The Simulation of Point Contact Stress State for APS Coatings

D Chicet1, A Tufescu1*, C Paulin1, M Panturu1 and C Munteanu1
1Gheorghe Asachi Technical University of Iasi-Romania, Department of Materials Science and Engineering, Blvd. Mangeron, No. 41, 700050, Iasi, Romania
2Gheorghe Asachi Technical University of Iasi-Romania, Department of Mechanical Engineering, Blvd. Mangeron, No. 43, 700050, Iasi, Romania

E-mail: ana.tufescu@yahoo.com

Abstract. Surface engineering has been conquered in recent decades by the versatility of the layers produced by thermal spraying, both in terms of spraying methods, of the materials types and their applications. In some cases, the coatings can be subjected during operation to rolling contact fatigue, with the main wear factors: thermal spray coatings structure and state of stress and strain in the contact area. In this paper was studied how three types of coatings deposited by APS (Atmospheric Plasma Spray) behaved at the contact fatigue tests. Subsequently they were carried out simulation of pressures and von Mises stresses distribution. It has been observed that the presence of asperities on the surface causes the development of local micro-contacts and therefore high values of pressure and local stresses in the vicinity of the surface.

1. Introduction
Plasma spray coatings have begun to be increasingly used in recent years to improve the life span of key components operating in hostile environments. These coatings act as the “first line of defence” against the usual surfaces degradation mechanisms, such as: wear of any type, corrosion, oxidation, defects caused by overheating and so on [1].

Obtaining a high performance coating on a particular alloy / metal piece with high mechanical strength provides an attractive way to combine surface and track requirements for just about any imaginable application. This concept of surface modification plays an important role in reducing the destruction frequency of relatively costly components [1,2,3].

One of the most common wear-related cases occurs in rolling parts with point-to-point contact - rolling bearings, in which wear is caused by contact fatigue.

It has the following main damage modes in the case of superficial coatings: abrasion wear, spalling wear, inlayer and interfacial flaking [4,5].

In this case, the surfaces of the two tribo-elements (the ball and the bearing ring surface - which represent a class I tribological coupling) are in direct contact with the development of normal and tangential stresses on the surface and in the depth, as well as with local deformation of the surfaces in the contact area.

This tension and deformation state in the contact area can be characterized by applying the theory of elastic contact, established by Hertz, in 1880, according to which, if there is a point or a contact line between two elastic bodies under the influence of the external forces, which are normal on the contact area, on this one appear normal stresses and the conjugated bodies elastically deform.
The hypotheses admitted by Hertz make this theory to maintain its validity today [6,7,8]:
1. the first hypothesis is relative to the shape of the contact field, which is assumed to be elliptical;
2. each body was considered to be an elastic semi-space;
3. the surfaces are considered as ideal, without roughness, between the bodies being transmitted only a normal pressure distribution;
4. although the real contact surface may not be flat, the body idealization by semi-spaces considers that the normal load is transmitted in a direction parallel to the Oz axis, and the tangential border stresses act in the xOy plane.

2. Methods and materials

2.1. Materials
In this paper, the research was carried out on three types of plasma sprayed coatings on a bearing steel substrate with the axial bearing ring geometry (with a 9MBM spray gun), realised using the following powders:
- a tungsten carbide powder with the nominal composition WC10Co4Cr, especially used for applications where both wear resistance (abrasion, erosion, fretting) and corrosion is required at a working temperature of up to 500°C (Test 1 - P1);
- a powder of Ni-based materials with nominal composition Ni 5Al 5Mo, used for high density coatings, high oxidation and corrosion resistance, good wear and erosion resistance, and a low contraction coefficient (Sample 2 - P2);
- a ceramic grade powder with the nominal composition Al2O3 - 13 TiO2, used for abrasion and slipping coatings with good oxidation resistance at working temperatures of approximately 550°C and good behaviour in alkaline or acidic environments (Test 3 - P3).

There were produced three types of axial bearing ring samples coated with the above mentioned layers, with a maximum thickness of 100μm, which were then tested for contact fatigue wear on a specially designed device.

2.2. Methods
In order to evaluate how the coatings underlying this study had behaved in contact fatigue tests and to compare the real and theoretical aspects, a modelling of the pressure and von Mises stress distribution was performed. For this purpose, a program developed in C ++ and Matlab was used [6,8].

In order to increase the efficiency of the numerical algorithm, a computational routine dedicated to the discrete convolution technique and rapid techniques (DC-FFT) for the convolution products specific to three-dimensional elastic contact problems has been developed. The algorithm used admits an elastic behaviour of the material, without imposing the flow limit of the material according to an plastic-elastic behaviour.

To evaluate the samples after the contact fatigue test on ball groove surfaces, they were transversally cut and metallographic prepared by sanding, polishing and reagent attack with a 3% nital solution to see their microstructure.

This was done using an electron microscope Quanta 200 3D, obtaining secondary electron topography images. There were used both the LowVacuum mode at a pressure of 60 Pa with Large Field Detector (LFD) and High Vacuum mode with ETD detector at working distance WD ≈ 14-16 mm and at different magnification (1500x ÷ 16000x).

3. Results and discussions
The distribution graphs were made for each of the three samples, both for the smooth and real contact, using the roughness values of each.

The variables according to which these models were made are: the modulus of elasticity and the roughness represented by the standard deviation, the input and output data being synthesized in table 1 for each of the three samples.
### Table 1. The input and output data for each of the three samples.

| Sample | P1 | P2 | P3 |
|--------|----|----|----|
| **Input data** | | | |
| Normal load per ball, Q [N] | 72,6153 | | |
| Plane, R1 [mm] | 10000 | | |
| Ball radius, R2 [mm] | 8 | | |
| Modulus of elasticity, E1, E2 [MPa] | 1,798·10$^5$; 2,1·10$^5$ | 1,329·10$^5$; 2,1·10$^5$ | 1,46·10$^5$; 2,1·10$^5$ |
| Poisson coefficient, ν1, ν2 | 0,3; 0,3 | 0,3 | 0,7 |
| Roughness Ra [μm] | 0,05 | 0,11 | 0,7 |
| **Output data** | | | |
| Maximum stress, σ0 [MPa] | 1356 | 1207 | 1254 |
| Contact ellipse major semi-axis b0 [mm] | 0,159920 | 0,169472 | 0,16631 |

### 3.1. Sample 1 - P1

In case of sample P1, the distribution graphs are presented in figures 1 - 3. Figure 1 shows the pressures and von Mises stresses distribution in the case of hertzian contact, and it can be observed that von Mises stresses have maximum values at a depth between 0.05 - 0.1 mm (about 850 MPa) and the maximum stress calculated in the Ox plane is $σ0 = 1356$ MPa.

![Figure 1](image1.png)

**Figure 1.** The distribution of pressures and von Mises stresses in the case of smooth contact with P1 surface.

![Figure 2](image2.png)

**Figure 2.** The pressures distributions in the case of the contact smooth ball – rough P1 surface.
In the real case of the contact smooth ball - rough surface shown in figures 2, 3, it is observed that the presence of surface asperities determines the realization of local micro-contacts with contact micro-areas and consequently with high pressure values (as can be seen in figure 2, where the maximum stress in the Ox plan is \( \sigma_0 \approx 3700 \text{ MPa} \)). Thus, local high values are determined, as can be seen in figure 3 in the immediate vicinity of the surface, at a depth of 0 to 6 \( \mu \text{m} \) with a von Mises stress caused by roughness at a depth of 2\( \mu \text{m} \) of about 600 MPa.

It should be noted, however, that at depths corresponding to the maximum value of von Mises stress for smooth contact, the distribution of tensions is practically not influenced by the presence of roughness. This can be seen in figures 2 and 3, and von Mises stresses have maximum values at a depth of 0.05-0.1 mm, about 850 MPa.

Figure 4 shows a detail of the coating microstructure in the superficial area (at a depth of 16 \( \mu \text{m} \)), which is composed of successive layers of sprayed particles, which crystallize under polygonal geometries of different sizes. By correlating with the von Mises stresses distribution graph in figure 3, we can see that in the area where these stresses reach the maximum value (at 2 \( \mu \text{m} \) below the surface) no changes in particle geometry have occurred, but the degree of cohesion between them, which led to material separation (abrasion and spalling wear).

3.2. Sample 2 – P2
In case of sample P2, the distribution graphs are shown in figures 5-7. For sample P2, the pressure and von Mises stresses distribution for the smooth contact is shown in figure 5, where it can be observed that they have maximum values at a depth between 50-100 \( \mu \text{m} \) (about 750 MPa) and the maximum stress determined in the Ox plan is \( \sigma_0 = 1207 \text{ MPa} \).
Figure 5. The distribution of pressures and von Mises stresses in the case of smooth contact with P2 surface.

Figure 6. The pressures distributions in the case of the contact smooth ball – rough P2 surface.

Figure 7. Von Mises stress distribution in case of the contact smooth ball – rough P2 surface.

It is obvious the effect of the surface roughness on the pressure distribution (see figure 6) and the maximum values that can be recorded: $\sigma_0 \approx 8000$ MPa, but also on the von Mises stresses distribution, as can be seen in figure 7. In this figure one can see a maximum of stress recorded near the surface at a
depth of about 2 μm with a value of 1200 MPa. In the case of sample P2, there was a coating delamination in 4 areas of the bearing race. Figure 8a presents the aspect of the coating - substrate interface in the area outside the bearing race, being obvious the influence of the spraying process on the substrate through the yielded temperature at the moment of impact and the high kinetic energy of the sprayed particles. Figure 8b shows the marginal delamination area of the coating with the exposure of the bearing steel substrate (at the bottom of the image).

![Figure 8. Sample P2. Secondary electron images of the: a) coating – substrate contact area (outside the bearing race area, 7700x); b) marginal delamination area of the bearing race, 3000x.](image)

3.3. Sample 3 - P3
In case of sample P3, the distribution graphs are presented in Figures 9-11. For the sample P3, as in the case of the other two samples, it can be seen from figure 9 that in the case of herzian contact, the von Mises stresses have maximum values at a depth of 0.05 - 0.1 mm (about 780 MPa), and on the pressure distribution graphs in the Ox and Oy plans it is observed that they reach a maximum value of $\sigma_0 = 1254$ MPa.

![Figure 9. The distribution of pressures and von Mises stresses in the case of smooth contact with P3 surface.](image)
In the case of the contact smooth ball - rough surface, the roughness effects on the pressure distribution are obvious, with a maximum stress value of $\sigma_0 \approx 4 \cdot 10^4$ MPa, which occurs in the immediate vicinity of the surface, as can be seen in Figure 12, at a depth of 0 to 8 $\mu$m, the maximum of these stresses being at a depth of 6 $\mu$m with a value of 1000 MPa. It is obvious that we are dealing with an area where the maximum values of the von Mises stresses are much higher than the maximum values for smooth contact, the latter being at much greater depths.

![Figure 10](image_url1)

**Figure 10.** The pressures distributions in the case of the contact smooth ball – rough P3 surface.

![Figure 11](image_url2)

**Figure 11.** Von Mises stress distribution in case of the contact smooth ball – rough P3 surface.

![Figure 12](image_url3)

**Figure 12.** Sample P3. Secondary electron images in the superficial area of the: a) coating, in the bearing race area, 3700x; b) coating, outside the bearing race area 2800x.
In figure 12 there are presented details of the coating both in the bearing race area (figure 12 a) and in the outside of the bearing race area (figure 12 b). It is possible to observe the lamellar aspect of the layer and the good cohesion of the splats as resulted after the spraying process. In these images it can also be seen that the von Mises stresses peak (located at a depth of approximately 6 μm according to the graph in figure 11) did not significantly affect the microstructure of the coating.

4. Conclusions
After examining the results obtained by modelling the distribution of pressures and von Mises stresses in the case of hertzian contact and after correlating them with the microstructural images of the samples subjected physically to rolling contact tests, the following observations can be made:
- the lesser the height of the roughness, the more the pressure distribution obtained in the rough contact is closer to the Hertzian distribution;
- at depths corresponding to the maximum value of von Mises stresses for smooth contact, the stress distribution is not influenced by the presence of roughness;
- the presence of asperities on the contact surface determines the realization of local microcontacts with contact micro-areas and consequently with high pressure values, which also cause local high values of stresses;
- the depth distribution of the von Mises equivalent stress highlights the concentrating effect of the stresses on the layer in the immediate vicinity of the surface as a result of the roughness presence;
- in the immediate vicinity of the surface the maximum values of the von Mises stresses are much higher than the maximum values corresponding to the smooth contact, the latter being also located at much greater depths.

References
[1] Suryanarayanan R 1993 Plasma spraying: theory and applications (Singapore; World Scientific Publishing)
[2] Avram P, Imbrea M S, Istrate B, Strugaru S, Benchea S I and Munteanu C 2014 Indian Journal of Engineering and Materials Sciences 21 315-321
[3] Zhong-yu P, Bin-shi X, Hai-dou W and Chun-Huan P 2010 Surface & Coatings Technology 204 1405–1411
[4] Fujii M, Yoshida A, Ma J, Shigemura S and Tani K 2006 Tribology Inter. 39 856–862
[5] Crețu S 2009 Contactul concentrat elastic-plastic (Iași; Ed. ”Politehnium”)
[6] Crețu S and Antaluca E 2003 Analele Universitatii Dunarea de Jos Galati I f VIII (Tribology) 39-47
[7] Crețu S 2006 The Influence of the Correlation Length on Pressure Distribution and Stress State in Concentrated Rough Contacts, Proc. of ASME/ASLEIJTC (track 15, USA)
[8] Urzică A, Bălan R and Crețu S 2009 AMM 52 vol. III 341-346