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Evaluation of the fretting wear damage on crowned splined couplings

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Abstract

Splined couplings are widely used in many industrial fields and one of the most problematic failure mode of these components is fretting wear. Fretting wear appears because of the relative motions between teeth and it is mainly due to angular misalignments. Aim of this paper is to set up a procedure in order to identify the entity of the fretting wear damage in crowned splined couplings in real working conditions. The first Ruiz parameter has been chosen to quantify the wear damage being relatively easy to be obtained from the calculation point of view. Experimental tests have been performed by means of a dedicated test rig to validate the theoretical results, in terms of iso-Ruiz maps. The damage entity has also been quantified by measuring the angular rotation before and after each test. Obtained results confirm that, where the fretting map shows higher values of the Ruiz parameter, the fretting damage becomes more important.

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Keywords: spline coupling; test rig; fretting; misalignment; Ruiz parameter

1. Introduction

At the beginning of the last century, the increase in machine performance has led to the evidence of new damage events or premature failure in components, due to the phenomenon generally referred as fatigue.

Similarly, in recent decades, the progresses in technology have led to further improvements in machine performance in terms of power, dynamic behavior and weight reduction but, on the other hand, they have led to the arising of new types of damage, in particular the damaging phenomenon known as fretting (Waterhouse (1992)).

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Generally, the first failures due to fatigue were difficult to interpret and only in-depth studies of this phenomenon, from the beginning until now, led to its in-depth understanding and to the formulation of related laws describing the evolution of damage. This approach allowed to the creation of more or less complex design criteria.

In the same way, nowadays the fretting is a phenomenon not easy to understand and to quantify, which creates big problems to producers and users of machines in general, in many industrial sectors (aerospace, rail, automotive, biomedical, etc.) (Waterhouse (1992)).

Currently robust design criteria that may be applied to components to predict fretting damage are not available. Nevertheless, design criteria are necessarily needed in order to check components about this phenomenon, avoiding the formation of this type of damage or at least to keep it under control. Being able to formulate standardized procedures for fretting verification at the design phase would also result in a reduction of costs (caused by the need to replace worn components).

For these reasons, in recent years an increasing interest for the study of fretting phenomena is growing up, with regard to both scientific community and industrial world.

Fretting appears when two bodies in contact, pressed by a force, undergo small displacements (often due to vibrations, but not only ...), and this friction leads to the rise of damage (Waterhouse (1992)). It may be divided into two categories: fretting wear and fretting fatigue. Due to the great need of industry to prevent fretting damage in each of its aspects, it has been widely studied for more than twenty years (Waterhouse (1992), Vincent et al. (1992), Shinde et al. (2005)).

Thanks to the fretting mapping approach described by Zhou et al. (2006), both fretting wear and fretting fatigue are now recognized to be at the origin of the two main mechanisms of damage, in particular wear being associated with particle detachment and crack nucleation and propagation, which can lead to failure of parts. Palliatives have been analyzed both theoretically and experimentally by Vincent et al. (2002); soft and hard coatings were shown to be possible palliatives, depending on the tribosystem.

Even if some understanding nowadays exists to explain why a coating can prevent or diminish fretting damage, it is still very difficult to propose guidelines for material or coating selection and to predict and quantify wear and cracking.

Fretting resistance cannot be considered as an intrinsic property of a material, or even of a material couple. Recognizing that fretting can induce material loss (wear) or deep cracking, it is obvious that these two types of damage cannot be interpreted in terms of the same properties of the bodies. Wear induced by cracking is clearly identified as the response of materials to global overstraining of the surface, while cracking induced by fretting usually appears as the consequence of local overstressing (Vincent et al. (1993)). These two kinds of loading (overstraining and overstressing) can appear in a vibrational contact.

For instance, depending on the amplitude of the displacement or on the normal load entity, the fretting conditions can be partial slip or gross slip. These two situations do not induce the same local loading of the surface. Moreover, depending on the amplitude of the displacement, the environmental atmosphere may be suspected of having a different effect.

Fretting damage in both its types is very tricky and dangerous, as components that are statically and fatigue verified or even oversized may have the onset of fretting that, once triggered, is a degenerative process that leads to the failure of the component. Furthermore, fretting is influenced by the complex interaction of many parameters that must be accounted and the unification of these is critical.

It is clear that contact slip induces surface damage (Medina et al. (2002)). One key barrier to be overcome in the solution of the fretting problem is the determination of the relative significances of both stress gradient effects and surface damage effects.

There are a lot of models that may predict the fretting fatigue, like the Smith-Watson-Topper (SWT) parameter (Smith et al. (1970)), Fatemi and Socie approach (Fatemi et al. (1988)), the method proposed by Madge, Leen and Shipway (Madge et al. (2008)) and the second Ruiz parameter (Ruiz et al. (1984)), while for predicting the presence of fretting wear the most known is the first Ruiz parameter (Ruiz et al. (1984)).

In any case, the general difficulty of formulating a quantitative model for fretting damage does not allow to date the availability of robust verification procedures for simplified models of contact. Things are even more complicated considering components with complex geometries, as splined couplings (Curà et al. (2012)). These components are widely used in many industrial fields and one of the most problematic failure mode of these components is fretting wear.

In this work the study is focused on fretting wear damage (Waterhouse (1992)), appearing on splined couplings because of the relative motions between teeth, mainly due to angular misalignments of these components.

Aim of this work is to set up a procedure in order to quantify the entity of the fretting wear damage in crowned splined couplings subjected to experimental tests reproducing the real working conditions.

To do that, a general parameter, the first Ruiz one (Ruiz et al. (1984)), has been identified to characterize the most critical areas on the component teeth subjected to fretting wear.

The first Ruiz parameter R1 has been chosen Ruiz et al. (1984) being relatively easy to be calculated by considering both geometry and working conditions of the component.

In particular, it is expressed as a function of the magnitude of the coefficient of friction (COF), the contact pressure and the contact slip.

Experimental tests performed in this work are able to take into account the effect of transmitted torque, angular misalignment and lubrication condition, so reproducing the real working conditions, above all in aerospace applications. A mechanical parameter, the variation of the angular rotation (Cuffaro et al. (2014)), has been also taken into account to identify the fretting damage affecting the splined couplings after the wear test. This last parameter may provide some indications about the global entity of damage, while the R_1 parameter gives a corresponding local value referred to the interested area.

Nomenclature

R_1	First Ruiz Parameter [N/mm]
τ	Surface shear traction [MPa]
δ	Relative slip amplitude between the two surfaces in contact [mm]

2. Analytical model for the fretting wear estimation

The first Ruiz parameter R_1 (Ruiz et al. (1984)) is considered in the present work for the practical case of splined couplings for its emphasis about the slip amplitude as a key variable on fretting wear. It corresponds to the frictional work expended during a fretting cycle, being expressed as follows:

$$R_1 = \tau \cdot \delta \tag{1}$$

where is the surface shear traction (that is the multiplication between the COF μ and the pressure of the contact points P) and δ is the relative slip amplitude between the two surfaces.

To obtain R_1, the contact pressure P between the engaging teeth and the relative displacements δ have been calculated.

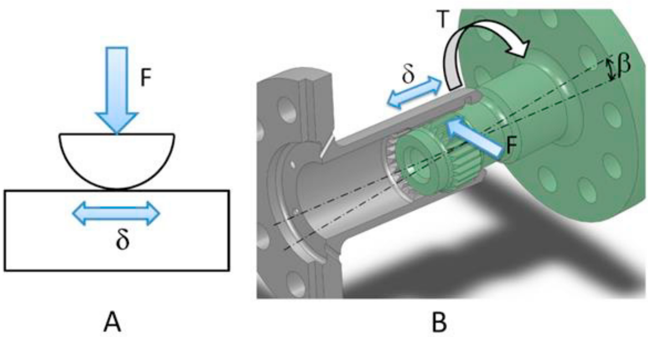

Fig. 1. contact parameters in a simplified model (A) and in a misaligned crowned spline coupling (B).

A basic example of contact pressure (force F) and relative displacement δ is represented in Figure 1 A.

In crowned splined couplings the pressure distribution is generated by the transmitted torque T, that is balanced by a contact force F acting on each tooth (see Figure 1 B); as already pointed out, the contact between crowned splined couplings teeth may be considered as an Hertzian contact and the relative pressure distribution may be calculated by the classical equations.

Pressure distribution depends on both contact geometry and load conditions, while the relative displacement, involving the misalignment components, may be calculated by means of kinematical considerations.

Concerning the coefficient of friction (COF) of the contact surfaces, it has been chosen according to the literature (Shen et al. (2013)). Ruiz parameter R_1 has been here calculated along both spline axial direction (x-axis) and transverse tooth involute (y-axis).

3. Experimental set up

The experimental procedure consists of a wear tests campaign to produce fretting damage on splined couplings teeth. Before and after each wear test, the angular rotation between shaft and hub has been determined by a measuring device.

Wear tests have been performed by means of a dedicated spline coupling test rig (Figure 2) (Cuffaro et al. (2014)).The test rig operates on a torque-regenerative principle in which torque is circulated in a loop; this allows low energy consumption to load the components with a constant torque up to 5000Nm and a maximum rotating velocity of 2000 rpm (Cuffaro et al. (2014)).

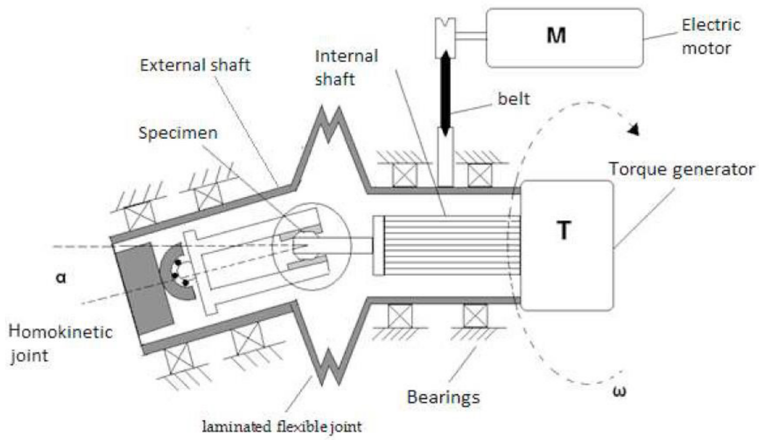

Fig. 2. schematic layout of the test rig, Cuffaro et al. (2014).

Fig. 3. spline coupling used for wear tests.

Wear tests (object of the work) have been performed on steel made test articles (42CrMo4) nitrogen-hardened, represented in Figure 3 (26 teeth, 1.27mm modulus, 12.5mm teeth width, 160mm crowning radius).

Table 1. tests parameters.

Test	Torque [Nm]	Speed [rpm]	Misalignment [‘]	Lubrication	Number of cycles
MB1	700	1500	0	YES	10M
MB2	700	1500	5	YES	10M
MB3	700	1500	10	YES	10M
MB4	700	1500	10	NO	10M
MB5	1000	1500	0	YES	10M
MB6	1000	1500	5	YES	10M
MB7	1000	1500	10	YES	10M
MB8	1300	1500	0	YES	10M
MB9	1300	1500	5	YES	10M
MB10	1300	1500	10	YES	10M

Ten tests have been performed by varying misalignment angle, applied torque and lubrication conditions, in order to investigate the influence of all factors on fretting wear.

Table 1 resumes the working parameters set on the test rig for each test. In particular, the first column reports the test identification, the second and third ones respectively torque and speed values, the fourth column refers to the misalignment angle, the fifth one indicates the lubrication condition, in the last one is reported the total number of cycles. Each test lasts in five days and totally all test have been taking about two months and half to be concluded.

Another important consideration is that all teeth of the specimen have worked, during a test, in the same condition; in this way, to the damage characterization, the results related to all teeth have been taken into account for each test.

4. Results

The teeth surfaces have been analyzed and the damaged zones have been compared with the analytical Ruiz model results. Figure 4 shows the teeth surface of all tests performed with lubrication active; wear phenomena are evident on the contact surfaces, visible approximately at the middle point of the teeth width.

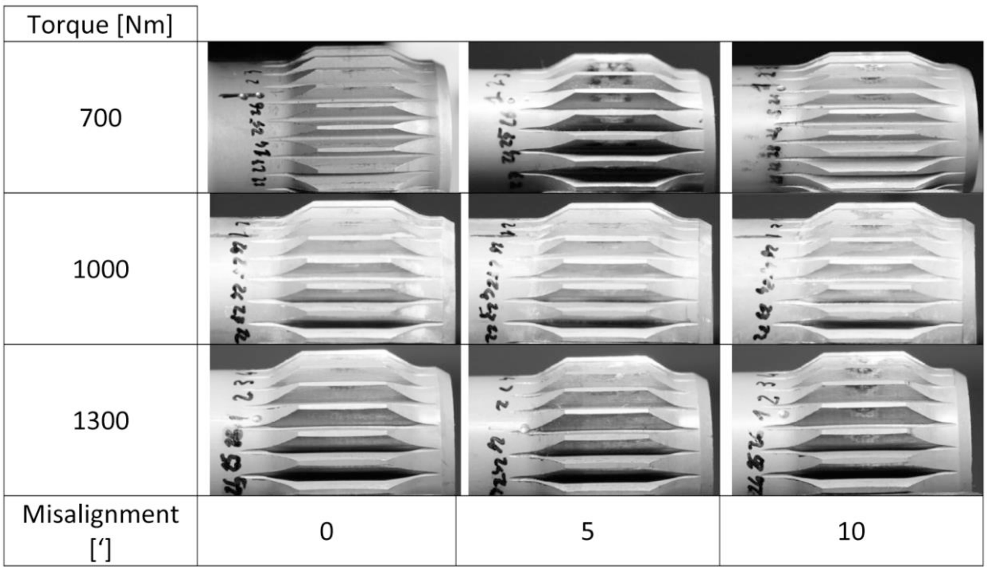

Fig. 4 spline coupling after wear tests.

In particular, the right column of Figure 4 shows the highest level of wear damage (10’ misalignment), the central column shows specimens after tests performed with 5’ misalignment and the left column represents tests performed without misalignment (in these last cases no wear damage has been detected on the teeth surfaces).

Figure 5 reports the Ruiz model maps (second column) of four test cases (first column, a, b, c, d), respectively MB3 (Figure 5a), MB7 (Figure 5b), MB10 (Figure 5c) and MB4 (Figure 5d); in the third column the Ruiz model maps have been superimposed to the corresponding damaged zone of the splined coupling tooth taken into account.

In particular, abscissa and ordinate axis (second column) represent the Ruiz parameter values for x and y dimensions of the contact area.

The analytical Ruiz maps provide concentric elliptic curves representing iso-damage conditions, decreasing from the centre to the edge of the contact area in terms of first Ruiz parameter values.

For as concerns the experimental wear tests, it is possible to observe that the damaging effect is substantially caused by the angular misalignment and by the corresponding sliding during the tests. As a matter of fact, when a sliding is present, the damaging phenomenon becomes evident and increases by increasing the angular misalignment.

The wear area shows approximately an elliptic shape, due to the crowned geometry of the tooth, providing a contact phenomenon well represented by the Hertz theory, as already observed.

Also the lubrication has a very important role, as emphasized from the comparison between Figure 5a and Figure 5d (images of damaged areas)

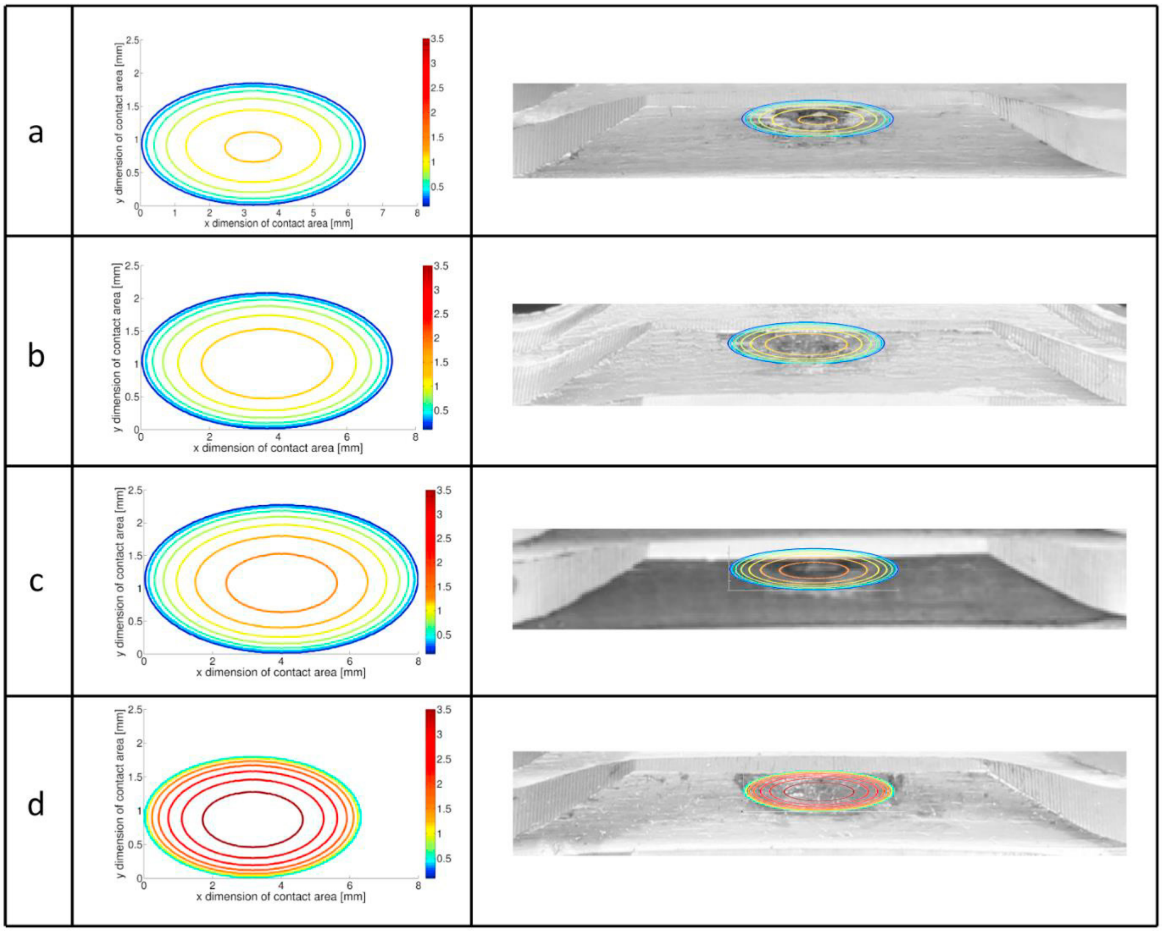

Fig. 5 Ruiz maps overlapped on the components a) test MB3, b) test MB7, c) test MB10, d) test MB4.

Finally, to perform a more deep investigation about the parameters affecting fretting damage, some simulations about analytical models have been done. In particular, in Figure 6 the trend of the maximum first Ruiz parameter R_1 calculated as a function of both applied torque and angular misalignment is shown. In the same Figure R_1 values corresponding to the experimental conditions are also be emphasized by symbols (■, □, ●, ○, ▲, Δ), together with some images related to the highest misalignments test conditions (■, ●, ▲).

The effect of all test parameters (angular misalignment, transmitted torque and lubrication condition) may also be observed by measuring the angular rotation due to the gap between teeth before and after each test; this damage index is representative of the global amount of loss material due to the wear phenomena.

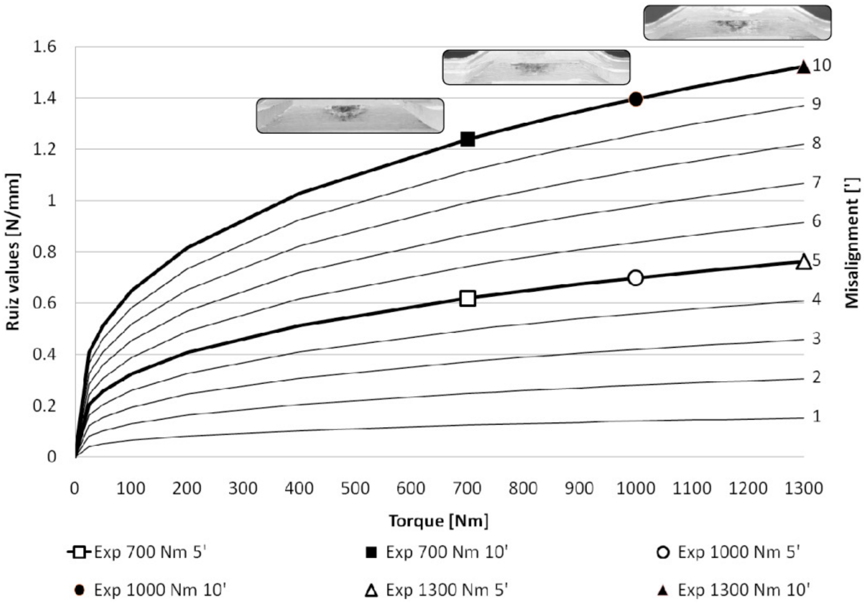

Fig. 6 maximum Ruiz parameter vs torque and misalignment angle.

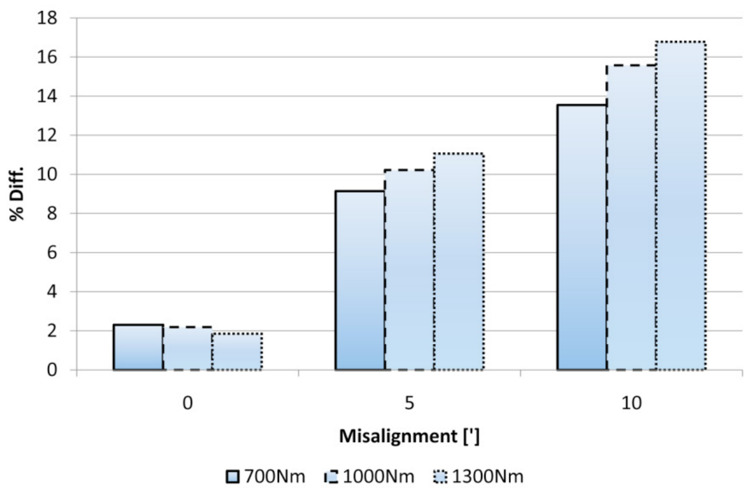

Fig. 7 variation of angular rotation before and after tests.

Figure 7 shows the difference between the angular rotation before and after each test; it is possible to observe that the angular rotation variation increases by increasing the angular misalignment (Cuffaro et al. (2014)), also in the case of crowned splined couplings object of the present paper.

5. Conclusions

In this work, a theoretical and experimental study about fretting wear damage in a practical case consisting with crowned splined couplings working in misaligned conditions has been carried on.

In particular, a methodology for fretting wear damage identification has been developed and verified.

For damage characterization, the first Ruiz parameter has been chosen, due to the possibility to easily calculate the referring quantities: coefficient of friction, contact pressure and contact slip.

Wear damage results have been represented in terms of iso-Ruiz maps.

Experimental tests have been performed by means of a dedicated test rig on specimens (representative of the real components) working in misaligned conditions; the effect of angular misalignment, torque values and lubrication condition have been analyzed.

The comparison between experimental tests and theoretical iso-Ruiz maps appears very promising.

Firstly, results show how the wear damage is more important where the corresponding Ruiz parameter value is higher. This is evident by observing both images of damaged teeth and Ruiz maps with color representation.

Furthermore, the wear phenomenon produced by tests causes damaged elliptical zones well described by both theoretical (Hertzian) and kinematic (due to the related movement) models. In other words, the iso-Ruiz maps well match with the real images of the damaged teeth, above all in the cases of maximum angular displacement, with or without lubrication.

On the basis of the previous described results, it is possible to conclude that the theoretical model based on the Ruiz parameter may be used to predict the attitude of a crowned spline coupling to be affected by fretting wear damage during its real working conditions.

Then, from the global point of view, the damage entity has been quantified by measuring the angular rotation before and after each test. It is possible to observe that the angular rotation variation increases by increasing both angular misalignment and torque value, showing a damage evolution when the working conditions become more severe.

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