Morphological and tribological studies of thermal plasma jet deposited coatings used in cardan joints

A Dascălu¹, B Istrate¹, C Munteanu¹*, C Paleu Cîrlan¹ and V Paleu¹

¹Mechanical Engineering, Mechatronics and Robotics Department, “Gheorghe Asachi”
Technical University of Iasi, Iasi, Romania

E-mail: cornelmun@gmail.com

Abstract. All wheels drive (AWD) and railway vehicles require a longitudinal transmission. Double cardan joint is one of the most employed transmission, as it allows misalignments between the shafts. This transmission must support the maximum motor torque and high dynamic loads. In such situation, from tribological viewpoint, cardan joints are subjected to abrasive wear. To increase wear resistance of cardan joints, its rolling elements can be coated with ceramic or metal-ceramic coatings. This paper presents an experimental research on microstructure and dry friction characteristics of two steel samples obtained from cardan crosses (40Cr10 and RUL2), coated by two types of metallic powders (METCO32 and METCO72). Microstructural studies of both surface and cross-section of samples were performed using scanning electron microscopy (SEM). Dry tribological tests at constant speed and load were carried out on AMSLER machine. The microstructural experiments revealed a structure with a relatively homogeneous character, partially melted particles and several micro-cracks being detected. Following the tribological tests, it was found that the METCO72 coating provides the lowest coefficient of friction, near values being obtained for both substrates of 40Cr10 and RUL2. The best combination is formed by 40Cr10 substrate and METCO72 coating.

1. Introduction
Automotive parts suffer frequent failures, their high cost of production and the importance that they have for the good functioning of the vehicle requesting ways to reduce the wear of the parts and to improve their reliability. All wheels drive (AWD) vehicles and railway vehicles require a longitudinal transmission. Double cardan joint is one of the most employed transmission, as it allows misalignments between the shafts. In automotive, this transmission must support the maximum motor torque and high dynamic loads, usually being connected on demand just for off-road climbing. In such situation, from tribological viewpoint, cardan joints are subjected to abrasive wear. For this purpose, such parts can be coated with anti-wear materials by thermal spray coating process.

Thermal spraying deposition is a modern process and it differs from classical methods through the multitude of possibilities of depositing layers of various coatings: metallic, ceramic-metallic (cermet), ceramic, and polymeric. The thickness of such coatings ranges from nanometers to millimeters. [1,11-16].

Atmospheric thermal spray (APS) allows the deposition of any type of powder. In this spraying process, the particles in the thermal spraying beam do not interact with each other, the flux being directed to the target material surface and following an imposed trajectory [2]. Thus, a multi-layer is deposited on the substrate by successive covering layers, the final thickness being defined by the
number of covering layers (5 to 20 layers). The main properties of thermal spray coatings are porosity, hardness, substrate adhesion, modulus of elasticity and mechanical strength [3-4].

Cardan joints are subjected to intensive wear because of severe running conditions: heavy loads, unfavorable lubrication kinematics and abrasive contamination between the sliding surfaces [5-6]. This paper presents an experimental research on surface and cross-section microstructure and dry friction characteristics of two steel samples obtained from cardan crosses (40Cr10 and RUL2), coated by two types of metallic powders (METCO32 and METCO72). Tribological dry friction tests are carried-out on AMSLER machine. Microstructural study of both surface and cross-section of samples are performed using scanning electron microscopy (SEM) and optical microscopy.

To the best of our knowledge, there is no published systematic research on this topic.

2. Materials and methods
For the proper functioning of vehicles’ cardan joints, we are looking for ways to reduce the wear of parts and improvement methods to withstand longer operation. The wear and deformation of spindle surfaces of cardan systems forming the longitudinal transmission of AWD vehicles is one of the main causes of their failure. For the improvement of the wear resistance of the spindles, thermal plasma spray depositions with various coatings was realized. Figure 1 represents some failed cardan joints. In this case, pitting seems to be the main cause of the failure, due to the high stresses, but the uneven functioning of non-homokinetic misaligned double cardan joints creates variable loads as high as the main load [6].

The causes of severe deformations of cardan crosses are described in figure 2.
2.1. Materials
In the study, we have used two faulty cardan crosses: one from a Mercedes Benz transporter and the other from an ARO Romanian vehicle. The composition of the materials was determined by spectral analysis performed using the ARL 3560 type spectrometer (Foundry-Master 01J0013 Optik 01J0013 equipment) from the laboratory of the Faculty of Materials Science and Engineering in Iasi. It was found by spectral analysis, that the material of cardan cross of ARO is RUL2 (Romanian standards) and those of cardan cross from Mercedes Benz is 40Cr10.

All over the paper, the authors denoted the two cardan crosses as cardan cross 1 (40Cr10) and cardan cross 2 (RUL2). For the experimental test on cardan cross 1 there have been used cylindrical samples of 40Cr10 and for the cardan cross 2 - samples made of RUL2.

The chemical composition of the base materials is given in table 1.

| Table 1. Chemical composition of CARDAN 1 and CARDAN 2 samples. |
|-------------------|---|---|---|---|---|---|---|
| Element, %        | Fe | C  | Si | Mn | P  | S  | Cr |
| CARDAN 1          | 98,26 | 0,39 | 0,21 | 0,62 | 0,03 | 0,04 | 0,45 |
| CARDAN 2          | 96,1 | 0,98 | 0,42 | 1,03 | 0,03 | 0,02 | 1,42 |

In table 2, the chemical composition of the two Oerlikon-METCO powders, from certificates of conformity issued by the manufacturer, are given.

| Table 2. Chemical composition of METCO32 and METCO72 powders, in wt. % |
|-------------------|---|---|---|---|---|---|---|---|
| Element           | W  | C  | Co | Fe | Ni | Cr | B  | Si | Others |
| METCO 32C         | 0,5 | 0,5 | 11,5 | 70 | 17,5 | 4 | 4 | 1,0 max |
| METCO 72F         | 81 min | 5,25 | – | 1,5 max |
| NS                | max | 13,0 | |

In the friction tests, carried out on AMSLER machine, the tested upper disks of 30 mm diameter were of 40Cr10 and 100CrMnSi6-4 (according to SR EN ISO 683-17 ) or RUL2 steel (Romanian standard), coated with METCO32 and METCO72 coatings. The lower disk of 60 mm diameter is made of AISI52100 steel (RUL 1), hardness 64 HRC, and roughness Ra=0.4 µm. The hardness of the lower disk is a mean value obtained by measurements on CETR UMT-2 micro-tribometer. It was kept the same lower disk during tests, but after each test it was gently polished and cleaned with acetone.

For a better understanding, all the tested combinations of materials are presented in Table 3.

| Table 3. Materials used in experimental research. |
| Notations | Lower disk | Substrate | Upper disk | Coating |
| TEST 1    | AISI52100  | 40Cr10    | without   |
| TEST 2    | AISI52100  | RUL2      | without   |
| TEST 3    | AISI52100  | 40Cr10    | METCO32   |
| TEST 4    | AISI52100  | 40Cr10    | METCO72   |
| TEST 5    | AISI52100  | RUL2      | METCO32   |
| TEST 6    | AISI52100  | RUL2      | METCO72   |

2.2. Sample preparation
Metallographic sampling must be carried out in such a way that it does not produce changes in the structure of the material. The samples were cut with the following dimensions: plates of 30 x 60 x 2 mm and disks of outer diameter 30 mm, inner diameter 16 mm and thickness 10 mm.
Firstly, the material for the testing samples were chosen according to the Romanian standard for the two cardan crosses: 40Cr10 and RUL2, respectively. Then, according to the manufacturer’s specification, two METCO powders were selected to be used for coating deposition on specimen surfaces: METCO32 and METCO72.

Nowadays, deposition by atmospheric plasma spray (APS) is one of the most effective recommended methods, providing the possibility to deposit layers of various thickness (nm to mm) for a large diversity of materials that can be used to obtain wear-resistant coatings.

The samples were coated by deposition of plasma jet spraying with SULZER METCO 9MCE equipment, using the following parameters: spraying distance 15 cm, 500 A, 63 V, 50 m³/h argon pressure and 70 m³/h hydrogen, injector 1,8 and were done in 5 successive passes.

SEM analysis was performed on specimens coated with METCO32 and METCO72 powders, respectively. The samples were polished and cleaned with foundry, and then they were cut and embedded in a BAK-R resin produced by Metkon. The polishing of the samples was carried out with 7 metallographic papers from the granulation 180-1200. Then the metallographic attack was performed using the Nital reagent, with a concentration of 5% HNO₃.

2.3. Testing equipment

Microstructural analysis was performed on the SEM Quanta 200 3D equipment from the Faculty of Mechanical Engineering from the Gheorghe Asachi Technical University of Iasi, using a LFD detector in low-vacuum mode, with a working distance of 15 mm. An optical microscope Leica DMI5000 M from the Laboratory of Materials Study of the Faculty of Mechanics of the Technical University "Gheorghe Asachi of Iasi was used to obtain optical images. Taylor Hobson profilometer was employed to measure the roughness of the tested disk samples on radial and axial direction.

Tribological friction tests were carried out on AMSLER machine equipped with data acquisition system based on Vishay P3 Strain Gauges Bridge (figure 3a). The testing arrangement is presented on figure 3b.

![Figure 3. General View of AMSLER machine (a), and disks testing arrangement (b) (Image)](image)

3. Results and discussions

3.1. Microstructural and surface analysis results

The results of SEM microstructural analysis is presented in figure 4.
The cause of the internal tensions that appear in the cooling process lead to micro-cracks. These internal tensions result from the uneven contraction during the cooling process. The cracks appear at the interface between the layers and the base material. They are characteristic to APS (Atmospheric Plasma Spraying) process [1, 4].

The morphological aspect of the surface covered with METCO 32, METCO 72 are presented in figure 5. Morphological analysis of the layers present a good adhesion to the substrate, but with the presence of small micro-pores at the substrate and coating interface, the average thickness of the deposited layers being 57.70 μm for METCO32 coating and 127 μm for METCO72. Thicknesses oscillate in layers and can result from the different particle size arrangement during deposition.

Figure 4. Surface morphology analysis by SEM images of METCO32 coated samples at 500X (a) and 2000X (b), and of METCO72 coated samples at 500X (c) and 2000X (d)
Figure 5. Cross-section SEM images of METCO32 coated samples at 500X (a), 1000X (b), and 2000X (c), and of METCO72 coated samples at 500X (d), 1000X (e), and 2000X (f).

In figures 6-7, optical microscopy images of coatings are observed. Similar to SEM images, the coatings are adherent to the base substrates. The base material has a predominant pearlite structure with the appearance of primary and secondary carbides, which give hardness and wear resistance.

Figure 6. Cross-section optical microscopes images of substrates METCO 32: 
(a) 40 Cr 10;  b) RUL2
The components of Co + WC in METCO72 have an important role to the increase in hardness and wear resistance [7]. Sprayed tungsten can form so-called "auto-binders" as it is part of the metal category with high capability to create metallurgical or diffusion bonds. These diffusion bonds are produced locally on small depths of max. 0.5 μm. The METCO32 powder have components Nickel, Chromium and have the role of supporting oxidation and corrosion resistance at high temperatures and increasing the hardness of the coating. Another component, Boron has the role of lowering the melting temperature and helps in the formation of hard phases, especially with Ni- Ni₃B [7-9], it increases the hardness of the coating. Silicon is added to increase the self-fluxing properties of the exposed alloy.

3.2. Tribological investigations results

The roughness of the disks on radial and axial direction, measured on Taylor Hobson profilometer, are shown in table 4.

| Disk substrate | Coating   | Roughness Ra (µm) | Radial | Axial |
|----------------|-----------|-------------------|--------|-------|
| 40Cr10         | without   | 1.96              | 5.40   |
| RUL2           | without   | 0.37              | 2.23   |
| 40Cr10         | METCO32   | 7.54              | 5.77   |
| 40Cr10         | METCO72   | 5.97              | 9.49   |
| RUL2           | METCO32   | 5.55              | 7.69   |
| RUL2           | METCO72   | 4.43              | 7.43   |

All information regarding sensor calibration, friction torque measurement, friction coefficient computation, and LabVIEW data acquisition program are described in [10].

Tribological friction results were obtained from tests carried out on AMSLER machine (figure 3). The tests were performed in a dry environment, without lubrication, at a constant speed of 100 rpm at constant load of 20 N and running time of each test was 10 minutes. Due to contact between the roughness of the surfaces, measured values of friction torque manifested during experiments with high oscillations, this being specific to dry friction. From this reason, figure 8 presents just linear trend approximation of the friction torque evolution during tests, as the real curves were superposed because of their oscillating nature.
Studying the variation of the friction torque (figure 8) and the computed mean values of friction coefficient (figure 9), one can be deduced that METCO72 coating provides the lowest coefficient of friction, and the values keep close no matter the substrate (40Cr10 or RUL2).

Table 5. Values of friction coefficient (COF).

| Material | TEST 1 | TEST 2 | TEST 3 | TEST 4 | TEST 5 | TEST 6 |
|----------|--------|--------|--------|--------|--------|--------|
| COF      | 0.228  | 0.216  | 0.256  | 0.184  | 0.260  | 0.182  |

Figure 9 and table 5 show the average values for the coefficient of friction (COF) reported during the tests. Low COF values were obtained for METCO72 coatings and high values of COF were found for METCO32 coatings. Anyway, the combination of 40Cr10 substrate and METCO72 coating seems to be the best possible (TEST 4), as friction torque kept almost constant during the whole test span and the mean COF has low value.
4. Conclusions
Cylindrical samples from cardan crosses made of 40Cr10 and Ru12 steels were coated by APS process with METCO 32 and METCO 72 powders. Both the coated surfaces and cross sections of the deposited coatings were morphologically analyzed by SEM and optical microscopy.

The coatings proved good adhesion to the substrate, but with the presence of small micro-pores at the substrate and coating interface, the average thickness of the deposited layers being 57.70 μm for METCO32 coating and 127 μm for METCO72. Variable thicknesses of coating layers resulted from the arrangement during deposition of various particles with different size. Cracks appeared at the interface between the layers and the base material. They are characteristic to APS deposition technique, being the result of internal tensions from uneven contraction during the cooling process.

In order to find the best combination between two base metallic materials and two different coatings from tribological point of view, tribological test were carried out at constant load and speed on AMSLER machine in dry environment. The friction tests in dry conditions prove that the best combination of substrate and coating is that using METCO72 on 40Cr10, a constant coefficient of friction during test being evidenced for this case. The least values of COF are obtained for METCO72 coatings.

Further tests will focus on grease lubricated contacts, as in real functioning of cardan joints.

References
[1] Pawlowski L 2008 The Science and Engineering of Thermal Spray Coatings - 2nd ed. (New York: Wiley)
[2] Niranatulumpong P and Koiprasert H 2010 The effect of Mo content in plasma–sprayed Mo-NiCrBSi coating on the tribological behavior, Surfaced & Coatings Technology 205 (2) pp 483-489 doi:10.1016/j.surfcoat.2010.07.017
[3] Torres B, Campo M and Rams J 2009 Properties and Microstructure of Al-11Si/SiCp Composite Coatings Fabricated by Thermal Spray, Surfaced Coatings Technology 203 (14), pp 1947-1955
[4] Gell M, Jordan E H, Sohn Y H, Goberman D, Shaw L and Xiao T D. 2001 Development and implementation of plasma sprayed nanostructured ceramic coatings Surf Coat tech 146-147 pp 48-54
[5] Krause H and Hammel C 1984 The wear behaviour of copper alloy-steel and polyamide-steel sliding pairs for heavily loaded cardan joints WEAR (93) pp 127-143
[6] Vesali F, Rezvani M A and Kashfi M 2012 Dynamics of universal joints, its failures and some propositions for practically improving its performance and life expectancy Journal of Mechanical Science and Technology 26 (8) pp 2439-2449
[7] Axinte C, Avram P, Bârcă E S, Istrate B and Munteanu C, Comparativ studies of corrosion resistance on 21TMC12 steels uncoated and coated with WC-Co-Cr. 2012 Buletin IPI. Tom LVII(LXI) Fasc. 2, Sectia Constructii de masini
[8] Jin H, Park C and Kim M 2001 In situ TEM heating studies on the phase transformation of metastable phases in Fe–Cr–B alloy spray coatings, Materials Science and Engineering A304-306 pp 321–326
[9] Zhang X C, Xu B S, Xhau F Z, Tu S T, Wang H D, and.Wu Y X, Porosity and Effective Mechanical Properties of Plasma-Sprayed Ni-based Alloy Coatings, Appl. Surface Sci., 2009, 255(8), pp 4362-4371
[10] Paleu V, Georgescu S, Baciu C, Istrate B and Baciu E R 2016 Preliminary experimental research on friction characteristics of a thick gravitational casted babbitt layer on steel substrate, IOP Conf. Series: Materials Science and Engineering 147 012028 doi:10.1088/1757-899X/147/1/012028
[11] Nicolae N, Robert C, Octavian T and Iulian AV 2019 Materials for automotive industry and their influence on the dynamics of a car crash, Journal of Engineering Studies and Research
25 (2) 25-32

[12] Navodariu N, Branzei M, Ciocoiu R, Ciuca I and Coman R 2019 Effect of Local Heating on the Mechanical Characteristics of Repaired Automotive Panels, *Materiale Plastice* **56** (4) 750-758

[13] Matei AA, Pencea I, Stanciu SG, Hristu R, Antoniac I, Ciovica E, Sfat CE and Stanciu GA 2015 Structural characterization and adhesion appraisal of TiN and TiCN coatings deposited by CAE-PVD technique on a new carbide composite cutting tool, *Journal of Adhesion Science and Technology* **29**(23) 2576-2589

[14] Branzei M, Pencea I, Matei AA, Sfat CE, Antoniac I, Turcu RN and Manoliu V 2017 Influence of high temperature exposure on the adhesion of a micro-composite refractory enamel to a Ni-18Cr-12W superalloy, *Journal of Adhesion Science and Technology* **31**(23) 2555-2570

[15] Cimpoesu N, Gurlui S, Bulai G, Cimpoesu R, Paun VP, Irimiciuc SA and Agop M 2020 In-situ plasma monitoring during the pulsed laser deposition of Ni60Ti40 thin films, *Symmetry* **12**(1) 5605

[16] Florea CD, Munteanu C, Cimpoesu N, Sandu IG, Baciu C and Bejinariu C 2017 Characterization of advanced ceramic materials thin films deposited on Fe-C substrate, *Revista de Chimie* **68** (11) 2582-2587