Investigation of the abrasion resistance of stainless-steel composites with Al$_2$O$_3$ reinforcement phase produced by using the capillary forming method

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Abstract. The present paper is relevant with the production and investigation of abrasion resistance of MMCs (Metal Matrix Composites) with metal matrix AISI 304 stainless steel and Al$_2$O$_3$ reinforcement phase. An innovative production method is used for the obtaining of the MMCs by using the conception of the “capillary forming”, where the metal matrix (AISI 304) was forcedly infiltrated in the space between the reinforcement phase (Al$_2$O$_3$) particles by vacuuming the space between reinforcement particles. A weighting method is used to determine the wear resistance by radial load in liquid and dry friction mode. The dynamics of mass variation in the wear process and the wear intensity are determined.

1. Introduction

Metal matrix composites (MMCs) reinforced with hard ceramic particles have received considerable interest because they can offer relative ease of treatment and better mechanical properties compared to fiber-reinforced composites. MMCs are increasingly used as construction materials for industrial applications requiring high strength and wear resistance compared to other monolithic materials. Composites of Fe-C alloys, reinforced with ceramic particles such as carbides and oxides, are widely used to make tools, matrices, wear-resistant and corrosion resistant products [1, 2, 3].

Composites with metal matrix AISI 304 stainless steel and Al$_2$O$_3$ reinforcement phase, which are obtained by the technology for obtaining multiphase MMCs with controlled geometry of the reinforcing phases and a metal matrix different from the conventional methods known so far, have been investigated [3]. First of all, in all known technologies for obtaining MMCs, there are no variants for their production in disposable moulds [4, 5]. The other major point is that MMCs are produced as a result of the forced infiltration of the melt into the capillary spaces between the reinforcement phase elements by vacuum moulding using the advantages and potentials of the patent-protected capillary forming method [6].

Stainless steels, particularly austenitic, have better corrosion resistance but have relatively low wear resistance due to their low hardness. The hardness of stainless steels can be greatly increased by the addition of hard ceramic particles, making them the preferred wear-resistant and corrosion-resistant materials used in the mechanical, mining and chemical industries [1]. This circumstance implies that the present work should focus on the wear-resistance study of MMC with metal matrix AISI 304 stainless steel and Al$_2$O$_3$ reinforcement phase in liquid and dry friction mode.
2. Exposition
The purpose of the conducted tests was to determine the abrasion wear resistance of the MMC (metal matrix AISI 304 stainless steel and Al₂O₃ reinforcement phase), obtained in cement expendable moulds by innovative technology based on the capillary moulding method. For a more accurate wear assessment, the following criteria were analysed: structural changes, wear kinematics, alteration in the size and shape, and weight alteration.

The MMCs obtained by this method are of the "in vitro" type. The method is also economically effective for the preparation of single work-pieces by using conventional methods for making casting moulds and synthesizing the tested MMCs in them. In the specific case, a moulding mixture of quartz sand and cement was used to make the moulds.

2.1. Production of the investigated MMCs
The tested composite consisted of 43% AISI 304 (metal matrix) and 57% Al₂O₃ particles (reinforcement phase). The Al₂O₃ particles were irregular in shape with a size of 2.5 - 3.5 mm.

In the classical method for preparing „in vitro“ composites, a mechanism is applied to forcefully introduce the reinforcement phase into the prepared melt followed by homogenization of the composite structure. In the specific case, the mixing of the matrix with the reinforcement phase was carried out on the principle of capillary molding. First, the reinforcing phase (Al₂O₃) was poured into the mould, and then the metallic matrix (AISI 304 stainless steel) in the form of melt, was infiltrated forcefully into the spaces between the metal pellets by vacuuming [4,5]. In order to accomplish the given task, a laboratory system was developed, the schematic representation of which is shown in figure 1.

![Figure 1. A general view of the MMCs production chamber](image)

The main element in this schematic representation is the developed chamber where the vacuuming of the chamber is carried out in three directions. This is achieved by perforating the flask of the cement casting mould, figure 2. In this way, the pressure along the side surfaces of the mould becomes equal to the pressure on the bottom surface, which gives an extra compaction to the melt and to the components making up the composite.

The casting mould is placed in a laboratory assembly for MMC obtaining and heated to 1200°C. After reaching this temperature, the melt from (AISI 304 stainless steel is added (overheated to 1500°C). The melt self-hermetizes the system and is forcefully infiltrated into the capillary spaces of the reinforcement phase (Fe) with a pressure \( \Delta \rho = p_a - p_v \) (figure 1). The atmospheric pressure acts over the melt, but the pressure under the melt is lower, because the space in this zone is connected to the vacuum.
system. The composite obtained by this method is cylindrical in shape and its sizes are $\varnothing 30$ mm and $h = 60$ mm (figure 3).

2.2. The methodology of abrasion wear study
The tests were conducted in conditions as close to the real ones as possible by using the laboratory stand shown in figure 4. A weighting method was used to determine the wear resistance of the sample by radial loading under semi-dry friction conditions. The test sample was pressed against the counterbody 2 at a force of 20 N. By using a frequency converter, the revolutions of the counterbody and the corresponding wear path were adjusted. As abrasive material was used water sandpaper P220, which was mounted on the disk of the removable stand. The disk moved at a speed of 100 rpm. The mass of the sample was measured initially, and then at every 25 minutes, by using electronic scales with accuracy up to 0.001 g. For a better basis of comparison while studying the changes in the properties of the obtained composite, a sample was made which was analogous in the form and made of the same alloy from which the matrix (AISI 304) was built up.

![Figure 2. The perforating flask of the cement casting mould.](image)

![Figure 3. The obtained MMC.](image)

The methodology of abrasion wear study consists in measuring the mass wear $m$ of each sample along a specific friction path $L$ (number of friction cycles) and calculating the wear intensity $V$ by the formula (1) [7, 8, 9, 10]:

$$V = \frac{\Delta m}{L} \text{ [g/m]}$$

(1)

where: $\Delta m$ - change in the mass of the sample; $S$ - the friction path of the surface area during the wear test,

$$\Delta m = m_1 + m_2 \text{ [g]}$$

(2)
where: \( m_1 \) - mass of the sample at the beginning of the test, mg; \( m_2 \) - mass of the sample (roll, sector at the end of the test)

\[
L = \pi D \omega t \ [m]
\]  
(3)

where: \( D \) - diameter of the disc; \( \omega \) – number of revolutions of the friction disc per minute; \( t \) – total test time in min. Wear resistance \( E \) is a reciprocal value of the wear intensity (4), and the relative wear resistance \( \varepsilon \) is determined by the dependence (5)

\[
E = \frac{1}{v} \ [g/m]
\]  
(4)

\[
\varepsilon = \frac{E}{E_r} \ [g/m]
\]  
(5)

where: \( E \) – wear resistance of the friction surface, \( E_r \) – wear resistance of the friction surface of a reference sample).

3. Results and analysing

With the above-described lab assembly, samples were obtained of complex-configuration MMC with metal matrix AISI 304 and \( \text{Al}_2\text{O}_3 \) reinforcement phase of “in vitro” type, from which samples were made for macro and microstructural analysis. Structural changes were studied, as well as size, shape and weight changes after abrasive wear under semi-dry friction conditions. Figure 5 shows a macrostructure which makes it clear that the reinforcement particles are evenly distributed over the entire volume of the composite and a dense structure is visible and a very good infiltration of the melt in the capillary spaces formed between the particles of the reinforcement phase.

![Figure 5. Macrostructure of the obtained MMC: a) before abrasion wear test \( \times 25 \); b) after abrasion wear test \( \times 50 \).](image)

The Vickers microhardness measured on the composite in the matrix area before the abrasion wear test (figure 6 a) is close to the reference value of the technical description. The measured microhardness of MMC in the matrix area, as well as the measured microhardness of the reference sample (AISI 304 alloy) after abrasion wear, show a slight increase in comparison with the previous ones (figure 6 b) and c). This fact proved a change in the initial structure after the abrasion wear due to the mechanical reinforcement. Figure 6 b) and figure 5 b) clearly shows that the traces on the abrasive are only on the surface of the matrix and are not observed in the reinforcement phase.

Based on the experimentally obtained values for the wear parameters (table 1), a comparative diagram of the dynamics of the mass change in the wear process (figure 7) and a diagram of the change of the wear intensity against the friction path (figure 8) were made. Table 1 gives the values of wear resistance \( E \) of the two samples. The relative wear resistance \( \varepsilon = 5 \). As expected, higher wear resistance...
was observed with MMC. Also, more intensive wear was observed in the first cycle with both samples, since the contact area of the samples with the counter-body was less at the beginning of the study. The obtained value of wear resistance determines its class of wear resistance as class \((n) - 4\). The expectations were for higher wear resistance values with MMC since the reinforcement phase \(\text{Al}_2\text{O}_3\) has a 9 unit-hardness on the Mohs scale. The lower value than expected is most likely due to the fact that the matrix is composed of a low-hardness alloy and, as a result of the loading, the reinforcement phase sinks into the mould volume. This is the most likely cause because in the last wear cycle, the wear intensity of the composite decreases due to the increase of the hardness of the matrix from the cold hardening.

![Image of microstructure](image1)

**Figure 6.** Microstructure by measured Vickers microhardness of the obtained MMC in the area of the matrix: a) before abrasion wear test \(\times 400\); b) after abrasion wear test \(\times 400\) and microstructure of the reference sample \(\times 400\).

| MMC          | \(\Delta m\) (g) | 0.31 | 0.35 | 0.39 | 0.41 | 0.47 | 0.52 |
|--------------|------------------|------|------|------|------|------|------|
| \(L\) (m)    | 300              | 600  | 900  | 1200 | 1800 | 2625 |
| \(V\) (g/m)  | 0.001            | 0.0002 | 0.00007 | 0.00005 | 0.00007 | 0.00008 |
| \(E\)        | 300              | 600  | 900  | 1200 | 1800 | 2625 |
| \(E_r\)      | 12500            | 12500| 12500| 12500| 12500| 12500|

| Steel 304    | \(\Delta m\) (g) | 0.417 | 0.453 | 0.498 | 0.579 | 0.634 | 0.877 |
|--------------|------------------|------|------|------|------|------|------|
| \(L\) (m)    | 300              | 600  | 900  | 1200 | 1800 | 2625 |
| \(V\) (g/m)  | 0.0014           | 0.0004 | 0.0003 | 0.0002 | 0.0002 | 0.0004 |
| \(E\)        |                  | 2500  | 2500  | 2500  | 2500  | 2500  | 2500  |

**Table 1.** The experimentally obtained values for the wear parameters.
Figure 7. The diagram of the dynamics of the mass change in the abrasion wear process

Figure 8. The diagram of the change of the wear intensity against the friction path.

4. Conclusion
After the investigate conducted, based on the results obtained, the following more important conclusions can be drawn.

The methodology developed for the preparation of complex-relief MMCs using single blanks implementing conventional methods for mould production (in expendable cement mould), provides good results in relation to the infiltration of the melt (AISI 304 stainless steel) in the capillary cavities formed among the reinforcement phase particles (Al₂O₃), and as a result the composite has a dense structure.

The microhardness measured has revealed an increase in the hardness in the matrix area of the obtained MMC and of the reference sample (AISI 304 alloy) after the abrasion wear, approximately 100 – 180HV units, due to the mechanical reinforcement (cold hardening).

The experimentally obtained values for the wear parameters (\( E = 12500, \ E_r = 2500 \), class of wear resistance (n) - 4), show that the hardness of stainless steels can be greatly increased by the addition of hard ceramic particles, making them the preferred wear-resistant and corrosion-resistant materials. The obtained lower value than expected is due to the fact that the matrix is composed of a low-hardness alloy and, as a result of the loading, the reinforcement phase sinks into the mould volume.

References
[1] Tjong S and Lau K 2000 Comp. Sci. and Technol. 60 p 1141-46
[2] Slavov S and Dimitrov D 2016 Евразийский союз ученых (4-2) p 11-22
[3] Dimitrov D, Stoyanova A and Jordanov K 2014 7th IPMCE 56-7
[4] Spasova D, Atanasov N and Radev R 2017 Pr. Inst. Odlewn. 57 315 – 17
[5] Spasova D 2016 TEM Journal 5 80-1
[6] Radev R Spasova D Atanasov N and Ivanova R 2010 Patent BG 65955 B
[7] Yankova R, Spasova D and Petrov P 2017 Abrasion of welded layers in dry friction NDT days p 251 - 56
[8] Barykin N, Fazlyakhmetov R and Valeeva A 2006 Met. Sci. and Heat Treat. 48 88 – 9
[9] Mechkarova T 2017 Mech.1 Eng. and Technol., 1 54 – 56
[10] Kirov S and Yankova R 2016 Trib. Journ. Bultr. VI 209-11