RHEOLOGICAL MODEL OF COMPOSITE SLIDING BEARING COMPRISING HARD COATING ON SOFT POLYMER INTERLAYER

M.V. Kireitseu^{*}, L.V. Yerakhavets^{*}, Ion Nemerenco^{**}, M.Istomin^{**}, M.A. Belotserkovski^{*}, A.Fedaravichus^{*} <u>indmash@rambler.ru</u> E-mail of principal author * Department of Mechanics and Tribology Institute of Machine Reliability (INDMASH), National Academy of Sciences of Belarus Lesnoe 19- 62, Minsk 223052, Belarus, Tel: 011-375-17-2023771 e-mail: indmash@rambler.ru **Department of Mechanics, University of Florida. Tel.: (386)-795-0858

Abstract

In the paper, summarizing results of experimental investigations and theoretical analysis, new approach to development of composite bearing like alumina-aluminum-polymer-steel substrate has been revealed. Better understanding of fundamentals of thermal flame spraying process used to produce both aluminium and polymer layers and micro arc oxidizing process used to transform aluminum into hard alumina have discovered semi-empirical relations to be used in the bearing design providing preferred by customer mechanical properties and performance. An analysis of fatigue behavior of the bearing revealed an effect of structure and porosity of alumina on degradation and overall strength of the composition. Of interest is revealed very close correlation between developed rheological model and real mechanical behavior of the bearing under indentation. Actually, an experimental research of load rating is in good agreement with rheological model to be applied in analysis of the composite bearing mechanics.

Bearing development

Powder metallurgy of aluminum constructions is developed rapidly. Nowadays composite bearings based on aluminum or its alloys are produced in a wide range [1]. In engineering practice, a lot of composite sliding bearings [2, 3] are have to know comprise of soft base (aluminum, polymer etc.), on which one a layer of friction resistant material like alumina is formed.

The developed bearing construction consists of sequentially arranged steel substrate, polymer layer, aluminium or its alloy layer and oxide ceramic layer. Both aluminium and polymer layers were produced by thermal flame spraying process because by this processing the layers reshape the surface profile reaching strong adhesion (data see below). At optimal regimes, the process does not overheat sprayed materials and substrate. The polymer was selected from the group including polyamide, polyvinylchloride, polyethylene, polyethylene(terephthalate). The steel base has ledges and cavities arranged in preferably the quincunx order. The depth of the profile ranges between 1.2-1.8 thicknesses of polymer layer. The layer of aluminium or its alloy was produced with complementary surface. Thickness of Al layer is found to be effective calculating by the following equation (1) detailed in see [8, 9]:

$$\delta A = (0.6 \div 0.8) \cdot K \cdot \sqrt[3]{\frac{C_{yd}}{E_a}}$$
⁽¹⁾

For example, cylindrical sliding bearing has semi-empirical coefficient K equal to R, where R is the radius of the working surface of the cylindrical sliding bearing.

It has been revealed that thickness of the polymer layer depends on technological regimes applied at deposition of the aluminium layer. Large fragments of Al particles and its temperature should be deposited on thicker layer of polymer to eliminate its over heating, welding and destruction due to thermal impact produced by hot Al particles dropping on polymer surface. The semi empirical relations were revealed through a set of experimental tests conducted before [8,9].

Manufacturing technology of the composite sliding bearing includes step-by-step deposition on the steel base the polymer layer and the layer of aluminium or its alloy produced by thermal flame spraying technology, and then top oxide ceramic layer produced by micro arc oxidizing. To prevent destruction and degradation of mechanical properties of polymer layer in result of impact of heated Al particles the equation has been developed through better understanding of fundamentals and processes of the applied technology.

In this case, thickness of the polymer layer depends on technological regimes to be applied while deposition of the next aluminum layer. Usually, greater size of Al particles have higher temperature should be

deposited on thicker polymer layer to prevent localized destruction and degradation of mechanical properties in the polymer in result of heat impact of Al particles. This effect has been revealed in result of the following experimental and theoretical procedure.

In the case when heated Al particle of approximately round shape distributes a heat in a constant mode in the definite time an increase of temperature in a contact point of Al particle with the polymer layer can be described with an increase of temperature in a point of semi-infinite body. The process of heat distribution can be approximated to a process of heat distribution at a surface of semi-infinite body if the heat during the time eq. (2). Distributes at the surface of the body only, and then it distributes in both directions at the surface and in the depth of the body. In the equation (2), a is the thermal conductivity of the polymer layer. κ is coefficient of concentration of heat flow). If it is stated two conditions that (a) the relatively isotropic body does not significantly change parameters of heat flow; and (b) in initial time, the temperature of the body T_o stills constant in all the body and equals to zero, then the temperature of sprayed Al drop can be shown as the following equation (3):

$$\tau_{0} = 0.25 \, \mathcal{AK}$$
 (2) $T = \frac{2q}{c\rho (4\pi a\tau)^{3/2}} e^{-\frac{\kappa}{4a\tau}}$ (3)

n2

Reducing a volume of heat transfer of heated drop with an air, the decrease of temperature in rounded space with radius R describes the following coefficient

$$e^{-\frac{R^2}{4 a \tau}}$$
 (4) Whereas the coefficient can be found from $\frac{q}{c \rho (4\pi a \tau)^{3/2}}$ (5)

and it reveals a change of temperature in the point with radius R = 0 during the time (τ).

Transforming equation (3) by the new elements, it gives the following equation (6). Modifying equation (6) to the base of heat of a drop, it is transformed in equation (7) as follows:

$$\Delta T = \frac{2q}{c\rho} \frac{e^{-\frac{R^2}{4a(\tau+\tau_o)}} e^{-\frac{Z^2}{4a\tau}}}{4\pi a(\tau+\tau_o)\sqrt{4\pi a\tau}} \quad (6); \qquad q = \frac{c\rho\Delta T 4\pi a(\tau+\tau_o)2\sqrt{\pi a\tau}}{2e^{-\frac{R^2}{4a(\tau+\tau_o)}} e^{-\frac{Z^2}{4a\tau}}} \quad (7)$$

The depth of distribution of heat flow from the heated Al drop δ can be described with equation (3) (here the depth δ is measured along the vertical axis Z and it follows that δ =Z). Have some mathematical transformations and including the conditions the equation (8) can be rewritten as follows:

$$\delta = \left[4a\tau \ln \left(\frac{2q}{c\rho} \frac{e^{-\frac{R^2}{4a(\tau+\tau_o)}}}{4\pi a(\tau+\tau_o)\sqrt{4\pi a\tau}T} \right) \right]^{1/2} (8); \quad \delta = N \sqrt{a \cdot \tau \cdot \ln \left[K \frac{D^3 \rho_1}{c\rho} (c_1 T + \lambda)\right]} (9)$$

The time τ is calculated here with the equation (10):

$$\tau = (\mathbf{T} \cdot \mathbf{c}_1 \cdot \mathbf{\rho}_1 \cdot \mathbf{V}) / (\boldsymbol{\alpha} \cdot \mathbf{S} \cdot \mathbf{T}_0)$$
(10)

Polymer type	Diameter of sprayed Al drops, µm	Temperature of sprayed Al drops, ⁰ C	Thickness of polymer layer, μm
Capron-polyamide	8 – 16	700 - 800	120
	15 - 40	750 - 900	175
	35 - 110	1050 - 1300	445
Polyethylene (dense	10 - 20	700 - 800	142
type)	15 – 35	750 - 900	271
	30 - 120	1050 - 1300	595

Table 1. Parameters of Al and polymer layers

Table 1 lists data [8, 9] involved in equations (9). Obtained data shows an effect of diameter of sprayed aluminum drops and its temperature on minimal thickness of polymer layer that can be overheated by Al particles without catastrophic welding, degradation and failure of polymer. Results revealed that to prevent degradation of mechanical properties and to provide overall strength of the bearing, thickness of polymer layer should be at least 400 μ m to form on it aluminium layer with the particles above 50 μ m in diameter and about 1000 ⁰C temperature.

Analyzing the equation (9), we revealed that the thickness of polymer layer is proportional to temperature and size of sprayed Al particles. For example, at thermal spraying of Al powder Al particles of 40-160 μ m diameter at the 165-230 μ m distance from substrate have the temperature ranged in 900-1700^oC; at thermal spraying of Al cord the Al particles of 10-50 μ m diameter at the 120-200 μ m distance from substrate have the temperature ranged in 750-850^oC.

Experiments

The theoretical calculations by equations (1, 9) and practical approach show that aluminum layer formed by thermal flame spraying do not overheat polymer layer as temperature of Al particles do not exceed 1200C. Some of technologies applied to produce aluminum such as Osprey technology /5/ use special expensive equipment.

To form aluminum layer was used both aluminum cord with diameter of 2 mm or aluminum powder with granules size of 60-100 μ m and purity of 99.85%. Thickness of the aluminum and polymer layers was calculated with equations (1, 9) respectively. Finally, sprayed aluminum layer was transformed into hard oxide aluminum with micro arc oxidizing process during processing in 60 min. An analysis of structure and porosity in depth of alumina revealed that the structure of the layer contains α , γ phases of aluminum oxides, porosity ranges in 5-11%. Microhardness of the layer reaches up to 15 GPa, that is very high result for alumina layer on sprayed aluminum in contrast to traditionally produced on cast aluminum alloys.

Considering data of Young's modulus, thermally sprayed aluminum is found to be produced with an advanced Young's modulus in contrast to welded aluminum alloy with the same structure. There is two possible mechanisms to be considered in view of strength and modulus of elasticity of sprayed Al layers. On the one hand, energy of impact of flying Al particles on substrate destructs oxide film on aluminum particles due to its oxidation in a flight. On the other hand, in thermally sprayed aluminum layer processes of diffusion are intensified by high temperature of Al particles that reaches above 660°C. Intergranular diffusion and contact of particles improves modulus of elasticity of thermally sprayed aluminum in comparison with known prototypes based on welded alloys [2, 3]. The sprayed layer contains up to 30 % of α , γ oxide phases of alumina that grounds the choice of sprayed aluminum and its technology to produce composite layers providing an advanced strength of the bearing.

Rheological model and behavior

To investigate mechanical properties of composite systems there are many rheological models including integral elastic-tenacious-plastic systems [9, 13-16]. However, despite of some advantages known models do not completely describe mechanical behavior (law of deformation rate and stresses) of the composites like alumina-aluminum-polymer-steel substrate.

Based on recent researches of mechanical properties of alumina-based ceramics [14-16], polymers [13] and its composites the requirements to the rheological model have to be formulated to develop adequate model describing tight - strained state of the composite. Based upon the investigations we have suggested the following requirements to be used in rheological model of the composite:

- 1. Since the composite include hard alumina layer and steel substrate that exhibit plasticity, the irreversible deformations has to be considered as plastic in nature. Deformations develop only after excess of some critical yield strength for the particular layer of the composite.
- 2. if the deformations are smaller then yield strength, the deformations at constant stress have to grow up step-by-step to final value;
- 3. Cyclic loading increases summarized plastic deformation of the composite;
- 4. Curve of deformation vs. time at constant load exhibits a linear dependence in one of plotted region.
- 5. At unloading the retardation of deformations (elastic return) has to be observed;
- 6. Stress at constant deformations is relaxed.

Along with above stated items, it is important to use the following requirements of mathematical nature: (a) the system has to be solved (order of a required differential equation on stress and deformation should not exceed numbers of possible conditions of physical limitations); (b) the system and formulated problems have to be solved concerning stress or strain rate.

Actually, based on above stated requirements describing aspects of mechanical behavior of the composite materials there can be found many rheological models, for example, for the elementary single dimensional deformation. However, to check an adequacy of rheological models within suggested approach we have to

consider the following model. To simplify development and analysis of the system of differential equations we take advantage of the applicable rheological models. The selection of model that adequate to the studied composite material is determined by comparison of developed models and experimental results.

The composite of hard alumina-aluminum can be presented as elastic-tenacious-plastic rheological model of the composite (see fig. 1 center). The mechanical prototype of the model is described in [17]. Structural equations of the integral model of the composite looks like $(H \parallel N \parallel St-V) - (H-N \parallel H)$. In general, the kind of the rheological equation depends on a level and form of stress applied on model. The polymer layer can be presented as the rheological model consisting from two elastic elements and one tenacious element. As a prototype of the model, we can consider connection of the Maxwells' model and elastic element (see fig. 1 left) as described in [13-16]. Summary of deformation of the system is calculated as follows:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_1 + \boldsymbol{\varepsilon}_2 \tag{14}$$

If the loaded system has the stress σ more then initial stress $\sigma \leq \sigma \sigma$, whereas before the loading the system has no deformations, hence the equation of the system can be shown as follows:

$$\boldsymbol{\sigma} = \mathbf{E}_2 \cdot \boldsymbol{\varepsilon} \tag{15}$$

However, if the loaded system has the stress σ less then initial stress $\sigma \leq \sigma \sigma$, but before the loading the system has residual deformations, the equations of the system has to include equations describing mechanics of deformation.

If $\sigma > \sigma \sigma$ rheological equation of the elastic-tenacious-plastic part of the composite can be written as follows:

$$\sigma = \sigma_0 + E_1 \varepsilon_1 + \eta \frac{d \varepsilon_1}{dt}$$
⁽¹⁶⁾

where $\sigma_0 \sigma$, are stresses at initial and final time of the loading sequentially; E1 is modulus of elasticity of the layer; η is coefficient of viscosity; ε is deformation.

For the second part of model including polymer – steel a differential equation can be as follows:

$$\frac{d\sigma}{dt} + \frac{E_{22}}{\eta_2}\sigma = (E_{21} + E_{22})\frac{d\varepsilon_2}{dt} + \frac{E_{21}E_{22}}{\eta_2}\varepsilon_2 \qquad (17)$$

Where E_{21} , E_{22} are modulus of elasticity of the materials; η is coefficient of viscosity of polymer.

If the law of deforming $\varepsilon(t)$ vs. time is known, the general solution of the equation (17) is found to be as follows:

$$\sigma(t) = (E_0 + E_1) \cdot \varepsilon(t) - \frac{E_1}{\eta} \int_0^t \varepsilon(s) \cdot e^{-\frac{E_1}{\eta}(t-s)} ds$$
⁽¹⁸⁾

Mathematical transformations can give the following equations revealing deformation and velocity of deformation in metal-polymer-based part of the system:

$$\varepsilon_1 = \frac{1}{\Delta} \left[\eta_1 r - \beta (\sigma - \sigma_0) \right] \qquad (19); \qquad \frac{d\varepsilon_1}{dt} = \frac{1}{\Delta} \left[\frac{E_{21}}{\eta_2} (\sigma - \sigma_0) - E_1 r \right] \tag{20}$$

Integrally, the solution of the first and second parts of the system can be summarized in the mathematical system at random low of loading as follows:

$$\frac{\eta_1}{E_{22}} \frac{d^2 \sigma}{dt^2} + \left(\frac{E_1}{E_{22}} + \frac{\eta_1}{\eta_2} + \beta\right) \frac{d\sigma}{dt} + \frac{E_1 + E_{21}}{\eta_2} \sigma - \frac{E_{21}}{\eta_2} \sigma_0 =$$

$$\beta \eta_1 \frac{d^2 \varepsilon}{dt^2} + \left(\frac{\eta_1}{\eta_2} E_{21} + \beta E_1\right) \frac{d\varepsilon}{dt} + \frac{E_1 E_{21}}{\eta_2} \varepsilon$$
(21)

In this case, the equation allows to estimate the dynamics of a contact, where the stress $\sigma(t)$ is determined not only by deformation value $\varepsilon(t)$ in the given time, but also all dynamic of deformation in time $\varepsilon(s)$, $s \in (0, t)$. Using mathematical transformations involving parameters of the Hertz's' theory, the system of the equations is found to be solved in respect of applied load and acting stresses in the composite.

Above general equation can be transformed to the case of Hertz contact, when contact load depends on stresses, geometry of contact track and indenter as well as velocity of loading. The equation (15) describes a case of loading at constant velocity and no deformation before loading.

$$P(t) = \sigma(t) \left[\pi R V t + \frac{\pi d^2(t)}{4} \right]$$
⁽²²⁾

Based on revealed models, we have found the equations describing contact stresses and loading vs. time of loading or depth of contact track. The system includes all mechanical parameters of composites' layers of elastic, tenacious and plastic model.

Figure 1 right shows indentation depth vs. relative strain curve plotted as mechanical response of the composite under Hertzian indentation at constant rate of loading with sintered alumina ball of 4 mm diameter. The composite exhibits linear relation of stress curve, whereas unloaded composite shows retardation of deformations (elastic return) shown as downfall segment of the curve. The plotted relations of experimental data at the curve1 and calculated data at curve 2 have revealed very close agreement of developed rheological model and real mechanical behavior of the composite. The above stated conditions are found to be used in investigations of mechanical and rheological properties of the alumina-aluminum-polymer-steel composite systems.



Figure 1. (From left to right order): Parallel connections of Maxwell's model (2) and elastic element (1), Elastic, tenacious and plastic elements, Indentation depth vs. relative stress.

Conclusion

Applied soft intermediate composite layer of aluminum and polymer provide both rigid and adaptive structure of the composition that, however, is deformed under applied loading. Deformation of the soft layers might prevent the hard overlaying composite coatings from ultimate failure. Under applied loading the composite bearing has both strength and the ability to adapt under applied localized contact stresses.

Thermal flame spraying process is found to be effective to produce polymer-aluminum composition to be used to form alumina layer by micro arc oxidizing. Experiments show that thickness of polymer layer should be at least 400 μ m to form on it aluminum layer with Al particles above 50 μ m in diameter and its 1000^oC temperature. Revealed technological regimes and equations to calculate thickness of polymer and Al layers give an approach to an engineering design of the composite in view of Young's modulus, adhesion and strength. Structure of alumina layer formed on sprayed Al layer consists of α , γ phases of aluminum oxides. Porosity of alumina ranges in 5-11 %. Microhardness of the layer reaches 15-17 GPa.

Developed rheological model is found to be used in analysis of mechanical behavior of the composite bearings based on metal-polymer-ceramics system. The rheological model comprising Maxwell's and elastic elements gives reliable results when thickness of polymer layer predominates in the system. On the other hand, rheological model based on parallel connected elastic, tenacious and plastic elements gives well understanding of rheological behavior if metal-ceramics layers predominate in thickness of the metal-polymer-ceramics system. Hopefully, the thickness of polymer-based layer should be at least 1 mm to apply the former developed model in rheological analysis. Of interest is adaptive ability of the construction in which the polymer-aluminum composition plays key role. Since the paper highlights only top of our work we expect to present our project in progress in future works.

Nomenclature

- C_{yd} specific contact rigidity of a polymer that is relation of Young's modulus vs. surface area.
- Ea Young modulus of aluminium or its alloy.
- δ_a minimum depth of aluminium or its alloy, mm.
- R radius of deformed drop of aluminum;

- q heat of a drop;
- τ_0 initial time when a heat from drop distributes in the depth of polymer layer.
- δ layer depth, m.
- D diameter of a drop of the sprayed aluminium or its alloy;
- τ time of heat diffusion into the polymer layer;
- T temperature of drop of sprayed aluminium;
- V volume of a drop (m3).
- S area of a drop surface, m2.
- $\alpha \qquad \qquad \text{coefficient of heat rejection, W/ (m2 \cdot oC).}$
- To temperature of a cooled drop (To \approx 100°C).
- N semi empirical coefficient that is in the range of 2.2-2.6.
- λ local heat to melt aluminium or its alloy, J/kg.
- ρ_1 density of aluminium or its alloy, kg/m3.
- c₁ local thermal capacity of aluminium or its alloy, J/ (kg·oC).
- a thermal conductivity of the polymer layer.
- c heat capacity of the polymer layer, $J/(kg \cdot oC)$.
- ρ_2 density of the polymer layer, kg/m3.
- K semi-empirical value that depends on the form of processed surface of the bearing ($K=1.15\cdot10^{11}$.).
- Subscripts
- a aluminum
- yd local
- 1 aluminum
- 2 polymer

References

- [1] Jerry L. Patel, Nannaji Saka, Ph.D. A new Coating Process for Aluminum. Microplasmic Corp., Peabody, Mass. www.microplasmic.com, (2000)
- [2] DE № 3934141, F 16 C 33/12, 1990.
- [3] DE № 4038139, F 16 C 33/10, 1990
- [4] Wiktoreks S. Studies of physical properties of hot sprayed aluminum metal coatings to steel substrates. Fnti. Corrosion. 33, 1986, p. 4-9.
- [5] Lavernia E.J., Grant N.J. Spray deposition of metals: a review // Material Sc. and Eng. 1988, 98, p. 381-384.
- [6] Willis T. Spray deposition process for metal matrix composites // Metals and Materials. 1988, 4, p. 485 488.
- [7] Friction and wear behaviors of alumina-based ceramics in dry and lubricated sliding against tool steel. Yang C. "Wear", 1992, 157, №2, p.263-277
- [8] Berestnev O.V., Basenuk V.L., Kireytsev M.V. et al. Composite coating and technology of its manufacturing. C 23 C 28/00. Patent RU №2000111046/02, 2001.
- [9] V. Basenuk ed. in chief., M. Kireitseu et al. "Development of fundamentals for technology and design...". Report, the theme "Material-65". Reg. № 19962944. INDMASH NAS of Belarus, Minsk, (2000), p. 165.
- [10] Kireytsev Maxim V.. Mechanical properties of composite coatings based on hard anodic oxide ceramics. Proc. of the SEM Annual Conference and Exposition. Best Student Paper Competition. June 4-6, Portland, Oregon, USA (2001) pp.12-13
- [11] M. Kireytsev, V. Basenuk. Study of load rating of the CrC-Al2O3-Al composite coating. Proc. of 2nd Int. symposium on modeling the performance of engineering structural materials (MPESM - II) TMS-2001, Nov., Indianapolis, USA, pp.124-127.
- [12] M. Kireytsev, V. Basenuk, M. V. Investigation of tribological properties of the CrC-Al2O3-Al. Proc. of 2nd Int. symposium on modeling the performance of engineering structural materials (MPESM - II) TMS-2001, Nov., Indianapolis, USA, pp.342-346.
- [13] Rudnitski V.A., Kren A.P. and Shilko S.V. Rating the behavior of elestomers by their indentation at constant rates. Wear, Vol. 22, №5, Sept-Oct. 2001, pp. 502-508.
- [14] V. Basenuk, M. Kireytsev, A. Fedaravichus. Application of rheological models to composite sliding bearings based on polymer-metal-ceramics composition. Proc. of the Symposium of Material&Construction Failure.23-25May01 Augustov,Poland. pp.12.
- [15] V.L.Basenuk, M. Kireytsev. Failure model of the composite coatings based on oxide ceramics. Proc. of Symposium of Material &Construction Failure.23-25 May 01 Augustov, Poland. p.13.
- [16] Vladimir Basenuk, Maxim Kireytsev. Study of failure process of oxide ceramics coatings. Proc. of Symposium of Material and Construction Failure. 23-25 May 2001 Augustov, Poland. pp.14.
- [17] Shulman et al. Rheological behaviour of the composite systems and structures. Published by "Nauka", Minsk, 1978, p.378.