When two steel balls collided with each other, because the duration time is very short relative to the speed of heat transfer, this collision is supposed as an adiabatic process. The collision produced the work done by collision pressure and transferred it to heat which increased the temperature and lead to burning of paper sheet or melting of metallic sheet.

**Introduction**

**Question:**
Colliding two large steel balls with a thin sheet of material (e.g. paper) in between may “burn” a hole in the sheet. Investigate this effect for various materials.

In general physics, collision is an interesting topic to study kinematics and dynamics. We can start from some special conditions, through the laws of mechanics and get precise results. However, there are only few studies about the details of collision process during the impact time in experiment. In this article, we demonstrate the collision of two steel balls with a sheet of various material between them and analyze physical quantities about the collision through change of the inserted sheet.

**Experiment**

Two steel balls were mounted on the end of aluminum frame, the shape of frame is rod-like and it was set up vertically (Fig. 1). We chose sheets made of two kinds of materials, i.e., inflammable and non-flammable, and put it on the bottom steel ball. The inflammable material is paper, and non-flammable materials are plastic, aluminum and copper. We let the upper steel ball to fall down at rest and recorded the collision process by high speed video (230 μs/frame) simultaneously. After collision, we would observed the impact zone of the inserted sheet. By tuning the height of the released steel ball, we may tune the relative collision speed of the two steel balls.

**Results and Discussion**

The results for inflammable and non-flammable material are quite different. Figure 2 shows the sheet of each material after collision. For paper (Fig. 2a), it was burned a hole, but for all of non-flammable materials the impact zone was melted and the edge was compressed (Fig. 2b-2d). We can observe that the heat produced by collision is large enough to melt and distort the sheet.

We can change the height H between the two steel balls to produce different impact energy, so it will be expected that the damage is increased when H is increased. Figure 3 shows the relation between hole diameter and height H, it reveals that the hole diameter becomes larger with increasing H. However, the diameter of inner melting area of aluminum (Al-Rin) is 1.58±0.08 mm and almost invariant with height H. It implies that Al-Rin is the diameter of collision area. Although, the diameter of inner melting area of copper (Cu-Rin) is increased with H, it can be realized from the concept of thermal conductivity σ. Because of σCu≈1.7 σAl (Table 1), the heat transfer of copper is easier than aluminum.

**Fig. 3:** The impact hole diameter is plotted as a function of the height H between the two steel balls. Al-Rin denoted as filled circles, which is invariant with H and supposed as the impact diameter.

**Table 1:** Thermal parameters of aluminum and copper

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Capacitance</td>
<td>900</td>
<td>385</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>237</td>
<td>401</td>
</tr>
</tbody>
</table>

To measure the duration time, we use the high speed video (230 μs/frame) to observe the collision.
Unfortunately, because of the limited speed of our camera, we can conclude the duration time is less than 230 $\mu$s merely. The average pressure $P$ during the collision process can be estimated as follows:

$$P = \frac{F}{A} = \frac{\Delta P}{\Delta t} \times \frac{1}{A}$$

where $P$ is the pressure created by the collision force, $F$, $A$ is the impact area, and from

$$\Delta P > m\sqrt{2gh} = p_0$$

where $\Delta P$ is momentum change of the falling steel ball, $A$ is impact duration and $H$ is height of the falling steel ball. Basing on our condition,

$$\begin{align*}
\Delta Q &= \frac{\Delta T}{\Delta t} = \sigma \times A \times \Delta T \\
\end{align*}$$

where $\sigma$ is thermal conductivity. If $\Delta T \approx 1000$ K, for copper, $\sigma_{\text{Cu}} = 401$ W/m·K

$$\Delta Q < 401 \times (2 \times 10^{-6}) \times 1000 \times 2.3 \times 10^{-4} \approx 1.8 \times 10^{-4} \text{ J}$$

for aluminum, $\sigma_{\text{Al}} = 237$ W/m·K

$$\Delta Q < 237 \times (2 \times 10^{-6}) \times 1000 \times 2.3 \times 10^{-4} \approx 1.1 \times 10^{-4} \text{ J}$$

According to $\Delta W \gg \Delta Q$, the two steel balls collision can be considered as an adiabatic process.

Assuming the lowest heat transferred $\Delta H$ from the work done on Al sheet, we can get the temperature difference $\Delta T$ after collision

$$\Delta T = \frac{\Delta H}{m \times \rho_{\text{Al}} \Delta A} \cdot \frac{\Delta A}{\Delta t}$$

$$= \frac{2700 \times (2 \times 10^{-6}) \times 10^{-4} \times 900}{0.39}$$

$$= 802.47 \text{ K}$$

We can get

$$P > m\sqrt{2gh} \times \frac{1}{A}$$

$$= 0.257 \times \sqrt{2 \times 0.5} \times 2 \times 10^{-6}$$

$$= 1.9 \times 10^{-9} \text{ atm}$$

i.e.

$$P \geq 1.9 \times 10^4 \text{ atm}$$

The work $\Delta W$ done by collision is

$$\Delta W = P \times \Delta V = P \times (A \times \Delta d) > 0.39 \text{ J}$$

where $\Delta d = 10^{-4} \text{ m}$ is the thickness of the sheets. The heat conduction rate $\Delta Q/\Delta t$ is

$$\begin{array}{|c|c|c|c|}
\hline
\text{Sheets} & \text{Paper} & \text{Plastic} & \text{Aluminum} & \text{Copper} \\
\hline
\text{Burning/Melting point (K)} & 403-505 & 379-387 & 933 & 1356 \\
\hline
\end{array}$$

Table 2: The burning/melting point of sheets