ISSN 1027-5495. Functional Materials, 31, No.3 (2024), p. 387-390
doi:http://dx.doi.org/10.15407/fm31.03.387 © 2024 — STC "Institute for Single Crystals"

The influence of a rapidly-quenched filler on the wear resistance of ultrahigh molecular weight polyethylene

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Received March 28, 2024

The paper investigates the influence of the content of Al-Co alloys quenched from the liquid state on the abrasive wear index of ultrahigh molecular weight polyethylene with rigidly attached abrasive particles. The studies have shown that: 1) quenching from the liquid state leads to the formation of highly supersaturated single-phase substitution solid solutions of Al-Co based on the FCC lattice of aluminum; 2) the introduction of 5–30 mass% of quenched aluminum alloy into ultrahigh molecular weight polyethylene reduces the rate of abrasive wear by ~ 50%. This result is due to the high microhardness, dislocation density, and microstresses in rapidly-quenched Al-Co alloys.
Keywords: ultrahigh molecular weight polyethylene, supersaturated solid solution, lattice constant, microhardness, microstress, dislocation density, index of abrasive wear, abrasive particles.

Вплив швидкозагартованого наповнювача на зносостійкість надвисокомолекулярного поліетилену. *В.Ф. Башев, А.-М.В. Томіна, К.А. Микита, Т.В. Калініна, С.І. Рябцев, О.І. Кушнерьов*

У роботі досліджено вплив вмісту загартованих з рідини сплавів системи Al-Co на показник абразивного стирання надвисокомолекулярного поліетилену по жорсткозакріпленим абразивним частинкам. Дослідження показали, що: 1) гартування з рідкого стану призводить до формування у структурі сплавів Al-Co сильнопересичених однофазних твердих розчинів заміщення на базі ГЦК-решітки алюмінію; 2) введення до надвисокомолекулярного поліетилену 5–30 мас.% загартованого алюмінієвого сплаву зменшує показник абразивного стирання на ~ 50%. Покращення даного показника обумовлено високими значеннями мікротвердості, густини дислокацій і мікронапружень швидкозагартованих сплавів Al-Co.

1. Introduction

Nowadays, polymeric materials (PMs) confidently displace non-ferrous and scarce metals [1] from many industries like agricultural, machine-building, and mining due to their unique functional properties (stable operation under the influence of UV radiation, acids and alkalis, low weight and ease of production). However, PMs are mainly not used in their pure form due to the high coefficient of thermal linear expansion [2], low thermal conductivity, and wear resistance under the influence of high loads and abrasive particles. One of the solutions to this problem is the use of fillers, including metal fillers. The analysis of literary sources showed that the introduction of pure metals (Al, Ni, Fe, Ti, Cu), metal alloy PKh25R10Yu10I, self-fluxing alloy PR-N65 Kh25S3R3, "FINEMET" soft magnetic nanocrystalline alloy, and cast microwire into thermoplastic PMs allows us to obtain metal-polymer composites (MPCs) with high wear resistance, hardness, strength, thermal and electrical conductivity, and low coefficient of thermal linear expansion [2-9]. This paper is aimed at the development and research of new MPCs with higher functional properties.

2. Experimental

Ultrahigh molecular weight polyethylene (UHMWP) (Jiujiang Zhongke Xinxing New Material Co., Ltd., China) was chosen to create a new MPC. UHMWP is a high molecular weight linear polyolefin (polymerization product of α-olefins) consisting of long polyethylene chains with a very high degree of parallel orientation and a high level of crystallinity. Extremely long, unbranched, linear chains transfer the load to the polymer base more efficiently due to strong intermolecular interaction. Therefore, UHMWP compares favorably with other thermoplastic polymer materials due to its extremely high impact strength even at low temperatures (73 K). Technical characteristics of UHMWP are given in [10].

Binary Al-Co alloys, whose components are characterized by high anti-corrosion properties, were chosen as the metallic fillers (Fl) for UHMWP. The Al-Co phase diagram from the aluminum side is characterized by: 1) practically zero solubility of Co in the aluminum lattice: in an equilibrium state (< 0.02 mass%); 2) the presence of a peritectic Al_9Co_2 phase as a result of the $Al + Al_{13}Co_2 \rightarrow Al_9Co_2$ phase reaction [11].

A well-known method of liquid quenching (LQ) [12] at high cooling rates (HCRs) (10^6–10^8 K/s) allows for significant disruption of equilibrium crystallization processes and obtain highly supersaturated single-phase solid solutions (SSPSSs), in this case, based on the FCC lattice of aluminum, under conditions of non-equilibrium quenching. Since the radii of Al and Co atoms are very different, 0.40494 and 0.1260 nm, respectively, the substitution of Al by Co in SSPSS is accompanied by a constant change and a significant elastic distortion of the aluminum crystal lattice. Al-Co alloys were obtained in a laboratory liquid quenching setup.

The LQ-binary Al-Co alloy was ground in the original laboratory mill. The MPCs based on UHMWP containing 5–30 mass% of dispersed (50-100 μm) alloy Al-(3, 5, 10 mass%) Co were formed by the method of dry mixing in an apparatus with a rotating electromagnetic field (0.12 Tl); ferromagnetic particles removed from the resulting mixture by the method of magnetic separation were used. The mixture was loaded into the mold at a temperature of 288 K, heated to T_1=363 K, and kept at this temperature for 3 min without load, then heated to T_2=453 K and kept at this temperature for 10 min under constant load (10 MPa). Then, the samples were cooled under constant load to a temperature of 313 K and removed from the mold.

Microstrains or residual strains of the second kind ($\Delta a/a$, a is the period of the crystal lattice) [12] were studied on an X-ray diffractometer DRON-2.0 in monochromatized Cu-$K\alpha$ radiation. The precise values of the FCC lattice parameter were obtained from the diffraction line (222) with subsequent extrapolation of the reflection angle up to 90° [13]. The microhardness of the rapidly quenched samples was measured using a PMT-3M microhardness tester under a load of 20 g. The $\Delta a/a$ values for the LQ-samples were calculated according to the methodology given in [13]:

$$\frac{\Delta a}{a} = \frac{\beta}{4 \cdot \mathrm{tgë}}$$

where β is an integral width of the diffraction line (222); θ is the reflection angle.

To determine the wear resistance of UHMWPP, experiments were conducted on a HECKERT testing machine using rigidly fixed abrasive particles of MPC (dispersion 100 μm) for their abrasive wear. Before the start, each sample was pre-tested in working mode until full contact with the abrasive layer was achieved. The load on the sample during the experiment was 10 N, and the friction path was 40 meters.

The index of abrasive wear (V_i, mm^3/m) was determined by the formula:

$$V_i = \frac{\Delta G \cdot 1000}{\rho \cdot L}$$

where ΔG is the value of mass wear, g; ρ_e is an experimental density of the wear material, g/cm^3; L is a friction path (40 m) per cycle.

The experimental density of MPCs was calculated as the ratio of the mass of the sample in air (m_1) to the difference between the mass of the sample in air and isopropyl alcohol (m_2):

$$\rho_e = \frac{m_1}{m_2 - m_1} \cdot \rho_c$$

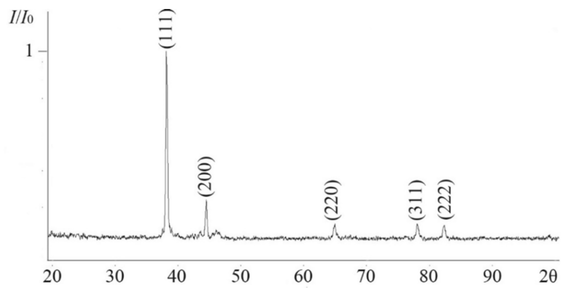

Fig. 1 – Diffraction pattern of the initial LQ sample Al-10 mass% Co

here m_1 is the mass of the test sample in air, g; m_2 is the mass of the experimental sample in alcohol, g; ρ_c is the density of isopropyl alcohol (0.786 g/cm^3).

The structure of the friction surfaces of UHMWP and MPCs was studied using a BIOLAM-M microscope. The roughness of the friction surfaces was measured with a 170621 probe profilometer on the R_a scale (μm).

3. Results and Discussion

X-ray studies show that as a result of LQ, a highly supersaturated single-phase substitution solid solution of Al-Co with variable crystal lattice parameters depending on the cobalt content is formed (Figs. 1-3).

Based on the data obtained, the following can be established: 1) the magnitude of microstrains ($\Delta a/a$) correlates well with the values of the crystal lattice constant of the SSPSSs and the values of the microhardness of the LQ-samples.

The results of tribological tests of the MPCs (Fig. 4) show that the use of a dispersed LQ Al-Co alloy is promising for reducing the intensity of abrasive wear of UHMWP by almost 50%. This indicator is improved due to the high strength of the filler, caused by elastic strain in the Al lattice due to a significant difference in the sizes of Al and Co atoms in highly supersaturated solid substitution solutions. The difference in the atomic radii of the components also causes a 1% decrease in the shortest interatomic distances and the occurrence of a significantly increased density of dislocations up to $5 \cdot 10^{11}$ cm^{-2} [13]. The elastic disorder in the crystal lattice is the main reason for the increase in hardness; as a result, MPCs are more resistant to the mechanical destruction of surfaces [10], which is also confirmed by a decrease in surface roughness by about 25%.

From the analysis of microstructures (Fig. 5) of UHMWP and MPCs based on it, it can be concluded that the introduction of a dispersed Al-Co metal LQ-alloy as a reinforcing component strengthens the polymer matrix, and, as a result, the resistance of the composite surface to mechanical destruction due to friction increases. According to the Al-Co phase diagram, the melting temperature of an alloy with a cobalt content of 10 mass% reaches 1173 K, which allows us to predict the possibility of using this MPC under thermal loads without deterioration of operational properties. This will be the next stage in further work.

It should be noted that a decrease in the abrasive abrasion index of UHMWP is observed

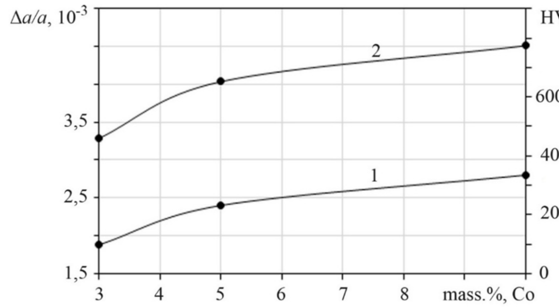

Fig. 2 – Dependence of the values of microstrains ($\Delta a/a$) (1) and microhardness (HV) (2) of LQ-samples on the content of Co

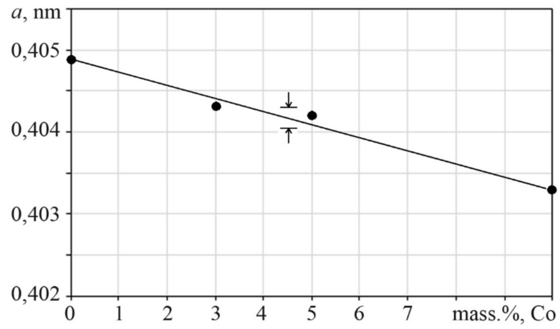

Fig. 3 – Crystal lattice constant of LQ-samples of the Al-Co alloy depending on the Co content

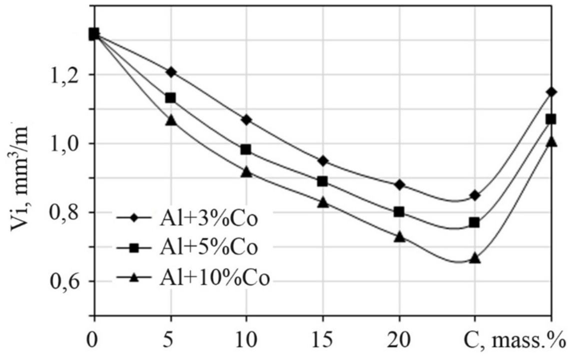

Fig. 4 – The influence of the percentage content of the filler (C, mass%) on the index of abrasive wear of ultrahigh molecular weight polyethylene

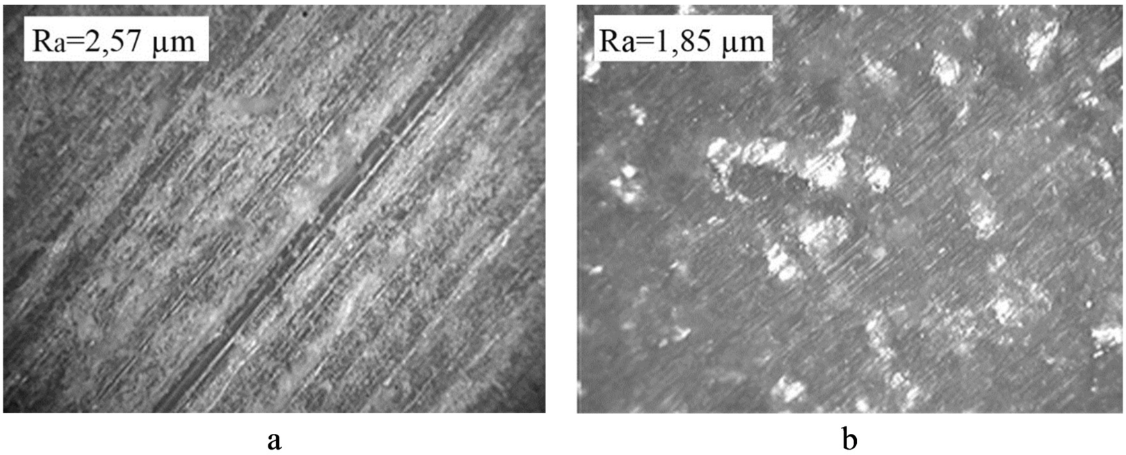

Fig. 5 – Friction surfaces (×200) of ultrahigh molecular weight polyethylene (a) and MPCs (b) based on it containing 25 mass.% of the Al-Co alloy with a Co content of 5 mass.%

with a content of Al-Co alloys in the amount of 5–25 mass%. Its further increase to 30 mass% in UHMWP leads to deterioration of this indicator. The obtained experimental data are explained by the fact that with an increase in the content of the filler, its uniform distribution in the PM volume becomes difficult, and the formation of fairly large agglomerates (clusters) is observed, which leads to a deterioration in the functional properties of the metal-polymer composite.

4. Conclusions

The analysis of the obtained results of the functional properties of the developed PCMs indicates potential advantages of using aluminum-transition metal alloys rapidly-quenched from the liquid state as fillers for UHMWP. The method of quenching from the liquid state with the formation of highly supersaturated single-phase substitution solid solutions used in the work leads to very high elastic strains of the lattice, which determines the obtained high level of microhardness; this significantly reduces the abrasive wear rate by ~ 50%, while simultaneously reducing the surface roughness by ~ 25%. The effective concentration of the filler is 25 mass%. New MPCs are characterized by high resistance to abrasive wear and can be successfully used in a wide range of applications, such as industrial pumping equipment, protective coatings for pipelines, elements of special equipment, etc.

References

1. M. Sufyan, M. Hussain, H. Ahmad, N. Abbas, J. Ashraf, N. Zahra, *Biomedical Physics & Engineering Express*, **5** (2019).
2. A.I. Burya, O.A Naberezhnaya, Cui Hong, Feng Xiao Song. *J. Machines. Technologies. Materials*, 10, 6 (2016).
3. Ye.A. Yeriomina, Development, research of properties and application of metal polymers on the basis of heat-resistant aromatic polyamide of phenylone: dis. for the degree of cand. tech. science (2017).
4. L.N Yashchenko, L.O. Vorontsova, T.T. Alekseeva, T.V. Tsebrienko, L.P. Steblenko, A.M. Kuryliuk, O.O. Brovko, *Nanosistemi, Nanomateriali, Nanotehnologii*, 17, 4 (2019).
5. O. Burya, Ye. Yeriomina, O. Lysenko, A. Konchits, A. Morozov, Polymer composites based on thermoplastic binders, Srednyak T. K. Press (2019).
6. Patent 120871 Ukraine, MPK (2006) C08L 77/00.
7. Patent 126282 Ukraine, MPK (2006) C08L 77/00.
8. Patent 125857 Ukraine, MPK (2006) C08L 77/00.
9. Patent 116925 Ukraine, MPK (2006) C08L 77/00.
10. A.-M.V. Tomina, O.V. Yeromenko, *J. Functional Materials*, **30**, 3 (2023).
11. T.B. Massalski. Binary Alloy Phase Diagrams, (1986).
12. H. Jones, *Materials Science and Engineering*, A.413 (4) (2005).
13. S.I. Mudryi, Y.O. Kulik, A.S. Yakymovych, X-ray structural analysis in materials science. teaching method manual. LNU named after I. Frank., Lviv (2017).