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Wear of Gadfield steel-base sintered composite at current collection sliding

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1. Introduction

As a rule, materials used for making sliding electrical contacts (SEC) have either carbon-graphite or copper-graphite base. High content of graphite in these materials is necessary to provide good electrical sliding current collection with minimal both friction and wear of copper counterbody. However, putting more graphite results in higher electrical resistance both in SEC and contact zone. Therefore, it is necessary to increase the contact area in order to pass higher currents, i.e. to increase the unit dimensions whereas it may not be desirable in many practical cases. There is a potential to reduce electric resistance and provide high current collection by increasing the content of metal component in the composite. Such an approach may, however, increase the wear rate of the copper counterbody. The solution of this problem may be found by using a steel-base counterbody instead of a copper-base one.

Sliding contact experiments have been carried out for current densities <50 A/cm^2 and with a copper counterbody [1]. Few experiments conducted at higher current densities did not allow clear understanding of wear and electric conductance processes occurring in the tested materials. It also remains unclear what kind of a hard constituent should be used for optimal current collection of currents above 100 A/cm^2 combined with at least satisfactory wear resistance.

Not much attention has been given to the study of interaction between metallic material and steel counterbody in sliding electrical contact. The reason may be rather intense electric current oscillations in sliding which occur due to stronger specimen / counterbody adhesion on contact spots. Furthermore, there might not have been a commercial interest in using such sliding couples up to now. However, the electric resistance of metal/steel sliding contact will be always lower as compared to that of a carbon-graphite / copper couple.

It should be noted also that carbon-graphite sliding contact materials can not be used either in rarefied air nor in vacuum. Nevertheless, it is an essential requirement for electric machines working under conditions of high mountains, open space or superconductivity. Therefore, materials of both good conductivity and wear resistance for sliding over steel counterbodies are of high interest. It is possible to satisfy this interest only by experimenting with various metallic materials brought in sliding electric contact with steel. To begin with, it is worthwhile to test model materials prepared using some wear resistant steel as a base material.

Such experiments have been carried out on metal matrix composites (MMCs) reinforced by particles made of recycled ball bearing steel chips but the possible applications of this material were not considered [2].

Nevertheless, it seems reasonable to use high manganese steel particles to reinforce the conductive MMCs. Wear of Gadfield steel–base composite under the condition of passing electric current through it is of interest both for research and practical application.

The aim of this work is to determine the effect of contact voltage drop on the contact current density and the wear of a model Gadfield steel-base MMC.

2. Testing procedures

Model material has been obtained by single compaction of the powder mixture consisting of Mn 13% steel, copper (Cu) and graphite. The resulting green compacted samples move the composition Cu – 10% vol graphite – 70% vol. Gadfield steel was sintered in vacuum at 1050°C for 2 hours. The resulting material was characterized in comparison to two commercially available materials used for making trolleybus current collection units, which contact to copper trolleys.

One of these commercial materials was made of carbon-graphite, another is a commercially available material of the composition 43% Fe, 42% Cu, 10% Pb, 2% Zn and graphite. To characterize the composition we used X-ray fluorescent spectrometer BRUKER-S4 PIONEER. It may happen that commercial material of the composition 76% Fe, 10% Cu, 12% Pb and graphite reported [3] is just a mistake.

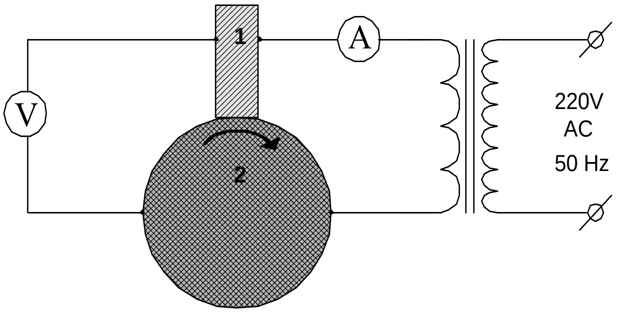


Fig. 1 Scheme of tribotechnical tests (*1* - specimen; *2* - steel counterbody (50 HRC))

The bending strength was determined using testing machine Instron-1185. Metallographic studies were carried out on optical microscope NEOPHOT -21. Specific electric resistance was determined using ampermeter-voltmeter method. Porosity of composite materials was measured by hydrostatic weighing on analytical scales.

Tribotechnical tests were carried out on SMT-1 testing machine using the block-on-shaft testing procedure. Wear path length was more than 30 km at sliding speed of 5 m/s and contact pressure 0.1 MPa. Electric current of standard frequency 50 Hz was applied to friction-mated couple in tribotecnical tests (see Fig. 1). The wear rate was determined as a ratio of the change in specimen height and corresponding wear path length.

3. Results

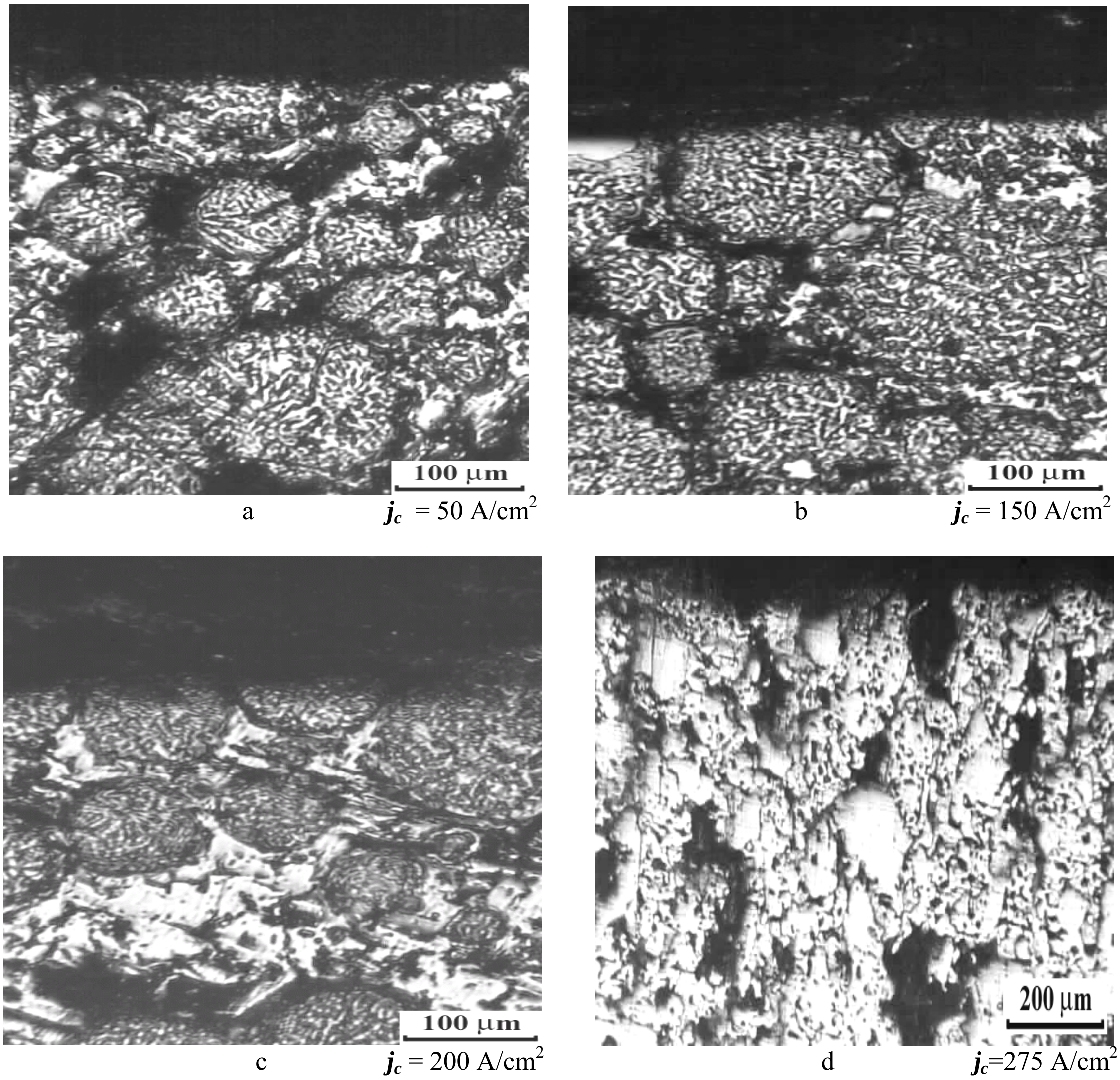
Materials for making high-current SEC should have good bulk strength and continuous structure of the matrix [3-5]. In accordance to these requirements, we obtained a matrix-filled composite, where the Gadfield steel particles are enveloped by copper matrix – Fig. 2, a-c. Table 1 shows the properties of this model material in comparison to the commercial one. The composite's structure consists of functionally different constituents analogous to the described elsewhere [6].

One could see that the steel particles form isolated sintered agglomerates and thus enhance the mechanical strength of the composite. The microstructure of commercial metallic composite looks as non-sintered compacted powder mixture (Fig. 2, d) and therefore its mechanical strength could not be high enough (see Table 1).

Table 1

Physical and mechanical properties of sintered composites

Composition/property	*HV*, MPa	σ_{ben}, MPa	*P*, %	ρ, μΩ·m	*f*
1. Cu 10%, graphite 70 % Gadfield steel	170	440	13	1.0	0.21
2. Commercial metallic composite	42	142	-	0.34	0.15
3.Carbon-graphite	-	-	-	532	0.1



a j_c = 50 A/cm^2

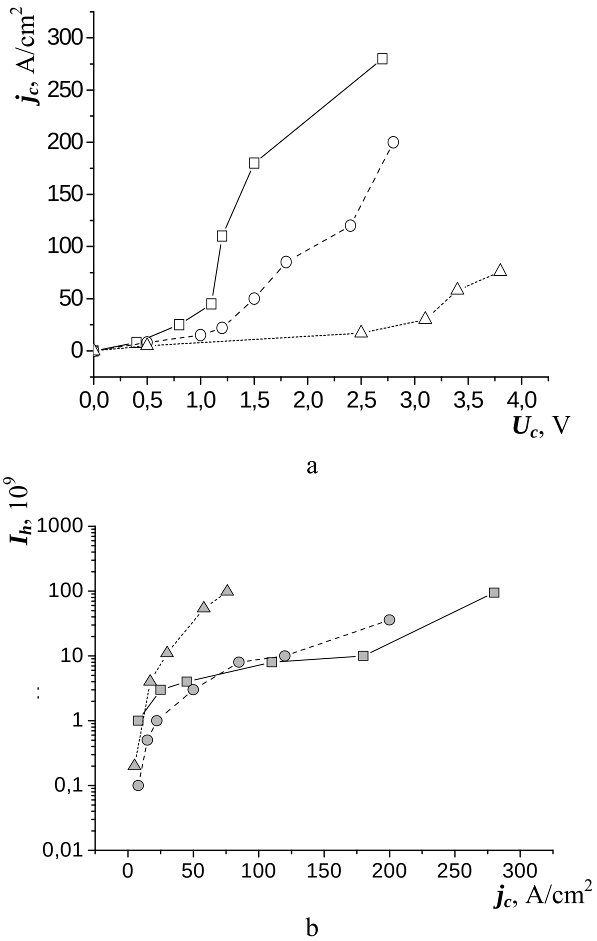
b j_c = 150 A/cm^2

c j_c = 200 A/cm^2

d j_c=275 A/cm^2

Fig. 2 Friction surface of Cu-10% vol graphite –70% vol. Gadfield steel composite (a-c) and commercially available MMC in the plane perpendicular to the direction of sliding (d) (black fields – graphite and/or pores)

Contact electric resistance, coefficient of friction and wear rate are basic service characteristics of sliding current collection materials. Coefficient of friction does not depend on the magnitude of electric current in above-mentioned contacting materials (Table 1). Contact resistance characterizes conductivity of a tribo-couple and it is convenient to consider it by studying the dependence of the current density $\boldsymbol{j_c}$ and contact voltage $\boldsymbol{U_c}$ (Fig. 3).



a

b

Fig. 3 Current density j_c vs. contact voltage U_c (a) and linear wear rate vs. current density j_c in sample/counter body contact (b). □ – commercial sample, ○ – Cu-10 vol % graphite – 70 vol % Gadfield steel, Δ - carbon-graphite composite

4. Discussion

It is easy to see that the commercial sample has higher conductivity as compared to the model one since the latter has higher specific resistance (see Table 1). Furthermore, lead-enriched transfer films are formed on the wear surface of steel counter body rubbed against the commercial sample. These films serve to protect the wear zone against heavy oxidation and simultaneously provide good electric conductivity. It is also possible that fine-grain structure of commercial MMC may form great number of contact spots in sliding so that total contact area would be enough to pass high density current. This is an explanation why the structure of commercial MMC is not sensible to the changes in current density – Fig. 2, d. Electric contact spots of model MMC occur only on the Gadfield steel particles (see Fig. 2, a-c). Their higher resistance leads to heating and oxides may form on both interphase and interparticle boundaries in the vicinity of sliding surface. Wear in this case is by oxidation and delaminations of oxide wear debris. One can see no secondary structures formed on the sliding surface at different current densities since mechanical wear is intense enough to carry them away from contact zone.

Formation of oxide films on the surfaces of model sample and counter body is also an intense process. In this case, the conductivity may be maintained by plastic deformation developing at the contact spots [7]. Strain in manganese steels occurs according to mechanisms disclosed elsewhere [8]. The ductility of this steel under sliding-induced strain is not high enough to provide formation of large contact area. Electric contact area will always be smaller that of a pure mechanical contact and oxidation serves to further diminishing of this area. The results are higher contact resistance and lower current density. Carbon-graphite commercial material has the lowest conductivity due to its high specific resistance – Table 1.

It is notable that there are intense oscillations of current when it passes through a contact spot due to fluctuations of both the total contact area and electric resistance on the contact spot. The model MMC showed current density oscillations at the level of ±0.15 j_c, the commercial MMC at the level ±0.1 j_c and carbon graphite < ±0.01 j_c.

When contact voltage drop is increased to be above 1 V, the metallic materials show higher conductivity due to electric discharges occurring in the contact zone. For commercial metallic material, the discharges show up at voltage higher that of model one. The reason may be that sliding wear zone of the commercial material is enriched with lead.

Carbon-graphite composite shows discharges at voltage drop to be above 3 V – Fig. 3.

Structural changes on the Gadfield steel-base composite's surface cannot be noticed using the optical microscopy only – Fig. 2. The microhardness numbers of the Gadfield steel particles are scattered widely across the field of vision and do not represent the friction induced work hardening. One could see the plastic strain traces resulting from ploughing and edging on the worn surfaces unless they are covered by thick oxide films. The higher current density provokes heavy oxidizing at the contact surface and wear is by both the oxidation and electric erosion. The wear rate is rather low in the range of low temperatures and erosion, i.e. wear by plastic strain is not crucial for Gadfield steel at contact pressure about 0.1 MPa.

Increasing copper content in the model composite up to 40 % vol. results in establishing higher friction coefficient (up to 0.35) and catastrophic wear by erosion of copper at 100 to 150 A/cm^2. During these experiments we noticed the intense copper transfer from the sample to the counterbody. Also the intense erosion of copper in this case is from its large spots existing at the sliding surface. Taking this into account, one may suggest that both higher wear resistance and good conductivity could be achieved by forming fine or even ultrafine structure. On the contrary, lower and even zero copper contents leads to higher porosity (up to 20%) and specific resistance 3.3 μΩ·m. Therefore, it is possible that the model composite of optimum composition must contain about 60 to 70% vol of Gadfield steel.

Current density is the main factor to determine deterioration of the wear surfaces in sliding contact. Therefore, it may be more convenient to consider wear rate as a function of current density. One may see in Fig. 3 that linear wear rate (I_h) dependencies of both the model and commercial material show almost the same behavior up to current density as high as 100 A/cm^2. By increasing the current density in the contact one may see that wear rate of the model sample is higher than that of the commercial metallic one. The difference in size of structural constituents may be the reason behind it. Possibly, such a behavior is due to more intense electric erosion on the model sample, which cannot form a protection film such as the lead one formed on the commercial one.

Carbon-graphite material is not intended for passing high density currents due to possible chemical decomposition of its constituents and that is why its wear rate grows sharply at j_c>25 A/cm^2.

According to the conception of self-organization, a tribological system passing electrical current may suffer a transition to a state where wear rate will minimize [9,10], i.e. if the contact resistance falls for higher current densities this may be an indication of instability of the current collection sliding system and the formation of secondary friction-induced structures. Such a behavior should appear itself as a sharp fall in wear rate since the non-equilibrium structures usually show low wear rate. We did not see such an effect and therefore may state that self-organization phenomenon is not the case with MMC/steel sliding contact experiments carried out in this work.

5. Conclusions

1. Rather low heat resistance of Gadfield steel does not allow it to be a good filler for making MMC for high current wear resistant sliding contact. Furthermore, the model MMC did not show clear advantage over the commercial MMC in wear rate at current densities above 100 A/cm^2.

However, Gadfield steel can be used as a filler for making sliding conductive composite intended to work at medium current density j_c < 50A/cm^2 when both oxidation and electroerosion wear rates are low enough. However, it is possible that high manganese steel is not optimal source material for developing wear resistant high current composite sliding contact.

2. It follows from general considerations that composite material capable of passing high density current in sliding contacts should have structure, phase and chemical compositions to provide appropriate level of heat resistance and strength. Also it is important that this material would be able to form both diffusion fluxes to sliding surface and secondary structures of necessary properties, i.e to reveal signs of synergetic behavior. It is impossible to derive such a material from only theoretical considerations. Therefore, it makes sense to continue testing materials of different structures and phase compositions.

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KOMPOZITO GATFILDO PLIENO PAGRINDU DILIMAS ESANT SLANKIAJAM SROVEI LAIDŽIOS MEDŽIAGOS KONTAKTUI

Reziumė

Palyginti su standartinėmis elektros srovei laidžiomis slankiojo kontakto medžiagomis, metalo matriciniai kompozitai su vario matrica, sustiprinti manganinio plieno dalelėmis, pasižymi didesniu mechaniniu stiprumu ir laidumu. Standartinės elektros srovei laidžios slankiojo kontakto medžiagos skirtos srovei tiekti į varinį kontaktą. Straipsnyje parodoma, kad sukepinti kieti kompozitai įgauna didelį tūrinį stiprumą. Nustatyta, kad kontakto kompozicijoje naudojamas manganinis plienas trinties (dilimo) paviršiuose padeda susidaryti vadinamosioms antrinėms struktūroms. Šias struktūras sudaro mišrūs oksidai, didinantys kontaktinę varžą. Intensyviausiai medžiagos oksiduojasi, kai srovės tankis pasiekia 50 A/cm^2. Standartinės ir modeliuojamos kompozicinių medžiagų lyginamųjų, tyrimų rezultatai rodo, kad modeliuojamoji medžiaga turi didesnę varžą, kai srovės tankis didesnis kaip 25 A/cm^2, tačiau modeliuojamosios medžiagos dilimo intensyvumas, palyginti su standartine, nesant intensyvaus oksidavimosi, yra mažesnis. Tirtas ir grafitinės anglies – dilimo intensyvumas esant identiškoms sąlygoms. Nustatyta, kad 25 A/cm^2 srovės tankis šioms medžiagoms jau yra neleistinas, nes jos pernelyg intensyviai dyla.

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WEAR OF GADFIELD STEEL-BASE SINTERED COMPOSITE AT CURRENT COLLECTION SLIDING

Summary

Model copper-matrix MMCs reinforced by high manganese steel particles have been characterized for mechanical strength and conductivity in comparison to commercially available current collection material. The commercial material is intended for current collection while sliding over a copper trolley. As shown, solid phase sintering allows obtaining composites of high bulk strength. Friction coefficient and wear rate of so obtained composites in sliding over steel counterbody while passing alternating electric current have been determined. It was found that high-manganese steel facilitates the formation of so-called secondary structures on the sliding surfaces. These structures consist of mixed oxides, which increase the sliding contact resistance. Most intense oxidizing occurs at current density 50 A/cm^2. The results of comparison carried out between the model and commercially available materials show that model MMC has somewhat higher electrical resistance at current densities above 25 A/cm^2. However, the wear rate of the model material in the absence of intense oxidation is lower than that of commercial one. To complete the picture, we determined also the wear rate of carbon graphite material under the same experimental conditions. As shown, carbon graphite fails to pass the current of densities above 25 A/cm^2.

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ИЗНОС КОМПОЗИТА НА ОСНОВЕ СТАЛИ ГАТФИЛЬДА В РЕЖИМЕ СКОЛЬЗЯЩЕГО ТОКОСЪЕМА

Резюме

Модельные металл-матричные композиты с медной матрицей упрочненные частицами высокомарганцовистой стали характеризуются механической прочностью и проводимостью в сравнении с серийным токосъемным материалом. Серийный материал предназначен для скользящего токосъема по медному контртелу. Показано, что твердофазное спекание придает полученным композитам высокую объемную прочность. Было обнаружено, что высокомарганцовистая сталь способствует формированию так называемых вторичных структур на поверхностях износа. Эти структуры состоят из смешанных оксидов, которые увеличивают контактное сопротивление. Более интенсивное окисление происходит при плотности тока 50 А/см^2. Результаты проведенного сравнения между модельным и серийным материалом показали, что модельный материал имеет несколько более высокое сопротивление при плотностях тока свыше 25 А/см^2. Однако, темп износа модельного материала в отсутствии интенсивного окисления является более низким, чем темп износа серийного материала. Для полноты картины, мы определили также темп износа углеграфитового материала при тех же самых экспериментальных условиях. Показано, что плотность тока свыше 25 А/см^2 является недопустимой для углеграфитового материала.

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