A comparative study on tribological behavior between metal and polymeric composites used to repair bronze made parts in dry reciprocating sliding tests

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Abstract. The paper presents the researches on tribological behaviour of two materials used for parts subjected to friction, under dry sliding conditions. The composite material is a product of the company Diamant Metallplastic GmbH, Germany and the manufacturer recommend it for repairing or reconditioning worn or damaged bronze made parts. The material belongs to Multimetall category, which is a highly resistant 2-component repair system. This polymer composite material was tribologically tested in dry friction reciprocating conditions, in ball-on-flat configuration, using the tribometer UMT-2 (Bruker, former CETR). The counterpiece was a steel ball. Typical test conditions were as follows: normal loads of 20, 30, 40 and 50 N, sliding distance of 100 m, stroke length of 5 mm, average sliding speed of 3.5 mm/s, room temperature and relative humidity of 50-60%. After testing, wear tracks were examined by electronic microscopy (SEM), laser profilometry and the profilometric module of the tribometer CETR-UMT-2. The results of the composite material analysis were compared with the similar ones obtained under similar test conditions for the bronze (metal material).

1. Introduction
Researches carried out on polimeric composite materials have shown the advantages of using them in several different areas: automotive industry, manufacturing, shipbuilding, oil and gas industry, foundries, chemical industry, pump construction, housing construction etc [1, 2, 3, 4, 5, 6]. By reinforcing plastic materials with fibre or metallic particles, polimeric composites with remarkable properities were obtained, properities such as: low density, good stiffness, higher strength/ density ratio, low friction coefficient, good surface quality, etc. [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17].

Due to some advantages such as easy molding processing, good adhesion to metal surfaces and development of functional surfaces without machining, polymer composites reinforced with fibers or particles are used in repairing metal parts [15, 16, 17].

Composite materials are frequently used for replacing expensive and energy consuming metallic materials. Lately, the fields of application for these materials have expanded in areas such as: automotive maintenance and repair, machine manufacturing, steel industry, etc. [1, 2, 3, 4].

Tribological tests of composite materials are carried out using different methods in various test configurations, such as ball-on-flat test configuration in reciprocating dry sliding [7, 8, 9, 10, 11].
the mentioned papers, the variation of friction coefficient and surface morphology are presented, depending on parameters such as: loading force, sliding distance, test duration, movement frequency.

In the papers [12, 13] the results for tribological tests are presented. The tests were carried out on a few polymeric composite materials. In many papers, the topography of wear traces is used as an indicator of wear behavior for the tested material [14]. Surface topography is studied using digital profilometers and microscopic analysis.

2. Experimental procedure

2.1. Materials’ properties

Tribological research presented in this paper were performed on samples made from two materials: 1. composite material (code SBC) used for the correction and repairing of defects of bronze work pieces and 2. bronze – metallic material (code SB).

The composite material is produced by the German company "Diamond Metallplastic GmbH" [5]. In the epoxy matrix, particles of Cu, Zn, Sn and various allotropic forms of SiO\textsubscript{2} are introduced. Composite consists of two components: the epoxy resin and the hardener supplied in the correct quantities recommended by the producer. The components are mixed and then applied with spatula on the specially manufactured metallic surfaces of samples.

Before the testing, the active surfaces were cleaned, washed and dried (approx. 18 h) [5]. After drying, surface of samples was manufactured by machining.

The main characteristics of the composite material are shown in Table 1.

| Material code | Tensile Strength [MPa] | Compressive Strength [MPa] | Bending Strength [MPa] | Shear Strength [MPa] | E-Modulus [MPa] | Hardness [Shore D] | Specific Weight [g/cm\textsuperscript{3}] | Temperature Resistance permanent [˚C] | Temperature Resistance temporary [˚C] |
|---------------|------------------------|-----------------------------|------------------------|----------------------|----------------|------------------|------------------|----------------------------------------|----------------------------------------|
| SBC           | 62                     | 155                         | 79.5                   | 16.5                 | 5800           | 86               | 2.2              | -32 to +160                           | +350                                   |

The metallic material (bronze) has the mechanical characteristics shown in Table 2 and the roughness parameters presented in Table 3.

| Material code | Tensile Strength $R_m$ [MPa] | Yield Strength $R_{p0.2}$ [MPa] | Elongation at Break $A_5$ [%] | Brinell Hardness HB | Specific weight [g/cm\textsuperscript{3}] |
|---------------|-------------------------------|---------------------------------|-----------------------------|-------------------|------------------|
| SB            | 506                           | 405                             | 12                          | 134               | 7.6              |

Table 3 The roughness of samples.

| Material code | $R_a$ [μm] | $R_q$ [μm] | $R_t$ [μm] | $R_{sk}$ [-] | $R_{ku}$ [-] |
|---------------|------------|------------|------------|-------------|-------------|
| SBC           | 1.81       | 6.67       | 32.68      | -3.72       | 25.33       |
| SB            | 0.32       | 0.42       | 3.66       | -0.18       | 4.90        |

The final dimensions of the samples were $\Phi76\times7$.

The counterpiece was a steel ball (AISI 52100 GCr15, grade SKF like) with a diameter of 6 mm and hardness of 80HRC. The surface roughness was about $R_a=0.06$ μm.
2.2. Experimental setup and procedures

For carrying out the tests, the reciprocating module of UMT-2 tribometer was used. The reciprocating tests were conducted in accordance with ASTM G133-05 standard [18], at temperatures between 20 and 26 °C and a relative humidity of 50-60%. For the loading force four values were used: 20, 30, 40 and 50 N. The other test parameters were: the stroke length - 5mm, the sliding distance - 100 m and the test duration - 475 min. Before testing, the samples were cleaned with an organic solvent and then dried in hot air (50 °C).

Tribometer software provided the following parameters: coefficient of friction (μ) and the depth of linear wear (Uₜ), measured for the two materials for all load forces.

After testing, the wear traces were studied using the μSCAN profilometer (®NanoFocus) and analyzed with SPIP software (™ Image Metrology, Hørsholm) and with the UMT-2 tribometer profilometric module.

Data acquisition of the digital profiles for 2D profilometric analysis was made in three cross-sectional profiles at the distance of 2 mm from each other: i – inside, e – outside of the disc and m – middle of the disc (figure 1). Also, the 3D profile for the 40 N and 50 N load force was obtained, in the case of the two materials (figure 9 and 10).

The profilometric analysis was carried out by using following parameters: (a) average cross sectional area and (b) average width of the profile of wear tracks. The measured area is up limited by the highest peaks of adjacent points of the profile and below by the lowest point of the profile.

Investigations on images were carried out with Quanta 200 SEM (®FEI Co., Czech Republic) and the optical microscope Neophot-2 (®Carl Zeiss, Germany).

3. Results and discussions

3.1. Variation of the coefficient of friction

Figure 2 presents the variation of the coefficient of friction (COF) during the tests of the composite material (code SBC) and bronze (code SB). The graphs have been constructed by plotting the acquired data for the sampling interval of 1/10s. In the case of the composite material (code SBC), the variation of the coefficient of friction shows three stages for all four loading forces (figure 2a). In all three stages, the friction force increases with the increasing of the loading force:

- COF increases linearly in the first stage, the rate having higher values at higher load forces; in the second stage there is a rapid increase of COF about 3-4 times, and in the third stage of COF variation one could observe the lowest rate. In this stage the instability of the process is higher comparing with the other stages;
- in contrast to the first and second stages, in the third stage the rates of variation of the coefficient of friction are comparable.

Studying the variation of COF for bronze (code SB) (figure 2b) significant differences comparing to the composite material are observed:

- a sharp increase in first stage of the variation of COF (on a length of approx. 1-2 m) was observed; then COF increases at a rate slightly bigger than for the composite material, regardless of loading force;
- bronze friction behavior is similar for all the range of loading forces.

Figure 1. Graphical modeling of wear tracks [15].
Figure 2. Variation of the coefficient of friction (F=20, 30, 40 and 50N, Lf=100m): a) composite material for bronze (code SBC); b) bronze (code SB).

Figure 3 presents the variation of the average COF (calculated as the average of the values acquired over the last 25 m of the length of friction). One could observe that the two materials (composite material (code SAB) and bronze (code SB)) have the average coefficient of friction about the same. This observation could recommend the using of composite material in reconditioning bronze metal parts.

Figure 3. Variation of the average coefficient of friction (F=20, 30, 40 and 50N, Lf=100m): a) composite material for bronze (code SBC); b) bronze (code SB).

3.2. Variation of the linear wear

Figure 4 shows the variation of the linear wear (values directly obtained from the testing equipment). For the composite material (figure 4a), two stages of the evolution of linear wear could be observed. In a first stage, linear wear rate has a very small increasing, bigger for the increasing load forces. Also, the length of this first stage decreases with the increasing of the load force. An explanation could be the occurring of more contact points between the reinforcement particles of the composite and the spherical surface of the counterpart.

In the second stage the linear wear has a rapidly increasing, at rates that increase with increasing of the force. It follows a slowly decreasing of the rate of linear wear increasing, due to the flattening of the peaks and the polishing metal particles embedded in the composite material structure.

For the metallic material (code SB) linear wear increases, with relatively constant rates (figure 4b).
In this case the higher rate is observed at the end of the range of applied forces. The values of linear wear for the studied friction length (100 m) are higher in the case of the composite material (code SBC) comparing to the metal (bronze, code SB).

![Graph showing linear wear vs. force](image)

**Figure 4.** Variation of linear wear (F=20, 30, 40 and 50N, L_f=100m): a) composite material for bronze (code SBC); b) bronze (code SB).

3.3. Variation of volumetric wear

Some parameters related to the wear volume were calculated, taking into account the material loss volume, V1 (figure 1) on the cylindrical part of wear track ([18]):

- wear volume (V) [18]:

\[ V = A \cdot s \] (1)

- wear intensity (I_v) [6,19]:

\[ I_v = \frac{V}{L_f} \] (2)

- specific wear rate coefficient (k) [6]:

\[ k = \frac{V}{F \cdot L_f} \] (3)

where:

- \( A_w \) - average cross-sectional area of wear track;
- \( L_f \) - stroke length, mm;
- \( F \) - normal loading force, N.

The average cross-sectional area of the wear track (A) has been calculated as the average of the three areas of sections A_1, A_2 si A_3. Areas A_i were determined based on measurements made with the laser profilometer:

\[ A = \sum_{i=1}^{3} A_i \] (4)

The figure 5 shows that for load forces up to about 43N, composite material has lower values of volume wear than bronze. For repairing bronze parts, composite material can be recommended, but only for forces smaller than 43N.
3.4. Profilometric studies

The results of the processing of 2D digital profiles of wear tracks for the two materials are presented in figure 6.

![Figure 6](image)

**Figure 6.** Profiles (2D) for the loading forces 20÷40N and \( L_f = 100m \):

a) composite (code SBC); b) brass (code SB).

It can be observed that the composite material behaves better than bronze at lower loading forces (20N and 30N). The width and the depth of wear tracks are larger in the case of bronze. For high load forces (40N and 50N), 2D-profiles wear tracks of the two materials are comparable, previously mentioned parameters having almost similar values. At higher loading force 50N, the both parameters of cross-sectional area are higher in the case of the composite material.

Also, analyzing the values of cross-sectional area and of the width of wear tracks, one could observe that both parameters have increased considerably in the case of the composite material comparing to bronze (figure 7 and figure 8).

Figures 9 and 10 present the 3D profiles of the wear tracks for both materials, for the load forces of 40N and 50N.

Figures 11 and 12 present the 3D plots of the wear track for the composite material and for bronze, respectively, for a scanned area of 0.5x0.5 mm.

In figure 11, for the composite material, it can be observed small and smooth hallows, which can become bigger and bigger, once the load force increases. In the case of bronze, scratches and furrows can be observed (figure 12), once the load force increases. Also, it can be observed that for higher loading forces, particles of material are ripped apart. It can be concluded that the dominant wear
mechanism in the case of composite material is the adhesive wear, and for bronze the dominant wear mechanism is the abrasive wear.

![Figure 7. Variation of the cross sectional area of the track vs. loading force.](image1)

![Figure 8. Variation of the width of the track vs. loading force.](image2)

![Figure 9. Wear track (3D plots) for the composite material, for two values of the loading force: a) F=40N; b) F=50N.](image3)

![Figure 10. Wear track (3D plots) for the bronze, for two values of the loading force: a) F=40N; b) F=50N.](image4)

![Figure 11. Details of the wear track for the composite material (code SBC) for four values of the load force: a) F=20N; b) F=30N; c) F=40N; d) F=50N.](image5)
Figure 12. Details of the wear track for the bronze (code SB) for four values of the load force: a) F=20N; b) F=30N; c) F=40N; d) F=50N.

To highlight the wear phenomena, the wear traces were studied with the Quanta 200 SEM and the optical microscope Neophot-2. In figure 13 images of wear tracks for composite material (code SBC) and bronze (code SB), obtained with the optical microscope Neophot-2 are presented.

Figure 13. Microscopic image magnitude x12,5 (F=30 N, Lₕ=100m) a) composite material for bronze (code SBC); b) bronze (code SB).

Figure 14. SEM images obtained with Quanta 200 SEM, magnitude 1000, F=30 N, Lₕ=100m: a) composite material (code SBC); b) bronze (code SB).
Images emphasize phenomena of particles’ conglomeration for the composite material, metal particles and traces of their dislocation (figure 14a).

In the case of bronze, one could observe the effects of the dominant wear mechanism, abrasive wear (figure 13b) but also small area of bonding material, as effects of delamination wear on the metal surface (figure 14b).

4. Conclusions

In the present paper, the authors meant to develop a comparison between a metallic particles reinforced polymer composite and a metallic material, both frequently used in technical applications.

The aim of this work was a comparative study of the wear and the topography of wear tracks of two materials, composite material and bronze.

The results of testing both materials, in dry friction reciprocating ball-on-flat conditions, show:
- composite material has tribological characteristics similar to those of bronze and can be used for reconditioning of bronze;
- adhesive wear is the dominant wear mechanism for the composite material, covering also the abrasion wear;
- for bronze, the dominant wear mechanism is abrasive wear, in the presence of some effects of adhesive wear;
- for loading forces up to 40N, the polymer composite material behaves better than bronze, presenting lower values for depth, width and area of wear tracks;
- for loading force 40N, both materials have a similar wear behavior;
- for the highest loading force of 50N, bronze has a better wear behavior than the polymer composite material.

References

[1] Brydson J A 1999 Plastics Materials Seventh Ed. (Oxford: Butterworth-Heinemann)
[2] Crawford R J 1998 Plastics engineering Third Ed. (Oxford: Butterworth-Heinemann)
[3] Friedrich K 1993 Advances in composites tribology Composite Materials Series 8 (Amsterdam: Elsevier)
[4] Ashby M F and Jones D R H 1998 Engineering materials 2: an introduction to microstructures, processing and design Second Ed. (Oxford: Butterworth-Heinemann)
[5] *** Cold welding: top quality connection without thermal stress available at http://diamant-polymer.de/en/products/ultametal/ (14.03.2016)
[6] Stachowiak G W 2005 Wear – Materials, mechanisms and practice (Hoboken: John Wiley & Sons)
[7] Li J and Xia Y C 2009 The reinforcement effect of carbon fiber on the friction and wear properties of carbon fiber reinforced PA6 composites Fiber. Polym. 10 519-525
[8] Li J and Cheng X H 2007 Effect of rare earth solution on mechanical and tribological properties of carbon fiber reinforced thermoplastic polyimide composite Tribol. Lett 25 207-214
[9] Li J and Li X Z 2010 Evaluation of the tribological properties of carbon fiber reinforced poly(vinylidene fluoride) composites J. Mater. Eng. Perform. 19 1025-1030
[10] Li J and Sheng X H 2010 The effect of PA6 content on the mechanical and tribological properties of PA6 reinforced PTFE composites J. Mater. Eng. Perform. 19 342-346
[11] Nie W Z, Li J. and Li X Z 2010 The addition of carbon fiber on the tribological properties of poly(vinylidene fluoride) composites Fiber. Polym. 11 559-564
[12] Olea-Mejia O, Brostow W and Buchman E 2010 Wear resistance and wear mechanisms in polymer + metal composites J. of Nanosci. Nanotechno. 10 8524-30
[13] Myshkin N K, Petrokovets M I and Kovalev A V 2005 Tribology of polymers: adhesion, friction, wear, and mass-transfer Tribol. Int. 38 910–921
[14] Lee J H, Xu G H and Liang H 2001 Experimental and numerical analysis of friction and wear behavior of polycarbonate Wear 251 1541–56
[15] Iliuţă V, Rîpă M, Preda A and Andrei G 2005 Friction and wear behavior of moglice polymer composite through dry sliding ball-on-flat reciprocating test Applied Mechanics and Materials 808 137-142
[16] Iliuţă V, Preda A, Andrei G and Bîrsan I 2014 Wear assessment of polymer composite filled with metal particles through ball-on-flat reciprocating test Mater. Plast. 51 (4) 359-362
[17] Iliuţă V, Rîpă M, Andrei G, Preda A, Suciu C and Javorova J 2014 profilometric evaluation of the worn surfaces under dry reciprocating wear conditions of a composite material to repair brass made parts Applied Mechanics and Materials 657 437-441
[18] *** ASTM G 133–05 Standard test method for linearly reciprocating ball-on-flat sliding wear
[19] Rîpă M and Deleanu L 2008 Deteriorări in tribosisteme (Galaţi: Ed. Zigotto)