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Damage identification on spline coupling teeth by means of roughness parameters

Vincenzo Cuffaro¹⁾, Francesca Curà¹⁾, Andrea Mura¹⁾

¹⁾ Department of Mechanical and Aerospace Engineering, Politecnico di Torino,
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract

The aim of this work is to use the surface roughness to identify the fretting damage on spline coupling teeth. These components are subjected to fretting phenomena above all when they are working in misaligned conditions and so the teeth surface morphology may change according to the corresponding working parameters (misalignment amplitude, presence of lubrication, etc). Experimental tests have been performed by means of a dedicated test rig, using steel made spline coupling specimens (42CrMo4) nitrogen-hardened. The teeth roughness has been measured before and after tests. In order to emphasize the different surfaces status, the measured roughness values have been treated considering different parameters both traditional and sophisticated as kurtosis and skewness. Experimental data have been statistically analyzed by means of ANOVA. Preliminary results show that roughness values change according to the working conditions (transmitted torque and misalignment angle).

Keywords: splined couplings, roughness, fretting, wear

1. Introduction

Components subjected to contact stress and relative displacements may be affected by fretting wear damage.

Fretting occurs commonly in clamped connections and demountable couplings and involves surfaces in contact subjected to cyclic small amplitude relative displacements [1]. Contact surfaces may be damaged also by metallic debris that play a critical role in fretting wear. In general, when debris accumulates on the contacting surfaces form compacted oxide beds, the wear rate is reduced significantly [2, 3]; but, if debris stay inside the contact region, these create with the lubrication oil an abrasive paste which speeds up the wear phenomenon.

The debris oxidizing gives rise to very small abrasive particles (order of microns), which are deposited and cause the worsening of wear process.

The damage consequent from this phenomenon may consist in the most common case in the formation of surface craters or in the removal of a considerable amount of material or otherwise in a simple surfaces discoloration.

Relative motion between surfaces in contact causes the surface layers erosion, exposing new areas to the phenomena of welding and breaking parts.

The fretting strength varies strongly according to the materials in contact.

In addition, the lubricant characteristics may influence the fretting damage: lubricants characterized by low viscosity and high strength tend to reduce the intensity of fretting by maintaining the oxygen out from the interface area and by carrying away the debris created by wear.

Fretting is currently an interesting field of research, also considering that there is not a standard giving a guidance concerning both components design and testing [4].

For the surface damage characterization, it is very important to identify the different surface aspects according to the fretting mode [5].

To characterize a damaged surface it is necessary to identify a suitable parameter, as an example the surface roughness [6].

Many fundamental problems such as friction, contact deformation, heat and electric current conduction, tightness of contact joints and positional accuracy are strongly influenced by surface roughness [7].

Some authors used the variation of roughness parameters to analyze fretting phenomena. As an example, Kucharski et al. investigated the evolution of the contact zone, by means of both wear scar depth and surface roughness measurements [5].

Kubiak et al. [8] developed an experimental study about the influence of the finishing surface and the machining process on the fretting damage arising in both partial and full sliding regimes.

In this work, some surface roughness parameters have been used to identify the fretting damage in spline coupling teeth [9].

Splined couplings are mechanical components used to connect two rotating shafts. they find several applications, particularly in the aerospace field.

A common failure mode of these components is the fretting damage caused by the relative motion between teeth in contact, above all when they work in misaligned conditions [9]

Spline coupling teeth surface morphology may change according to the working conditions such as misalignment amplitude, presence of lubrication, etc.

To reproduce fretting damage on spline coupling specimens, some experimental tests have been performed by means of a dedicated test rig, designed to apply and to monitor a specific angular misalignment between shaft and hub and able to reproduce the real operating conditions to which the component is subjected [10].

Roughness parameters available in literature [5] have been used to identify the surface topography variation of teeth due to the wear damage; in particular, more sophisticated

roughness parameters, such as kurtosis and skewness, have been considered for surface characterization [11].

All chosen parameters have been measured before and after each test, and a statistical analysis have been performed by means of ANOVA.

2. Experimental set up and data processing techniques

Experimental tests presented in this work have been carried on by means of a mechanical power recirculation spline couplings test rig [12]. Splined couplings specimens are steel made (42CrMo4) nitrogen-hardened (Figure 1); they have crowned tooth profile and the main characteristics are: 26 teeth, 1.27mm modulus, 30° pressure angle, 200 mm crowing radius and 12 mm face width.



Here: Figure 1 Spline coupling specimen

Test parameters considered in this work are resumed in Table 1, all tests have been performed with oil lubrication active. Test severity increases by increasing both torque and angular misalignment values. Each test duration is 10M cycles and lasts in five days; totally all tests presented in this work were performed in about 2.5 months.

Test	Torque [Nm]	Speed [rpm]	Misalign. [°]	N° of cycles
MB1	700	1500	0	10M
MB2	700	1500	5	10M
MB3	700	1500	10	10M
MB4	1000	1500	0	10M
MB5	1000	1500	5	10M
MB6	1000	1500	10	10M
MB7	1300	1500	0	10M
MB8	1300	1500	5	10M
MB9	1300	1500	10	10M

Here: Table 1 wear tests parameters

2.1 Roughness evaluation

The surface of all teeth of each specimen has been analyzed before and after the wear tests with an Alpa SM RT-70 profilometer; the roughness trend of the teeth surface has then been obtained.

Profile measurements before and after the tests have been done by means of a dedicated device in order to achieve a perfect parallelism of the specimen axis respect to the support plane of the profilometer touch probe [6]. The evaluation length has been 9,6 mm with 0.8mm cut-off and 4200 samples; the measuring resolution is 0.01 μm ,

Three different roughness parameters groups (amplitude, spacing and hybrid parameters) have been considered to process experimental signals provided from the profilometer.

Amplitude parameters are the most important ones to characterize the surface topography. They are generally used to measure the vertical characteristics of the surface deviations [6].

Spacing parameters may measure the horizontal characteristics of the surface deviations [6].

Hybrid property is a combination of amplitude and spacing. Any changes, which occur in either amplitude or spacing, may have effects on the hybrid property [6].

In this work the most representative parameters of these three groups have been chosen to analyze the variation of the surface topography with the aim to determine which parameter best emphasizes the presence of wear on the teeth surface.

According to [6] and [13], seven amplitude parameters, R_a , $R_{z(ISO)}$, R_{tm} , R_v , R_p , R_{sk} and R_{ku} , one spacing parameter P_c and one hybrid parameter Δa have been considered.

Parameter R_a is defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length [6].

The mathematical definition of the arithmetic average height parameter is expressed as follows:

$$R_a = \frac{1}{N} \sum_{i=1}^N |y_i| \quad (1)$$

where N is the points number of the profile and y_i is the amplitude value at i -th point.

Parameter $R_{z(ISO)}$ is defined by the International UNI EN ISO [13] as the sum of height of the largest profile peak height and the largest profile valley depth within a sampling length.

The mathematical definition of R_z is expressed as follows:

$$R_{z(ISO)} = \frac{1}{n} \left(\sum_{i=1}^n p_i - \sum_{i=1}^n v_i \right) \quad (2)$$

where n is the number of samples along the assessment length, p_i and v_i are respectively the five highest peaks and the five lowest valleys of the profile trend.

Parameter R_{tm} is defined as the mean of all maximum peak to valley heights obtained within the assessment length of the profile [13].

The mathematical definition of R_{tm} is expressed as following:

$$R_{tm} = \frac{1}{n} \sum_{i=1}^n R_{ti} \quad (3)$$

where n is the number of samples along the assessment length of the profile and R_{ti} the maximum peak to valley height [6].

Parameter R_v is defined as the maximum depth of the profile below the mean line within the assessment length [6]. Parameter R_p is defined as the maximum height of the profile above the mean line within the assessment length [6]. Parameter R_{sk} is the third central moment of profile amplitude probability density function, measured over the assessment length and used to measure the symmetry of the profile about the mean line. This parameter is sensitive to occasional deep valleys or high peaks; a symmetrical height distribution, i.e. with as many peaks as valleys, has zero skewness. Profiles with peaks removed or deep scratches have negative skewness. Profiles with valleys filled in or high peaks have positive skewness [6].

The mathematical definition of R_{sk} is expressed as following:

$$R_{sk} = \frac{1}{NR_q^3} \left(\sum_{i=1}^N Y_i^3 \right) \quad (4)$$

where R_q is the RMS roughness parameter [6] and Y_i the height of the profile at point number i .

Parameter R_{ku} is the fourth central moment of profile amplitude probability density function, measured over the assessment length. It describes the sharpness of the probability density of the profile. If $R_{ku} < 3$, the distribution curve is said to be platykurtic and has

relatively few high peaks and low valleys; if $R_{ku} > 3$, the distribution curve is said to be leptokurtic and has relatively many high peaks and low valleys [6].

The mathematical definition of R_{ku} is expressed as following:

$$R_{ku} = \frac{1}{NR_q^4} \left(\sum_{i=1}^N Y_i^4 \right) \quad (5)$$

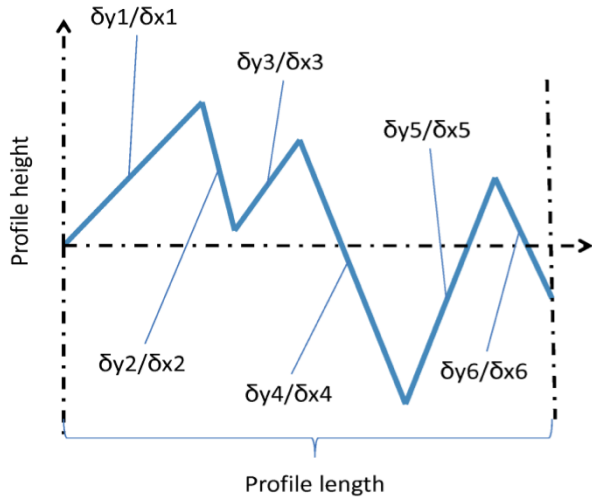
Parameter P_c is defined as the number of local peaks, which is projected through a selectable band located above and below the mean line by the same distance. The number of peak count is determined along the assessment length and the result is given in peaks per centimeter [6].

Parameter Δ_a is defined as the mean absolute profile slope over the assessment length [6].

The mathematical definition of Δ_a is expressed as following:

$$\Delta_a = \frac{1}{N-1} \sum_{i=1}^{N-1} \frac{\delta_{yi}}{\delta_{xi}} \quad (6)$$

where $\frac{\delta_{yi}}{\delta_{xi}}$ is the slope between each two successive points of the profile (see Figure 2).



Here: Figure 2 Representation of the profile slope trend for Δa calculation

2.2 Wear damage identification and evaluation

Wear damage has been identified in order to evaluate the fretting regime [14]. This is done by identifying the sliding regime (partial slip or gross slip). There are different methods for a quantitative determination of the transition between partial and gross

Slip, one of the most common consist on the energy ratio A [14]:

$$A = 1 - \frac{W_{et}}{4 \cdot Q \cdot \delta} \quad (7)$$

where W_{et} is the elastic energy at the transition, Q (given as the product of the contact load P and the coefficient of friction μ) is the tangential force and δ is the sliding amplitude.

The elastic energy at the transition W_{et} may be obtained by [14]:

$$W_{et} = \frac{16(\mu \cdot P)^2 \cdot K}{5 \cdot a} \quad (8)$$

where a is the Hertz contact radius and K is a constant relative to the materials in contact.

The Hertz contact radius is defined as [14]:

$$a = \left(\frac{3 \cdot P \cdot R^*}{4 \cdot E^*} \right)^{1/3} \quad (9)$$

where R^* is the equivalent radius (in this case equal to the crowing radius) and E^* is the equivalent elastic modulus, being in this case the surfaces in contact made of the same material ($E^* = E = 210000 \text{ MPa}$).

Finally, the constant K , related to the case of two identical materials in contact is obtained from equation (10):

$$K = \frac{3}{8} \left(\frac{2 - \nu}{G} \right) \quad (10)$$

where ν is the Poisson ratio and G is the shear elastic modulus of the material.

According to Fouvry [14], over the limit $A_t = 0.2$ the sliding regime belongs to the gross slip behavior.

In our case, considering the coefficient of friction $\mu = 0.3$ (as proposed by Ding [15] for lubricated spline couplings) and considering the worst case test (misalignment = 5° , torque = 700 Nm) it is possible to obtain the energy ratio $A = 0.84$ higher than the energy ratio limits, meaning that the tests sliding behavior is gross slip.

Now the wear amount should be evaluated. For this purpose, the Archard law has been used to obtain an estimation of the volume V of removed material [16]:

$$V = K \frac{P}{H} \quad (11)$$

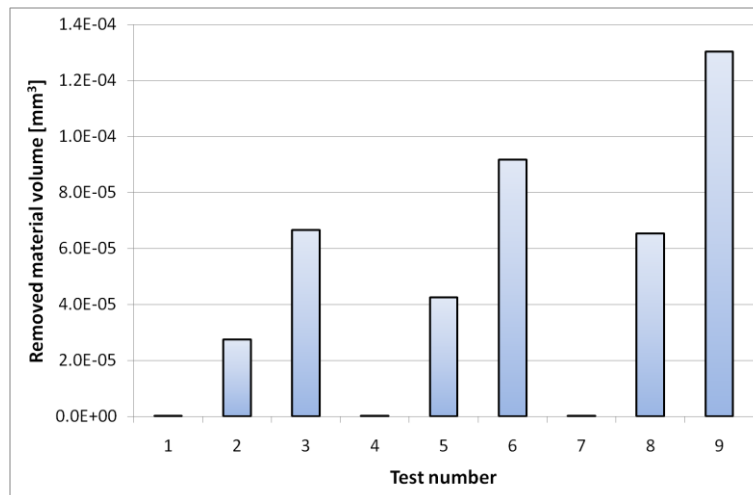
where P is the normal load, H is the hardness of the material (in this case $H=660\text{HV} = 2210\text{MPa}$ [17]) and K is the wear coefficient that is defined as:

$$K = \frac{w \cdot b \cdot h}{4 \cdot \delta \cdot N_t \cdot P} \quad (12)$$

where w is the wear scar width, b the width of the specimen (in this case it may be considered equal to the tooth height = 2.73mm) and h is the average wear scar depth, δ is the displacement amplitude (calculated by kinematical equations knowing the specimen geometry and the misalignment angle [12]) and N_t is the total number of wear cycles (in this case equal to 10M).

The average wear scar depth h has been obtained by measuring the spline coupling clearance as described in [12] and the wear scar width w has been measured on the components.

Figure 2 shows the trend of removed material obtained for the wear test presented in this work.

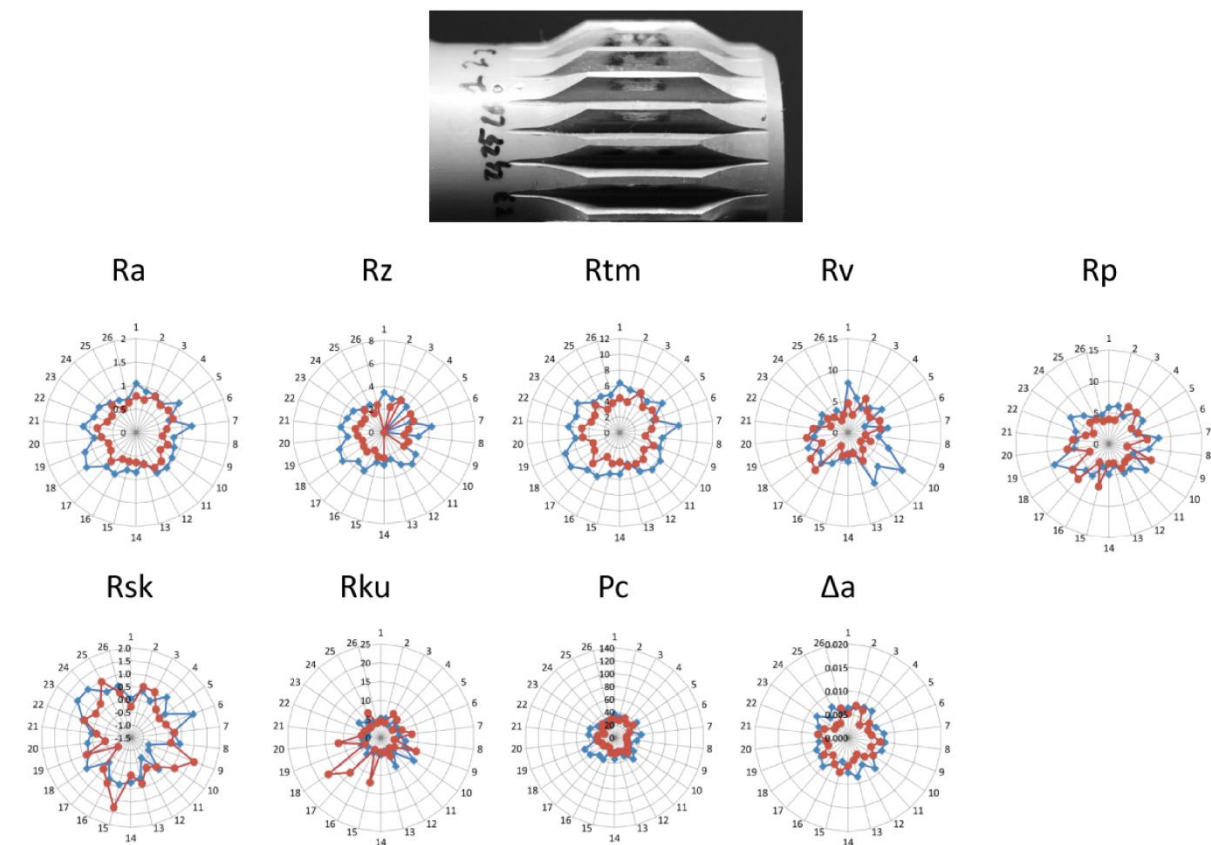


Here: Figure 3 Amount of removed material during the wear tests

It is possible to observe that the volume of removed material increase by increasing both the torque and the misalignment angle.

3. Results and discussion

Roughness parameters have been compared before and after tests. As an example Figure 4 shows the polar graphs obtained for each roughness parameter (respectively R_a , R_z , R_{tm} , R_v , R_p , R_{sk} , R_{ku} , P_c , Δa) before and after test MB3. The quadrant of the polar graph has been divided into 26 parts corresponding to each tooth of the specimen; the roughness parameter values before (pre test) and after (post test) wear tests may be seen on the corresponding radius.



Here: Figure 4 Behavior of roughness parameters R_a , R_z (ISO), R_{tm} , R_v , R_p , R_{sk} , R_{ku} , P_c , Δa) for test MB3

The difference between roughness parameters measured before and after tests have been threaded by means of ANOVA analysis, than the average variation of selected parameters have been analyzed. Finally, in order to better understand the roughness trends, the topology of the teeth worn surfaces have been analyzed.

3.1 Statistical analysis

Experimental roughness data have been statistically threaded by means of the ANOVA analysis. In particular, the difference between roughness values measured before and after tests has been considered. Table 2 resumes the results, where DoF are the degrees of freedom, SS is the sum of squares, MS is the mean squares. The P- value allows to define if a parameter is significant or not; this value tells us whether the means level is significantly different from each other: if the P-value is lower than a critical one (equal to 0.05 [18]), so there are significant differences in roughness behavior between the tests taken into account (that differ in torque level and misalignment angle). In this case all roughness parameters show P-values lower than 0.05 except for the R_{sk} .

Table 2

	DoF	SS	MS	Error DoF	Error SS	Error MS	Total DoF	Total SS	P-Value
R_a	8	118028	14753.6	225	64064	284.7	233	182093	0.000
R_z	8	28677	3585	225	251610	1118	233	280287	0.002
R_{tm}	8	81940	10242.4	225	64380	286.1	233	146319	0.000
R_v	8	196665	24583	225	286827	1275	233	483492	0.000
P_c	8	31319	3914.9	225	117607	522.7	233	148926	0.000
R_{pk}	8	118872	14859	225	209192	929.7	233	328065	0.000
R_{sk}	8	1567838	195980	225	204858328	910481	233	206426166	0.988
R_{ku}	8	330738	41342	225	982691	4368	233	1313429	0.000
Δa	8	120974	15122	225	818726	3639	233	939700	0.000

Here: Table 2 ANOVA results

Table 3 shows the value of the average of the difference between roughness parameters measured before and after tests and the corresponding standard deviation. It is possible to observe that in all considered cases the standard deviation is higher or at least has the same order of greatness of the average values, meaning that the roughness results are very scattered.

	TEST																	
	MB1		MB2		MB3		MB4		MB5		MB6		MB7		MB8		MB9	
	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.	Av.	St. D.
Ra	-11.5	13.2	25.6	14.5	21.6	15.1	1.9	17.8	37.8	9.7	-44.6	24.1	5.5	8.9	-0.2	23.8	5.6	17.8
Rz	-5.9	13.4	15.6	30.9	29.6	18.0	0.4	41.3	18.4	36.5	8.1	36.4	3.7	27.5	-3.8	35.7	0.0	47.1
Rtm	-8.4	12.0	20.6	24.5	25.6	16.3	4.9	14.1	35.2	9.8	-32.2	20.8	7.9	8.9	0.6	22.7	5.3	15.7
Rv	-10.2	32.5	-3.8	58.8	15.9	37.3	2.9	18.8	24.3	21.2	-83.3	59.2	-5.6	15.9	-4.0	23.7	3.7	21.2
Pc	0.5	16.1	5.7	47.2	23.3	24.4	4.9	15.9	33.9	10.6	5.2	16.6	6.7	12.3	-4.4	21.6	-0.1	19.3
Rpk	-11.7	26.6	13.8	44.0	22.3	25.4	8.0	26.2	20.9	18.9	-55.5	52.1	0.7	19.8	8.6	20.8	11.2	22.4
Rsk	131	1950	219	630	101	257	12.3	54.4	-9.0	1664	164.1	275	86.7	288	38.1	46.7	234	998
Rku	6.2	27.4	-50.0	113.6	-30.5	86.8	9.0	45.1	-115.3	92.1	-25.8	59.9	-15.6	27.7	11.0	44.5	-4.7	35.5
Δa	-10.5	29.2	-52.8	162.7	20.3	24.4	16.6	19.0	-30.4	41.8	-23.0	42.0	2.2	12.7	10.9	18.7	-1.8	21.2

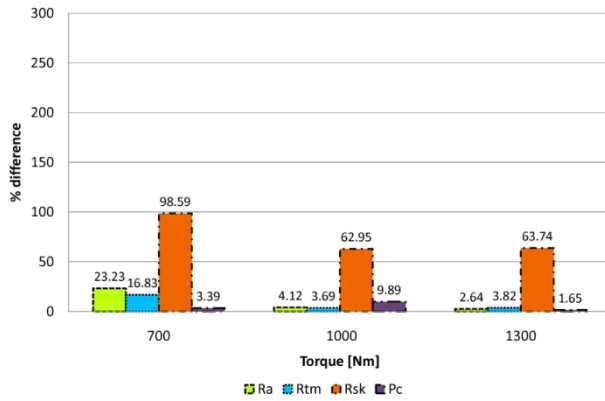
Here: Table 3 means and standard deviation

3.2 Average roughness parameters trends

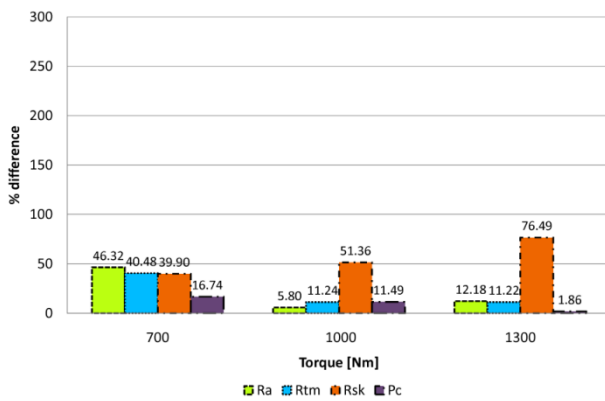
In the following, for sake of clarity of explanation, only the most representative parameters are considered. In particular, R_a , R_{tm} , R_{sk} , and P_c have been chosen to represent the wear damage because they show the most significant variation before and after all tests. In the following Figures (5 to 10), the data have been obtained considering the average value of the respective roughness parameters measured, for each test case, on all specimen teeth.

To better emphasize how the roughness parameters may vary after a test and also to point out the influence of both torque and misalignment angle, the percent difference of the sub-area of the curve representing the trend of the roughness parameter related to the 26 teeth has been considered. In particular Figures 5, 6 and 7 represent the effect of the

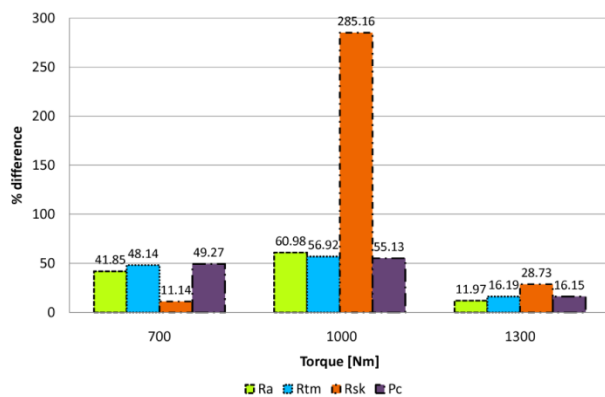
applied torque on the difference of the sub-area of the roughness curve respectively for tests performed aligned ($\alpha = 0^\circ$, Figure 5), and misaligned conditions, as $\alpha = 5'$, (Figure 6) and $\alpha = 10'$, (Figure 7).



Here: Figure 5. effect of the applied torque on mean roughness area variation ($\alpha = 0'$).

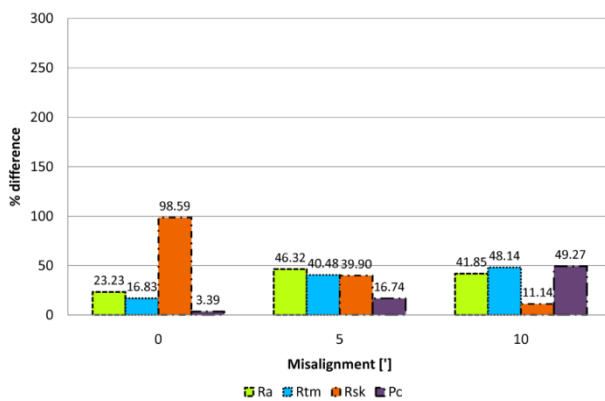


Here: Figure 6. effect of the applied torque on mean roughness area variation ($\alpha = 5'$).

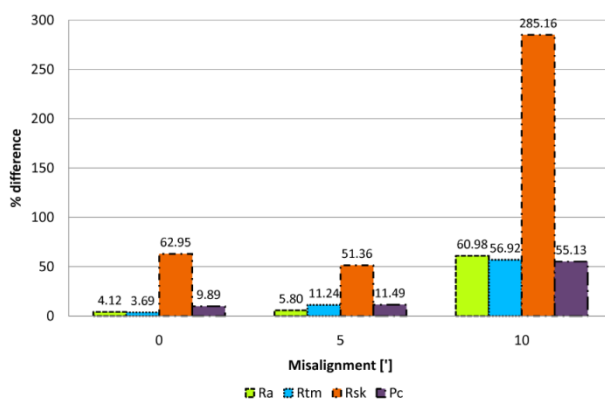


Here: Figure 7. effect of the applied torque on mean roughness area variation ($\alpha = 10^\circ$).

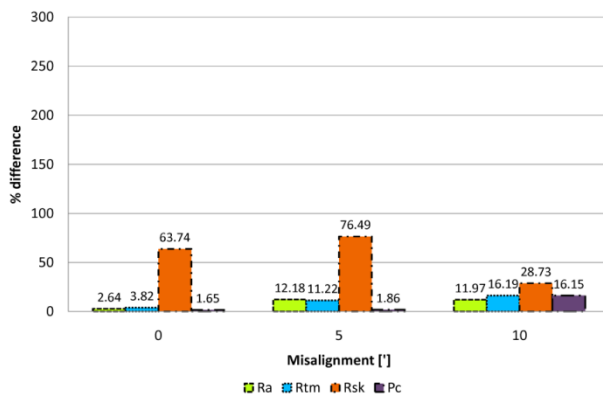
Figures 8, 9 and 10 represent the effect of the angular misalignment on the difference of the sub-area of the roughness curve, respectively for tests performed with 700Nm torque (Figure 8), 1000Nm (Figure 9), and 1300Nm (Figure 10).



Here: Figure 8. effect of angular misalignment on mean roughness area variation (Torque = 700Nm).



Here: Figure 9. effect of angular misalignment on mean roughness area variation (Torque = 1000Nm).



Here: Figure 10. effect of angular misalignment on mean roughness area variation (Torque = 1300Nm).

From the analysis of the showed results, some comments may be drawn.

Firstly, as already observed in previous studies [6], test conditions related to aligned spline couplings do not emphasize wear damage traces on teeth surfaces and also any appreciable difference in roughness parameters.

Only R_{sk} parameter shows a different behavior (see Figure 8) referring to the lowest torque (700Nm).

Moreover, it may be observed that all percent differences of roughness parameters refer to global damage phenomenon, being related to averaged data obtained from measurements performed on all specimen teeth. In addition, diagrams shown in Figures 5 to 10 are influenced by this way of processing.

R_a and R_{tm} parameters provide results difficult to be interpreted; on the contrary, P_c parameter increases by increasing the angular misalignment emphasizing an appreciable sensitivity to the damage phenomenon.

R_{sk} parameter is the most influenced by the morphologic surface variation, thanks to its mathematical formulation able to provide high values on percent difference.

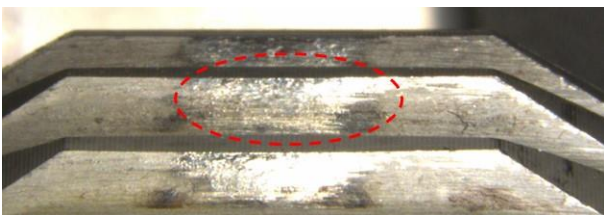
The test conditions involving the most important variation in roughness parameters, above all emphasized by R_{sk} parameter, is that related to test MB6 (Figure 7 and 9).

On the basis of this result, it may be concluded that test MB6 corresponds to the most severe working conditions related to fretting wear damage, being strongly influenced by the angular misalignment.

Finally, from the torque values point of view, it may be observed that the cases related to 1300Nm (tests MB7, MB8 and MB9) are misrepresented by the roughness parameters variation, due to surfaces plasticity phenomena causing a strong asperities smoothing.

3.2 Topological analysis of damaged surfaces

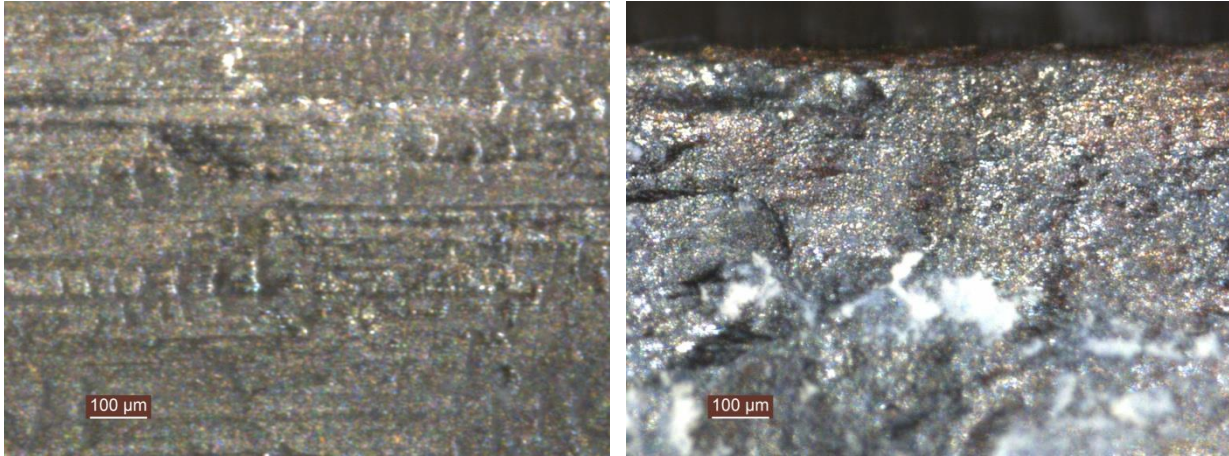
In this section, the surface topology of the worn surfaces is analysed. Teeth surfaces have been acquired by an optical microscope with 115x magnification. The images represent the area near the middle of the tooth face width, where the wear damage is higher. Figure 11 shows the area where the pictures have been captured.



Here: Figure 11 wear area.

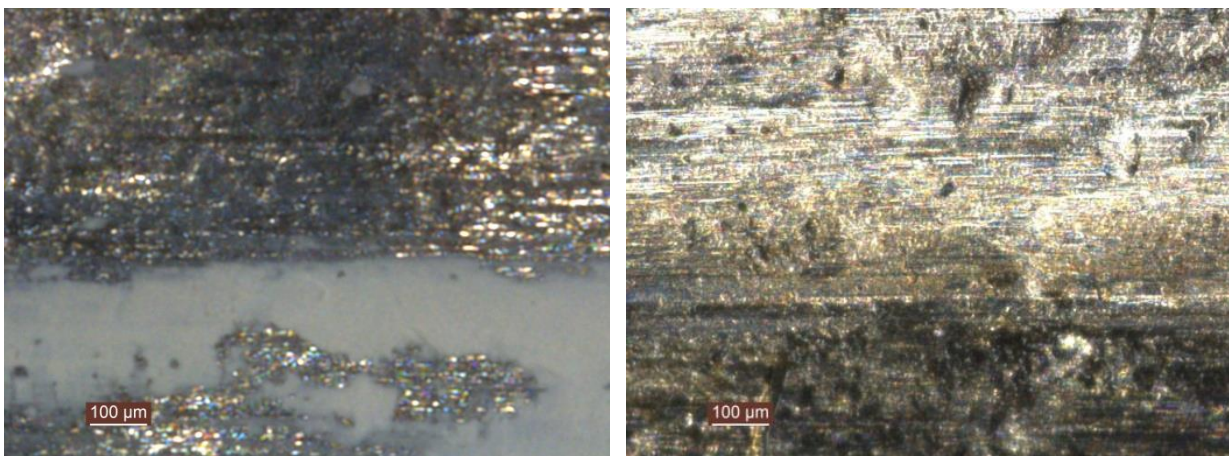
In particular, Figure 12 shows an example of the effect of misalignment angle: the picture on left is relative of the test MB5 performed with 1000Nm torque and 5' misalignment angle and the picture on the right is relative of test MB6 performed with the same torque, but with higher misalignment angle ($\alpha = 10'$). it is possible to observe as the higher misalignment angle brings to a different aspect of the worn surface: the case with $\alpha = 5'$

has little scares and scratches while the case with $\alpha = 10'$ shows big craters and the surface is very irregular. In both cases the nitrogen hardened layer is completely removed.



Here: Figure 12 worn surfaces 115x magnification: Test MB5: torque 1000Nm, $\alpha = 5'$ (left),
Test MB5: torque 1000Nm, $\alpha = 10'$ (right)

Figure 13 compares the surfaces of test performed with the same misalignment angle ($\alpha = 5'$), but different torque levels: 700Nm (test MB2) on left, and 1300Nm (test MB8) on right. It is possible to observe that in the test performed with lower torque some traces of the nitrogen hardened layer are present (the gray traces in Figure 13 left), while with higher torque there is no traces of nitrogen hardened layer, moreover little craters (seems to be as vaioleture) may be observed.



Here: Figure 13 worn surfaces 115x magnification: Test MB2: torque 700Nm, $\alpha = 5'$ (left),
Test MB8: torque 1300Nm, $\alpha = 5'$ (right)

Conclusions

In this paper, the surface damage topography in splined couplings teeth subjected to fretting damaging has been analyzed and characterized in different working conditions by means of roughness parameters.

Tests have been performed with different misalignment angles and load conditions, with lubricant oil. The sliding regime in all test is gross slip.

Nine roughness parameters have been firstly chosen to identify teeth surface morphology.

The roughness profiles have been measured on the teeth surface before and after each test by a profilometer and the corresponding signals have been processed and the related roughness parameters calculated. Experimental data have been statistically analysed by means of ANOVA, showing that all roughness parameters are very scattered.

In particular, four parameters (R_a , R_{tm} , R_{sk} and P_c) have been taken into account,

Although it is not easy to identify an unique correlation between roughness parameters and the component working parameters, two roughness parameters are particularly meaningful, P_c and R_{sk} , showing a significant trend for increasing the misalignment angle and the corresponding damage condition.

In other words, by increasing the tests severity, both P_c and R_{sk} parameters variation increases too, even if R_{sk} appears easier to be interpreted due to its mathematical expression giving high numerical values. In particular, P_c seems to have an unique trend respect to misalignment angle as it always grows as the misalignment angle grows.

Tests referring to the maximum torque entity (1300Nm) provide roughness parameters uncoupled from the actual component damage, being not so representative of the fretting

wear phenomena. In these cases, surface plasticization effects make roughness measurements substantially insignificant.

Magnified images of the worn surfaces shows different kind of surface topology, in particular the surface damage increases by increasing both torque and misalignment angle. Tests performed with higher levels of torque and misalignment angle show not uniform surfaces with big craters and scars, moreover the nitrogen hardened layer is completely removed; on the other hand, surfaces of specimens working with lower torque and misalignment angle show little scars and scratches, the nitrogen hardened surface is not completely removed.

In conclusion, results show that the procedure described in this paper is suitable to characterize surface damage in real components.

Roughness parameters may give a quantitative evaluation of the surface morphology variation, even if it is difficult to correlate the roughness variation to the amount of worn material.

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