Stable dispersibility of bentonite-type additive with gemini ionic liquid intercalation structure for oil-based drilling

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Abstract: In this study, the direct intercalation of gemini ionic liquids (ILs) with different alkyl chains into the bentonite (BT) interlayer as a high-performance lubricating additive for base oil 500SN was investigated. The purpose of modifying BT with an IL is to improve the dispersion stability and lubricity of BT in lubricating oil. The dispersibility and tribological properties of IL–BT as oil-based additives for 500SN depend on the increase in interlamellar space in BT and improve as the chain length is increased. More importantly, the IL–BT nanomaterial outperforms individual BT in improving wear resistance, owing to its sheet layers were deformed and sprawled in furrows along the metal surface, thereby resulting in low surface adhesion. Because of its excellent lubrication performance, IL-modified BT is a potential candidate for the main component of drilling fluid. It can be used as a lubricating additive in oil drilling and oil well construction to reduce equipment damage and ensure the normal operation of equipments.

Keywords: ionic liquid; modified bentonite; nanomaterial; oil-based additive

1 Introduction

Oil drilling operations are vital in petroleum exploration. The demand for lubrication in these operations is high owing to the various types of friction between the bit/drilling tool and borehole wall, which occur under different operating conditions [1]. Drilling fluids, also known as “drilling mud” in drilling engineering, can be categorized into clear water, mud, clay-free washing fluid, emulsion, foam, and compressed air according to their composition, as well as provide numerous functions such as wellbore stabilization, transfer of hydrodynamic force, cooling and lubrication, and balance in formation pressure and rock lateral pressure [2]. Drilling fluids are scientifically classified into three primary categories: oil-based [3], synthetic-based [4], and water-based drilling fluids [5, 6]. In practical and complex conditions, it is particularly important that the performance of drilling fluids is improved and stabilized, as it would otherwise result in equipment damage, downhole risk, and economic losses.

Bentonite (BT), a layered soil mineral, is one of the basic formulations used in drilling fluids. It has a certain interlayer spacing owing to its sheet-like inner structure, which can easily accommodate more functional chemical compounds compared with other minerals, thereby affording more varied modifications

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[7–9]. Owing to its specific properties, such as high specific surface area, ion-exchange capacity, and expandability, BT is widely used in drilling fluids. BT can not only reduce shear damping in friction due to adjustable interlayer spacing, but can also regulate the thixotropy and rheological properties of drilling fluids [10, 11]. When used in oil-based drilling fluids, BT primarily offers advantages in terms of its high-temperature resistance, good lubrication, excellent reservoir protection, and reduced environmental pollution. However, subpar dispensability caused by large particle size and surface hydrophilic functional groups in oil render it difficult to satisfy the demands of modern drilling fluids.

Ionic liquid (IL) lubricants possess outstanding friction-reducing and anti-wear properties owing to their robust physicochemical properties [12–14]. When ILs are used as lubricant additives, the hydrophobic interactions of alkyl chains are crucial [15, 16]. Gemini ILs, a new class of ILs, contain two cationic sites and hydrophobic alkyl chains, which can be intercalated more efficiently in BT [17–20]. Their long alkyl chains are advantageous for increasing interlayer spacing, which improves interlayer slippage and reduces friction. Furthermore, long alkyl chains reduce the polarity, and improve the dispersion stability in oil. Meanwhile, double-ion-targeting sites enhance both intercalation and adsorption. By fully exploiting the lubrication characteristics of ILs, Gemini ILs and IL–BT nanocomposites were prepared based on previous literatures [17, 24]. A simple preparation process was performed: The stoichiometric amount of IL corresponding to 0.5 and 1.5 times the cation exchange capacity of BT was dissolved in a 50 mL solution, in which a 50 mL BT dispersion was added and vigorously stirred for 15 min. A system combining microwave and ultrasound was applied for the reaction of the aforementioned mixture for 60 min at 60 °C, whereas the operating power of the microwave and ultrasound was set to 500 and 450 W, respectively, and an interval of 1 s was allocated for each 2 s of ultrasonication. The obtained product was centrifuged, washed, desiccated, ground, sieved, and labeled as IL–BT.

2 Experimental

2.1 Chemical materials and preparation of IL and IL–BT nanocomposites

Bentonite (sodium salt) was purchased from J&K Reagent Co., Ltd. N,N,N',N'-tetramethylethylenediamine, bromotetradecane, bromohexadecane, and octadecyl bromide were purchased from Sigma–Aldrich, USA. The procedure for synthesizing gemini ILs and IL–BT nanocomposites was based on previous literatures [17, 24]. A simple preparation process was performed: The stoichiometric amount of IL corresponding to 0.5 and 1.5 times the cation exchange capacity of BT was dissolved in a 50 mL solution, in which a 50 mL BT dispersion was added and vigorously stirred for 15 min. A system combining microwave and ultrasound was applied for the reaction of the aforementioned mixture for 60 min at 60 °C, whereas the operating power of the microwave and ultrasound was set to 500 and 450 W, respectively, and an interval of 1 s was allocated for each 2 s of ultrasonication. The obtained product was centrifuged, washed, desiccated, ground, sieved, and labeled as IL–BT.

2.2 Characterization of IL–BT nanocomposites

XRD analysis was performed using an automated X-ray diffractometer (DMAXU1TIM AIV, Hitachi, Japan) fitted with a monochromatic Cu Kα radiation (λ = 1.5418 Å) source operating at 40 kV and 40 mA, with a 2θ scanning range varying from 2° to 40° with a step size of 0.02°. IR spectra were recorded using a FT-IR spectrophotometer (Perkin Elmer 1725, Thermo Fisher Scientific, USA) with a deuterated triglycine sulfate (DTGS) detector, with a wavenumber range of 4,000 to 400 cm⁻¹, configured to a resolution of 2.0 cm⁻¹. TGA was performed on a Netzsch synchronous thermal analyzer (STA 449 F3, NETZSCH, Germany) under nitrogen gas flow (50 mL·min⁻¹). The temperature was set from 25 to 800 °C at a heat increment of 10 °C·min⁻¹.

Morphological differences before and after the modification of BT were observed on the surface of the BT and IL-modified BT using an SEM (FEI Quanta FEG 250, USA) equipped with a secondary electron detector at an accelerating voltage of 20 kV. Composition analyses were conducted on an SEM (FEI Quanta FEG 250) equipped with an energy dispersive spectroscopy
(EDS) X-ray analyzer and a feature image processing software. EDS element scanning was performed on the surface of the BT and IL–BT at 1000× magnification and a resolution ratio of 256 × 200.

2.3 Lubrication performance of IL–BT nanocomposites as oil-based additives

The tribological properties of the obtained samples as additives were characterized by evaluating their coefficient of friction (COF) and wear volume (WV) using an oscillating reciprocating friction and wear tester (Optimol SRV-IV, Germany), which was assembled in a ball-on-disk configuration, where the friction couple was an upper ball (Ø = 10 mm, AISI 52100) with relative sliding against a lower steel disk (AISI 52100; diameter = 24 mm; height = 7.9 mm; hardness = 750–850 HV). The friction experimental parameters were as follows: Load = 100 N, frequency = 25 Hz, amplitude = 1 mm, temperature = 25 °C, and humidity = 30%–40%. The abrasive resistance was detected using a three-dimensional (3D) non-contact surface mapping microscope profiler (Bruker-Npflex, USA) by evaluating the wear volume. The morphology and elemental distribution of the wear spot surfaces were detected using SEM. Changes in the elements inside and outside the wear spot were analyzed via EDS line scanning and energy spectrum analysis.

3 Results and discussion

3.1 Dispersibility of IL–BT nanocomposites

Sodium BT, as shown in Fig. 1(a), exhibits an excellent lamellar structure, offers high cation exchange capacity and layer expansion ability, and has a large specific surface area [25]. Figure 1(b) shows a series of prepared gemini ILs (IL14–2–14, IL16–2–16, and IL18–2–18), which are characterized by their identical spacer chain lengths and different alkyl chain lengths. They were selected for modifying the BT. The effect of the alkyl chain length of the gemini ILs on the structure, morphology, and surface properties of the IL–BT nanocomposites were investigated systematically. Figure 1(c) shows a schematic diagram of the preparation of the intercalated IL–BT nanomaterials. The synthesis method was simple. One clear difference was that after the gemini ILs

![Image of pure bentonite, Structure of ILs, Schematic diagram of preparation of IL–intercalated BT composites and image of intercalated BT, Photographs of dispersed IL–BT nanocomposites in 500SN: (I) IL18–2–18–BT, (II) IL16–2–16–BT, (III) IL14–2–14–BT, and (IV) BT with 1% concentration, whose stability and dispersibility are evident after 24 h.](www.Springer.com/journal/40544)
were intercalated with BT, the IL–BT obtained seemed significantly darker in color (Fig. 1(c)). The insertion of the IL into the layers of the BT significantly improved the slip performance of the BT layers and the dispersion stability of the IL–BT nanomaterials in the base oil. As shown by the optical camera images in Figs. 1(d) (I–III)), after 24 h, the IL–BT nanomaterials remained dispersed in 500SN, and the longest chain IL–BT performed the best, demonstrating its good stability and dispersibility (Fig. 1(d) (I)). By contrast, the stability of BT without intercalation modification was inferior, where subsidence was evident (Fig. 1(d) (IV)). This is because the increase in the alkyl chain length increased the interlayer spacing of the composite, whereas the lipophilic properties of the alkyl chain improved its dispersion stability in the base oil.

3.2 Characterization of IL–BT nanocomposites

The FT-IR spectra of BT and IL–BT nanocomposites were compared to further confirm the intercalation of ILs within the interlayer spacings of BT. A comparison among the FT-IR spectra of pure BT, IL–BT, and IL–BT is shown in Fig. 2(a), and the FT-IR spectra of all IL–BT nanocomposites are shown in Fig. 2(a1). The BT spectrum exhibited vibrational band characteristic of aluminosilicate minerals, showing absorption bands at 3,625.90 (OH stretching vibrations of structural groups) and 3,421.43 cm⁻¹ (water molecules) [26]. Additionally, spectral peaks were observed at 1,638.13 and 1,034.04 cm⁻¹, which may be ascribed to the H–O bending vibration and Si–O stretching vibration bands, respectively, whereas the bands in

![Fig. 2](image-url) (a, a1) FT-IR spectra, (b, b1) XRD patterns, (c) Raman spectra, and (d) TG curves of BT and IL–BT nanocomposites.
the 400–600 cm\(^{-1}\) region were attributed to Si–O and Al–O bending vibration bands. Owing to the contribution of IL cations, the intensity of the structural OH stretching vibration band of IL–BT was greater than those of the others [27]. Take IL\(_{18-2-18}\)-BT as an example, in addition to the existing characteristic peaks, new peaks appeared at approximately 2,927.23 (antisymmetric \(\nu(CH_2)\) stretching bands) and 2,862.23 cm\(^{-1}\) (symmetric \(\nu(CH_2)\) stretching bands), which can be assigned to the methylene groups in the molecules of ILs, accompanied by the bands for the C–H bending vibration of alkyl chain at 1,468.70 cm\(^{-1}\) [28]. Similar analytical results were obtained for all the IL–BT samples shown in Fig. 2(a1). The longer the length of the IL alkyl chain, the greater was the intensity of the characteristic peak, which can be ascribed to the increase in the interlayer stacking density of the alkyl chain. The presence of these bands confirmed the formation of the IL–BT nanocomposites. Additionally, their intensities and the presence of characteristic peaks implied the generation of intercalation materials.

A comparison of the XRD patterns of BT and IL–BT composites is shown in Figs. 2(b) and 2(b1). To confirm the intercalation structure and interlayer spacing after intercalation, Bragg’s equation \((n\lambda = 2d\sin\theta)\), where \(d\) is the interplanar spacing; \(\theta\) is the angle between the incident X-ray and the corresponding crystal plane; \(\lambda\) is the wavelength of the X-ray, \(\lambda = 1.5418\,\text{Å} n\) is the diffraction order, \(n = 1\) was used to calculate the layer spacing for BT and IL–BT composites, which is denoted as the \(d\)-value. The \(d_{001}\) value of BT is 12.2 Å, which represents typical sodium BT and implies a typical Na\(^+\) form within the interlayer spacing of BT [29, 30]. After modification with various ILs, the XRD patterns of all IL-modified BT composites exhibited evident changes (intense reflections at lower \(2\theta\) values) in the basal spacing. The \(d_{001}\) values of IL\(_{12-2-12}\)-BT, IL\(_{14-2-14}\)-BT, and IL\(_{18-2-18}\)-BT were 13.1, 13.5, and 14.2 Å, respectively. The interaction between BT and the gemini IL resulted in a shift in the \(d_{001}\) diffraction peak of IL–BT composites toward larger \(2\theta\) values, implying the expansion of the interlayer spacing due to the intercalation of gemini IL [31]. The alkyl chain length of the inserted IL was long, and the layer spacing of the obtained IL–BT composites was larger after the modification.

Figure 2(c) shows the Raman spectra of BT and IL\(_{18-2-18}\)-BT. The spectrum of BT contained several strong, sharp bands at approximately 335, 468, 621, and 771 cm\(^{-1}\), which correspond to the antisymmetric vibration of Al–O, symmetric vibration of Si–O, stretching vibration of Al–O, and antisymmetric vibration of Si–OH, respectively, representing the structural characteristics of BT. For IL–BT composites, the Raman bands at 148 and 800 cm\(^{-1}\) were assigned to the \(\nu(C–C)\) stretching vibration bending due to the molecular structure of the \(+CH_2\) moiety. The bands appeared at 873 and 1,077 cm\(^{-1}\), which were attributed to the C–N bond vibrations and C–C stretching, respectively. Additionally, well-defined bands appeared at 1,246 cm\(^{-1}\) owing to the deformation vibration \(\delta(C–H)\), further confirming that IL was successfully intercalated on the surface and interface of BT [32].

Figure 2(d) shows the thermogravimetric (TG) curves of BT and IL–BT nanocomposites. For BT, two stages were observed: The first one was at 90 °C, which was due to the loss of physically adsorbed water and other volatiles; the second stage of mass losses showed an intense endothermic band that occurred between 500 and 800 °C, which was typical of the strong interactions with the BT layers, corresponding to the dehydroxylation of hydroxyl groups in BT [33, 34]. When the ILs were intercalated in BT, their molecular environments and the interlayer arrangement primarily affected their thermal decomposition temperature \((T_d)\). For IL\(_{18-2-18}\)-BT, the TG curves show three significant mass losses: First, a slight initial weight loss (3%–4%) from 40 to 110 °C may have contribution to moisture evaporation. Second, weight loss between the first and second peak occurred between 200 and 300 °C, which indicated the decomposition of physically absorbed ILs between layers or surfaces of BT. Third, mass loss between 300 and 600 °C was ascribed to the decomposition of intercalated ILs. As the chain length of the modified ILs elongated, the \(T_d\) of the corresponding IL–BT increased accordingly. Consequently, the \(T_d\) of the decomposed 25% for IL\(_{14-2-14}\)-BT, IL\(_{16-2-16}\)-BT, and IL\(_{18-2-18}\)-BT increased, owing to the higher molecular weight of IL\(_{18-2-18}\)-BT and its tightly packed arrangement in the layers.
3.3 Morphology and elemental analysis of IL–BT nanocomposites

The morphologies of the BT and IL–BT composites are shown in Figs. 3(a) and 3(a1), respectively. As shown, the BT measures 3–5 μm. The surface of the BT is dense and thick, resembling a lump surrounded by small and well-separated particles [35, 36]. Meanwhile, owing to the loose lamellar structure of IL–BT, the stacks of multilayers became thin and dispersive, indicating that the dispersion of IL–BT improved because of the intercalation of the ILs. The cationic chain length increased; the polarity of the ionic liquid decreased; and the repulsive force between the BT particles decreased, thereby increasing the dispersibility of the nanomaterial in the base oil [9, 37]. Furthermore, this phenomenon was more evident in IL_{18–2–18}–BT, which may be attributed to the fact that longer chain lengths facilitated the separation of the layers, which is consistent with the TGA and XRD results.

Figures 3(b) and 3(c) show the EDS spectra of the element contents of BT and IL_{18–2–18}–BT, respectively. They were used to obtain the chemical information and element distributions of BT and IL_{18–2–18}–BT, respectively. As shown by the column illustration of the element content in Fig. 3(c), the modified IL_{18–2–18}–BT contained not only 21% carbon and 1.4% nitrogen, but also indicated a decreased amount of the corresponding aluminum, silicon, and oxygen, indicating the presence of IL in the layers of BT. Meanwhile, based on the EDS spectrum analysis of the worn surface, it can be inferred that a significant amount of elemental oxygen was presented on the friction surface. Furthermore, the results of the
surface distribution show that metal elements were enriched on the worn surface. Therefore, the oxidation of metal elements in BT was accelerated by the promotion of oxidation and permeation, due to that an oxide lubricating film protective layer was formed. The corresponding results can be directly and clearly observed from the element distribution diagram (Figs. 3(b1) and 3(c1)).

3.4 Tribological properties of IL–BT nanocomposites as additives

As lubricant additives, BT and modified IL–BT composites were added to base oil (500SN), and their tribological properties were investigated. First, the effect of IL18–2–18–BT concentration on the lubricity of 500SN was investigated (Fig. 4(a)). The COFs of different concentrations of IL18–2–18–BT added to 500SN remained in the range of 0.12–0.13, and the main difference was the improvement in anti-wear properties. As shown in Fig. 4(a), the WV decreased at first and then increased as the concentration increased; therefore, the optimum concentration was 1 wt%.

Compared with the COF of reference sample 500SN, those of 1 wt% BT and IL–BT-added 500SN decreased, and their curves were smooth. Figure 4(b) shows that this is consistent with the results of the three average COFs. Meanwhile, Fig. 4(c) shows that this type of lamellar structure of BT and IL–BT additives is crucial in improving friction-reducing performance. The lamellar structure reduced shear damping in the horizontal direction during friction, and performed better in terms of anti-wear performance. Compared with the WV of 500SN, that of the BT additive decreased by 70%, whereas the decrease range of wear volume for the modified IL–BT additive was higher. Furthermore, as the chain length of the intercalated IL increased, the WV of the modified IL–BT additive decreased. The considerable improvement was attributed to the increase in the interlayer spacing after intercalation using ILs of different alkyl chain lengths, which is more conducive to the relative sliding of the laminates under the action of friction, allowing shear to occur more easily in the horizontal friction. More importantly, these modified IL–BT composites, as a type of two-dimensional nanomaterial additive, decreased the friction factor and repaired the surface abrasion [38]. Therefore, IL18–2–18–BT demonstrated the best friction-reducing and anti-wear properties among all the samples.

The extreme pressure bearing capacity of the IL–BT additives was further investigated via a load ramp test (Fig. 4(d)). The maximum carrying pressure values

![Fig. 4](image-url) (a) COF and WV of steel discs lubricated by different concentrations of additive IL18–2–18–BT at 100 N. (b) COF of steel discs lubricated by 1 wt% of different lubricants. (c) WV and Average COF of steel discs lubricated by different lubricants. (d) Variations in COFs with time for 500SN, 500SN with additives BT and IL18–2–18–BT under load ramp test from 50 to 750 N at 25 Hz.
for pure 500SN, BT additive-added, and IL\textsubscript{18–2–18–BT} additive-added 500SN are 150, 550, and 650 N, respectively. Hence, it can be concluded that the lubrication performance of 500SN improved significantly by using the intercalated modified BT as an additive. The enhancement in the extreme pressure carrying capacity of the IL–BT composites was due to the synergistic effect of the layered nanostructures of the BT and the flexibility of the long alkyl chains in the molecular structures of the ILs.

3.5 Surface and element analysis of worn surface

The SEM measurements of the lower steel discs lubricated with different samples are shown in Fig. 5. The steel surface lubricated by 500SN exhibited wide wear spots and severe wear, accompanied by wide and deep concave grains and pear grooves (Figs. 5(a) and 5(a1)). By contrast, the surface of the additive BT improved significantly (Figs. 5(b) and 5(b1)). The worn scars lubricated by the IL–BT composites (Figs. 5(c)–5(e) and Figs. 5(c1)–5(e1) for IL\textsubscript{14–2–14–BT}, IL\textsubscript{16–2–16–BT}, and IL\textsubscript{18–2–18–BT}) were narrow, shallow, and smooth, owing to the lamellar structure forming a discontinuous self-compensation-repairing organic film on the worn surface, which filled the surface with cracks and pits. The anti-wear effect caused by the IL–BT composites became more prominent. For IL\textsubscript{14–2–14–BT}, IL\textsubscript{16–2–16–BT}, and IL\textsubscript{18–2–18–BT}, the wear marks on the steel surface of the site were shallower, and scratches were barely observed as the alkyl chain length increased, which can also be clearly observed from the 3D depth profile (Figs. 5(a2)–5(e2)).

Fig. 5 SEM of worn scars lubricated by (a, a1) 500SN, (b, b1) BT, (c, c1) IL\textsubscript{14–2–14–BT}, (d, d1) IL\textsubscript{16–2–16–BT}, and (e, e1) IL\textsubscript{18–2–18–BT}. Magnification: (a–e) 180× and (a1–e1) 3000×. Color images show 3D and depth profiles of worn scars lubricated by (a2) 500SN, (b2) BT, (c2) IL\textsubscript{14–2–14–BT}, (d2) IL\textsubscript{16–2–16–BT}, and (e2) IL\textsubscript{18–2–18–BT}. 
from the 3D and depth profiles of the worn scars shown in Fig. 5 is consistent with the SEM images.

Figure 6 shows a line analysis of atoms from the inside to the outside of the worn surface. It was observed that the element distribution varied with distance. Meanwhile, no significant changes were observed in terms of the contents of all elements outside the worn spot.

For the worn surface lubricated by 500SN, only a slight amount of carbon was detected inside the worn surface (Fig. 6(a1)). For the worn surface lubricated by the BT additive, a few oxygen atoms were detected; however, a certain amount of carbon and nitrogen atoms were detected, which can be assumed to have adsorbed on the worn surface without chemical reaction when BT reacts with the metal surface (Fig. 6(a2)). Compared with that of 500SN, the oxygen content in the wear spot of IL$_{18-2-18}$-BT (Fig. 6(c1)) as an additive decreases significantly, which proves that fewer oxidation products were generated in the friction process. Additionally, a significant number of nitrogen element signals were detected, suggesting that the newly formed iron surface was not oxidized to iron oxide during the friction process, but gradually formed complex tribochemical reaction films such as iron nitride. The distribution of the characteristic elements indicates the formation of a frictional protective film on the surface, which contributes to the excellent friction-reducing and anti-wear properties.

### 3.6 Mechanism analysis

More intuitive observations and detailed analysis of the tribo-film intercalated with IL–BT were obtained via focus ion beam (FIB) and high-resolution transmission electron microscope (HRTEM) analysis (Fig. 7). A tribo-film with a thickness of approximately 100 nm was formed on the sliding interface, which resulted in a superior lubricity. As shown by the step-by-step enlarged pictures of this lubricating protective film (Figs. 7(b)–7(e)), the formed film was

![Fig. 6](image-url) Line analysis of elements inside the worn surface after lubricated by (a, a1) 500SN, (b, b1) BT, and (c, c1) IL$_{18-2-18}$-BT, obtained via EDS spectrum imaging. Red line indicates location of line scanning. The scanning direction is marked from top to bottom with red lines in Figs. 6(a)–6(c).
not completely uniform, and do not show clearly visible nanocrystals dispersed in the tribo-film. This was attributable to the interaction between the layered IL–BT nanomaterials and the interface. These enriched nanocrystallites (Figs. 7(f) and 7(g)) may benefit from the structure of the modified BT, and improved the strength of the lubricating film to some extent. Furthermore, HRTEM observations (see Fig. 7(h)) imply that this film was primarily composed of crystals with a lattice spacing of 0.3012 nm, which corresponded to the lattice planes of metallic oxide (Fig. 7(h)). Moreover, the presence of the metallic nanoparticles supported the constructive participation and contribution of BT in the shear process, which is consistent with the elemental mapping analysis. The uniform distribution of all elements (C, O, N, Al, and Si) on the interface reflects the synergistic effect by the IL and BT. The active element N in the IL can react with the sliding asperity. In other words, the tribochemical reaction may be due to the structure of the gemini cation. Meanwhile, its optimized layered structure for BT nanomaterials is conducive to maintaining the shear resistance of the friction process.

The lubricity mechanism of the IL–BT intercalation material as an oil-based dispersion additive is discussed based on the data obtained from the analyses. Owing to the high stress on the contact surface, a high contact stress ($\sigma$) was generated on some micro-convex bodies (real contact points), causing the two surfaces (contact points) to be welded (adhesion) together in the friction process, which resulted in the maximum friction at the interface [39, 40]. As shown in the mechanism diagram (Fig. 8), when two asperity
peaks are close to each other, owing to its lamellar structure, IL–BT can wedge into the friction interface, and it directly resists direct contact and collision. Meanwhile, the lamellar structure skips along the direction of the friction pair, and reduces the shear damping in the sliding direction. Furthermore, owing to the escape of the electrons in the friction process, the metal surface is positively charged, whereas the intercalated IL–BT composite retains a negative charge on its surface [41, 42]. Their charge interactions allow nanomaterial deposition to the maximum extent, and impose a filling effect in the gully. At higher contact pressures, the IL–BT compound material is exfoliated and adsorbed on the surface of theasperity peaks. Meanwhile, its sheet layers incidentally glide along one another, as well as deform and sprawl on furrows along the metal surface, resulting in low surface adhesion. During the friction process, the IL adsorbed on the BT surface is resolved by the increase in pressure and temperature and by the dissociation in the base oil, which contributes to lubrication, namely, the lubrication protective film provided by the tribochemical reaction between the ILs is adsorbed or inserted into the interlayer and the friction interface [43–45]. Furthermore, the stability of the lamellar structure and the orderliness of the long molecular chains provided by the IL–BT composites contribute to the reduction in shear damping in the horizontal direction during the process of friction pair movement. The interposition of IL cations increases the interlayer spacing, which reduces the interaction force between the BT layers and allows the interlayer to slip more easily. Furthermore, an increase in the molecular chain can support the membrane structure and improve the bearing capacity and tribological properties.

4 Conclusions

In this study, three types of gemini ILs with different alkyl chain lengths were intercalated to generate IL–BT nanocomposites. The analysis results show that the gemini IL is more effective for the expansion of the BT interlayer spacing, and that a longer hydrophobic chain of ILs facilitates the expansion of the BT interlayer spacing. IL–BT, when used as an additive in 500SN, demonstrates excellent friction-reducing and anti-wear performance, which can be ascribed to the increase in the interlayer spacing caused by the intercalation of IL. The analyses of the lubrication mechanism show that a looser interlayer structure facilitates the interlayer slip and hence the formation of a wear-resistant layer. Furthermore, a tribochemical reaction occurs between the ILs adsorbed or inserted into the interlayer and the friction interface, thereby resulting in a lubricating protective film. Such intercalated lamellar nanomaterials would facilitate the investigation of more effective nano-lubricating additives. As an effective additive, the modified BT
can significantly improve the lubrication and efficiency of oil-based drilling fluids, affords certain economic benefits, and benefits practical applications.

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