Lasers in Manufacturing Conference 2015

Non-Uniform Micro-Texturing of Tribological Steel Surfaces by Femtosecond Laser Ablation

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Abstract

Femtosecond laser ablation (fsLA) allows fabricating surface micro-textures of complex shape and geometry with a micrometer precision. In this work, we exploit the intrinsic flexibility of fsLA technology to realize non-uniform micro-textures on steel thrust bearing (un-tapered) pad surfaces, which have been shown (within the recent Bruggeman Texture Hydrodynamics theory, BTH) to optimize the tribological characteristics of the bearing. Moreover, a complete tribological characterization of all the sample surfaces was performed. We found, in agreement with the BTH predictions, that the micro-fluid dynamics, occurring locally at the scale of the structural defect and induced by the same, is integrated out in term of a macro hydrodynamic regime in the friction curve, which would otherwise not exist for the macro-geometry of the contact.

Keywords: Ultrafast lasers, Laser Ablation, Laser Surface Texturing, Bruggeman Texture Hydrodynamics

1. Introduction

In the last decade, it has been extensively studied both theoretically and experimentally that regular and uniform patterns of micro-cavities, artificially created on the surface of a generic contact pair, significantly alter its macro-tribological behavior [Etsion, 2012]. In particular, for the specific case of lubricated conformal

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sliding contacts, a regular array of micro-dimples on a steel surface may enable a considerable reduction of its friction coefficient [Etsion et al., 2004; Scaraggi et al., 2013 and 2014]. Several microscopic physical mechanisms may concur to such a remarkable change of the frictional behavior. For relatively very low lubricant viscosity and sliding speed, in the so-called boundary and mixed lubrication regimes, the dimples array, besides decreasing the effective contact area, acts as oil reservoir and trap for wear debris [Etsion, 2012]. In the hydrodynamic lubrication regime, instead, depending on the macroscopic geometric properties of the contact, as well as on the extension of the micro-textured area to a fraction (known as partial surface texturing) or to the whole contact domain (total surface texturing), a number of competing local effects can occur, such as the reduction of the shear stress on the dimples location, cavitation or the formation of eddy-like flows at the bottom of the cavities. Those are responsible e.g. for the friction decrease or rather increase, depending on the dimples geometry and their lattice constants and networking on the surface [Scaraggi, 2012 and 2015; Scaraggi et al., 2013 and 2014]. Given the many parameters which regulate such a fluid dynamics at confinement, the research interest has been mainly concentrated on a regular array of surface micro-cavities, which is clearly the easiest choice both on the theoretical as well as on the micro-machining side.

However, only very recently [Scaraggi, 2015] it has been theoretically demonstrated that a regular array of surface micro-cavities is not able to provide the topmost tribological performance, which is however theoretically available for the given macro-contact geometry. Indeed, the adoption of optimized non-homogeneous array of surface defects can provide superior friction and load support performances, suggesting the existence of super bearings configurations. In particular, the adoption of a non-homogeneous distribution of defects allows to set the local micro-fluid dynamics in an extremely controllable fashion, as a consequence of the configurable local effective anisotropy of the interface flow conductance.

In this work, for the first time, we have realized the optimal non-homogeneous micro-texture predicted by the BTH theory [Scaraggi, 2012] for a square un-tapered bearing pad geometry. The resulting micro-structured surface has been then tribologically tested in wet conditions, in order to verify the existence of a macro-hydrodynamic friction regime (induced by the collective flow action of the micro-structural defects) which would otherwise not be possible for the initial (untextured) surface.

The manuscript is outlined as follows. In Sec. 2 the micro-texture minimizing the wet sliding friction for a square conformal macro-contact geometry is introduced, whereas in Sec. 3 the experimental procedure for the fsLA and its optical characterization is described. In Sec. 4 the frictional results as well as the discussion are provided.

2. Super-Bearings with enhanced load support and low-friction

In a recent paper, it has been theoretically postulated the existence of particularly effective texture geometries which maximize the load supported by a single thrust bearing pad of finite width 2B and length L (see the schematic of Fig. 1), subjected to a partial surface texturing [Scaraggi, 2015].

The texture consists of an array of small-scale defects like circular, elliptical or striped dimples and/or micro-grooves. Assuming that the sliding contact takes place between the partially textured and a plain parallel surfaces under the iso-viscous rigid lubrication regime and isothermal conditions, an analytical model has been developed which accurately describes the texture hydrodynamics [Scaraggi, 2012]. The theoretical model allows calculating the average flow dynamics at the contact interface in terms of flow and shear stress tensorial factors, provided that cavitation is absent or has a negligible effect (as usually the case of partial surface textures). The hydrodynamic problem can be solved for different texture geometries with variable area density, lattice constants, as well as dimple depths, shape and orientation.

Taking advantage of such an effective tool to investigate the optimal texture characteristics, it has been found that an efficient way to reduce friction and increase at the same time the load support in bearings is to design a special texture retaining the lubricant flow under the sliding interface, thus minimizing any side leakage. Although being beneficial to friction reduction, an isotropic lattice of circular dimples fails to redirect the lubricant flow because it provides isotropic conductivities [Scaraggi, 2015]. On the other hand, striped superficial defects are well known to produce anisotropic flow redistribution [Scaraggi, 2012 and 2015]. In the case of total texturing with micro-grooves extending from side to side of the contact surface (total texturing), a friction increase has been experimentally reported. However, this effect has been ascribed to the escape of the lubricant out of the contact area due to the flow conductivities along the parallel micro-ducts generated by the grooved texture [Scaraggi et al., 2013].Therefore, in order to maximize the flow retaining effect both the local micro-scaled geometry of the texture features and their mutual interaction at the macro-scale has to be optimized. The theoretical model predicts that the best solution consists of a partial texture characterized by a lattice of finite sized grooves having a certain local angular misalignment with respect to the sliding direction. The distribution of the striped dimples depends on the pad aspect ratio.

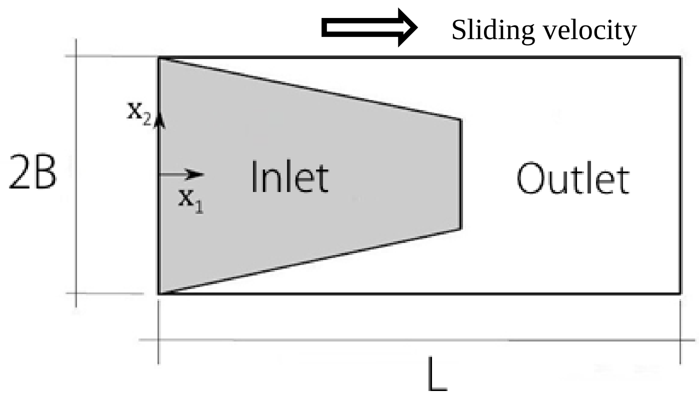

Fig. 1. Schematic of the single pad geometry

One of the proposed optimal texture geometries calculated by adopting a multigrid optimization procedure based on a genetic algorithm, is depicted in Fig. 2 for the square pad geometry. Here, the red stripes show the local angular alignment of the grooves, whereas the red circles indicate the *untextured* areas. The number of stripes which have been drawn in the figure has only a qualitative purpose, i.e., they do not represent in any way the lattice and dimensions of the defects, nor they have been somehow scaled. They only show the areas where the dimples are located over the squared pad and their orientation. The microgrooves have been aligned in such a way to hinder the flow of the lubricant towards the lateral direction, thus preventing any immediate leakage and hence friction increase. Conversely, the stripes inclination enables redirecting the fluid, at a scale larger than the scale of the grooves, towards the internal portion of the domain. This determines a large amount of fluid particles sheared at the contact interface and, consequently, an increase in the bearing pressure. It can be further noticed the presence of appositely designed suction fingers to increase the inlet flow. They are placed at the inlet corners and coupled with micro-herringbone geometry of the dimples on the inlet part of the lateral sides aiming to best harvest flow from the environment.

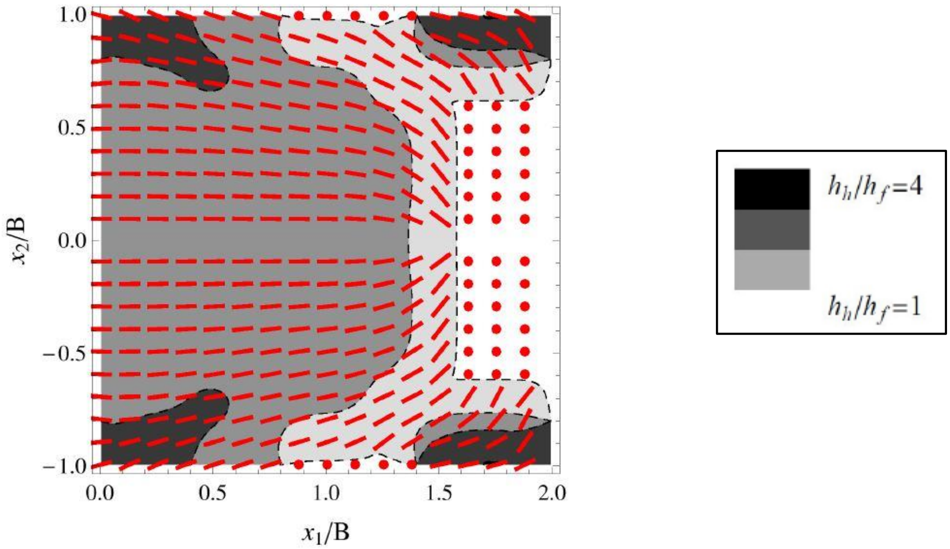

Fig. 2. Schematic of an optimized micro-grooved partial textured squared pad. The red circles indicate the untextured areas, while the red strips show the local angular alignment of the grooves. The gray scale indicates the dimple depths, where h_h is the dimple depth and h_f is the nominal separation between the two sliding surfaces.

In addition, expulsion fingers have been created on the outlet corners of the pad aiming to lengthen the fluid pattern under the pad domain. Indeed, the expulsion fingers redirect part of the flow, which normally would exit from the middle part of the rear side, toward the rear part of the pad. In this way, each fluid particle exerts a prolonged shearing action. Such a combination of suction fingers, rear fingers, and micro-herringbone geometry significantly increases the load support capabilities thanks to the extremely lengthened particle routing under the contact. This finally positively affects friction, which is consequently reduced due to an increased mean interfacial separation.

3. Experimental procedure

3.1. Sample preparation by femtosecond laser ablation (fsLA)

The samples chosen for the experiments were 100Cr6 steel spheres from commercial bearings, where the spherical caps have been truncated in order to obtain a flat circular surface with a diameter of about 4mm. Before being subjected to the laser surface texturing process, all the samples were polished at a root-mean-square surface roughness of about 20 nm, as verified by atomic force microscopy.

An ultrafast fiber CPA laser system (mod. Sci-series from Active Fiber Systems GmbH) was used to fabricate the LST surfaces, delivering 650 fs pulses at the wavelength of 1030 nm. The laser system is able to produce up to 50 Watt of average power or 100 µJ of pulse energy with repetition rates tunable in the range from 50 kHz up to 10 MHz, although the LST surfaces presented in this work have been produced by operating at the lowest achievable repetition rate of 50 kHz and an average power of 50 mW. Working at a near-threshold laser fluence enabled a high level of accuracy and reproducibility of the ablated micro-features. The linearly polarized beam exiting from the laser source was firstly converted into circularly polarized light through a quarter-wave plate, to prevent anisotropic absorption on the ablating surface, and then directed towards a 14-mm aperture galvo-scan head (mod. HurryScan from ScanLab GmbH) equipped with a 100-mm focal length F-Theta lens, after passing through a suitable beam expander. The focused spot size on the sample surface was about 15 µm.

Starting with the theoretical model described in Fig. 2, a texture pattern composed of five groups of micro-grooved dimples of limited size (200 µm length and 40 µm width) and different depths, ranging from 5 µm to 25 µm, have been designed as represented in Fig. 3. The area to be textured has a squared section of side about 2.8 mm which had to be inscribed in the circular sample surfaces. The overall area density of the texture is about 50%. The deeper dimples have been positioned in the suction and expulsion fingers located at the corners of the textured area. The variable inclination of the micro-grooves with respect to the sliding direction follows the red stripes shown in Fig. 2, aiming to guide the fluid towards the internal part of the pad.

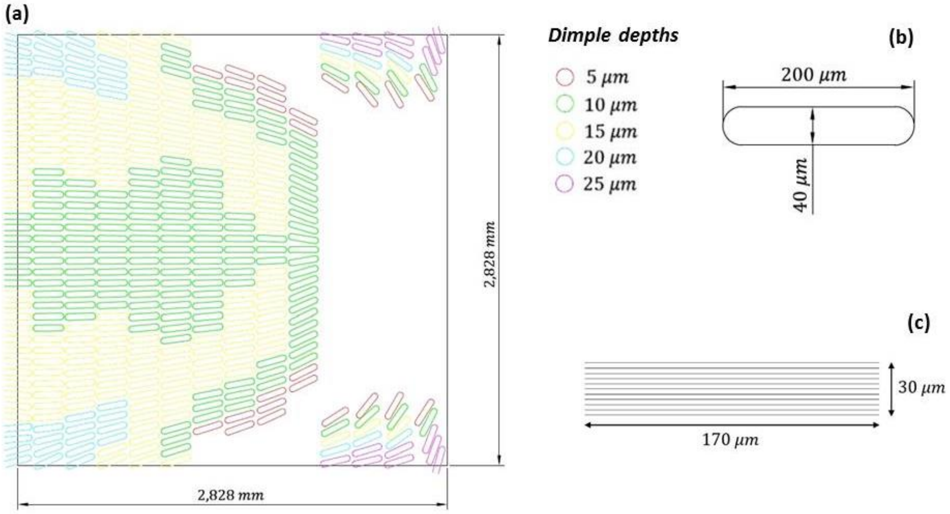

Fig. 3. (a) Schematic of the texture pattern; (b) dimple size; (c) ablation strategy to realize each dimple.

Each dimple of almost rectangular shape has been realized by drawing an array of eleven parallel ablation traces 170 µm long and with a lateral displacement of 3 µm one from each other (see fig.3c). The translation speed of the focused laser beam on the sample surface was held constant at 20 mm/s. Following the scheme of figure 3, the ablation depth of each dimple have been accurately controlled by finely adjusting the number of overlapped loops. Finally, the sample area outside the squared pad have been removed by femtosecond laser milling reaching a depth of more than 100 µm, which is an order of magnitude higher than the expected average fluid thickness under the bearing.

After the fsLA process, the morphology of the fabricated micro-features was accurately characterized by optical and scanning electron microscopy a well as using a white light confocal microscope by CSM-Instruments, with lateral and vertical resolution of, respectively, 1.1 µm and 0.005 µm. Figure 4 shows an overall view acquired with an optical microscope of the worked area and the detail of a single micro-grooved dimples. It can be noticed that the size of the dimple is within the specifications with a tolerance of a few micrometers. Furthermore, the machined part is completely free from melting and burrs, thanks to the high level of accuracy provided by the ultrashort pulse duration ablation regime together with the near threshold laser fluence selected for the LST process. Therefore, no further polishing was required after laser micro-machining. The confocal microscope analyses confirmed that also the dimple depths meet the required specifications with a micrometer precision.

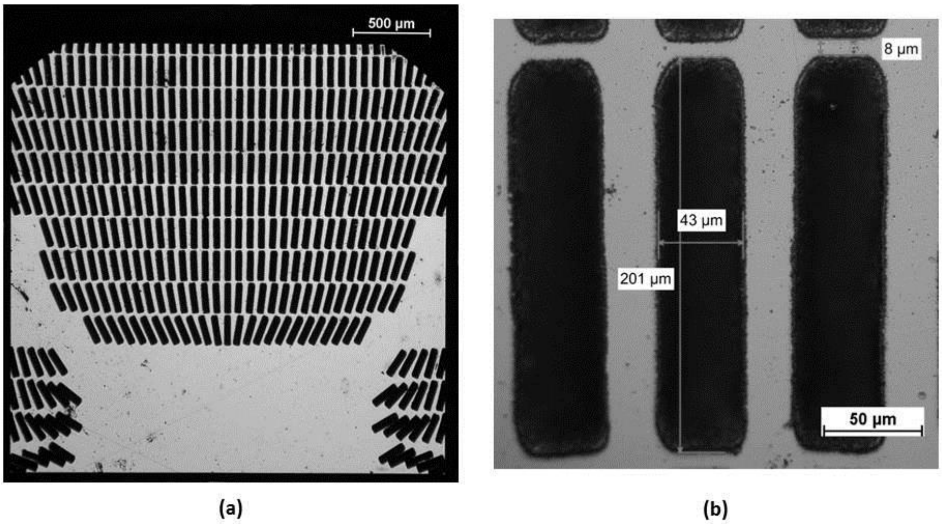

Fig. 4. (a) Optical microscope image of the overall textured area; (b) magnified detail of three parallel micro-grooved dimples.

3.2. Sample characterization

The tribological characterization of the LST samples was carried out on a CSM High Temperature pin-on-disk Tribometer (HTT). The core of the system is simply constituted by a rotating sample-disk (Aluminum Alloy 6061 sheet with a measured root-mean-square surface roughness of Ra=0.08 μm) in contact with the fsLA truncated spheres. The contact pair (disk and pin-end) were immersed in a lubricant bath, whose temperature was constantly monitored during the tests. The adopted lubricant is a pure mineral oil (Oroil Therm 7 from Orlando Lubrificanti S.r.l.). A normal load was applied to the sphere holder by means of a calibrated weight. Three different loads of 0.25 N, 0.5 N and 1.5 N, respectively, have been applied during our characterization experiments.

We have measured the friction coefficient of the laser textured pad and of a flat control squared pad where only the lateral portion of the circular sample outside the 2.8-mm-side square have been removed by femtosecond laser milling likewise the textured sample. The friction coefficient measurement has been carried out for different values of the sliding velocity *U* of the disk, from 324 mm/s to 15.0 mm/s, starting from the fastest speed, where the lubrication regime was always of the hydrodynamic type, to the slower value. This practice was adopted to strongly minimize any possible surface wear, which indeed resulted always undetectable.

During each measurement, the disc is rotated at a constant speed and the tangential displacement value of the elastic supporting arm of the ball holder is detected by a Linear Variable Displacement Transducer (LVDT). The displacement sensor signal is converted via software into a tangential force value T through a suitable calibration curve. Being known the normal load, the friction coefficient is obtained from the ratio of the tangential force T with the normal force N. The tribometer has been operated also in the reciprocating mode. Here, the rotation speed is periodically inverted with a frequency that can be set by software. Also in the reciprocating mode the LVDT sensor estimates the tangential force value T which is, however, in this case, alternatively positive and negative. This kind of measurement, which is obtained by alternately reversing the sliding contact direction with respect to the texture distribution, is highly significant to evaluate the hydrodynamic contribution of our specific anisotropic texture pattern compared to the untextured case.

4. Results and discussion

The tribological results have clearly shown that the designed anisotropic texture pattern generates a hydrodynamic lubrication regime, especially for loads below 1 N and higher sliding speeds. This is also confirmed by the fact that no sign of wear was detected on the sample surface after the measurement.

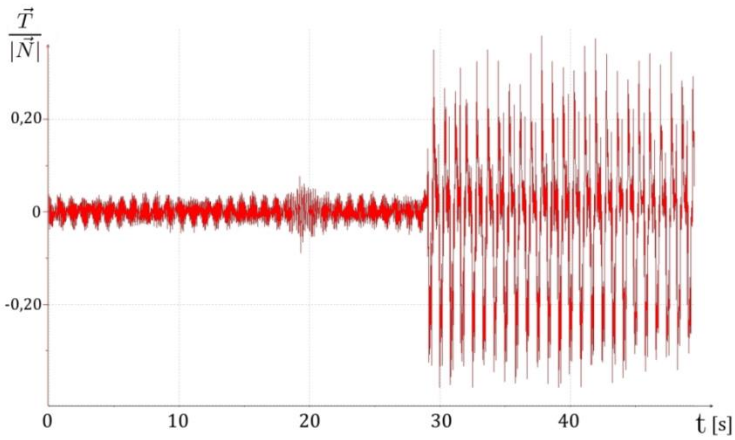

Fig. 5. (Apparent) friction coefficient behavior calculated as the (apparent) tangential force T to the normal force N ratio, measured in the case of the untextured sample with the tribometer operating in the reciprocating mode with isothermal conditions of the oil bath at a temperature of 24.2 °C, linear translation speed of 136 mm/s and a normal load of 0,25 N.

It is interesting to observe that a hydrodynamic lubrication regime cannot be obtained in case of conformal contact of two flat parallel surfaces (as for our untextured macro-geometry), at least not in the range of sliding speeds and lubricant viscosity of our experimental conditions. Therefore, it can be argued that such a hydrodynamic effect, if it exists, can only be generated by the collective and non-local micro-fluid-dynamic action induced by the anisotropic surface texture.

An experimental confirmation of the previous argument comes from the comparison of the behavior of the textured sample with respect to the flat control surface in the reciprocating contact mode, as shown in Fig. 5 and 6. These measurements have been performed keeping the oil bath temperature at the constant value of 24.2 ° C, the sliding linear speed at 136 mm/s and applying a normal load of 0.25 N. The sliding speed was periodically reversed with a frequency of 1 Hz. In both graphs the time evolution of the ratio between the measured (apparent) tangential force and the normal load is reported. For the first almost 30 seconds the arm of the tribometer is raised and the value of the tangential force exhibits small symmetric oscillations around zero. When the arm is lowered this oscillations are much more pronounced with positive/negative values depending on whether the direction of rotation is the one defined as positive or negative. In the case of the untextured control sample, shown in figure 5, the oscillations are symmetric with respect to the zero, as it was expected. The textured sample revealed, instead, a substantial asymmetry of the oscillation amplitudes (Fig. 6). Here, a tangential force which is twice more intense develops when the direction of rotation is opposite to that for which the texture pattern has been designed. The same measurement is repeated for four different time intervals, obtaining similar behaviors thus proving the reliability of the result, and supporting the existence of the micro-hydrodynamic collective contribution originating from the anisotropic surface micro-structures.

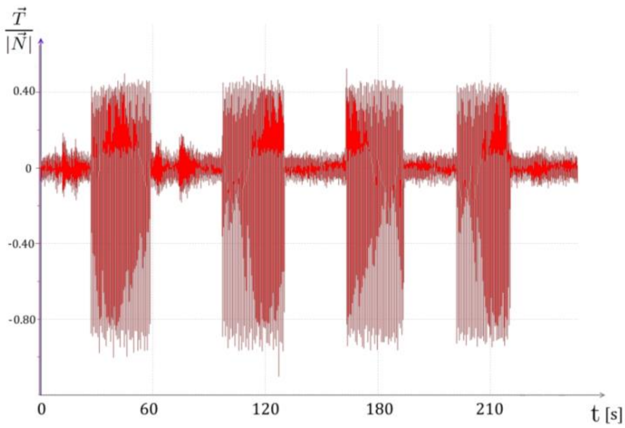

Fig. 6. (Apparent) friction coefficient behavior calculated as the (apparent) tangential force T to the normal force N ratio, measured in the case of the textured sample with the tribometer operating in the reciprocating mode with isothermal conditions of the oil bath at a temperature of 24.2 °C, linear translation speed of 136 mm/s and a normal load of 0,25 N.

5. Conclusions

Non-uniform micro-textures have been fabricated on the surface of steel samples with a square un-tapered bearing pad geometry, taking advantage of the high level of precision and flexibility achievable by the fsLA technology. The specific and innovative texture pattern design implemented in this work consists of a non-homogeneous array of surface micro-grooved dimples of different depths, inclinations and distribution on the pad surface. Such a geometry is inspired by previous predictions based on the BTH theory and it has been optimized aiming to obtain a macro-hydrodynamic friction regime during lubricated sliding contact. It is assumed that this regime, which would otherwise not be possible for the initial untextured surface, is induced by the collective flow action of the micro-structural defects. In particular, the striped micro-dimples inclination and their spatial distribution on appositely designed suction and expulsion fingers, enable redirecting part of the lubricant flow towards the internal portion of the pad, thus significantly increasing the load support capabilities thanks to the extremely lengthened fluid particles routing under the contact.

The experimental tribological results have clearly shown that the fs-laser textured samples undergo a hydrodynamic lubrication regime, especially for loads below 1 N and higher sliding speeds, which has not been observed in the case of an untextured flat control surface. This is further confirmed by the experimental observation that the measured friction coefficient of the textured samples is almost doubled when the direction of the sliding speed is reversed with respect to the non-uniform and anisotropic texture pattern orientation. The preliminary results shown in this work can potentially pave the way towards the development and fabrication of a new generation of so-called “super-bearings” with unique and enhanced tribological performances.

Acknowledgements

The authors acknowledge the Apulian Region and the Italian Ministry of Education, University and Research for having supported the research activity within the project TRASFORMA Laboratory Network cod. 28, and projects PON01_02238 “EURO6” and PON02_00576_3333604 “INNOVHEAD”. In addition, the authors gratefully thank Mr. Gerardo Decaro for helping during the experiments and Mr. Pietro Paolo Calabrese for the technical support .

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