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EXPERIMENTAL INVESTIGATIONS UPON CONTACT BEHAVIOR OF BALL BEARING BALLS PRESSED AGAINST FLAT SURFACES

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Abstract: *Experimental methods that offer point by point information regarding the investigated surfaces are preferred in the study of mechanical contacts. Such a method, advanced in [1-6], consists of investigating the contact model obtained by pressing a metallic punch against a flat, optically transparent, surface, by aid of laser profilometry. The variation of surface reflectivity is measured and used to accurately determine the shape and dimensions of contact areas. The present study employed the abovementioned method in order to experimentally investigate the contact behavior of various ball bearing balls, when pressed against the flat surface of a thick sapphire window with different normal loads. Experimental results were compared to theoretical predictions and good agreement was found between results.*
Keywords: *experimental investigations, mechanical contacts, contact area, laser profilometry, reflectivity*

1. INTRODUCTION

The present paper illustrates experimental investigations conducted on spherical punch-flat surface contact models, by aid of reflectivity. The experimental testing consists of mapping by aid of laser profilometer of the contact surface generated when pressing an equivalent punch against an elastic half-space. For the investigated contact model, the punch is bound by an equivalent surface that incorporates both surface geometries while the elastic half-space is modeled by a thick, optically transparent, plate. As the present investigations aimed to study steel-on-steel contacts, the transparent plate was made of sapphire. The material choice is due to the similarity between sapphire and steel elastic properties. Thus, the longitudinal elasticity modulus for sapphire is $E = 345\ GPa$, while for steel, it is $E = 210\ GPa$, and the sapphire's Poisson's ratio ($\nu = 0,29$) is also similar to the one for steel ($\nu = 0,3$). The maximum contact stresses tolerated by sapphire are also in the same size order as for steel ($\sigma_c \approx 2\ GPa$ for sapphire and $\sigma_c \approx 2,5\ GPa$ for bearing steel).
When a light beam falls onto the interface between two optically different media, it is partially reflected back to the first medium and partially transferred to the second medium, as illustrated by Figure 1.
When the presented contact model is scanned by aid of a laser profilometer, the light wave generated by the optical sensor passes through the sapphire plate and then either meets a sapphire-metal interface (corresponding to points inside the contact area) or a sapphire-air interface (corresponding to points outside contact area). As shown in [1-8], the light is reflected differently from in the two situations, which permits to generate 3D representations of the deformed punch surface and accurately asses contact area shape and dimensions.
As demonstrated in [3] *when the light is reflected by an absorbing medium, the reflected light intensity decreases with the increase of the refractive index of the primary transparent medium.* For the considered contact model, the refractive index for sapphire is higher than for air and lower than the one corresponding to metal. This translates, in terms of the above mentioned property, in a lower reflectivity measured at the sapphire-metal interface than the one determined when the light meets the separation between air and sapphire. This property allows accurate evaluation of the contact area, if the variation of surface reflectivity is known. Most modern laser profilometers can determine this parameter along with the measurement of surface microtopography.

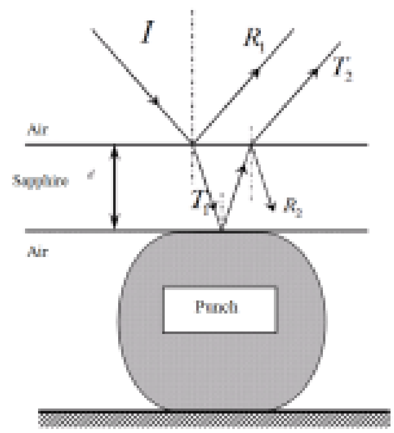
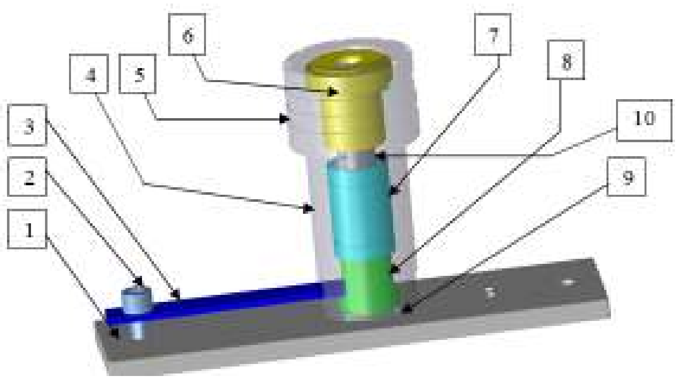


Figure 1: Reflection–refraction of light when the punch-sapphire window contact model is investigated by aid of laser profilometry

2. EXPERIMENTAL SET-UP AND EQUIPMENT

The main instruments employed to determine micro and macro characteristics of real surfaces are profilometers. Depending on the way data regarding the investigated surface is collected, these instruments can fall into two major categories: contact profilometers and non-contact profilometers. The present research was conducted by aid of a µScan® laser profilometer manufactured by NanoFocus, equipped with a CLA 10 chromatic optical sensor. This optical profilometer, belonging to the non-contact category, allows 2D and 3D measurements of real surfaces, and can be used for various applications, both for research and industrial purposes. The main component of the profilometer is its optical sensor, which can be moved along the vertical axis of the system, thus ensuring that the light is focused on the investigated surface. In order to place the investigated specimens under the optical sensor, the profilometer is equipped with a positioning unit (x-y axes) with sample stage.
The present investigations were conducted on contact models obtained by pressing various bearing balls against thick, sapphire discs. Several levels of normal load were applied to the contact, by aid of an experimental device as the one described in [7] and illustrated schematically in Figure 2.



Main components:

1	– Base plate
2	– Normal load screw
3	– Normal load elastic lamella
4	– Body
5	– Top nut
6	– Sapphire holder bush
7	– Ball bush
8	– Normal load pad
9	– Fastening screws
10	– Plunger

Figure 2: Experimental device for normal load application

The experimental device employed for the present investigations was designed to allow application of purely normal forces to contacts created between a ball, or another body, and a thick sapphire disc. The normal load application system consists of an elastic lamella, (3), supported on a cylindrical roller, thus forming a lever. The force applied to one end of the elastic lamella by fastening of the screw (2), is then multiplied by the lever system and applied to the plunger (10) by means of another roller. The plunger presses against the punch-support subassembly, which in its turn presses against the sapphire window, thus loading the contact (any translation of the sapphire window is blocked by the upper nut (5)).
In order to accurately determine the applied normal force, the strain of the elastic lamella is measured by aid of two 10/120 *LY* 11 Hottinger strain gauges placed on opposite sides of the lamella and linked to a model P3 Strain

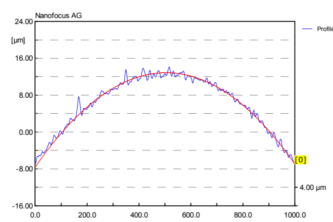
Indicator and Recorder, manufactured by Vishay, using a half-bridge connection. Figure 3 illustrates the experimental device used for the present research is, together with a detailed view of the strain gage placement on the elastic lamella.

Figure 3: experimental device for the study of mechanical contacts under normal load by aid of laser profilometry and placement of the strain gauges used to evaluate applied forces

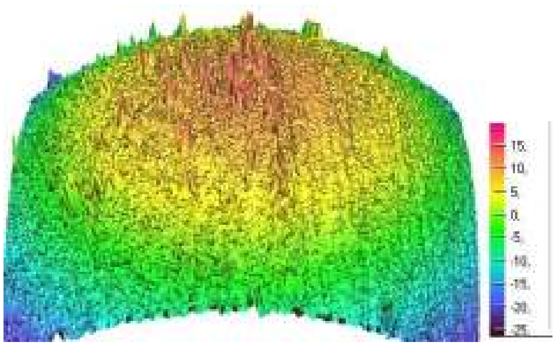
3. RESULTS AND DISCUSSIONS

The present study aimed to experimentally evaluate stress and strain states generated in ball bearing balls without apparent surface defects when in contact. To that end, the above-presented experimental method based on surface reflectivity assessment was employed. The experimental tests were conducted on three bearing balls, having different diameters. The surfaces of these spherical punches were first mapped by aid of laser profilometry and their dimensions were accurately determined. It was found that the used metallic spheres have respective mean curvature radii of $2{,}002mm$, $3{,}9513mm$ and $6{,}35mm$. For exemplification, a 3D representation of the surface microtopography corresponding to the ball having a $12{,}775mm$ diameter, is shown in Figure 4 a. Figures 4 b and 4 c illustrate two reciprocally perpendicular profiles of the surface, and their approximation by circular profiles, which allows for measurements of the surface curvature. The mapped area was $1 \times 1mm$, and the measurement was conducted at a resolution of $2 \times 2\mu m$.

b)

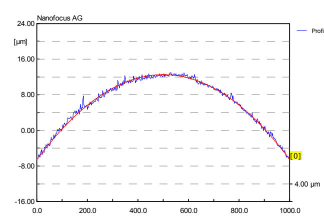


Radius (0) = 6215,01 µm



a)

c)

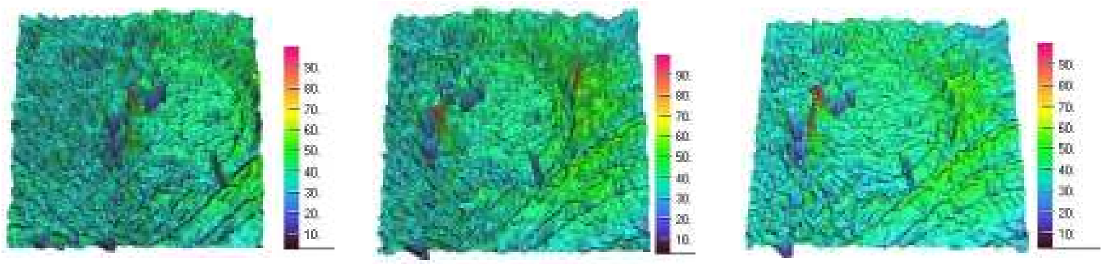


Radius (0) = 6560,13 µm

Figure 4: Surface microtopography and reciprocally perpendicular profiles for the $12{,}775mm$ steel ball

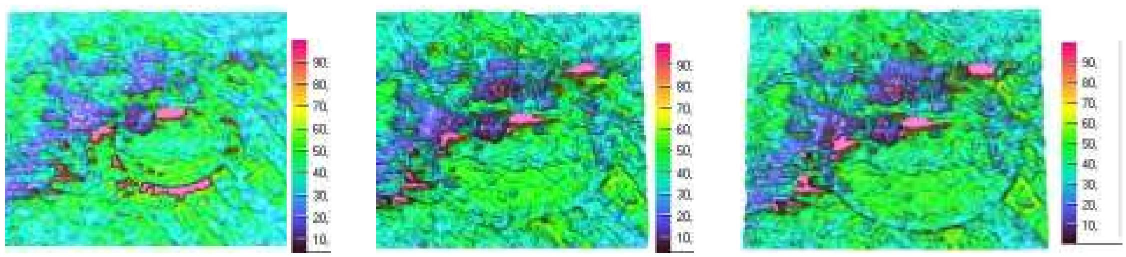
Using the presented experimental equipment, the three bearing balls were placed in contact with a $3mm$ thick sapphire window. The obtained contacts were subjected to various normal loads and contact regions were mapped by aid of laser profilometry. The experimental results consist of both 3D and plane representations of the contact surface reflectivity inside and near the ball-sapphire contact area. These plots can be further interpreted by aid of the specific functionalities for data display and processing available from the profilometer software. If further analysis is necessary the measurement data can be exported to other data processing software.

Typical experimental measurements of surface reflectivity in the contact proximity were represented by aid of three-dimensional plots as illustrated in Figures 5-7. In order to highlight the contact area shapes and dimensions, plane representations of surface reflectivities were plotted, as shown in Figure 8.



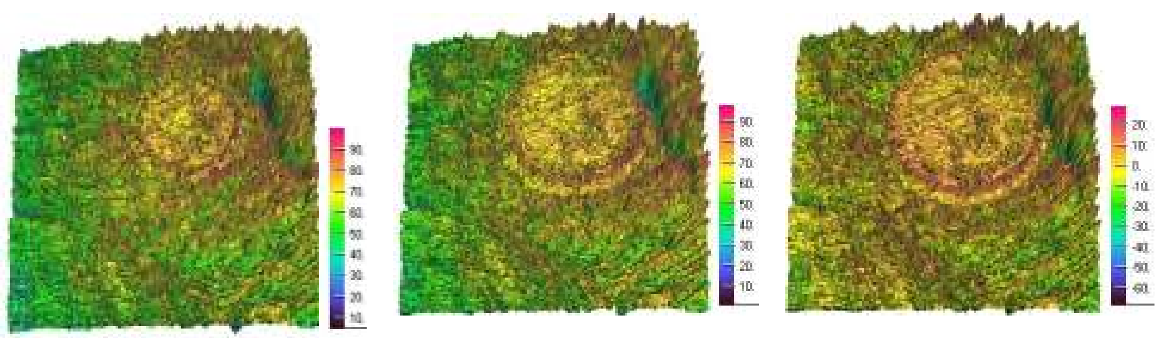
a) 48, 604 *N* c) 140,952 *N* e) 202,517 *N*

Figure 5: 3D representation of surface reflectivity of the contact region for a 4,004*mm* steel ball and a flat sapphire window at various normal load levels



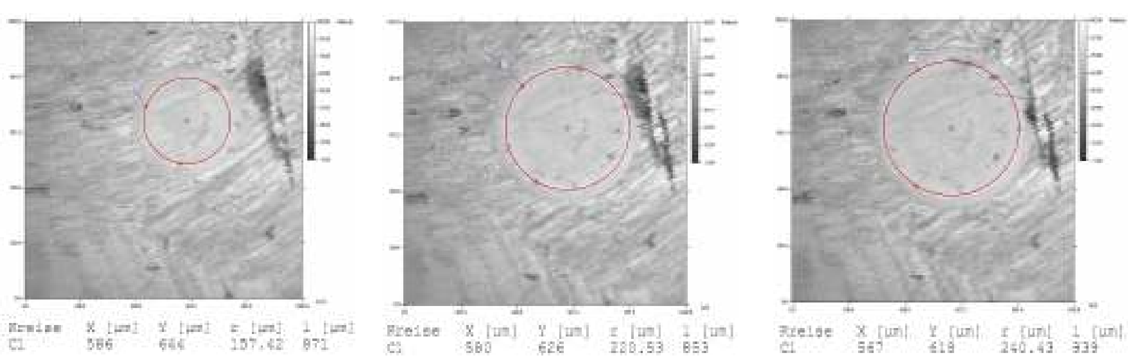
a) 24,302 *N* c) 123,130 *N* e) 179,835 *N*

Figure 6: 3D representation of surface reflectivity of the contact region for a 7,927*mm* steel ball and a flat sapphire window at various normal load levels



a) 116,650 *N* c) 311,066 *N* e) 414,755 *N*

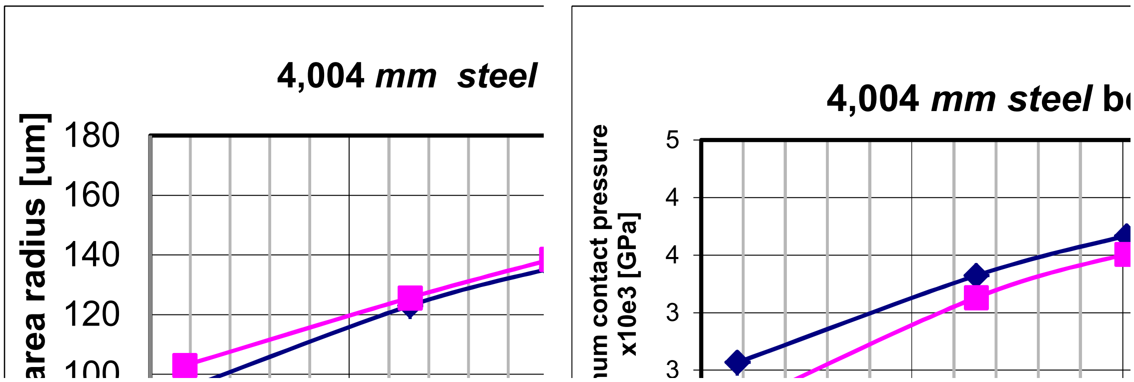
Figure 7: 3D representation of surface reflectivity of the contact region for a 12,775*mm* steel ball and a flat sapphire window at various normal load levels



a) 116,650 *N* c) 311,066 *N* e) 414,755 *N*

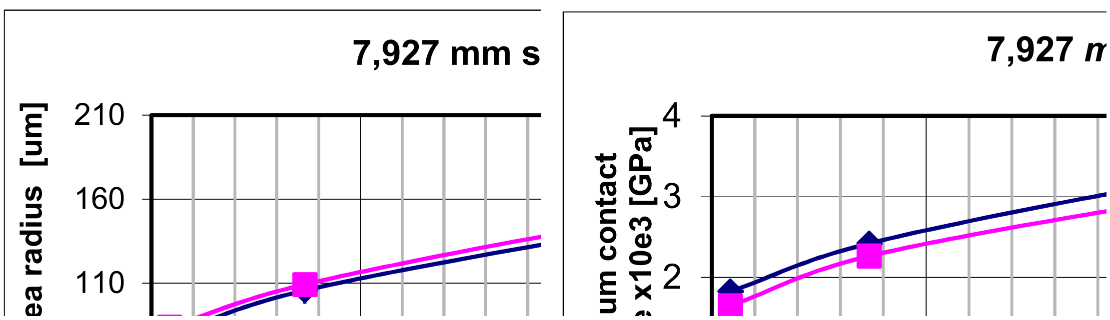
Figure 8: Plane representation by shades of grey for the surface reflectivity of the contact region for a 12,775*mm* steel ball and a flat sapphire window at various normal load levels

Using the experimentally measured contact areas as input data, the corresponding maximum contact pressures were determined. For verification, the experimentally obtained results for contact area radii and maximum generated contact pressures were compared to theoretical values, as illustrated by figures 9-12. The theoretical predictions were obtained by application of the classical Hertz formulae to the experimentally measured surface curvature radii and applied normal forces.



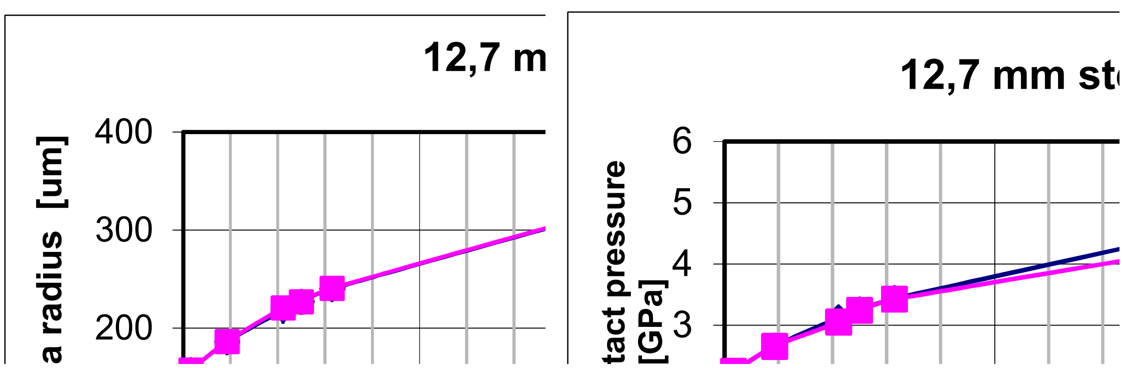
(a) (b)

Figure 9: Contact area radius (a) and maximum contact pressure (b) evolutions with load for the 4,004 *mm* steel ball pressed against a thick sapphire window



(a) (b)

Figure 11: Contact area radius (a) and maximum contact pressure (b) evolutions with load for the 7,927 *mm* steel ball pressed against a thick sapphire window



(a) (b)

Figure 12: Contact area radius (a) and maximum contact pressure (b) evolutions with load for the 12,775 *mm* steel ball pressed against a thick sapphire window

The experimental measurements were compared to theoretical predictions and the mean deviation between the two data sets was plotted against load variation, as illustrated in Figures 13 and 14. It can be noticed that the deviation is more important in the case of small diameter punches subjected to low level loads and it takes lower and almost constant values as dimensions and forces increase. It can be concluded that the employed method is more accurate in the case of larger diameter punches subjected to more significant loads.

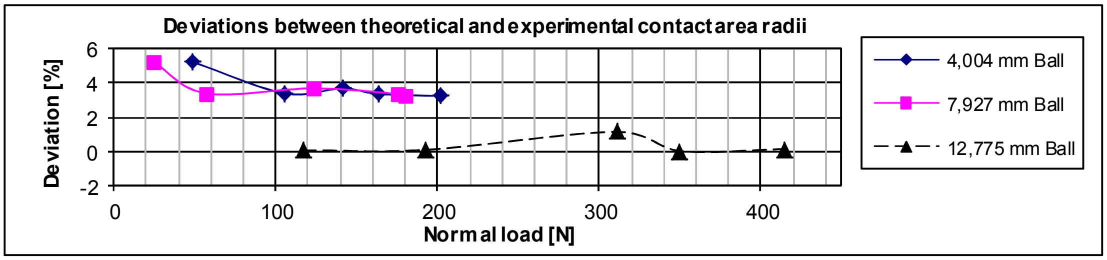


Figure 13: Variation of the relative deviation between theoretical predictions and experimental measurements of contact area radius, plotted against load variation

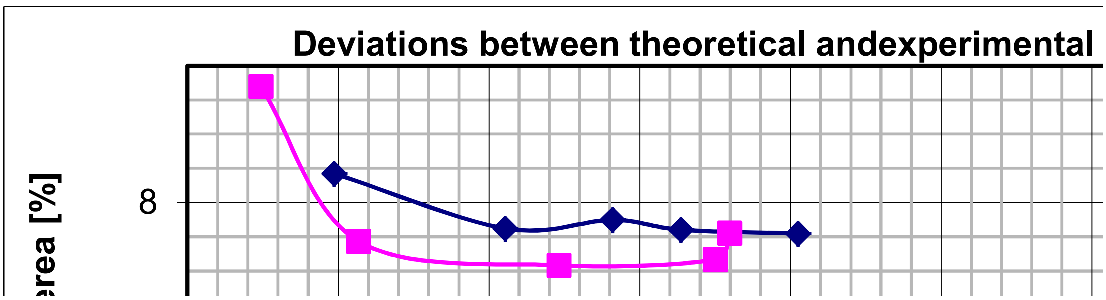


Figure 14: Variation of the relative deviation between theoretical predictions and experimental measurements of maximum contact pressure, plotted against load variation

4. CONCLUSIONS

The experimental investigations presented herein can be summarized by some conclusions, as follows:

- ✓ The present work consisted of investigating spherical punch-flat surface contacts by aid of reflectivity. It was experimentally verified that, as advanced in literature, in the case of a metal-on-sapphire contact, surface reflectivity is lower inside contact area than outside it, which allows for accurate evaluation of contact area shape and dimensions;
- ✓ Several tests were conducted for various punch diameters, and different normal forces. The experimental results can be visualized by aid of either three-dimensional representations or topographic representations in shades of grey of the reflectivity variations corresponding to the contact surface. These plots can be further processed and analyzed using the facilities offered by the profilometer software:
- ✓ After proper systematization of the obtained results, a comparative analysis was conducted between experimental measurements and theoretical predictions upon contact parameters and very good agreement was found.

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