

2010 Problem 3 : Steel Ball

Colliding two large steel balls with a thin sheet in between

Abstract

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 ($230 \mu\text{s}/\text{frame}$) 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.

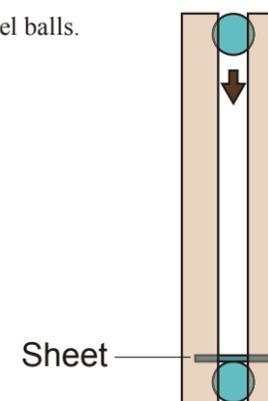


Fig. 1: The schematic of two steel balls collision. The inserted sheet is made of paper, plastic, aluminum or copper.

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.

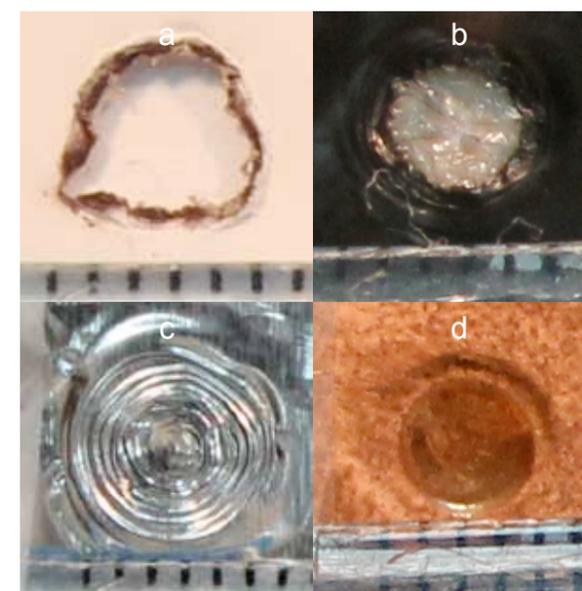


Fig. 2: The sheet of materials after collision. (a) paper, (b) plastic, (c) aluminum, (d) copper. For inflammable material (paper) the edge was burned, for non-flammable materials the center of impact zone was melted and the outer area was compressed.

We can change the height H between 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-R_{in}) is $1.58 \pm 0.08 \text{ mm}$ and almost invariant with height H . It implies that Al-R_{in} is the diameter of collision area. Although, the diameter of inner melting area of copper (Cu-R_{in}) is increased with H , it can be realized from the concept of thermal conductivity σ . Because of $\sigma_{\text{Cu}} \approx 1.7 \sigma_{\text{Al}}$ (Table 1), the heat transfer of copper is easier than aluminum.

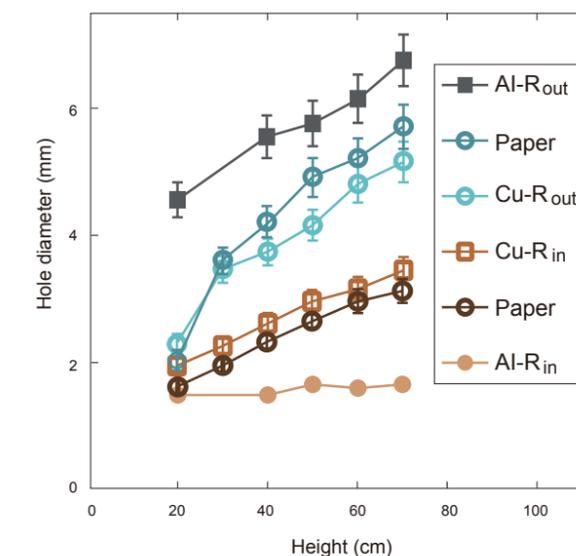


Fig.3: The impact hole diameter is plotted as a function of the height H between the two steel balls. Al-R_{in} denoted as filled circles, which is invariant with H and supposed as the impact diameter.

	Aluminum	Copper
Heat Capacitance (J/kg-K)	900	385
Thermal Conductivity (W/m-K)	237	401

Table 1: Thermal parameters of aluminum and copper

To measure the duration time, we use the high speed video ($230 \mu\text{s}/\text{frame}$) to observe the collision.

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Unfortunately, because of the limited speed of our camera, we can conclude the duration time is less than $230 \mu\text{s}$ 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 Δp is momentum change of the falling steel ball, Δt is impact duration and H is height of the falling steel ball. Basing on our condition,

$$\begin{aligned} m &= 287 \text{ g} \\ H &= 50 \text{ cm} \\ g &= 9.8 \text{ m/s}^2 \\ A &< \pi(0.8 \text{ mm})^2 \approx 2 \times 10^{-6} \text{ m}^2 \\ \Delta t &< 230 \mu\text{s} \end{aligned}$$

We can get

$$\begin{aligned} P &> \frac{m\sqrt{2gH}}{\Delta t} \times \frac{1}{A} \\ &= \frac{0.287 \times \sqrt{2 \times 9.8 \times 0.5}}{2.3 \times 10^{-4}} \times \frac{1}{2 \times 10^{-6}} \\ &= 1.9 \times 10^9 \text{ N/m}^2 \end{aligned}$$

i.e.

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

The work ΔW down 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

$$\frac{\Delta Q}{\Delta t} = \sigma \times A \times \Delta T$$

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

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

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

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

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

Assuming the lowest heat transferred ΔH from the work done on Al sheet, we can get the temperature difference ΔT after collision

$$\begin{aligned} \Delta T &= \frac{\Delta H}{m \times s} = \frac{\Delta H}{(\rho_{\text{Al}} A \Delta d) \cdot s} \\ &= \frac{0.39}{2700 \times (2 \times 10^{-6}) \times 10^{-4} \times 900} \\ &= 802.47 \text{ K} \end{aligned}$$

where $\rho_{\text{Al}} = 2700 \text{ kg/m}^3$ and $s = 900 \text{ J/kg}\cdot\text{K}$ is the density and the specific heat of aluminum, respectively. We can get

$$T_f = \Delta T + T_i = 802.47 + 300 = 1102.47 \text{ K} > 933 \text{ K}$$

The calculation demonstrates that the highest temperature induced by collision can reach 1102.47 K , which is above the burning point of paper, and the melting point of plastic and aluminum, but still below the melting point of copper (Table 2). Thus we can observe the burning of paper, the melting of plastic and aluminum, but only the softened copper sheet.

	Paper	Plastic	Aluminum	Copper
Burning/Melting point (K)	403-505	379-387	933	1356

Table 2: The burning/melting point of sheets

Conclusions

We experimentally demonstrated the two steel balls collision and analyzed the impact process by inserting a sheet between the two balls. The diameter of holes on paper sheet is increased when the height is increased, and Al-Rin is invariant which could be the diameter of collision area. From calculation, we get the final temperature of Al after collision, the value is higher than the melting point of Al itself, and thus consistent with experiment.

Reference

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