Collisional Growth Efficiency of Dust Aggregates and Its Independence of the Strength of Interparticle Rolling Friction

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Abstract

The pairwise collisional growth of dust aggregates consisting of submicron-sized grains is the first step of planet formation, and understanding the collisional behavior of dust aggregates is therefore essential. It is known that the main energy dissipation mechanisms are the tangential frictions between particles in contact, namely, rolling, sliding, and twisting. However, there is great uncertainty for the strength of rolling friction, and the dependence of the collisional growth condition on the strength of rolling friction was poorly understood. Here we performed numerical simulations of collisions between two equal-mass porous aggregates with various collision velocities and impact parameters, and we also changed the strength of rolling friction systematically. We found that the threshold of the collision velocity for the fragmentation of dust aggregates is nearly independent of the strength of rolling friction. This is because the total amount of the energy dissipation by the tangential frictions is nearly constant even though the strength of rolling friction is varied.

Unified Astronomy Thesaurus concepts: Protoplanetary disks (1300); Circumstellar disks (235); Planet formation (1241); Planetesimals (1259)

1. Introduction

The first step of planet formation is the pairwise collisional growth of dust aggregates consisting of submicron-sized grains (e.g., Wurm & Teiser 2021). Therefore, understanding the condition for collisional growth of dust aggregates is essential.

The collisional behavior of dust aggregates has been studied extensively, by using both laboratory experiments (e.g., Blum & Wurm 2008; Fritscher & Teiser 2021; Schräpler et al. 2022) and numerical simulations (e.g., Wada et al. 2009; Hasegawa et al. 2021; Umstätter & Urbassek 2021a). It is known that the threshold collision velocity for the fragmentation of dust aggregates, $\xi_{\text{crit}}$, depends on the strength of interparticle forces acting on constituent particles in contact.

The stickiness of dust particles has been investigated in a large number of studies (e.g., Güttler et al. 2012; Tanaka et al. 2012; Gundlach & Blum 2015). These studies found that the threshold velocity for the sticking in a head-on collision of individual dust particles is several times higher than that predicted for perfectly elastic spheres. Arakawa & Krijt (2021) concluded that the viscous dissipation for the normal motion would play a critical role in the collision between micron-sized water-ice particles.

Recently, Arakawa et al. (2022) performed numerical simulations of collisions between two equal-mass dust aggregates consisting of submicron-sized spherical ice particles. Surprisingly, they found that the main energy dissipation mechanism was not the viscous dissipation but the friction between particles in contact. Interparticle frictions are caused by tangential motions, and there are three types of tangential motions: rolling, sliding, and twisting (see Figure 2 of Wada et al. 2007). Therefore, we can imagine that the collisional behavior of dust aggregates would be affected by the strength of interparticle frictions.

The rolling friction is one of the strongest energy dissipation mechanisms. The interparticle rolling motion behaves elastically (i.e., without energy dissipation) when the length of the rolling displacement, $\xi$, is smaller than the critical rolling displacement, $\xi_{\text{crit}}$ (e.g., Dominik & Tielens 1995; Wada et al. 2007). The energy dissipation starts when $\xi$ exceeds $\xi_{\text{crit}}$.

As the interparticle rolling friction is the dominant mechanism for the energy dissipation within colliding dust aggregates, we can expect that the collisional outcome of dust aggregates must depend on $\xi_{\text{crit}}$; however, it is poorly understood how large $\xi_{\text{crit}}$ is for micron-sized spheres. Dominik & Tielens (1995) constructed the theoretical model of rolling based on the contact theory developed by Johnson et al. (1971). They mentioned that $\xi_{\text{crit}}$ should be of the order of the distance between atoms in the materials, and it is typically 0.2 nm. In contrast, Heim et al. (1999) measured the rolling friction torques between individual silica microspheres by using an atomic force microscope. They found, however, that the critical rolling displacement for silica microspheres with radii between 0.5 and 2.5 $\mu$m would be $\xi_{\text{crit}} = 3.2$ nm, which is 16 times larger than Dominik & Tielens (1995) assumed. We note that the upper limit of $\xi_{\text{crit}}$ would be given by the contact radius of spheres at the equilibrium state, $a_0$, and $\xi_{\text{crit}} = 3.2$ nm is still smaller than $a_0$.

Krijt et al. (2014) modified the analytical theory for the rolling friction based on the concept of adhesion hysteresis, and they reported that $\xi_{\text{crit}}$ would be given by $\xi_{\text{crit}} \sim a_0/24$ for silica microspheres when the crack propagation rate is 1–10 $\mu$m s$^{-1}$. Recently, Umstätter & Urbassek (2021b) performed molecular dynamics simulations of amorphous Lennard-Jones grains and confirmed that $\xi_{\text{crit}}$ depends on both the material parameters and the angular velocity for rolling.

Although the rolling friction is one of the main energy dissipation mechanisms for oblique collisions between dust aggregates, dependence of the collisional growth condition on...
\( \xi_{\text{crit}} \) is poorly understood. Wada et al. (2008) performed numerical simulations of head-on collisions between dust aggregates with various \( \xi_{\text{crit}} \). They used highly porous dust aggregates prepared by ballistic cluster–cluster aggregation in their simulations, and they investigated the condition for collisional compression and fragmentation. They reported that both the onset of collisional compression and the maximum compression linearly depend on \( \xi_{\text{crit}} \), but the size of the largest fragment formed after a collision is nearly independent of \( \xi_{\text{crit}} \).

These results would be naturally explained by the findings that the collisional compression is caused by interparticle rolling motions while the energy dissipation is primarily caused by the connection and the disconnection of particles (Wada et al. 2009). We note, however, that they focused on head-on collisions and did not study collisional behavior for oblique collisions. Suyama et al. (2008, 2012) also investigated the collisional compression of dust aggregates by sequential collision simulations, but they also focused on head-on collisions.

In this study, we report the results from numerical simulations of collisions between two equal-mass dust aggregates with various collision velocity and impact parameters. We changed the strength of the interparticle rolling friction systematically, which is controlled by \( \xi_{\text{crit}} \). Surprisingly, we found that the threshold collision velocity for the fragmentation of dust aggregates is nearly independent of \( \xi_{\text{crit}} \) when we consider oblique collisions.

### 2. Model

We performed three-dimensional numerical simulations of collisions between two equal-mass dust aggregates. The numerical code used in this study is identical to that developed by Arakawa et al. (2022), which considered the viscous drag for normal motion and also considered friction torques for tangential motions.

#### 2.1. Material Parameters

We assumed that the dust particles constituting dust aggregates are made of water ice, and all particles have the same radius of \( r_1 = 0.1 \, \mu m \). The material parameters of water-ice particles used in this study are listed in Table 1. The particle interaction model is identical to that used in Arakawa et al. (2022).

#### 2.2. Interparticle Rolling Motion

In this study, we regarded \( \xi_{\text{crit}} \) as a parameter. We applied a linear spring model with a critical displacement to the interparticle rolling motion (Wada et al. 2007). When the length of the rolling displacement is \( \xi \), the potential energy stored by the rolling displacement is given by

\[
U_\xi = \frac{1}{2} k_\xi \xi^2 ,
\]

and the spring constant, \( k_\xi \), is given by

\[
k_\xi = \frac{4F_c}{R} .
\]

Here \( F_c = 3\pi\gamma R \) is the maximum force needed to separate the two particles in contact, and \( R = r_1/2 \) is the reduced particle radius. The critical energy required to start rolling, \( E_{r,\text{crit}} \), is given by

\[
E_{r,\text{crit}} = \frac{1}{2} k_\xi \xi_{\text{crit}}^2 \\
= 6\pi\gamma \xi_{\text{crit}}^2 .
\]

Wada et al. (2007) introduced \( E_{r,\text{crit}} \) as the energy needed to rotate a particle by a \( \pi/2 \) radian around its contact point, which is given by

\[
E_{r,\text{crit}} = k_\xi \xi_{\text{crit}} \pi R \\
= 12\pi\gamma R \xi_{\text{crit}} .
\]

Figure 1 shows the dependence of \( E_{r,\text{crit}} \) and \( E_{\text{roll}} \) on \( \xi_{\text{crit}} \). We normalized \( E_{r,\text{crit}} \) and \( E_{\text{roll}} \) by \( F_c \xi_{\text{crit}} \), where \( \xi_{\text{crit}} \) is the critical stretching length for particle separation, which is given by

\[
\xi_{\text{crit}} = \left( \frac{9}{16} \right)^{1/3} a_0^2 \frac{3R}{a_0} .
\]

The contact radius of spheres at the equilibrium state, \( a_0 \), is given by

\[
a_0 = \left( \frac{9\pi\gamma R^2}{E^*} \right)^{1/3} \\
= 12.4 \, \text{nm},
\]

where \( E^* = E/[2(1 - \nu^2)] \) is the reduced Young’s modulus.

### Table 1

| Parameter                     | Symbol | Value |
|-------------------------------|--------|-------|
| Particle radius (\( \mu m \))| \( r_1 \) | 0.1   |
| Material density (kg m\(^{-3}\)) | \( \rho \) | 1000  |
| Surface energy (J m\(^{-2}\)) | \( \gamma \) | 100   |
| Young’s modulus (GPa)         | \( \xi \) | 7     |
| Poisson’s ratio               | \( \nu \) | 0.25  |
| Viscoelastic timescale (ps)   | \( T_{\text{vis}} \) | 6     |
The energy needed to break a contact in the equilibrium by the quasistatic process, $E_{\text{break}}$, is given by:

$$E_{\text{break}} = \left( \frac{4}{45} + \frac{4}{5} \times 6^{1/3} \right) F_c \delta_c$$

$$= 1.54 F_c \delta_c. \tag{7}$$

The blue horizontal line shown in Figure 1 represents $E_{\text{break}}$. We found that $E_{\text{break}} > E_{\text{r,crit}}$ when $\xi_{\text{crit}} \lesssim 3.2$ nm. Not only the potential energy related to the normal compression but also the potential energies stored by the tangential displacements dissipate when two particles separate. However, the contribution of the rolling displacement is negligible for $\xi_{\text{crit}} \lesssim 3.2$ nm. In addition, Arakawa et al. (2022) confirmed that contributions of sliding and twisting displacements also play a minor role; they are one order of magnitude smaller than $E_{\text{break}}$.

The collision velocity of two dust aggregates is $v_{\text{col}}$, and the initial kinetic energy per one particle with the velocity of $v_{\text{col}}/2$ is

$$E_{\text{kin,1}} = \frac{1}{2} m_1 \left( \frac{v_{\text{col}}}{2} \right)^2$$

$$= 33 \left( \frac{v_{\text{col}}}{50 \, \text{m.s}^{-1}} \right)^2 F_c \delta_c, \tag{8}$$

where $m_1 = 4\pi \rho r_f^3/3$ is the mass of each particle. Therefore, $E_{\text{col}} \gg E_{\text{kin,1}}$ for $\xi_{\text{crit}} \gg 3.2$ nm and $v_{\text{col}} \ll 50$ m s$^{-1}$, and the collisional deformation of dust aggregates due to rolling motion would be suppressed for large $\xi_{\text{crit}}$ and/or small $v_{\text{col}}$ cases.

### Figure 2

Snapshots of the collisional outcomes. Here we set $v_{\text{col}} = 39.8$ m s$^{-1}$ and $R_{d,1} = 6/12$. Panels (a)–(d) are the time series of snapshots for $\xi_{\text{crit}} = 0.2$ nm, 0.8 nm, 3.2 nm, and 12.8 nm, respectively. The time interval for each snapshot is 0.40 $\mu$s.

### 2.3. Initial Condition

As the initial condition, we use the two dust aggregates prepared by ballistic particle–cluster aggregation. These aggregates are identical to those used in Arakawa et al. (2022). The number of particles constituting the target aggregate, $N_{\text{tar}}$, is equal to that for the projectile aggregate, $N_{\text{pro}}$, and $N_{\text{tar}} + N_{\text{pro}} = 50000$. The total number of particles in a simulation, $N_{\text{tot}}$, is $N_{\text{tot}} = N_{\text{tar}} + N_{\text{pro}} = 10^5$. 

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Offset collisions of two dust aggregates are considered. We use the normalized impact parameter, \( B_{\text{off}} \) (see Arakawa et al. 2022). The square of the normalized impact parameter ranges from \( B_{\text{off}}^2 = 0 \) to 1 with an interval of \( 1/12 \). The collision velocity of the two dust aggregates is set to \( v_{\text{col}} = 10^{0.1 i} \) m s\(^{-1} \), where \( i = 13, 14, \ldots, 20 \). We also change \( \xi_{\text{crit}} \) that controls the strength of the interparticle rolling friction. We set \( \xi_{\text{crit}} = 0.2 \times 2^j \) nm, where \( j = 0, 1, \ldots, 6 \); the parameter range of \( \xi_{\text{crit}} \) satisfies \( 0.2 \text{ nm} < \xi_{\text{crit}} < 60 \text{ nm} \).

### 3. Examples of Collisional Outcomes

Figure 2 shows the snapshots of the collisional outcomes. Here we show the results for \( v_{\text{col}} = 39.8 \) m s\(^{-1} \) and \( B_{\text{off}}^2 = 6/12 \). We found that the collisional behavior is similar among different settings of \( \xi_{\text{crit}} \) as shown in Figure 2. We also analyzed the number of constituent particles in each fragment at the end of the simulation, \( t = 7.99 \) \( \mu \text{s} \). The numbers of constituent particles in the three largest remnants are \((N_{\text{lur}}, N_{\text{2nd}}, N_{\text{3rd}}) = (34042, 33299, 29827) \) for \( \xi_{\text{crit}} = 0.2 \) nm, \((34170, 32457, 30940) \) for \( \xi_{\text{crit}} = 0.8 \) nm, \((32571, 31598, 29338) \) for \( \xi_{\text{crit}} = 3.2 \) nm, and \((48491, 31900, 19003) \) for \( \xi_{\text{crit}} = 12.8 \) nm, respectively. For these cases, most of the particles are included in the three largest remnants.

### 4. Growth Efficiency

We discuss the parameter dependence of the largest fragment formed after a collision. The collisional growth efficiency, \( f_{\text{gro}} \)
is defined as follows (e.g., Wada et al. 2013):

\[ f_{\text{gro}} = \frac{N_{\text{frag}} - N_{\text{tar}}}{N_{\text{pro}}} \]  

(9)

Figure 3 shows the collisional growth efficiency for different settings of \( \xi_{\text{crit}} \), \( B_{\text{off}} \), and \( V_{\text{col}} \) Panels (a)–(d) show the results for \( \xi_{\text{crit}} = 0.2 \) nm, 0.8 nm, 3.2 nm, and 12.8 nm, respectively. For head-on collisions with \( B_{\text{off}}^2 = 0/12 \), \( f_{\text{gro}} \approx 1 \) when \( 20 \text{ m s}^{-1} \leq V_{\text{col}} \leq 100 \text{ m s}^{-1} \), and for grazing collisions with \( B_{\text{off}}^2 = 12/12 \), \( f_{\text{gro}} \approx 0 \). These trends are consistent with those observed in previous studies (e.g., Hasegawa et al. 2021; Arakawa et al. 2022).

We note that Schräpler et al. (2022) proposed a model for collisions between porous dust aggregates based on their experimental results. In their model, head-on collisions of porous aggregates result in bouncing when the collision velocity exceeds the sticking threshold, and the sticking threshold decreases with increasing \( \xi_{\text{crit}} \). However, we have never seen bouncing behavior for head-on collisions even though \( \xi_{\text{crit}} \) is varied. Although the real reason is unclear, this discrepancy might originate from the difference in the radius and/or the structure of aggregates; the radius of dust aggregates used in this study is approximately 7 \( \mu \text{m} \), while Schrapler et al. (2022) used centimeter-sized aggregates.

The impact parameter must vary with each collision event in protoplanetary disks. Then the average value of \( f_{\text{gro}} \), weighted over \( B_{\text{off}} \), would be useful to investigate whether dust aggregates can grow into larger aggregates in protoplanetary disks. The average value of \( f_{\text{gro}} \) weighted over \( B_{\text{off}} \) is given by

\[ \left\langle f_{\text{gro}} \right\rangle = \frac{1}{\pi} \int_{0}^{1} \text{d}B_{\text{off}} \text{ } 2\pi B_{\text{off}} f_{\text{gro}}. \]  

(10)

The gray lines in Figure 3 are the \( B_{\text{off}} \)-weighted collisional growth efficiency, \( \left\langle f_{\text{gro}} \right\rangle \). As \( \left\langle f_{\text{gro}} \right\rangle \) decreases with increasing \( V_{\text{col}} \), the threshold collision velocity for the fragmentation of dust aggregates, \( V_{\text{tra}} \), is defined as the velocity where \( f_{\text{gro}} = 0 \). We found that \( V_{\text{tra}} \) is nearly independent of \( \xi_{\text{crit}} \); \( 50 \text{ m s}^{-1} \leq V_{\text{tra}} \leq 60 \text{ m s}^{-1} \) for \( 0.2 \text{ nm} \leq \xi_{\text{crit}} \leq 12.8 \text{ nm} \).

Figure 4(a) shows the \( B_{\text{off}} \)-weighted collisional growth efficiency. Although \( \left\langle f_{\text{gro}} \right\rangle \) slightly depends on \( \xi_{\text{crit}} \) when we set \( 20 \text{ m s}^{-1} \leq V_{\text{col}} \leq 30 \text{ m s}^{-1} \), \( V_{\text{tra}} \) is nearly independent of \( \xi_{\text{crit}} \) in our simulations. Figures 4(b)–4(d) show the collisional growth efficiency for oblique collisions. As shown in Figures 4(c) and 4(d), for grazing collisions with \( B_{\text{off}}^2 \geq 6/12 \), \( f_{\text{gro}} \) is nearly independent of \( V_{\text{col}} \) around \( V_{\text{tra}} \). In contrast, Figure 4(b) exhibits a clear dependence of \( f_{\text{gro}} \) on \( V_{\text{col}} \) around \( V_{\text{tra}} \) if we focus on oblique collisions with \( B_{\text{off}}^2 \approx 3/12 \). Therefore, we can imagine that the energy dissipation for oblique collisions with \( B_{\text{off}}^2 \approx 3/12 \) and its dependence on \( V_{\text{col}} \) would be the key to unveiling the \( \xi_{\text{crit}} \) dependence of \( \left\langle f_{\text{gro}} \right\rangle \) and \( V_{\text{tra}} \).

5. Energy Dissipation

We check the energy dissipation due to particle interactions from the start to the end of the simulations. Figure 5 shows the energy dissipation due to rolling friction \( (E_{\text{dis},r}) \), sliding friction \( (E_{\text{dis},s}) \), twisting friction \( (E_{\text{dis},t}) \), connection and disconnection
of particles ($E_{\text{dis},c}$), and viscous drag force ($E_{\text{dis},v}$). We also show the total energy dissipation due to all particle interactions, $E_{\text{dis},\text{tot}} = E_{\text{dis},r} + E_{\text{dis},s} + E_{\text{dis},t} + E_{\text{dis},c} + E_{\text{dis},v}$, where $E_{\text{dis},r}$, $E_{\text{dis},s}$, $E_{\text{dis},t}$, $E_{\text{dis},c}$, and $E_{\text{dis},v}$ are the energy dissipations due to rolling friction, sliding friction, twisting friction, connection and disconnection of particles, and viscous drag force, respectively. Here we set $B_{\text{eff}}^2 = 3/12$.

Figure 5. Total energy dissipation due to particle interactions from the start to the end of the simulations. The total energy dissipation due to all particle interactions, $E_{\text{dis},\text{tot}}$, is given by $E_{\text{dis},\text{tot}} = E_{\text{dis},r} + E_{\text{dis},s} + E_{\text{dis},t} + E_{\text{dis},c} + E_{\text{dis},v}$, where $E_{\text{dis},r}$, $E_{\text{dis},s}$, $E_{\text{dis},t}$, $E_{\text{dis},c}$, and $E_{\text{dis},v}$ are the energy dissipations due to rolling friction, sliding friction, twisting friction, connection and disconnection of particles, and viscous drag force, respectively. Here we set $B_{\text{eff}}^2 = 3/12$.

Results for $B_{\text{eff}}^2 = 6/12$ and $9/12$ are shown in the Appendix as a reference (see Figures 6 and 7). The particle interaction energies for interparticle motions (e.g., $E_{r,crit}$ and $E_{v,\text{col}}$) are summarized in Table 2 of Arakawa et al. (2022).
We found that $E_{\text{dis, r}}$ does not monotonically increase with $\xi_{\text{crit}}$; there is a maximum value of $E_{\text{dis, r}}$. It is clear that $E_{\text{dis, r}} \to 0$ when $\xi_{\text{crit}} \to 0$ because $E_{\text{roll}}$ becomes zero. It is also natural that $E_{\text{dis, r}} \to 0$ when $\xi_{\text{crit}} \to \infty$; this is because the critical energy required to start rolling becomes $E_{\text{crit, r}} \to \infty$. Although it depends on $v_{\text{col}}$, $E_{\text{dis, r}}$ takes the maximum around $\xi_{\text{crit}} \approx 3.2$ nm for $v_{\text{col}} \sim v_{\text{fra}}$. As the kinetic energy per one particle, $E_{\text{kin, 1}}$, cannot overcome $E_{\text{roll}}$ for $v_{\text{col}} \sim v_{\text{fra}}$ and $\xi_{\text{crit}} \gg 3.2$ nm, the decrease of $E_{\text{dis, r}}$ for the large $\xi_{\text{crit}}$ would be consistent with the order of magnitude estimated in Section 2.2.

In contrast to $E_{\text{dis, s, r}}$ and $E_{\text{dis, d}}$, $E_{\text{dis, r}}$ take large values for both the lower and the upper limits of $\xi_{\text{crit}}$ (i.e., 0.2 nm and 12.8 nm, respectively). For low-speed collisions with $v_{\text{col}} \lesssim v_{\text{fra}}$, $E_{\text{dis, r}}$ plays the major role in energy dissipation when $\xi_{\text{crit}}$ is set to be close to the lower or the upper limits. For high-speed collisions with $v_{\text{col}} \gtrsim v_{\text{fra}}$, $E_{\text{dis, r}}$ plays the major role in the energy dissipation when $\xi_{\text{crit}}$ is set to be close to the lower or the upper limits. Conversely, $E_{\text{dis, r}}$ is the strongest energy dissipation mechanism when we choose a moderate $\xi_{\text{crit}}$ in the range of 0.8–3.2 nm for submicron-sized ice particles.

The strong dependence of $E_{\text{dis, r}}$ on $v_{\text{col}}$ is discussed in Section 5.2 of Arakawa et al. (2022). They claimed that the strong dependence could be originated from the magnitude relation between $E_{\text{dis, r}}$ and $E_{\text{kin, 1}}$, where $E_{\text{dis, r}}$ is the energy needed to slide a particle by a $\pi/2$ radian around its contact point.

Interestingly, the total energy dissipation due to all particle interactions, $E_{\text{dis, tot}}$, is nearly independent of $\xi_{\text{crit}}$. In other words, our numerical results suggest that three mechanisms of tangential frictions could complement one another. The weak dependence of $E_{\text{dis, tot}}$ on $\xi_{\text{crit}}$ might be the reason why $\langle f_{\text{gro}} \rangle$ and $v_{\text{fra}}$ are not strong functions of $\xi_{\text{crit}}$. As we prepared the initial particle interactions via sequential hit-and-stick collisions between an aggregate and multiple single particles (e.g., Mukai et al. 1992), they are highly porous and have only two interparticle contacts per particle on average. Therefore, we can expect that there are higher degrees of freedom for the deformation of dust aggregates, and all three tangential motions (rolling, sliding, and twisting) can potentially play a prominent role in the energy dissipation if the strengths of the springs and their critical displacements have moderate values. We note that $\langle f_{\text{gro}} \rangle$ and $v_{\text{fra}}$ considerably decrease when we perform numerical simulations of collisions between aggregates made of cohesive but frictionless spheres (S. Arakawa et al., in preparation). Although what controls the balance of energy dissipation via tangential frictions is still unclear, our results highlight the importance of three tangential motions on the collisional outcomes of porous dust aggregates made of submicron-sized particles.

6. Summary

The pairwise collisional growth of dust aggregates consisting of submicron-sized grains is the first step of planet formation, and understanding the collisional behavior of dust aggregates is therefore essential. It is known that the main energy dissipation mechanisms are the tangential frictions between particles in contact, namely, rolling, sliding, and twisting (e.g., Arakawa et al. 2022). However, there is great uncertainty for the strength of rolling friction, and the dependence of the collisional growth condition on the strength of rolling friction was poorly understood.

In this study, we systematically performed numerical simulations of collisions between two equal-mass dust aggregates made of submicron-sized ice spheres. We changed the strength of interparticle rolling friction, which is controlled by the critical rolling displacement, $\xi_{\text{crit}}$. As a result, we found that the threshold collision velocity for the fragmentation of dust aggregates is nearly independent of $\xi_{\text{crit}}$ when we consider oblique collisions (Figures 3 and 4).

We checked the total energy dissipation due to particle interactions from the start to the end of the simulation (Figure 5). We found that the total energy dissipation due to all particle interactions, $E_{\text{dis, tot}}$, is nearly independent of $\xi_{\text{crit}}$. The energy dissipation due to rolling friction, $E_{\text{dis, r}}$, takes the maximum when we chose a moderate $\xi_{\text{crit}}$, while $E_{\text{dis, r}}$ becomes small if $\xi_{\text{crit}}$ is set to be close to the lower or the upper limits (0.2 nm and 12.8 nm, respectively). Conversely, the energy dissipations due to sliding friction, $E_{\text{dis, s}}$, and twisting friction, $E_{\text{dis, t}}$, become large at both the lower and the upper limits of $\xi_{\text{crit}}$. Therefore, our numerical results indicate that three mechanisms of tangential frictions could complement one another.

Numerical simulations of granular matter are performed in many fields of science and engineering. We note, however, that the particle interaction models differ among numerical codes. Although the majority of these codes do not include the particle interaction for the twisting motion, our simulations showed that twisting friction plays an important role when the collision velocity of dust aggregates, $v_{\text{col}}$, is not significantly larger than the threshold collision velocity for the fragmentation, $v_{\text{fra}}$. Therefore, the details of particle interaction models would be crucial for investigating the collisional behavior of dust aggregates from numerical simulations.

We acknowledge that plastic deformation, melting, and fragmentation of constituent particles are not considered in this study. These effects might be important for high-speed collisions as shown in molecular dynamics simulations (e.g., Nietiadi et al. 2020, 2022). The angular velocity dependence of the strength of tangential frictions is also ignored in our simulations. Although our results revealed that $v_{\text{fra}}$ does not strongly depend on the strength of rolling friction alone, the collisional behavior might be affected when the strengths of all three tangential frictions increase/decrease simultaneously. Future studies on the particle interactions from laboratory experiments and molecular dynamics simulations would be essential.

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Appendix

Total Energy Dissipation Due to Particle Interactions

Figures 6 and 7 show the total energy dissipation due to particle interactions from the start to the end of the simulations. We set $B_{\text{off}}^2 = 6/12$ and $9/12$ for Figures 6 and 7, respectively. The total energy dissipation due to all particle interactions, $E_{\text{dis, tot}}$, is nearly independent of $\xi_{\text{crit}}$ not only for $B_{\text{col}} = 3/12$ but also for $B_{\text{col}} = 6/12$ and $9/12$. The Astrophysical Journal, 939:100 (10pp), 2022 November 10

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Figure 6. Same as Figure 5 but with $B_{\text{crit}}^2 = 6/12$. 
Figure 7. Same as Figure 5 but with $B_{\text{off}}^2 = 9/12$. 
We note that $E_{\text{dis,tot}}$ is smaller than the initial kinetic energy, $N_{\text{tot}}E_{\text{kin,1}}$. Figure 8 shows $E_{\text{dis,tot}}$ as a function of $B_{\text{off}}^2$ and $v_{\text{col}}$. Here we set $\xi_{\text{crit}} = 0.8$ nm. The dashed line is the initial kinetic energy, $N_{\text{tot}}E_{\text{kin,1}}$, which is given by Equation (8).

![Figure 8](image)

Figure 8. Dependence of $E_{\text{dis,tot}}$ on $B_{\text{off}}^2$ and $v_{\text{col}}$. Here we set $\xi_{\text{crit}} = 0.8$ nm. The dashed line is the initial kinetic energy, $N_{\text{tot}}E_{\text{kin,1}}$, which is given by Equation (8).

We note that $E_{\text{dis,tot}}$ is smaller than the initial kinetic energy, $N_{\text{tot}}E_{\text{kin,1}}$. Figure 8 shows $E_{\text{dis,tot}}$ as a function of $B_{\text{off}}^2$ and $v_{\text{col}}$. Here we set $\xi_{\text{crit}} = 0.8$ nm, although $E_{\text{dis,tot}}$ is nearly independent of $\xi_{\text{crit}}$. The reason why $E_{\text{dis,tot}}$ is smaller than $N_{\text{tot}}E_{\text{kin,1}}$ is clear; fragments have kinetic energies after collisions as shown in Figure 2.

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