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Investigation of lubricated rolling sliding behaviour of WC/C, WC/C-CrN, DLC based coatings and plasma nitriding of steel for possible use in worm gearing

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ABSTRACT

This paper presents the results of an experimental campaign based on lubricated rolling-sliding tests carried out in the disc on disc configuration for different material solutions.

The aim is to find alternative solutions to the couple bronze-quenched and tempered steel, recognised as standard solution for worm gearing. A steel-steel coupling was considered, providing different surface modifications (i.e. plasma nitriding, WC/C, WC-CrN, DLC coatings) in order to enhance the lubricated wear behaviour of the tribo-pair. The severe working condition of worm gearing applications, i.e. high sliding to rolling ratio, lubricant temperature and radial load have been reproduced in laboratory tests, which were conducted up to a very long sliding distance (about 1.6-1.8.10^6 m). During the tests periodic inspection were carried out to evaluate the progressive weight loss and to observe the surface modifications. At the end of the test the wear curves have been determined by correlating the weight loss with the sliding distance and the surface has been examined by optical microscopy to determine whether wear damage occurred. For all materials conditions very limited surface modifications and noticeable performance improvements with respect to the reference bronze-steel coupling was observed, thus suggesting their use as promising alternative solutions in worm gearing applications.

1. Introduction

In worm gearing a single- or multiple-threaded screw engages a spur gear with slightly angled and curved teeth to secure a large reduction of speed between non-intersecting driving and driven shafts with comparatively short center distances, thus allowing very compact constructions [1–3]. The meshing between screw and gear teeth produces a prevailing sliding action, which enables a smooth running, but causes considerable frictional power loss and efficiency lower than other types of gearing, that are characterized by conditions of prevailing rolling contact. For this reason lubrication conditions and materials coupling have a great impact on the efficiency of the transmission and the wear damage of the teeth [1,4–6]. The most common surface damage phenomena that occur in worm gearbox are due to abrasive and adhesive wear (scuffing, scoring) when the insufficient lubricant film does not prevent the metal to metal contact and pitting when the surface fatigue endurance limit is exceeded due to high contact pressure [5–10].

The materials recommended for worms are hardened steel and bronze for worm gears. The limited metallic compatibility of this tribo-pair has a beneficial effect on the resistance to scuffing and on the friction coefficient which usually ranges between 0.05 and 0.10. Moreover, the employment of bronze as a sacrificial material permits to relax the stringent requirements on gear geometric tolerances and surface finishing [4,6,10,11]. However, in view of the bronze's considerable cost and poor mechanical properties, and, on the other hand, the improvement in manufacturing techniques, allowing for greater accuracy and better surface finish, there is a strong interest in using materials alternative to bronze or innovative surface treatments and/or coatings. To this regard, the substitution of bronze-steel tribopair with steel-ductile cast iron has been extensively studied in the literature [12–15], but a conclusive proof of the feasibility of this solution for high performance gearboxes has not been provided yet.

Among surface treatments, nitriding is a classical solution adopted to improve surface durability; of particular interest appears the deposition by plasma treatment at low temperature,

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which ensures lower microstructural changes and smaller distortions of the treated parts [7,16,17]. In order to prevent scuffing phenomena in materials undergoing repeated rolling-sliding contact, it is very important not only to increase the surface hardness but also to strongly reduce the coefficient of friction [18]. For this purpose, several coatings have been developed with the aim of significantly lowering the affinity of the contact surfaces. DLC (diamond like carbon) coatings [19–22] and multi-layer coatings (e.g., WC/C or WC/CrN) on steel [23] seem to be particularly promising. Many mechanical applications proved to benefit from the excellent tribological behaviour of these coatings [24–26]. However, to our best knowledge, their application to the manufacturing of helical gear-worm screw transmissions has not been explored yet.

The present work aims to investigate the suitability different surface treatments or coatings for worm gearing solutions. For this purpose lubricated disk on disk rolling sliding tests were performed using the experimental set up described in [27,28] and a comparative analysis is carried out with results obtained on bronze steel coupling [27] as well as on steel–ductile cast iron coupling [28], allowing to identify some very promising solutions. The disk on disk configuration represents a considerable simplification since during the meshing between screw and teeth the evolution of the contact is very complex. Considering the typical operating conditions of the gearbox, the most significant parameters were identified and reproduced in the test. In particular: i) the high sliding to rolling ratio; ii) the highest sliding speed on teeth flanks; iii) the lubricating oil temperature typical of severe operating conditions; iiii) the Hertz pressure according to the design prescription of [3]. The damage observed for the bronze steel couple [27] was very similar to the damage arising in exercise, thus confirming that the simplified test can be considered as an useful approach in the materials selection phase.

2. Materials

The investigated tribo-pairs are reported in Table 1. The first three couples refer to data already published [27,28] and can be considered as reference solutions. The 42CrMo4V steel samples were machined from a production lot and partly subjected to surface treatments indicated in the table. In particular the low temperature plasma nitriding (NIP) has been chosen as alternative to the classic nitriding treatments thanks to its technological and microstructural benefits. The samples were treated for 1 h, at a temperature of 430 °C in a PE-CVD chamber (plasma enhanced chemical vapor deposition) with a mixture 20% N/80% Ar. The DLC coatings, the WC/C, and the WC/CrN fall within the DLC based coatings. In particular, the WC/C coating consists of an alternating sequence of WC and DLC layers, the WC/CrN coating replicates the same structure employing chromium nitride instead of DLC. The coatings are produced using the PVD technique (Physical Vapor Deposition) at a temperature of 180 °C. The coating layers of the four treatment conditions are shown in Fig. 1 To avoid damage to the surface layer, the specimens were prepared by cutting them starting from the bulk and moving toward the surface. A residual cross section 1 mm thick was kept and then broken in liquid nitrogen, thus preventing any modification that could be produced in the coating by the cutting operation. The estimated values of the surface layer thickness are listed in Table 1. In Table 1 the average values (10 measurements) of the coating harnesses determined with a Vickers nanoindenter using loading ramps up to 40 mN are also reported.

Table 1
Investigated tribo-pairs.

Disk ϕ=54 mm	Disk ϕ=26 mm	Comments
42CrMo4V-NIP	42CrMo4V-NIP	Layer thickness 2.8 μm Hardness 17.9 GPa (σ = 2.8 GPa) Roughness (Rq) 0.540 μm
42CrMo4V-DLC	42CrMo4V-DLC	Layer thickness 2.6 μm Hardness 21.3 GPa (σ = 2.8 GPa) Roughness (Rqa) 0.720 μm
42CrMo4V-WC/C	42CrMo4V-WC/C	Layer thickness 2.6 μm Hardness 15.2 GPa (σ = 1.1 GPa) Roughness (Rq) 0.712 μm
42CrMo4V-WC/CrN	42CrMo4V-WC/CrN	Layer thickness 2.5 μm Hardness 15.5 GPa (σ = 1.3 GPa) Roughness (Rq) 0.725 μm
42CrMo4V	CuSn12	[27]
42CrMo4V	42CrMo4V	[28]
42CrMo4V	GJS700	[28]

3. Experimental procedure

The experimental set up is the same adopted for the tests reported in [27,28], since the aim of the present study is to evaluate, by comparison with CuSn12 and GJS770, if hard surface layers can represent a promising solution for possible use in worm gearing. This choice is dictated by observation, made in previous works [27,28], that severe damage starts to occur at the onset of first pitting both for CuSn12 and GJS700. The hard surface layer con improve the surface fatigue strength and can also have a positive effect against scuffing.

In the following the experimental procedure is briefly summarized, more details can be found in [27,28]. In Fig. 2a picture of the Amsler A 135 machine and a schematic representation of the testing configuration is shown. The testing device was modified to increase the sliding speed up to values typical of worm-wheel transmissions. Disk specimens with a thickness of 8 mm and outer diameter respectively equal to 26 mm and 54 mm were machined.

Dip lubrication was provided, with lubricant maintained at a temperature of 80 ± 2 °C, by means of a thermostatic bath.

The specimens counter-rotate to produce concordant peripheral velocity in the contact region and to enhance the oil draining into the meatus as typical for meshing teeth. The speed values shown in Fig. 2 can be described by the following parameters:

a) average speed (rolling velocity):

$$\bar{U} = \frac{v_1 + v_2}{2} = 2.26 \text{ m/s} \tag{1}$$

b) relative speed (sliding velocity):

$$\Delta U = v_1 - v_2 = 3.74 \text{ m/s} \tag{2}$$

c) sliding to rolling ratio:

$$S = \frac{\Delta U}{2\bar{U}} = 0.828 \tag{3}$$

where S=0 correspond to pure rolling and S=1 to pure sliding).

The tests were conducted up to a sliding distance of about 1600–1800 km, which corresponds to nearly 10 million revolutions of the ϕ=54 mm disk and a duration of nearly 140 h. For each testing condition, two or three tests were performed. The number of tests is not such to allow to confidently determine the scatter, as for data reported in [27] for CuSn12, but can give at least