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Recent Advances in Spline Couplings Reliability

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Abstract

Spline couplings are mechanical components widely used to transmit torque between rotating parts. Although they are well known components, critical issues such as wear damage and un haven loads affect them especially when working in misaligned conditions. Wear damage appears on engaging teeth bringing to component failures. The main way to reduce wear damage is to lubricate the engaging teeth or to apply surface coatings. In this work wear damage on spline coupling was investigated and a compound made of grease added with graphene has been tested against standard lubricants in order to find out if it may improve the wear strength of these components. Experimental tests were performed by means of both standard testing machine provided by a particular testing device and dedicated test rig, designed to perform tests with misaligned spline couplings.
Preliminary results show that the presence of graphene improves the grease performance, reducing the coefficient of friction (bringing to a reduction of uneven overloads and wear).

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Keywords: spline couplings; wear; lubrication; graphene.

1. Introduction

Spline couplings are widely used to transmit torque between two rotating parts, a shaft and a hub. Although they are well known components, critical issues such as wear damage and un haven loads affect them especially when working in misaligned conditions.

The traditional spline couplings design methods, as Dudley (1957), Niemann et al. (2006), DIN 5466-1 Standard (2000), DIN 5480-1 Standard (2006), allow to perform static and fatigue dimensioning, but do not take properly into account the effect of wear.

Above all in high power transmissions, spline couplings have to be carefully designed due to the necessity to a weight reduction and a consequent increasing of machine efficiency. So, the most interesting question is: how do

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splines fail? Spline couplings are not critical in terms of fatigue behavior, while the wear damage and some other surface damage phenomena, as those classified in ANSI/AGMA 1010-F14 (2014) for gears, are particularly dangerous, bringing to component failures.

Wear damage in these components is often related to fretting caused by the relative movements between engaging teeth, due to the kinematic coupling (for example angular misalignments or vibrations), or by the teeth deformation caused by not constant loads.

The causes of spline wear, in its most general meaning, were discussed in detail by Ratsimba et al. (2004). They can be summarized as an inability of the coupling to adequately accommodate misalignment, a difficulty in maintaining sufficient lubrication, and a basic susceptibility to the process of fretting. Then, there is some motion between teeth which makes them vulnerable to wear.

A very interesting study related to the application of spline couplings used in modern wind turbine gearboxes to connect planetary and helical gear stages has been carried on by Guo and al. (2013); through the developed model, a greater understanding of the behavior of spline connections has been achieved and recommendations to improve design standards have been provided.

Some experimental studies were carried on by Curà et al. (2013, 2017) about spline couplings in order to focus these problems and to analyze the causes of wear in different working environments (aerospace and industrial transmissions).

On the basis of the previous experience on that topic it may be concluded, once both geometry and material characteristics were optimized, that the main way to reduce the wear damage is to well lubricate the engaging teeth or to apply surface coatings.

The first aim of this paper is to resume some experimental results in order to provide and to identify the most common types of failure that may be found in spline couplings for aerospace applications, where high power density is required. To do that, some fatigue tests were carried on by means of a special device connected to a standard fatigue machine, providing a variable torque on the spline coupling.

It is important to highlight that also after fatigue tests, performed in aligned conditions, the wear damage was evident, due to the relative sliding caused by the tooth deflection.

The second aim is to investigate how improved lubrication conditions may reduce the wear on the teeth surface. To achieve this goal, graphene nanoplatelets were added to a standard grease in order to create high performance compounds and to reduce the Coefficient of Friction (CoF) between teeth. The best compound obtained in terms of CoF decreasing, as indicated by Mura et al. (2018), was used on a spline coupling (specimen) for wind turbines and experimental tests were carried on by a dedicated test rig that allows to perform tests on component angularly misaligned, in order to correctly reproduce the actual working conditions (see Curà et al. (2014)).

Preliminary results show that graphene improves grease performance reducing the coefficient of friction (bringing to a reduction of uneven overloads).

2. Experimental activity

2.1. Fatigue tests: spline couplings for aerospace applications

The spline coupling considered in this first experimental activity has the following geometrical parameters: number of teeth z=26, modulus m=1.27mm, pressure angle α=30°, mean radius of the shaft r_m=16.51mm, length width L=12.5mm, tooth contact height h_w=1.63 mm.

The component is made of 42CrMo4 steel (tensile stress R_m=1000MPa, yield stress R_{P02}=700 MPa, fatigue limit σ_{D-1} = 420MPa, Young modulus 210 GPa, 0.3 Poisson coefficient).

Experimental tests were performed in order to reproduce the real working conditions of the components. In particular, a dedicated device (Fig. 1a) has been designed in order to allow testing the component with variable amplitude torque with a standard fatigue machine (Figure 1b).

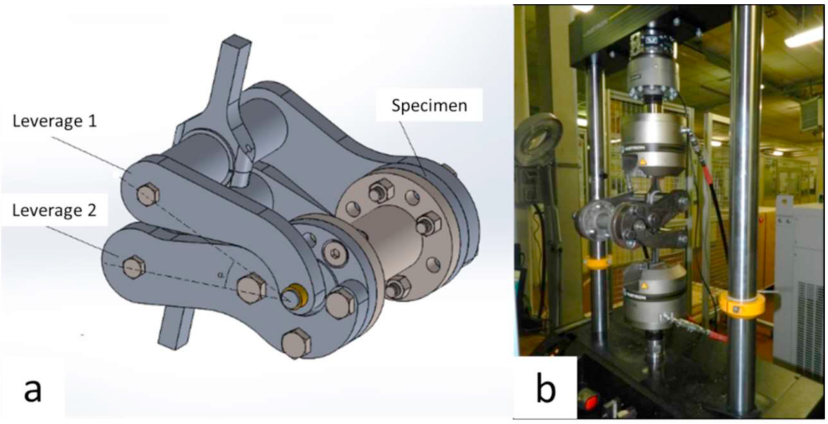

Fig. 1. Testing device to apply torque to the spline coupling (a) and fatigue testing machine (b).

The testing device (Fig. 1a) consists in two couples of leverages connected to the component to be tested. The leverages are fixed on the fatigue machine clamps and allow to transform the axial force generated by the fatigue machine to a torque. Tests were run with a loading frequency of 10 Hz and during $2x10^6$ cycles in total at ambient temperature (torque varying between 200 and 1050 Nm); the first one was performed during 500.000 cycles and the second one during 1.500.000 cycles. At the end of each test, the specimen was demounted and analysed by macro photographs and microscope investigations; also penetrant liquids were used to detect the presence of any micro cracks.

2.2. Wear tests: grease-graphene lubricated spline couplings

The second part of the experimental activity, consisting in testing misaligned spline couplings (lubricated with grease/graphene compound), was carried on by means of a dedicated test rig (Fig. 2) (Cuffaro et al. 2014).

Fig. 2. Spline couplings test rig

This test rig allows to perform tests on misaligned spline couplings, with 13’ maximum misalignment angle, with a maximum torque of 5000Nm at 2000rpm. The test rig is equipped with an oil lubrication system together with an oil debris monitoring system. The misalignment, during the shafts rotation, causes relative sliding between engaging teeth and therefore it may cause wear damage.

In this work, the wear behavior of a spline coupling lubricated by grease/graphene compound was investigated.

The spline coupling sample consists in a modified DIN 5480 (15 teeth, modulus 3mm, pressure angle 30°) designed in order to be representative of a full scale component used for wind mill applications.

The material is 18CrNiMo7-6 carburized.

The grease/graphene compound used to lubricate the component is made by SKF LGMT 2 grease added with 10% in weight of nano platelets GNP (particles thickness of about 2 nm and diameter less than 2 μm and average surface of500 m2/g). This percentage of GNP was selected, as it was the one allowing the best performance in coefficient of friction reduction as found in previous investigation (Mura et al. 2018a, Mura et al. 2018b).

In particular, the test was run with 300Nm constant torque at 1500rpm, with a misalignment of 4’. The test duration was 10M cycles.

3. Results

3.1. Fatigue tests: damage identification

Different damage typologies were identified on the teeth surface and described in the following.

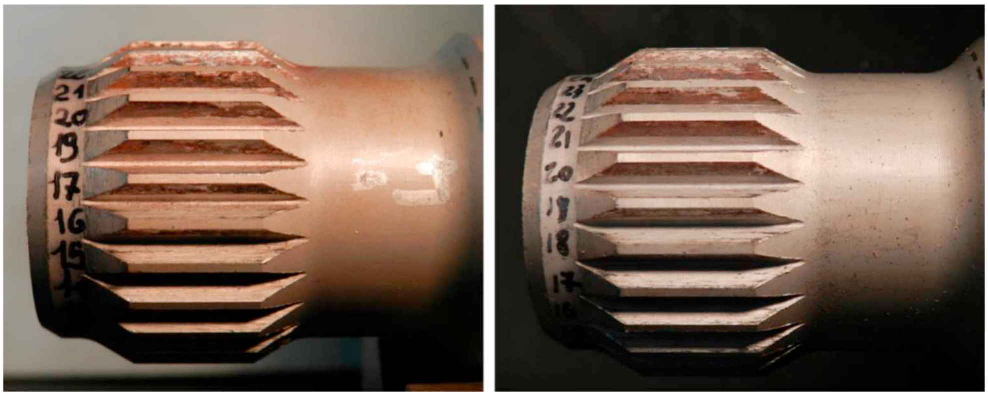

Fig. 3. Fretting wear: spline coupling after 500.000 cycles (left) and after 2.000.000 cycles (right).

Figure 3 shows the spline coupling after respectively 500.000 cycles (on the left) and at the end of the test (on the right). Surface damage identified as fretting wear can be seen in both images; iron oxide traces may be observed more evidently on the surfaces of teeth 21, 22, 23.

Figure 4 points out a particular zone related to the previous image represented in Fig. 3 on the right. On one side of the tooth, some adhesion may be noted.

Adhesion is caused by transfer of material from one tooth surface to another due to microwelding and tearing.

It generally can be categorized as mild or moderate if it is confined to surface films and oxide layers on the tooth surface, as in this case.

At the end of the test (2.000.000 cycles) it is evident (see Figure 5) the polishing effect on the teeth surfaces, that is more emphasized respect to the first part of the test (after 500.000 cycles).

As observed in ANSI/AGMA 1010-F14 (2014) for gears, polishing is fine-scale abrasion that causes the teeth surfaces to have a bright mirrorlike finish. Under magnification (see Figure 5), the surface appears to be covered by fine scratches that are oriented in the direction of sliding.

Also micropitting may be observed on the spline coupling at the end of the test, as shown in Figure 6.

Generally, micropitting is influenced by operating conditions, particularly load, speed, temperature, lubrication. Under magnification, as showed in Figure 6, the surface appears to be covered by very fine pits that are typically less than 10 - 20 μm deep.

Fig. 4. Tooth area subjected to fretting wear retting wear after 2.000.000 cycles.

Fig. 5. Polishing after 2.000.000 cycles.

Fig. 6. Micropitting after 2.000.000 cycles.

Some area of abrasion (scoring) may be also identified in the specimen. Abrasion is the removal or displacement of material due to the presence of hard particles: for example, metallic debris, scale, rust, sand, or abrasive powder, suspended in the lubricant or embedded in the flanks of the mating teeth. Abrasion causes scratches or gouges on the tooth surface that are oriented in the direction of sliding; under magnification, the scratches appear as parallel furrows that are smooth and clean, as shown in Figure 7. In this case, abrasion becomes more severe during the second part of the test.

Fig. 7. Abrasion (scoring) after 2.000.000 cycles.

3.2. Grease-graphene lubricated spline couplings: damage identification

Graphene is a recently discovered material that consists in one atomic layer of carbon (Novoselov 2011). This material has amazing properties that make it suitable for various technical applications, including friction and wear reduction additive (Fan 2014, Bahaa 2017).

The use of grease-graphene compounds as lubricant for spline couplings was recently tested, showing that graphene additive can reduce the coefficient of friction (Mura 2018).

In this work, preliminary results of this investigation are exposed, in order to identify how type of wear damage may appear on these components, lubricated only by the lubrication compound.

It may be observed that in the test rig usually an oil lubrication is active. In this case, no lubrication was utilized in the test rig, only the grease graphene compound was locally used to lubricate both shaft and hub.

This condition makes possible to point out wear damage phenomena related only to this particular set up.

Figures 8 and 9 show some examples of wear damage found on shaft teeth after the grease/GNP lubricated test.

The main identified wear damage is an extended corrosion that can be associated to fretting corrosion (Fig. 8). A kind of abrasion was also identified (Fig. 9).

In future works, wear tests on samples run with the base grease will be performed, in order to compare the wear damage types and therefore to better evaluate the performance of graphene when added in grease.

4. Conclusion

In this work different kinds of damage were identified on spline coupling teeth working in different loading conditions (aligned shafts with variable torque and misaligned shafts with constant torque).

Fatigue tests show that, from the fatigue durability point of view, the life of these components is always higher than that obtained by classical formula in the design phase.

On the contrary, wear damage phenomena are present due to the teeth sliding in all cases.

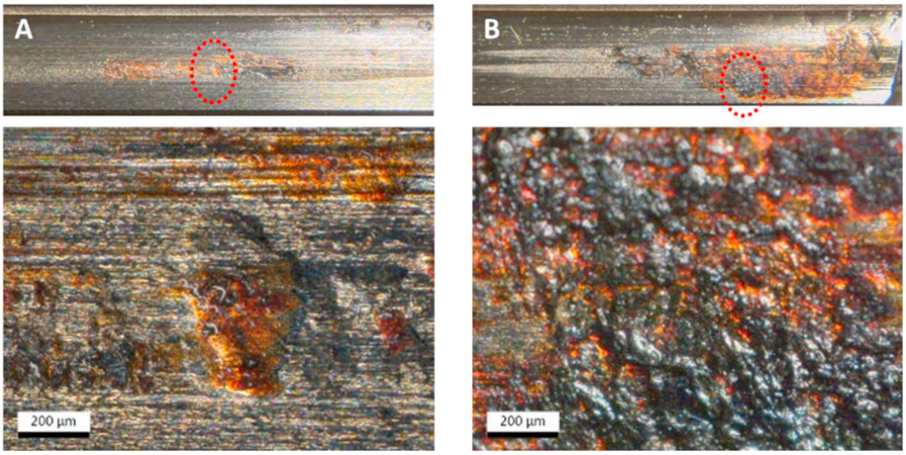

Fig. 8. Example of wear damage (fretting corrosion) on spline coupling lubricated with grease/GNP compound.

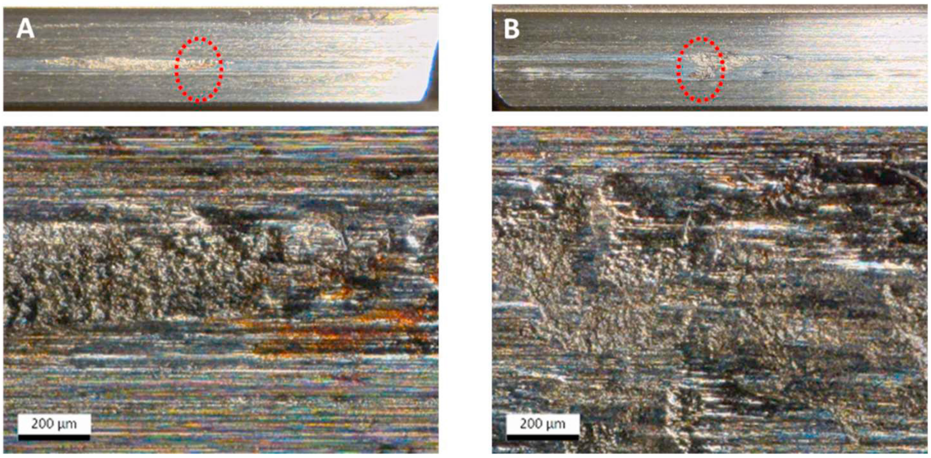

Fig. 9. Example of wear damage (abrasion) on spline coupling lubricated with grease/GNP compound.

In particular, tests performed with variable torque, in dry conditions, showed fretting wear damage along with micropitting mainly due to the lack of lubricant.

Other damages were related to abrasion and polishing.

Concerning tests performed in misaligned conditions with a grease/GNP compound, the most evident damages were related to fretting wear and abrasion.

Generally speaking, damage typologies identified in all samples and in both fatigue and wear tests can be correlate to those that may be found in gears, even if working and meshing conditions are different.

Contact pressure, sliding and lubrication play an important role in spline couplings behavior, causing wear damage phenomena that cannot be predicted in the design phase and that can be only identified once the damage occurs.

An attempt of this work and a future aim is to list all kind of damage and relate them to lubrication and operating conditions, also from a quantitative point of view.

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