Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 34, No. 4, August, 2024, pp. 457-464
Journal homepage: http://iieta.org/journals/rcma

Analytical Surface Energy Model of Fine Copper-Graphite Core-Shell Particles in Oil Lubricant

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https://doi.org/10.18280/rcma.340407

Received: 27 April 2024
Revised: 20 May 2024
Accepted: 4 June 2024
Available online: 27 August 2024

Keywords:
analytical solution, characteristics, core-shell, surface energy, tribological

ABSTRACT

Surface energy is a key quantity that controls many physical, mechanical, and tribological properties of materials. However, determining their values at various scales remains challenging to evaluate how they affect dispersion behavior and frictional performance. Analytical surface energy modelling for lubricating additives in die lubricant oil is made to evaluate the surface energy as a function of tribological characteristics with complex compositional dispersion in two conditions: (i) separately adding graphite and copper particles at the same time to the oil and (ii) adding the particles to the oil in the form of copper-graphite core-shell composite structure. We have introduced the surface-induced excess energy and discussed this value before and after friction according to the particle diameter and powder content wt.% in the lubricant oil. Results revealed that the adding of graphite and copper particles as a core-shell composite structure can play an excellent role as compared to separately adding the graphite and copper particles to the oil. The ratio of total surface energy after friction process to that of before friction in separately introduced the components, and in the form of core-shell composite was equal to 7 and 5, respectively. Meanwhile, the ratio of the total surface energy of the core-shell composite structure to that of separately introduced the components before and after the friction process is equal to 2 and 1.4, respectively. However, the composite with (2.5-3) wt.% content and a 10 μm diameter of particles indicates 3 and 3.4 values of the total surface energy ratio in cases of separate and core-shell structure conditions, respectively. The results indicate that the total surface energy for the core-shell composite is more effective than separate powders of graphite and copper added in oil.

1. INTRODUCTION

In materials science and engineering, surface energy is a significant topic. This may be determined for solids using contact angle data and several theoretical approximations [1]. Surface tension is the driving force behind the sintering of powdered metals, ceramic materials, and polymers. It is also the driving force behind particle growth in gases, liquids, and solids. It governs the distribution of solid and liquid sizes and forms in multiphase systems, as well as phase changes [2]. However, using a very simple technique, measuring the surface energy of a solid may offer a fair insight of its surface characteristics [3]. Surface energy is a challenging characteristic to quantify in materials. Nonetheless, this parameter is critical: the surface energy might be accountable for the overall characteristics of the material, particularly for nanomaterials, because the surface effect is inversely proportional to the grain size of the structural component in the material. As a result, using various approximations, the surface energy has been determined and predicted [4]. Contact angle measurements have been used to study surface energy, wettability, and adhesion properties [5]. The majority of lubricants made from mineral oil lack several of the ideal tribological characteristics. It has previously been demonstrated that incorporating solid particles into oils significantly enhances the tribological characteristics of lubricants [6, 7]. When solid particles are added to lubricants, rolling friction rather than sliding friction is present, which reduces wear and friction. Because of their superior ability to regulate excessive heat and friction between an engine's moving parts, solid lubricants have sparked a lot of interest in tribology management [8, 9]. Originally, only really difficult conditions, such as high temperatures, where organic lubricants are thought to be inappropriate, could be used with nanomaterials, particularly graphite, as dry lubricants [10]. Tribology establishes a highly interdisciplinary and cross-disciplinary connection between friction, wear, and lubrication and parts of materials science, chemistry, physics, and even biology [11-14]. Materials with core-shell structures have gotten a lot of interest recently because of their unique features and wide range of uses in energy storage and conversion systems. Various forms of core-shell structured materials with favorable qualities that play important roles in surface energy may be manufactured [15]. Liu et al. [16] created core-shell structures in carbon nanospheres and employed them as supercapacitor electrodes. The results demonstrated that carbon nanosphere core-shell structures exhibited high specific capacitance, high current density, and outstanding long-term cycle stability. Sun et al. [17] created an Ag-shell/Cu-core powder using electroless plating; the wear rate and friction coefficient of (Ag-shell/Cu core)-WS2 under 5 N were found to be 15.4×10^{-6} $mm^3/(Nm)$ and 0.21, respectively, which were 79% and 66% less than those of Cu-WS2 composites. Rajkumar et al. [18] examined the composites most suited for sliding contacts, which consisted of a solid lubricant reinforcement matrix with good electrical and thermal conductivity. Therefore, in order to assess the life parameters, accelerated wear testing was performed. The times-to-failure data was then analyzed, and reliability models were created. Thankachan et al. [19] showed how to use statistical techniques and machine models to estimate and analyze the rates of dry sliding wear on new copper-based surface composites. It has been demonstrated through statistical and experimental studies that the addition of BN particles may significantly lower the wear rate. Adhesive wear under low load conditions and an abrasive mode of wear under higher load conditions were found by analysis of the worn surfaces. The prediction profiles showed a good match with the results of the experiments. Wang et al. [20] examined the Cu-Ni-graphite composites prepared by powder metallurgy. Cu-Ni-graphite composites with varying graphite contents have tribological characteristics that varied according to their physical attributes. It is difficult to study the correlation degree between tribological characteristics and physical properties by the means of experiments. However, mathematic method is suitable for the correlation with each factor. The abrasive wear behaviour of Cu-SiC-Gr hybrid composites at varying percentages was examined by Senthil Kumar et al. [21] they suggested neural network model predicted the wear loss of the composite based on the observed parameters, which included graphite weight %, abrasive size, sliding speed, load, and sliding distance. The suggested networks' projected values match the experimental values. This work presented an analytical surface energy model for lubricating additives in die lubricant oil to evaluate the surface energy as a function of tribological characteristics with complex compositional dispersion in two conditions: (i) separately adding graphite and copper particles at the same time to the oil, and (ii) adding the particles to the oil in the form of copper-graphite core-shell composite structure.

2. THEORETICAL ANALYSIS

2.1 Formulation of the problem

It is natural to assume that the composition of the solid lubricant graphite additive with a metallized surface (core-shell) demonstrates the best antifriction and lubrication characteristics compared to the powder additive graphite and metal, where the powders are taken in the same quantitative ratios. The difference in the action of the additives, the core-shell, and the separately introduced components is that the triboactive materials are in a different colloidal state in the first and second cases. The key to understanding the lubrication process with the participation of the powder can be an estimate of the free surface energy of the dispersed phase for the two compared cases. When building a model, it is necessary to take into account the fact that in the process of friction, particles falling into the contact zone are deformed and destroyed, forming a new colloidal system of increased dispersion. In order to state the problem for the proposed theoretical calculation, we will make the following assumptions:

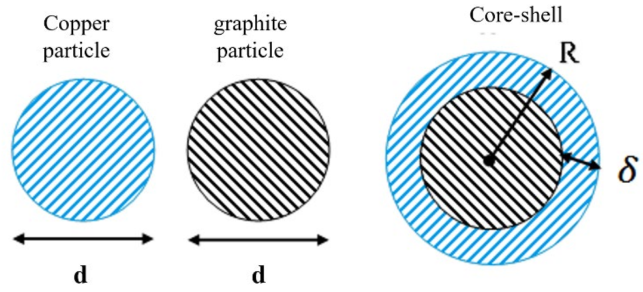

Figure 1. The compared model disperses systems: (a) core-shell structure; (b) separately monodisperse particles of graphite and copper

1. Let the compared systems, for simplicity, be monodisperse, with a particle size (d) as shown in Figure 1, and the core-shell composite has a coating of thickness δ. A sphere conveniently represents the shape of the particles in this approximation.
2. With the introduction of each of the three types of particles into the lubricating dispersion medium, their surface can be characterized by a specific free surface energy: - the energy of the (graphite surface - oil lubricant); (copper surface energy - oil lubricant) and the energy of the (surface of the copper - graphite).
3. We establish that the particles do not interact with each other and that there is also no chemical interaction of solid surfaces with a lubricant.
4. Suppose that in the process of friction, particles (both core-shell and separately) are crushed to a certain characteristic constant size, in order of magnitude comparable with the coating thickness ($\delta<d$).
5. Let the additive suspension in the oil have a mass concentration of c.
6. The influence of the internal surfaces of the base lubricant (at the boundary of oil thickener) is neglected.

2.2 Surface energy assessment

2.2.1 Evaluation of the surface energy of a two-component dispersed system with the separate introduction of components

Case I. Particles of graphite and copper powder having the same size, d, are introduced into the oil separately. Estimate the surface energy of this model system before and after friction.

I-a. Before friction

Let the particles of graphite and copper be in a dispersed-distributed state in a certain volume of lubricant with mass (m). The mass contents of graphite and copper are, respectively:

$$k_1 = \frac{m_1}{m} \times 100\% \qquad k_2 = \frac{m_2}{m} \times 100\% \tag{1}$$

where, K_1 and K_2 are the percentage mass concentrations of graphite and copper in the oil, respectively.

Then, the mass of graphite and copper in the oil will be, respectively:

$$m_1 = 0.01k_1 m$$
$$m_2 = 0.01k_2 m \quad (2)$$

On the other hand,

$$m_1 = N_1 \rho_1 V_1$$
$$m_2 = N_2 \rho_2 V_2 \quad (3)$$

where, N_1, N_2 respectively, the number of particles of graphite and copper contained in the mass of oil, and ρ_1 , ρ_2 respectively, the density of copper and graphite and the volume of particles of graphite and copper with a diameter d under the assumption of their spherical shape.

$$V_1 = \frac{\pi d^3}{6}$$
$$V_2 = \pi d^3/6 \quad (4)$$

Eqs. (3, 4) and Eqs. (5, 6):

$$0.01k_1 m = N_1 \rho_1 V_1$$
$$0.01k_2 m = N_2 \rho_2 V_2 \quad (5)$$

The number of particles of copper and graphite per unit mass of the oil, respectively:

$$n_1 = \frac{N_1}{m}$$
$$n_2 = \frac{N_2}{m} \quad (6)$$

Then from Eqs. (5) to (6):

$$n_1 = 0.01\frac{K_1}{\rho_1 V_1} = \frac{0.06K_1}{\pi \rho_1 d^3} \quad (7)$$

$$n_2 = 0.01\frac{K_2}{\rho_2 V_2} = \frac{0.06K_2}{\pi \rho_2 d^3} \quad (8)$$

The surface energies of graphite ε_1 and copper ε_2 per unit mass of the oil, respectively, will be

$$\varepsilon = \sigma_1 A n_1 \quad (9)$$

$$A = \pi d^2 \quad (10)$$

$$\varepsilon_1 = \sigma_1 \pi d^2 n_1$$
$$\varepsilon_2 = \sigma_2 \pi d^2 n_2 \quad (11)$$

Then, the total surface energy of particles of graphite and copper per unit mass of the oil will be:

$$\varepsilon_{toalt} = \varepsilon_1 + \varepsilon_2 = \pi d^2[\sigma_1 n_1 + \sigma_1 n_2] \quad (12)$$

where, σ_1 and σ_2 are the specific surface energies of graphite and copper at the boundary with the oil.

Taking into account Eqs. (10) to (11), we obtain the calculated value of the interfacial surface energy with the separate introduction of graphite and copper to friction.

$$\varepsilon_{total} = \pi d^2\left[\sigma_1 \frac{0.06K_1}{\pi \rho_1 d^3} + \sigma_2 \frac{0.06K_2}{\pi \rho_2 d^3}\right] = \frac{0.06}{d}\left[\sigma 1\frac{K_1}{\rho_1} + \sigma 2\frac{K_2}{\rho_2}\right] \quad (13)$$

I-b. After friction

Before calculating the change in the surface energy of a polydisperse system after friction, it is necessary to make an assumption that takes into account the different nature of fracture in the contact zone of brittle graphite and ductile copper. It is reasonable in the first approximation to assume that the particles of graphite of the initial size (d) will be ground to a much smaller diameter δ>d. In contrast, the copper particles will be plastically deformed, and a significant change in their specific surface will not occur. From here, we will assume that the surface energy of metal particles after friction will remain the same.

$$\varepsilon'_2 = \varepsilon_2 = \sigma_2 \pi d^2 n_2 \quad (14)$$

The volume of each of the crushed particles of graphite will be:

$$V = \frac{\pi \delta^3}{6} \quad (15)$$

Thus, the number of small particles formed from one large will be:

$$N = \frac{V_1}{V} = \left[\frac{d}{\delta}\right]^3 \quad (16)$$

The number of particles of graphite per unit mass of lubricant oil after grinding will be:

$$C_1 = n_1 N = n_1\left[\frac{d}{\delta}\right]^3 \quad (17)$$

The changed surface energy of graphite particles will be:

$$\varepsilon'_1 = \sigma_1 A_1 C_1 \quad (18)$$

where, $A_1 = \pi\delta^2$ (surface area of a particle of graphite with a diameter δ after friction)

$$\varepsilon'_1 = \sigma_1 \pi \delta^2 n_1 \left[\frac{d}{\delta}\right]^3 \quad (19)$$

Then

$$\varepsilon'_{total} = \varepsilon'_1 + \varepsilon'_2 = \sigma_1 \pi\delta^2 n_1\left[\frac{d}{\delta}\right]^3 + \sigma_2 \pi d^2 n_2 = \frac{0.06}{d}\left[\sigma_1 \frac{k_1 d}{\rho_1 \delta} + \sigma_2 \frac{k_2}{\rho_2}\right] \quad (20)$$

To compare the state of dispersed systems before and after friction, investigate the difference and the ratio of the surface energies of the systems under consideration (the components are introduced separately), taking into account the fact that: d/δ>1

$$\Delta\varepsilon = \varepsilon_1 - \varepsilon'_1 = \sigma_1 K_1 \frac{0.06}{\rho_1 \delta} \quad (21)$$

$$\frac{\varepsilon'_{total}}{\varepsilon_{total}} = \frac{\frac{\sigma_1}{\sigma_2}\frac{K_1}{K_2}\frac{\rho_2}{\rho_1}\frac{d}{\delta} + 1}{\frac{\sigma_1}{\sigma_2}\frac{K_1}{K_2}\frac{\rho_2}{\rho_1} + 1} \quad (22)$$

2.2.2 Evaluation of the surface energy of the core-shell composite dispersed system

Case II. Graphite and copper are introduced into the oil as a core-shell composite. Spherical particles with a characteristic diameter d: the particles are a graphite base coated with a copper coating of thickness δ_1 (δ<d).

II-a. Before friction

For the correctness of the proposed comparison of the surface energy characteristics of the composite and separate introduction of the components, the conditions of equality of the mass concentrations of copper and graphite for cases I and II were introduced. From this condition, estimate the volume of the copper layer located on one composite particle:

$$V_c = \pi d^2\, \delta_1 \quad (23)$$

Based on the condition of equality of concentrations, we assume that the concentration of graphite particles for the I and II cases is the same and amounts to n_1, defining the total volume of copper per unit mass of the oil:

$$V_{c\,total} = n_1 V_c = \frac{0.06\delta 1 K_1}{d\rho_1} \quad (24)$$

In case I, the volume of copper particles per unit mass of the oil was equal to:

$$V_2 = \frac{m_2}{m\rho_2} = \frac{0.01K_2}{\rho_2} \quad (25)$$

Since the condition of equality of concentrations, the thickness of the metal coating on graphite can be expressed:

$$\delta 1 = \frac{K_2\rho_1 d}{6K_1\rho_2} \quad (26)$$

Then, the total surface energy per unit mass of the oil for composite particles will be:

$$\varepsilon_{c\,total} = (\sigma_2 + \sigma_3)\, A\, n_1 = (\sigma_2 + \sigma_3)\frac{0.06K_1}{d\,\rho_1} \quad (27)$$

where, σ_3 is the specific surface energy at the graphite-copper interface.

II-b. After friction

In this case, graphite is also ground to size δ. Copper in the coating composition is already in a dispersed state - in the form of a surface film so that the particle size of the copper after friction can be set to approximately the same value δ. The mass concentration of graphite remains the same as in the case of I-b:

$$C_1 = n_1\, N = \frac{0.06}{\pi}\frac{K_1}{\rho_1\delta^3} \quad (28)$$

Then, the surface energy of the composite dispersion will be:

$$\varepsilon'_{c1} = \varepsilon'_1 = \sigma_1\, K_1\, \frac{0.06}{\rho_1\delta} \quad (29)$$

The number of copper particles per unit mass of the lubricant oil was found after the destruction of composite particles. After one composite particle of copper-coated graphite is destroyed, the following copper particles will be formed:

$$n'_2 = \frac{\mathrm{Vc}}{\pi d^3/6} = \frac{\pi d^2\delta}{\pi d^3/6} = \frac{6d^2\delta_1}{\delta^3} \quad (30)$$

Since the mass concentration of graphite particles will be:

$$n_1 = \frac{0.06K_1}{\pi\rho_1 d^3} \quad (31)$$

Then, the corresponding mass concentration of copper particles after friction will have the value:

$$n''_2 = n'_2\, n_1 = \frac{0.06K_2}{\pi\rho_2\delta^3} \quad (32)$$

Then, the surface energy of all copper particles newly formed during friction will be:

$$\varepsilon'_{c2} = \sigma_2\, A\, n''_2 = 0.06\,\frac{\sigma_2 K_2}{\rho_2\delta} \quad (33)$$

where, A= $\pi\delta^2$ (surface area of a particle of graphite with a diameter δ after friction)

The total surface energy of the graphite and copper components of the system after dispersion by friction for the case of a core-shell composite additive will be:

$$\varepsilon'_{c.total} = \varepsilon'_{c1} + \varepsilon'_{c2} = \frac{0.06}{\pi}\left[\frac{\sigma_1 K_1}{\rho_1} + \frac{\sigma_2 K_2}{\rho_2}\right] \quad (34)$$

Now, it is possible to estimate the difference in the energy states of the lubricant compositions supplied to the friction zone, in which the components are introduced separately or in a core-shell composite form. So, the energy difference will be the value:

$$\Delta\varepsilon_c = \varepsilon_{c.total} - \varepsilon'_{c.total} = [(\sigma_2 + \sigma_3)\frac{0.06K_1}{d\,\rho_1}] - [\frac{0.06}{\pi}[\frac{\sigma_1 K_1}{\rho_1} + \frac{\sigma_2 K_2}{\rho_2}]] \quad (35)$$

And the relation of these energies will be given by:

$$\frac{\varepsilon'_{c.total}}{\varepsilon_{c.total}} = \{\frac{0.06}{\pi}[\frac{\sigma_1 K_1}{\rho_1} + \frac{\sigma_2 K_2}{\rho_2}]\}/\{(\sigma_2 + \sigma_3)\frac{0.06K_1}{d\,\rho_1}\} = \frac{d}{\delta}\left[\frac{\frac{\sigma_1}{\sigma_2} + \frac{K_2}{K_1}\frac{\rho_1}{\rho_2}}{\frac{\sigma_3}{\sigma_2} + 1}\right] \quad (36)$$

3. ESTIMATED CALCULATION

For simplicity, we assumed that the mass concentrations of graphite and copper are the same, i.e.

$$k_1 = k_2 = 1.5\mathrm{wt} \quad (37)$$

To calculate the surface energy of solids, the classical theory does not provide a clear physical dependence due to the thermodynamic irreversibility of a possible increase in the solid interphase surface. Stefan's rule allows us to approximately estimate the possible values of the surface energy of solids [22]:

$$\sigma \cong \frac{A}{V_m^{\frac{2}{3}} N_A^{\frac{1}{3}}} \frac{Z_s}{Z} \quad (38)$$

A = the heat of sublimation or evaporation
V_m = the molar volume of the substance
N_A = the Avogadro number
Z_s = the coordination number of molecules located in the surface monolayer
Z = the coordination number (the number of neighbors of the molecule) in the volume of the condensed phase

The specific surface energy is proportional to the molar heat of sublimation and inversely proportional to the molar volume of the substance to the 2/3 degree. Since the heat of sublimation of copper is about 2 times higher than that of graphite

θ copper = 2θ graphite

The molar volumes of copper and graphite are approximately the same 7cm^3/mol and 6cm^3/mol, respectively:

$$V_{m.copper} = 7\ cm^3/mol$$

$$V_{m.graphite} = 6\ cm^3/mol$$

The specific surface energy of copper is approximately 2 times higher, similar to graphite.

$$\sigma_2 = 2\ \sigma_1$$

It was assumed that the mass concentrations of graphite and copper are the same

$$K_1 = K_2$$

The ratio of the densities of copper and graphite is approximately 3.9 (with rounding assumed 4). To determine the interfacial surface energy of graphite-copper σ_3, we also use Antonov's rule (the rule of additivity of surface energies), according to which the interfacial specific surface energy of condensed matter is determined by the difference in the specific surface energies of bodies [23]:

$$\sigma_3 = /\sigma_2 - \sigma_1/$$

- Assumed $\sigma_2 = \sigma_1$, $\frac{d}{\delta} = 10$

3.1 Calculation for lubricant components, entered separately

- Surface energy before friction:

$$\varepsilon_{total} = \frac{0.06K_1}{d}\left[\frac{\sigma_1}{\rho_1} + \frac{\sigma_2}{\rho_2}\right]$$

- Surface energy after friction:

$$\varepsilon'_{total} = \frac{0.06K_1}{d}\left[\frac{\sigma_1}{\rho_1}\frac{d}{\delta} + \frac{\sigma_2}{\rho_2}\right]$$

- The ratio of surface energies in the substitution of numerical values:

$$\frac{\varepsilon'_{total}}{\varepsilon_{total}} = \frac{\frac{\sigma_1}{\sigma_2}\frac{\rho_2}{\rho_1}\frac{d}{\delta} + 1}{\frac{\sigma_1}{\sigma_2}\frac{\rho_2}{\rho_1} + 1} = \frac{\frac{1}{2} \times 4 \times \frac{10}{1} + 1}{\frac{1}{2} \times 4 + 1} = 7$$

3.2 Calculation for core-shell lubrication

- Surface energy before friction:

$$\varepsilon_{c.total} = (\sigma_2 + \sigma_3)\frac{0.06K_1}{d\ \rho_1}$$

- Surface energy after friction:

$$\varepsilon_{c.total} = \frac{0.06}{d}\left[\sigma_1\frac{k_1 d}{\rho_1 \delta} + \sigma_2\frac{k_2}{\rho_2}\right]$$

- The ratio of surface energies:

$$\frac{\varepsilon'_{c.total}}{\varepsilon_{c.total}} = \frac{d}{\delta}\left[\frac{\frac{\sigma_1}{\sigma_2} + \frac{\rho_1}{\rho_2}}{\frac{\sigma_3}{\sigma_2} + 1}\right] = 10\left[\frac{\frac{1}{2} + \frac{1}{4}}{\frac{1}{2} + 1}\right] = 5$$

3.3 Finding the ratio of surface energies

- The ratio of the surface energies of the core-shell lubricant and lubricant with separate components before the friction process.

$$\frac{\varepsilon_{c.total}}{\varepsilon_{total}} = \frac{(\sigma_2 + \sigma_3)}{\left[\frac{\sigma_1}{\rho_1} + \frac{\sigma_2}{\rho_2}\right]} = \frac{3\sigma_1}{\sigma_1.\left[1 + \frac{2.\rho_1}{\rho_2}\right]} = \frac{3}{\left[1 + \frac{2.\rho_1}{\rho_2}\right]} = \frac{3}{\left[1 + \frac{1}{2}\right]} = 2$$

- The ratio of the surface energies of the core-shell composite lubricant and the lubricant with separate components after the friction process.

$$\frac{\varepsilon'_{c.total}}{\varepsilon'_{total}} = \frac{d}{\delta}\left[\frac{1 + \frac{\sigma_2\rho_1}{\sigma_1\rho_2}}{\frac{d}{\delta} + \frac{\sigma_2\rho_1}{\sigma_1\rho_2}}\right] = 10\left[\frac{1 + \frac{2}{4}}{10 + \frac{2}{4}}\right] = 1.4$$

4. RESULTS AND DISCUSSION

As a result of constructing a computational model and carrying out an evaluation calculation, Table 1 presents the variation of the total surface energy according to the introduction of the components of copper and graphite to the lubricant oil in separately adding or as a core-shell composite structure. It is observed that there is an increase in the total surface energy with a high energy dispersed system with the core-shell composite of the component. The ratio of total surface energies after the friction process to that of before friction in separately introduced the components and in the form of core-shell composite equal to 7 and 5, respectively. And the ratio of total surface energies of the core-shell composite structure to that of separately introduced the components, before and after the friction process, is equal to 2 and 1.4, respectively. This is related to the new "high-energy" dispersed system, which can interact more effectively with the friction surface and achieve an anti-friction effect. The ensemble effect contains the interconnections between the shell and core due to changes in the charge transfer between the components influenced by atomic vicinity, affecting the band structures.

For the case of separately adding the particles of graphite and copper to the oil before and after friction, respectively, Figures 2 and 3 present a comprehensive investigation into the particle's diameters impact on the composites total surface energy. The results reveal a consistent trend: a progressive increase in the diameter of the particles from 10 µm to 50 µm leads to a notable reduction in total surface energy composite, decreasing from 76.32 J/m^2 to 15.26 J/m^2 and from 76.32 J/m^2 to 59.45 J/m^2 before and after friction respectively with 2.5wt.% content of the particles. Interestingly, a distinct deviation occurs when incorporating 2.5wt.% content of the components in conjunction with the oil lubricant. The variation in total surface energy upon adding these additives can be attributed to these materials' distinctive properties and behaviours. On the other hand, adding copper and graphite typically leads to an increase in the active surface area of the composite in the contacting zone. However, their incorporation might introduce other beneficial attributes, such as improved wear properties or enhanced alloying effects, which could outweigh the total surface energy increment. The calculated surface energy from the analytical model is in good agreement with stated by the researcher [24]. Figures 4 and 5 display the outcomes of an investigation into how the inclusion of copper and graphite particles with the oil lubricant impacts the total surface energy ratio of the composite. Additionally, they investigated how different diameters and contents wt.% of the copper and graphite particles influenced the total surface energy ratio of the composite in separate state and core-shell structures, respectively.

Table 1. Shown the result of calculating surface energies and their ratios

Cases \ Surface Energy	Total Surface Energy: Separately Introduced Components of Graphite and Copper	Total Surface Energy: Composite Lubricant: Graphite with Copper (Core-shell)	The Ratio of Surface Energies in the Separate and Core-Shell Additives
Before friction process	ε_{total}	$\varepsilon_{c.total}$	$\varepsilon_{c.total}/\varepsilon_{total} = 2$
After friction process	ε'_{total}	$\varepsilon'_{c.total}$	$\varepsilon'_{c.total}/\varepsilon'_{total} = 1.4$
The ratio of energies after and before the friction process	$\frac{\varepsilon'_{total}}{\varepsilon_{total}} = 7$	$\frac{\varepsilon'_{c.total}}{\varepsilon_{c.total}} = 5$	

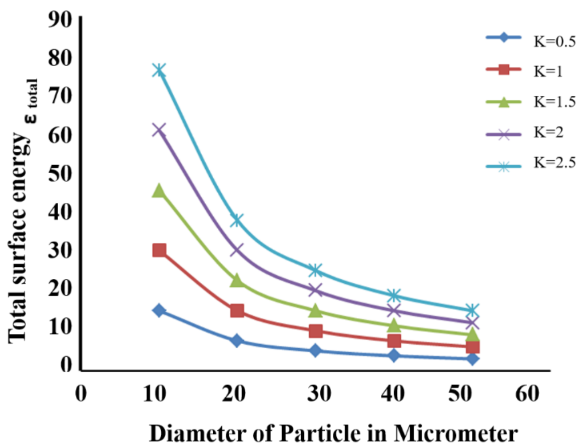

Figure 2. Total surface energy before friction versus diameter of particles in separately adding to the oil

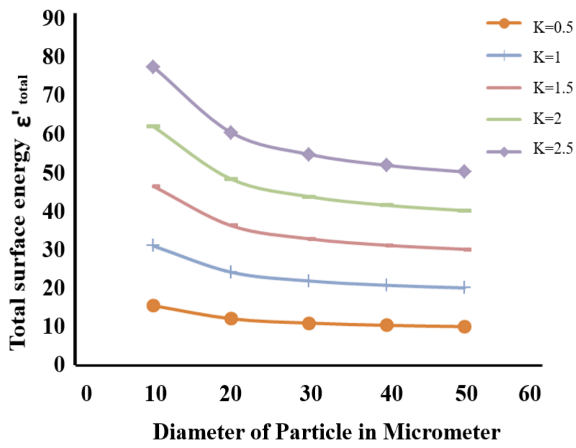

Figure 3. Total surface energy after friction versus diameter of particles in separately adding to the oil

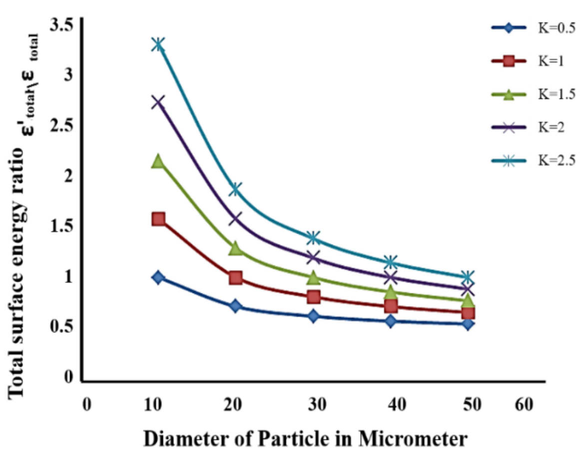

Figure 4. Total surface energy ratio versus diameter of particles in separately adding to the oil

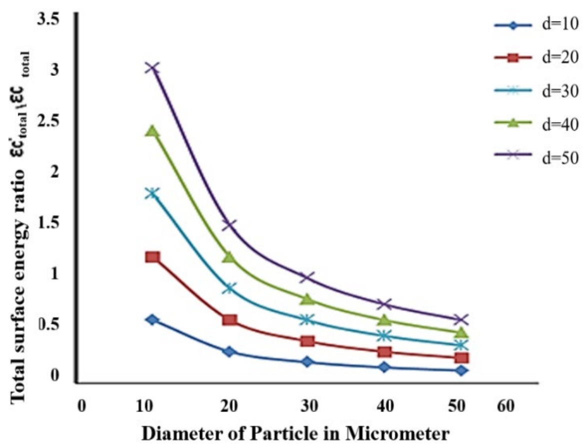

Figure 5. Total surface energy ratio versus diameter of particles in the form of core-shell composite

Figure 6 compares the ratio of total surface energy for the two cases, separately adding the components and in the form of a core-shell composite structure. However, the composite with (2.5-3) wt.% content and 10 mm diameter of particles indicates 3 and 3.4 values of the total surface energy ratio in cases of separate and core-shell structure conditions, respectively. Various diameters of the particles (10 to 50 µm) were used, with 2.5wt.% content of particles. For the case of separately adding the components, the total surface ratio fell from 3 to 0.5 as the diameter of the particles rising from 10 µm to 50 µm, respectively. In the case of core-shell composite structure, the total surface energy ratio fell from 3.4 to 1 as the diameter of the particulates rising from 10 µm to 50 µm, respectively. Core-shell structured micromaterials have gained increasing interest among all multicomponent micromaterials due to their exceptional features, which include (i) The ligand effect is dominated by the material's adsorption capability due to the presence of various atomic groups on its surface. (ii) The ensemble effect includes the linkages between the shell and core caused by variations in charge transfer between the components, which are impacted by atomic proximity and so alter the band structures. (iii) The structure effect is created by 3D structural restrictions, which results in a differential in surface atomic activity. Core-shell structured micromaterials have been widely employed in energy storage and conversion due to their unique physical and chemical features. This is supported by the researcher [15].

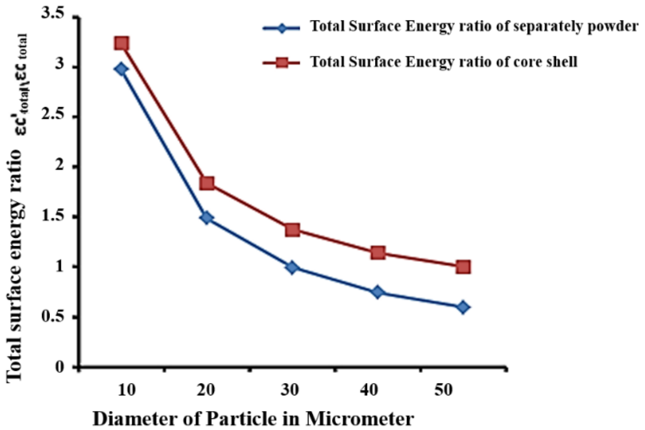

Figure 6. Total surface energy ratio versus particles diameter at 2.5wt.%

5. CONCLUSION

A result of constructing a computational model and carrying out an evaluation calculation, it was shown that the introduction of two-component additives as core-shell allows the dispersed system to obtain excess surface energy due to the formation of new "substrate-coating" interfaces. Then, the new "high-energy" dispersed system can interact more effectively with the friction surface and achieve an anti-friction effect. The above estimation calculation was performed under a fairly strong simplifying assumption that the additive particles are spherical. In contrast, colloidal graphite particles have the shape of flakes, and their actual surface is significantly larger than conventionally spherical particles. In this case, the actual thickness of the layer obtained from the condition of equal masses of the substrate and coating will be significantly less. Moreover, it is very likely.

ACKNOWLEDGMENT

The authors would like to thank Middle Technical University and Southern Technical University – Iraq for their support in the present work.

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