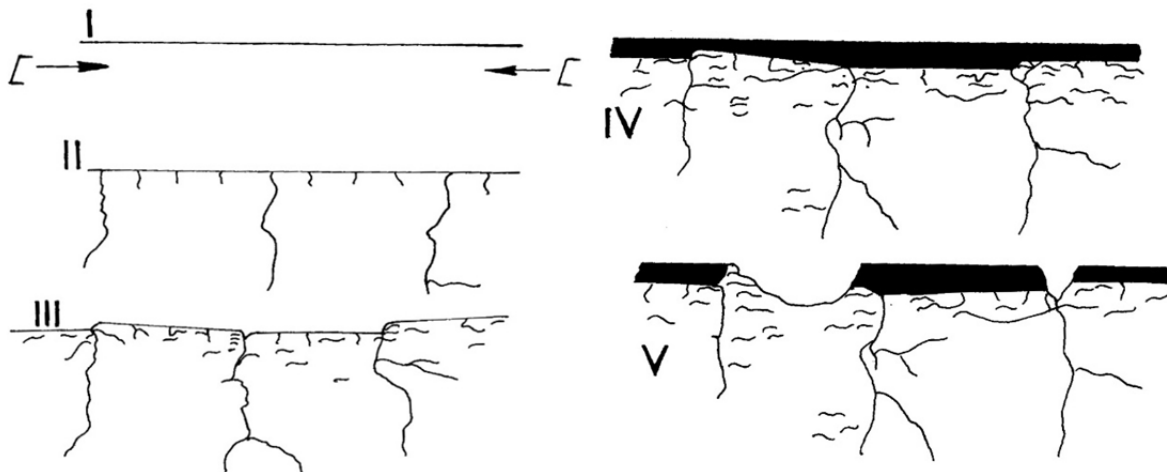

Figure 4. The five stages of destruction during thermomechanical contact fatigue [7]

Stage I – The region below the contact surface has a biaxial compressive residual stress;

Stage II – The formation of cracks (fissures) totally changes the tension characteristics during the running cycle stages. Tensions induced by pressure roller become more important as the surface is no longer constrained by the roller mass. The smaller cracks are the effect of the Jacq anomaly in thermal conduction, due to the increase of thermal stress values at that depth. During this stage, both thermal and mechanical deteriorations occur;

Stage III – Roller surface becomes progressively more irregular due to a variety of damaging forces. Inner cracks push upwards the contact surface, producing pitting and bumps.

Stage IV – The work surface is covered quickly by a shiny black oxide layer. Cracks continue to form and to bond together until only an external mechanical force can keep all surface areas together.

Stage V – It begins when the pieces of the oxidized surface are displaced; final destruction of the rolling mill occurs [7].

4. Manifestation of thermomechanical contact fatigue types

An experimental research made on several cylindrical samples [1], rolling under a normal load and in a thermal field (the two contact surfaces were at different temperatures) shows some areas of destruction characterized as small points of dislocation in the surface structure (figures 5 and 6).
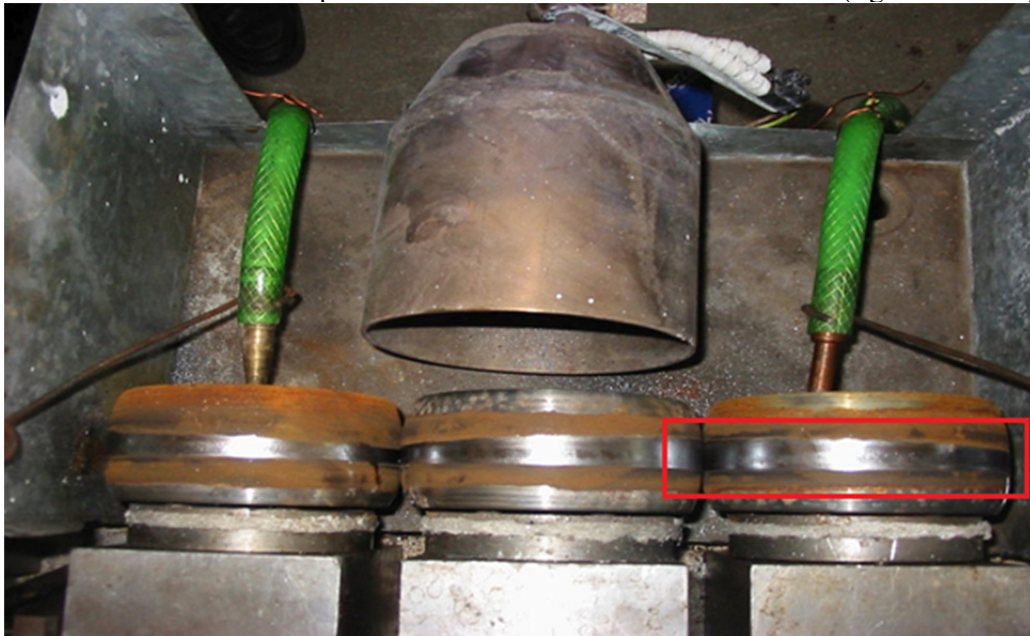

Figure 5. Areas of destruction characterized as small points of dislocation (pitting) on the surface structure during test phase (highlighted)

Figure 6. Same previously highlighted rolling mill with points of dislocation on the surface during test phase (enlarged)

5. Conclusions

The present paper describes a new approach on thermomechanical contact fatigue taking into account the same locations of the critical stresses for both mechanical load and thermal tide on the same contact surface. The existence of the Jacq thermal anomaly in heat conduction through the metal structure gives a possible explanation for the location of a significant thermal stress in the contact subsurface. If the two critical stresses, with both thermal and mechanical origins, have their maximum values at close depth, their combination as an equivalent stress [1] will determine the primary deterioration, provided a variable thermomechanical solicitation for a rolling contact exists. The form of primary contact fatigue destruction of the solicited surface is a field of small cracks in the material structure, as an incipient pitting phenomenon (figures 5 and 6). The present paper represents part of an extensive study, materialized in a PhD thesis [8], that for the first time ties the Jacq thermal anomaly to the thermomechanical contact fatigue.

6. References

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