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參展科別　物理與天文學

作品名稱　仙「鋁」奇「圓」

—探討鉻鋼球碰撞的力與能量

得獎獎項　大會獎：二等獎

荷蘭 INESPO 正選代表：2015 年荷蘭國際環境及永續發展競賽

就讀學校　高雄市立高雄女子高級中學

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關鍵字　碰撞、能量傳遞

作者簡介

一、張恬寧

我是張恬寧，如名字一般有著「恬靜」氣質，同時也在喜歡的領域盡情揮灑熱情，好比是繪畫，透過藝術，除了能畫出心裏所想，亦能透過簡單的設計帶給別人溫暖，增添高中生活的色彩。除此之外，因為從小抱持著對科學的興趣，於是報考且獲得資格進入雄女高瞻班，高中的日子裡，和兩位志同道合的朋友參加科展，從中學習對科學研究「合作」和「精益求精」的態度，希望未來能也能投身科學研究的領域。

二、楊馥榕

我是楊馥榕，目前就讀高雄女子高中三年級高瞻班，個性外向、活潑，在同學的眼中是個陽光的女孩。我喜歡跳舞、彈吉他，也熱愛從事科學研究，每次做實驗時，總能投入到忘記時間。我也熱衷於在台上發表自己，只要有上台報告的機會，我就會自告奮勇地爭取。我喜歡物理，因此參與物理科展，我喜歡其中一步一步分析的過程。未來希望能夠繼續從事科學研究，並期許自己能夠成為一個獨當一面的工程師。

三、張晴

我是張晴，現在就讀高雄女中三年級。個性陽光、開朗，在同學眼中是個認真、努力向學的女孩。因為熱愛科學，所以在高中時報考自然科學實驗班，有幸接觸到科展參賽機會。在研究期間，全心全力投入，花費將近一年的時間完成科展。雖然很辛苦，但學到如何操作實驗、分析數據以及製作海報，還體會到合作的重要性，有時甚至做到忘記吃飯呢！未來也希望投入科學這一領域。

仙"鋁"奇"圓"：探討鉻鋼球碰撞的力與能量

摘 要

本實驗主要在探討鉻剛球碰撞產生的情況與能量的傳遞，我們改變的變因有：(1)球落下高度、 (2)鉻剛球大小(兩種規格)、 (3)兩球撞擊的中間物材質(鋁箔、白紙、銅片)、(4)中間物材質的厚度。

發現球自愈高的高度落下後產生碰撞，中間物(置於底下鉻剛球的上方，如：鋁箔)所產生的同心圓面積愈大；而大球相撞產生的同心圓也比小球相撞所產生的大。就碰撞後反彈高度而言，大球碰撞後反彈高度比小球碰撞後反彈高度來的高。與銅片有相同厚度的 6 層鋁箔，其碰撞產生的面積與銅片的卻不相同，可見不同材質的硬度及彈性，亦是影響面積大小的因素之一。

Abstract

Our experiment mainly investigate the wave and energy generated by the two chrome steel balls. The followings are the influential factors we change ：
(1)height(80/100/120/140/160cm), (2)the sizes of the two chrome steel balls(there are two kinds of sizes), (3)the intermediate objects(aluminum foil ,white paper sheet, copper sheet), (4)the thickness of the intermediate objects.

We find out that the higher the ball on the top falls down to strike the ball beneath, the bigger the concentric circles on the intermediate objects(especially aluminum foil) was generated . And the concentric circles made by the larger ball are also bigger than those made by the smaller ball. In terms of rebound after impact, the larger ball owns bigger height than the smaller one. Aluminum foil of six layers, which shares the same thickness with copper sheet, produces different contact areas on the surface from the one on copper sheet. So we see that the hardness and elasticity of different materials could affect the sizes of contact areas.

壹、研究動機

在去年的二月的俄羅斯境內，爆發了難得一見的天文奇景——隕石撞擊。因此引發了我們的對此現象的興趣，進一步的去搜尋「隕石坑」的圖片。

我們想研究像隕石這類的重物，從高空中高速落下，撞擊所發生的結果與現象，因此設計了此實驗來觀察，並且改變變因做進一步的探討。

貳、研究目的

1、利用兩鉻鋼球撞擊，觀察其中間物被撞擊後的現象。

2、固定鉻鋼球的大小與高度，改變中間物的材料，觀察中間物被撞擊後的差異。

3、固定中間物的材料與高度，改變各鋼球的大小，觀察中間物被撞擊後的差異。

4、固定鉻鋼球的大小與中間物的材料，改變高度，觀察中間物被撞擊後的差異。

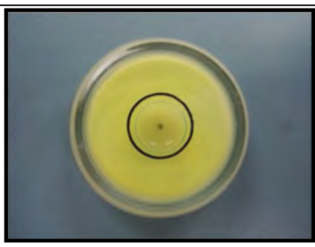
5、固定鉻鋼球的大小、中間物的材料、高度，改變中間物厚度，觀察中間物被撞擊後的差異。

參、研究設備及器材

<table>
<tr><th>名　稱</th><th>說　明</th></tr>
<tr><td>鉻鋼球
(4 個)</td><td>

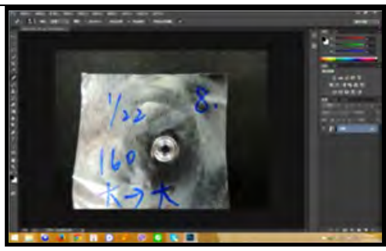
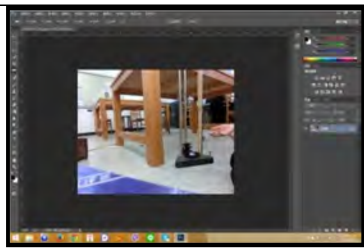
成分：
<table>
<tr><td>C</td><td>Si</td><td>Mn</td><td>Cr</td><td>Mo</td></tr>
<tr><td>1.0</td><td>0.25</td><td>0.5</td><td>1.1</td><td>＜0.08</td></tr>
</table>
規格：大：直徑 5.10cm、800gw、2 個
　　　小：直徑 3.00cm、110gw、2 個
用途：撞擊物
</td></tr>
<tr><td>A4 白紙
鋁箔紙
銅片</td><td>

用途：作為兩球撞擊的中間物，用以分析數據
</td></tr>
<tr><td>(1)瓦楞板
(2)水平儀</td><td>



用途：
(1)因為鉻鋼球每次被吸引在電磁鐵的位置都不同，因此在瓦楞板上挖一個合適的洞，以固定位置。
(2)檢測瓦楞板是否水平
</td></tr>
<tr><td>電磁鐵</td><td>


用途：吸放鉻鋼球
</td></tr>
</table>

支架 （自由落體實驗）	 用途：架設電磁鐵及量取高度
(1)游標尺 (2)螺旋測微器	  用途：(1)作為以 Photoshop 軟體計算面積時的標準刻度 (2)測量厚度
高速攝影機	 用途：拍攝反彈高度
Free Video to JPG Converter 軟體	用途：將影片畫面轉為圖片
Photoshop 軟體	  用途：計算面積

肆、研究過程或方法

一、前製作業

1、將瓦楞紙挖洞(圖 4-1、圖 4-2)，使大、小鉻鋼球恰可穿過瓦楞板與另一面齊平。

圖 4-1

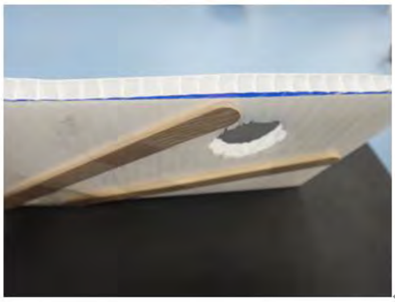


圖 4-2

2、裁剪面積大小相似的鋁箔(平整、無破裂、幾乎無皺褶)(圖 4-3)、白紙數百張。

3、以支架(170cm)上量尺量出所需高度，並黏貼膠帶標示。(如圖 4-4)。

圖 4-3

圖 4-4

4、將已挖洞的瓦楞紙架設在所需高度處，並以水平儀測其是否為水平。

5、將電磁鐵架設於瓦楞紙洞口上方。(圖 4-6)

圖 4-5

圖 4-6

6、在支架下方黏貼白紙。

7、將鉻鋼球就著洞口向上頂，至被電磁鐵緊緊吸住為止。(圖 4-7、圖 4-8)

圖 4-7

圖 4-8

8、在支架旁放置高速攝影機，拍攝鉻鋼球撞擊後的反彈高度。(圖 4-9、圖 4-10)

圖 4-9

圖 4-10

9、關掉電磁鐵電源，使球墜落。此步驟重複數次，直至確定白紙上因被撞擊產生的汙點位於同一位置。

10、將另一顆鉻鋼球置於白紙上汙點。

11、重複步驟 7、8、9，確定上方球墜落撞擊下方球後呈垂直向上反彈，如此確定兩球以質心對質心相撞。

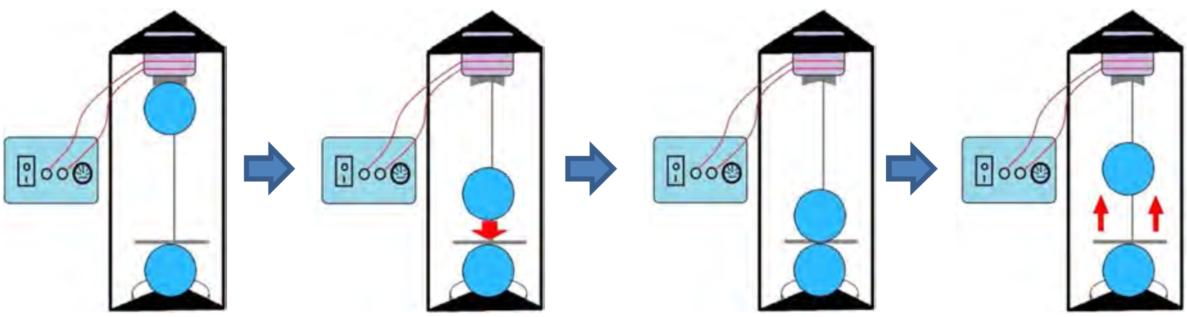


圖 4-11　實驗過程示意圖

二、實驗開始與改變變因

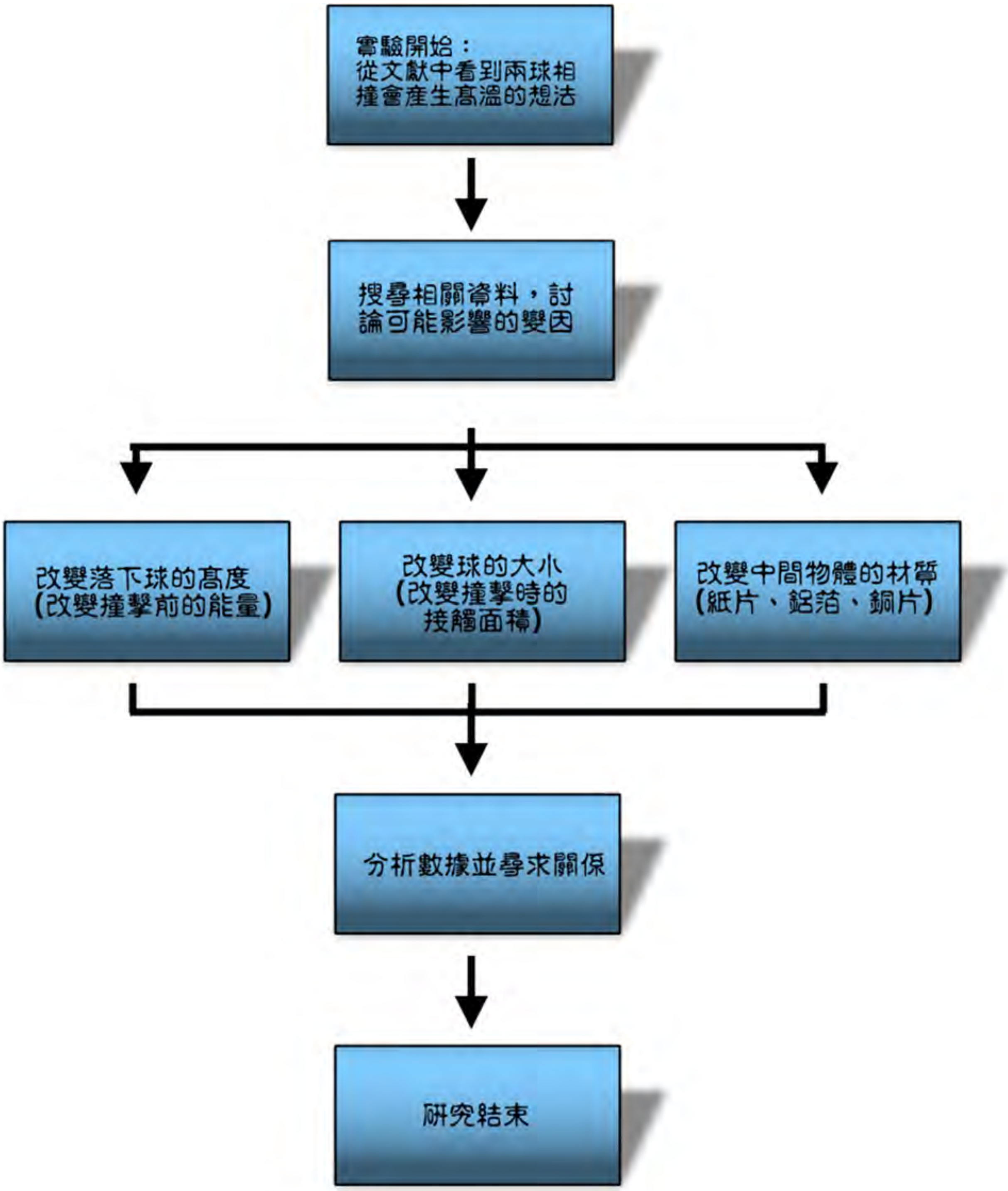
1、<u>改變多種高度</u>： 我們改變落下球的高度，分別為 80、100、120、140、160cm。

2、<u>改變撞擊物與被撞擊物大小</u>： 大(球)撞大(球)、大撞小、小撞大、小撞小。

3、<u>改變中間物材質</u>：三種中間物材質：鋁箔、白紙、銅片 。

4、<u>改變中間物厚度</u>：鋁箔：2 層、4 層、6 層、8 層。

三、流程圖：



四、數據分析方法

(一)面積：

1、將實驗完成的鋁箔、白紙置於游標尺(作為以 Photoshop 軟體計算面積時的標準刻度)旁，一併拍照紀錄。(圖 4-11)

圖 4-11

圖 4-12　photoshop 軟體

2、以 Photoshop(面積計算軟體)分析鋁箔被撞擊後形成的同心圓面積，及白紙被撞擊後燒出的面積。(圖 4-12)

3、圈選所要測量的內圈面積，並記錄度量。(圖 4-13)

圖 4-13 計算內圓與外圓的面積

4、儲存數據並製作成 Excel 折線圖。

(二)反彈高度：

1、將以高速攝影機拍攝的反彈高度影片轉為圖片(如右圖)，並找出反彈高度最大的圖片。

2、以 Photoshop(面積計算軟體)分析反彈高度。

四、實驗原理說明：

當鉻鋼球去撞擊物體表面時，其力學能會轉換成熱能，造成物體表面有"燒焦"的現象。
我們想知道幾件事：
(1)這個燒焦的表面跟鉻鋼球大小有什麼關係。
(2)撞擊不同材質表面時，會有什麼不同的現象。
(3)不同能量(不同高度)會造成什麼不同影響。

首先我們要定義一些物理量：當球下落撞到接觸物體時
(1)P：撞擊壓力 (dynamic pressure)
(2)A：撞擊時的接觸面積 (contacy area)

當球下落到最大深度時，其對物體的壓縮情形如圖：
位能轉換成動能後撞擊壓縮接觸面後再反彈，但反彈後損失的力學能轉變成其他能量。這些能量最大的可能是熱能，但隨著嘗試越多的材質後我們推論，力學能可能還會變成不同的能量傳遞出去，例如我們實驗中的鋁箔紙。

(一)硬度的測試：

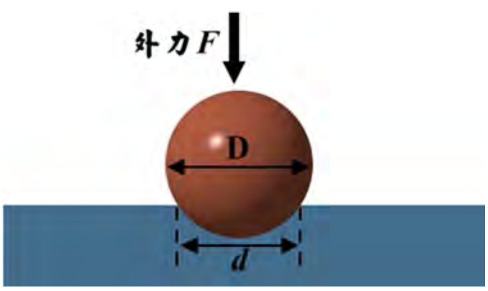
在物理上，硬度不是一種常見的基本屬性(ex：質量、時間或長度)。並沒有特別的物理量來定義硬度。但是一般比較常見的定義是指某種材料的抗永久壓痕程度，或受外力而抗滲透至第二層材料的能力。所以它的定義需由 "測試過程" 來決定。常見測試硬度度量衡的方法有：
(1)壓痕硬度試驗方法，分別由 Brinell, Vickers, and Rockwell 所定義。
(2)反彈的高度硬度試驗方法：由 Shore 所定義。
因為各方法使用相異的作法，所以硬度標準呈現不同的屬性。

(1) Brinell 硬度測試法：

此定義為瑞典工程師 Johan August Brinell 於 1900 年提出，這個定義首先被廣泛地用在工程學中。
計算球壓成的凹槽面積。以直徑為 10 毫米的鋼球慢慢地以 3000 公斤重的力(圖中 F)被壓向測試用的材料上。假設材料凹陷後半徑為 d，則硬度定義為：

$$\mathrm{BHN} = \frac{F}{\frac{\pi}{2} D\left(D - \sqrt{D^2 - d^2}\right)}$$

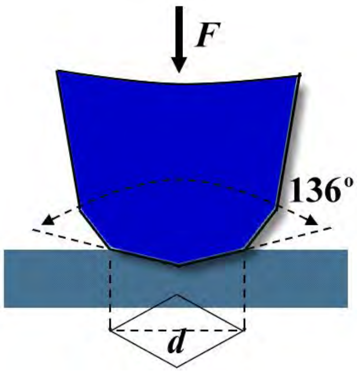
但由於需利用大面積的凹陷，所以會限制其實用性。



(2) Vickers 硬度測試法：

使用一個金字塔型的鑽石方底壓頭。壓頭的角度是 136 度，而測試的力是 120kgw 以下。

則硬度定義：$HV = \frac{2F\sin\frac{136^\circ}{2}}{d^2}$



(二)碰撞理論：

1、碰撞是指兩物體因其物體間的作用力而使運動狀態改變的過程。一般根據能量損失與否，分成彈性碰撞(elastic)和非彈性碰撞。

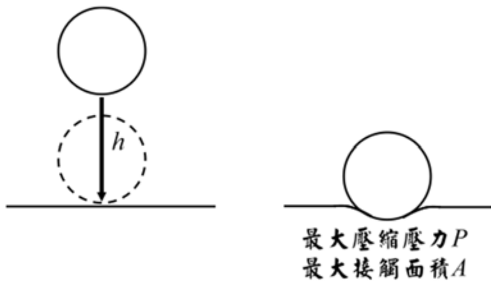
在彈性碰撞中，鋼球與測試物表面不會產生永久凹槽。就是雖然球撞擊測試物，在過程中測試材料有變形，試驗材料仍會恢復到其原始狀態。但在實驗中，我們的測試物表面均會有永久形變，代表有部分能量損失，傳遞給物體。

2、碰撞可分三階段：

(1)球與表面的撞擊：

球從高度 h 落下，位能轉化成動能：$Mgh = \frac{1}{2}Mv^2$

(M：球質量　；　v：撞擊前速度)



(2)純粹的彈性階段

定義 P 為動壓力(dynamic pressure)，即當球撞進測試物表面時表面施加在球上的壓力。A 代表接觸面積(contact area)。

表面材料經過暫時的壓痕。在此階段，當球穿過表面材料時，P 增加，A 也增加，兩者皆達最大值(當球停止使測試物變形)

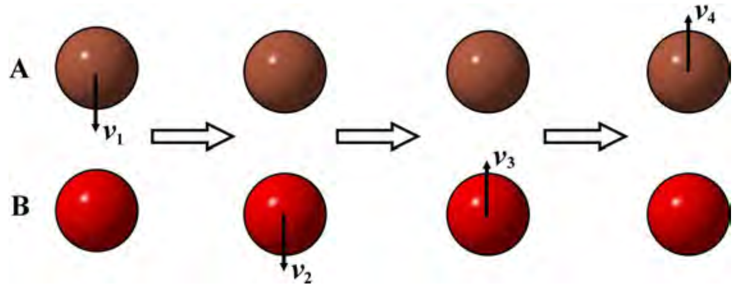
(3)彈性恢復及球的反彈

變形的測試物表面恢復原狀。球獲得動能後向上反彈。

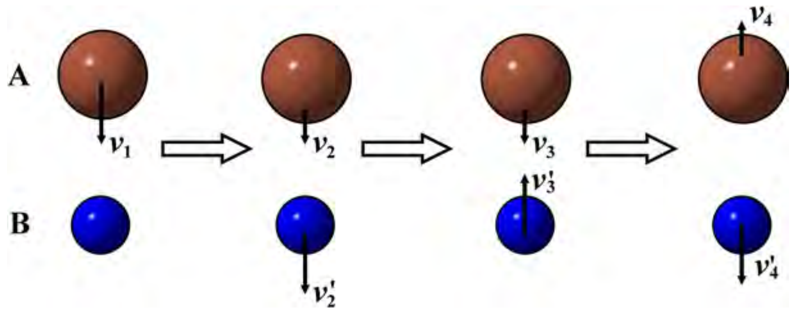
3、球與球的碰撞：

(1)兩相同的球相撞：(大球撞大球)

如果兩相同的球做碰撞，在近似為彈性碰撞的狀態下，其撞擊的示意圖如下。

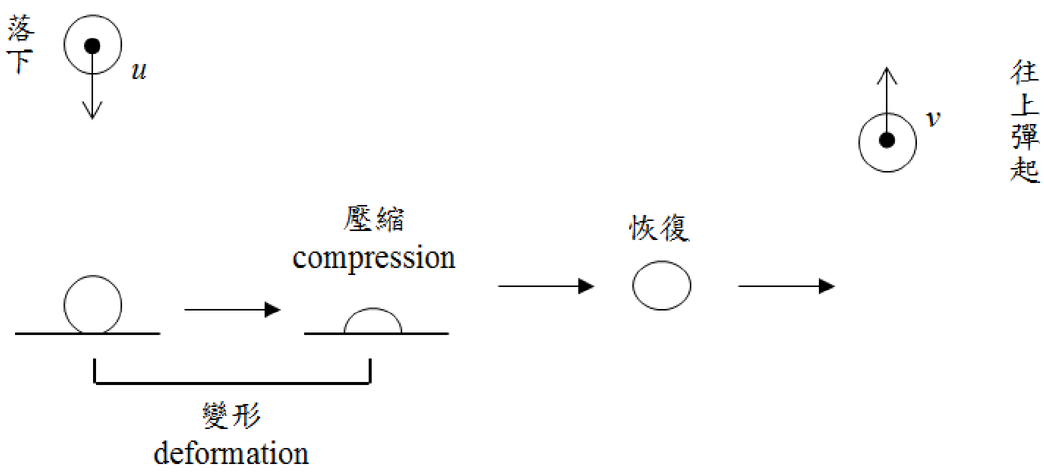


(2)大球撞小球：



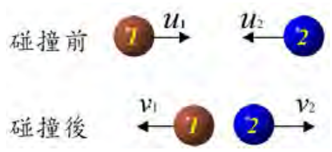
4、碰撞和恢復係數：

一個垂直下落的球與地面碰撞後，其受壓縮變形、恢復原狀、往上彈起的過程如下圖所示：



彈性 (elasticity)： 球被壓縮變形之後，要恢復原來形狀的特性，稱為彈性。
牛頓碰撞定律：當兩物體在一直線上碰撞時，其碰撞後速度之差與碰撞前速度之差的比例為一常數關係。其關係如下列公式所示：

$e=\dfrac{v_1-v_2}{u_2-u_1}$ ，亦即 $v_1-v_2=-e(u_1-u_2)$



公式中，u_1 = 物體 1 碰撞前之速度　　v_1 = 物體 1 碰撞後之速度
u_2 = 物體 2 碰撞前之速度　　v_2 = 物體 2 碰撞後之速度
e = 恢復係數 (efficicency of restitution)
亦即，$e=1$ 。彈性最好的情況是恢復係數 $e=1$，但通常都介於 0 和 1 之間。

如果球垂直落下與地面碰撞：
因為地球質量極大，球與地面碰撞，假定地球不動，亦即 $u_2=0$ ，$v_2=0$ ，代入公式中：$v_1-v_2=-e(u_1-u_2)$　　$v_1-0=-e(u_1-0)$

$-e=\dfrac{v_1}{u_1}$　$\cdots(1)$

（e 前之負號表示球在和地面碰撞前和碰撞後之方向相反）
如果球是從 H_d 的高度落下，則撞擊地面前的速度 u_1 可從等加速度公式來求：

$u_1^2=v_0^2+2gH_d=2gH_d$　　$u_1=\sqrt{2gH_d}$　$\cdots(2)$

假設撞及地面後反彈之速度為 v_1 ，到達最高點時速度 $v_f=0$，反彈高度 H_b

$0=v_i^2-2gH_b$ ，　$v_1=v_i=\sqrt{2gH_b}$ —　(3)

將 (2)、(3) 代入 (1)　　因落下與反彈方向相反，故

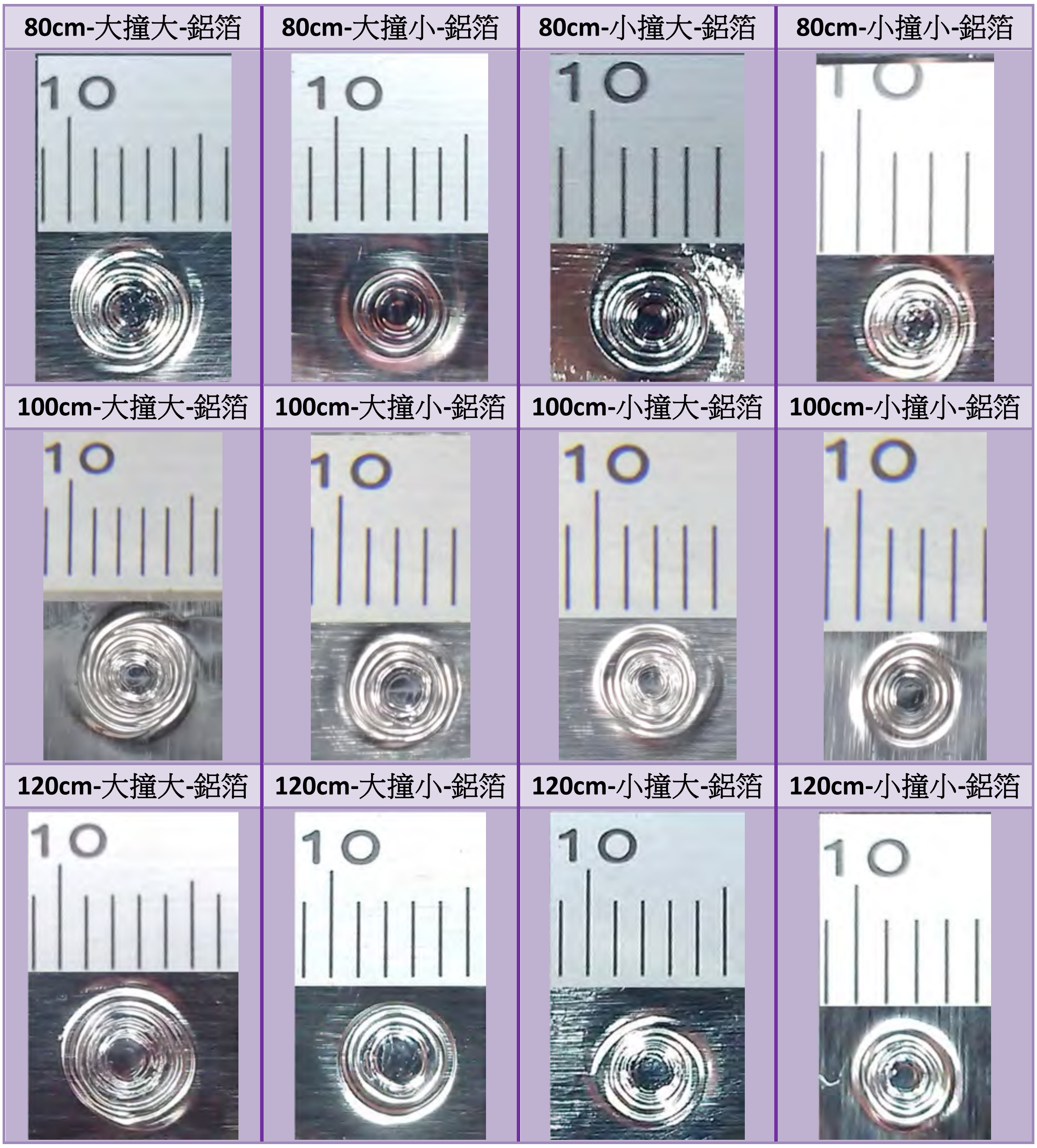
$$e=-\frac{V_1}{U_1}=\sqrt{\frac{2g\times H_b}{2g\times H_d}}=\sqrt{\frac{H_b}{H_d}}\quad —\quad (4)$$

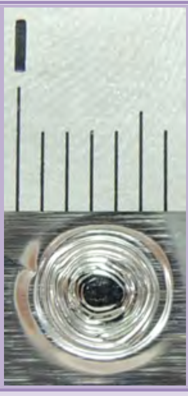
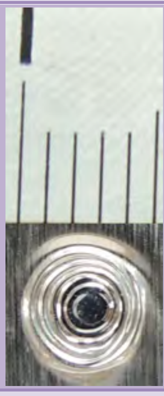
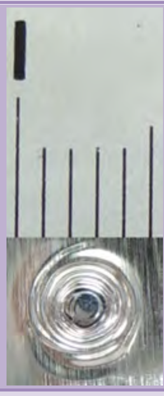
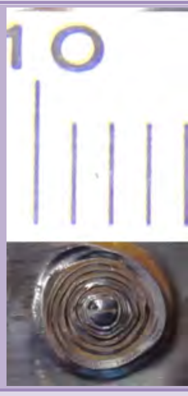
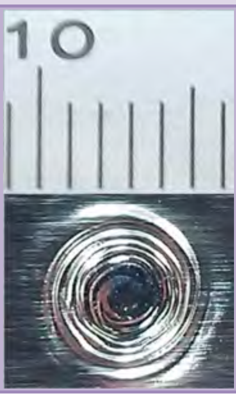
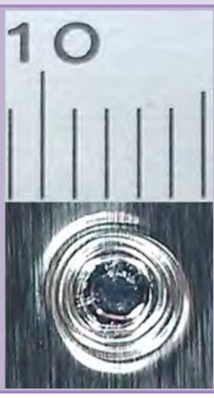
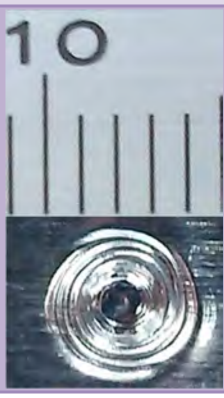
求出球與地面垂直碰撞前後的速度，比度量落下與反彈的高度較為困難，因此公式 (4) 較常用來計算球與地面之間的恢復係數 (彈性係數) e 。

伍、研究結果與討論

一、撞擊單層鋁箔：

圖 5-1-1　不同落下高度去撞擊鋁箔的圖形



140cm-大撞大-鋁箔	140cm-大撞小-鋁箔	140cm-小撞大-鋁箔	140cm-小撞小-鋁箔
			
160cm-大撞大-鋁箔	160cm-大撞小-鋁箔	160cm-小撞大-鋁箔	160cm-小撞小-鋁箔
			

1、我們先大致對圖形做觀察，發現所得到的結果有幾點歸納：

(1)不論大撞小或小撞大的組合，均會產生同心圓的痕跡，很類似點波源所產生的波形。我們猜測，這應該是因為撞擊瞬間球的能量減少後產生波的形式向外傳遞。而且因為撞擊時間很短(約小於 100 微秒[1])，所以會在撞擊處會產生很大的壓力和很高的溫度。

(2)在同心圓的中心處，大致都會產生一小區域的平坦區域。
(以下我們均稱為<u>**內圓**</u>，見示意圖 5-1-2)
我們好奇：這些區域是怎麼產生的？是單純被壓扁？抑或甚至是鋁箔被熔化呢？ (鋁的熔點為 660℃) 這些問題在後面的分析中我們將會試著解答。

(3)在部分狀況下(例如 160cm-小撞大)，緊鄰內圓的位置會產生很密的皺褶(或是說波長很小的同心圓)。在同心圓的外側有間距比較大的部分(以下均稱為<u>**外圓**</u>，見圖 5-1-2)，這些區域又是如何產生的呢？

圖 5-1-2 內圓、外圓示意圖

2、以下是不同高度下的內圓與外圓的面積資料：

表 5-1-1 不同落下高度去撞擊鋁箔的結果

	80cm-大撞大-鋁箔	80cm-大撞小-鋁箔	80cm-小撞大-鋁箔	80cm-小撞小-鋁箔
內圓面積(cm^2)	0.00683	0.00628	0.00296	0.00274
外圓面積(cm^2)	0.15701	0.11896	0.08387	0.07246
	100cm-大撞大-鋁箔	100cm-大撞小-鋁箔	100cm-小撞大-鋁箔	100cm-小撞小-鋁箔
內圓面積(cm^2)	0.00739	0.00642	0.00415	0.00324
外圓面積(cm^2)	0.19931	0.13295	0.10988	0.07505
	120cm-大撞大-鋁箔	120cm-大撞小-鋁箔	120cm-小撞大-鋁箔	120cm-小撞小-鋁箔
內圓面積(cm^2)	0.00794	0.00757	0.00445	0.00341
外圓面積(cm^2)	0.19694	0.14204	0.12183	0.09111
	140cm-大撞大-鋁箔	140cm-大撞小-鋁箔	140cm-小撞大-鋁箔	140cm-小撞小-鋁箔
內圓面積(cm^2)	0.00861	0.00837	0.00634	0.00395
外圓面積(cm^2)	0.24183	0.17067	0.13812	0.10444
	160cm-大撞大-鋁箔	160cm-大撞小-鋁箔	160cm-小撞大-鋁箔	160cm-小撞小-鋁箔
內圓面積(cm^2)	0.00968	0.00847	0.00686	0.00478
外圓面積(cm^2)	0.24605	0.16914	0.14805	0.09684

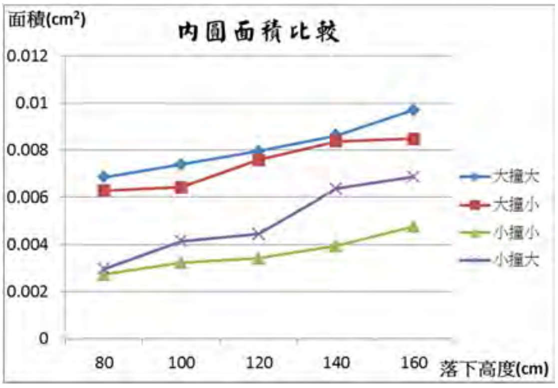


圖 5-1-3 不同狀況下的內圓面積比較

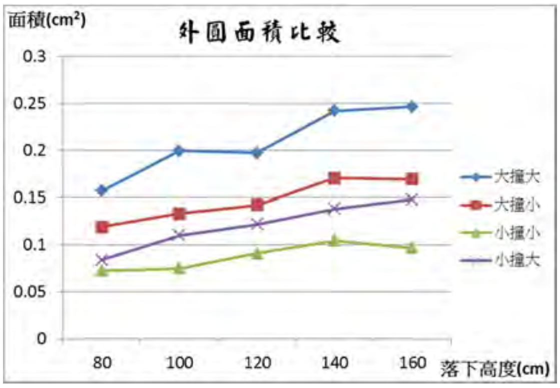


圖 5-1-4 不同狀況下的外圓面積比較

(1)由圖 5-1-3 (內圓面積比較圖) 可歸納出：

A、隨著落下高度變大，內圓面積會增加，這結果似乎合乎原先的預期。

B、落下球如果是大球(例如大撞大、大撞小)，其內圓面積會比較大。

C、如果落下的是小球，[小撞大] 會比 [小撞小] 內圓面積大。

D、觀察撞擊後的鋁箔發現：

造成內圓的原因，應該是由球和球碰撞擠壓所產生，因為內圓部分看起來相當光滑平整。

且我們由計算發現，球撞擊的瞬間，鋁箔可能有熔化的現象發生(見 21.22 頁)。

⇒所以內圓部分有可能是經過高壓高溫熔化後又再冷卻後的結果。

E、經由 ABCD 四點討論後，我們歸納出影響鋁箔內圓面積大小的因素，應該跟下列有關：

1、**底部接觸面積**：如果其中一顆是大球，理論上會比兩顆都是小球時的撞擊接觸面積為大。

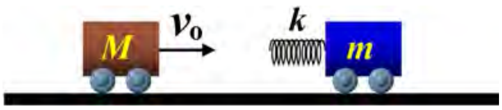
⇒**所以我們推測如果有大球時（例如大撞大、小撞大)時，內圓的面積會比較大(見圖 5-1-5)**。

2、**撞擊前的初動能**：如果撞擊球的初動能越大，則兩球撞擊時壓縮的量也會比較大，故內圓的面積也會越大。

⇒**落下高度越大時，內圓面積也會越大**。

3、**接觸時間**：如果兩種相同的球相撞（例如大撞大、小撞小），將其近似為如下圖的狀況，則兩車的接觸時間為：

$t=\frac{1}{2}T=\frac{1}{2}(2\pi\sqrt{\frac{\mu}{k}})=\pi\sqrt{\frac{\mu}{k}}$ 。 $\mu=\frac{Mm}{M+m}$ （近似為雙振子)



(1)如果兩顆相同的大球相撞： $\mu_1=\frac{MM}{M+M}=\frac{M}{2}=0.4(kg)$

(2)如果一大一小球相撞： $\mu_1=\frac{Mm}{M+m}=\frac{0.8\times0.11}{0.8+0.11}=0.097(kg)$

(3)如果兩顆相同的小球相撞： $\mu_1=\frac{mm}{m+m}=\frac{m}{2}=0.055(kg)$

(4)把球想像成不同長度的彈簧作並聯，則總彈力常數 $k=\frac{k_0}{nR}$

（k_0 為單位長度的彈力常數，我們假設跟材質有關)

(5)如果是大撞大，彈力常數 $k_1=\frac{k_0}{nR_大}\times\frac{1}{2}=\frac{k_0}{2nR_大}$

如果是大撞小，彈力常數 $k_2=\frac{1}{\frac{nR_大}{k_0}+\frac{nR_大}{k_0}}=\frac{k_0}{nR_大+nR_小}$

如果是小撞小，彈力常數 $k_1=\frac{k_0}{nR_小}\times\frac{1}{2}=\frac{k_0}{2nR_小}$

(6)所以大撞大的時間 $t_1=\pi\sqrt{\frac{0.4}{k_0/2n\times2.55}}=\pi\sqrt{\frac{2.04n}{k_0}}$

小撞小的時間$t_2=\pi\sqrt{\dfrac{0.055}{k_0/2n\times1.5}}=\pi\sqrt{\dfrac{0.165n}{k_0}}$

大撞小的時間$t_2=\pi\sqrt{\dfrac{0.097}{k_0/n(2.55+1.5)}}=\pi\sqrt{\dfrac{0.393n}{k_0}}$

所以碰撞時間長短為：大撞大 ＞ 大撞小 ＝ 小撞大 ＞ 小撞小

⇒ **當接觸時間較大時，理論上內圓面積也會比較大**。

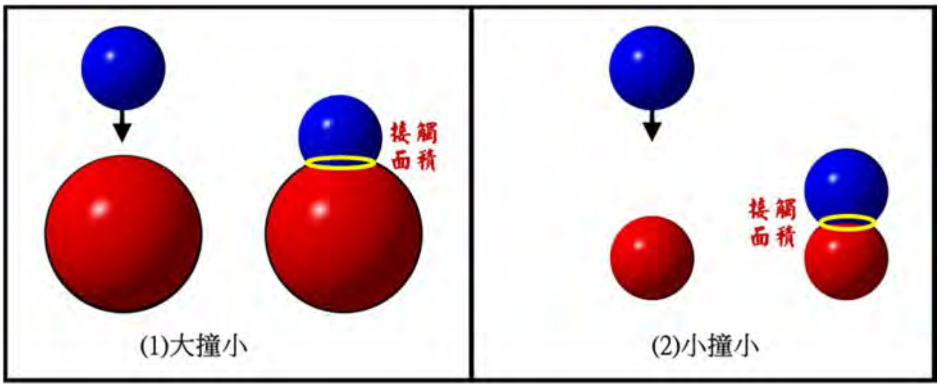


圖 5-1-5　不同底部的撞擊接觸面積示意圖

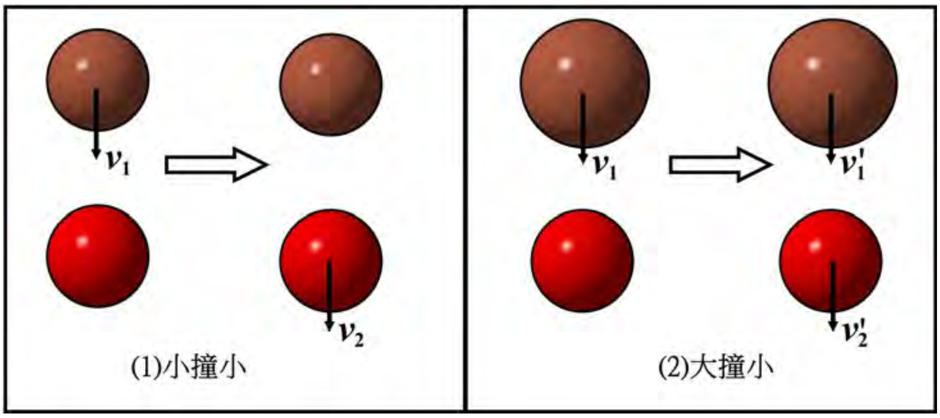


圖 5-1-6　不同球的撞擊接觸時間示意圖

(2)由圖 5-1-4 (外圓面積) 可歸納出：

A、隨著落下高度變大，外圓面積會增加，這結果似乎合乎原先的預期。

B、落下球如果是大球(例如大撞大、大撞小)，其外圓面積會比較大。

C、小撞小的外圓面積最小。

D、大圓看起來很像是點波圓所造成的波動，似乎跟撞擊瞬間能量的傳遞是有關係的。請參照圖 5-1-7 到圖 5-1-9，我們發現外圓的大小跟能量有某種程度的相關，**所以我們想像成撞擊瞬間形成能量波向外傳遞**。

E、改變外圓面積大小的因素，我們猜想應該跟下列有關：

①撞擊前後損失的動能：如果落下是大球，損失的能量比較多，大圓面積會比較大。

②接觸面積：從下圖可以發現如果落下是大球，則損失的能量幾乎一樣，然而為何會造成大圓面積不同，推估是撞擊瞬間面積不同，故向外傳遞的大圓也不同。

表 5-1-2 球下落時的反彈高度和損失能量

落下高度(cm)	種類	反彈高度(cm)	反彈角度(度)	恢復係數 e	損失的能量(J)
160	大撞大	45.52	89.71-90.12	0.53	8.98
	大撞小	40.84	89.76-90.21	0.51	9.34
	小撞大	57.93	89.89-90.11	0.60	1.10
	小撞小	52.61	89.90-90.10	0.57	1.16
140	大撞大	37.50	89.94-90.11	0.52	8.04
	大撞小	31.91	89.95-90.14	0.48	8.47
	小撞大	53.09	89.93-90.09	0.62	0.94
	小撞小	50.46	89.96-90.03	0.60	0.97
120	大撞大	27.15	89.86-90.13	0.48	7.28
	大撞小	24.32	89.86-90.13	0.45	7.50
	小撞大	49.74	89.88-90.12	0.64	0.76
	小撞小	44.45	89.95-90.00	0.61	0.81
100	大撞大	21.97	89-83-90.13	0.47	6.12
	大撞小	18.06	89.91-90.08	0.42	6.42
	小撞大	41.78	89.84-90.14	0.65	0.63
	小撞小	39.56	89.95-90.09	0.63	0.65
80	大撞大	17.39	89.83-90.16	0.47	4.91
	大撞小	13.01	89.90-90.18	0.40	5.25
	小撞大	33.66	89.94-90.10	0.65	0.50
	小撞小	27.95	89.87-90.19	0.59	0.56

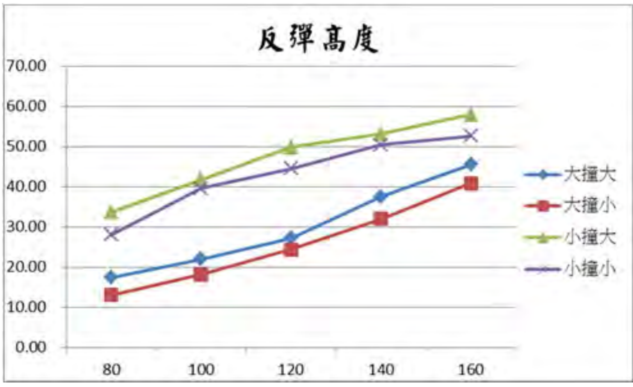


圖 5-1-7 球碰撞後的反彈高度

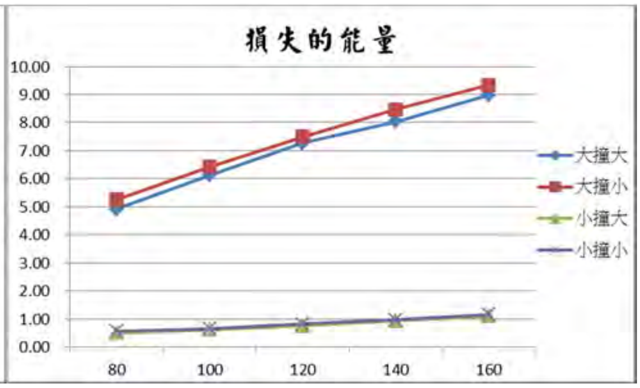


圖 5-1-8 球碰撞後所損失的能量

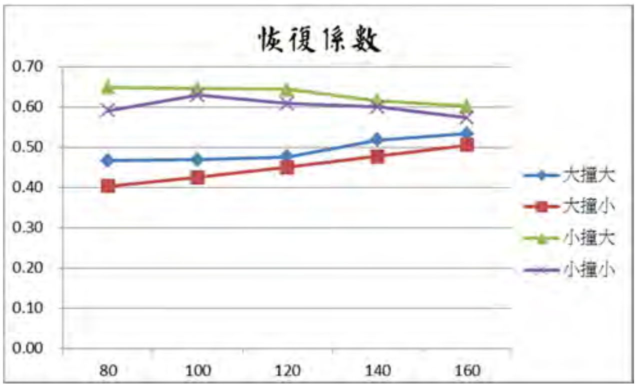
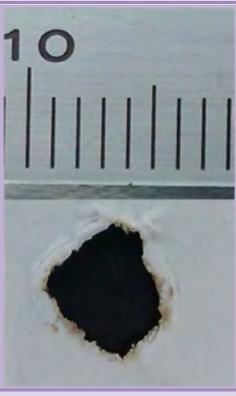
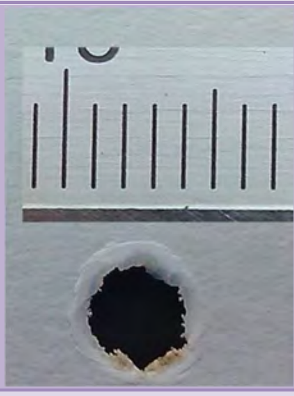
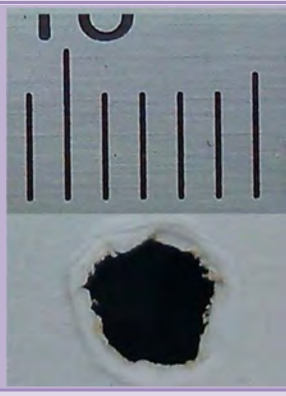
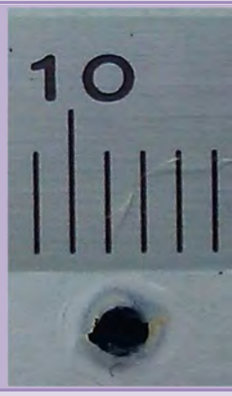
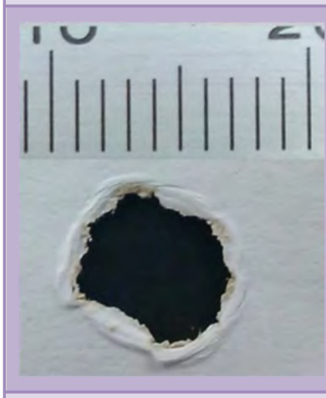
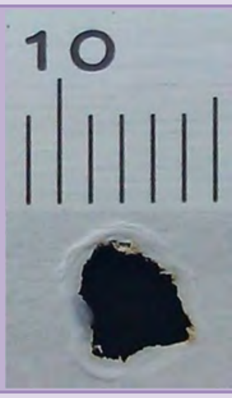
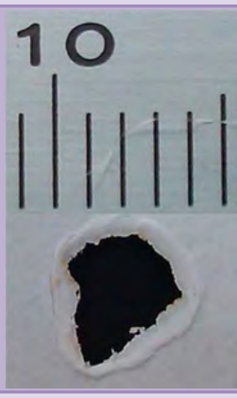
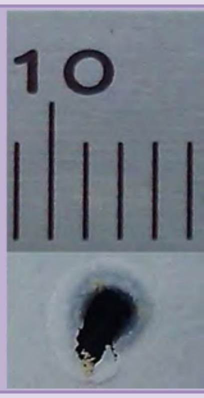
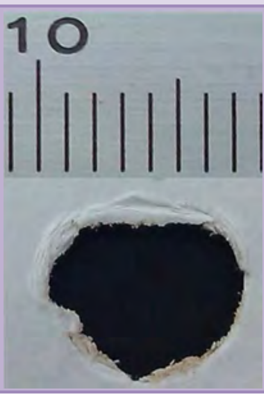
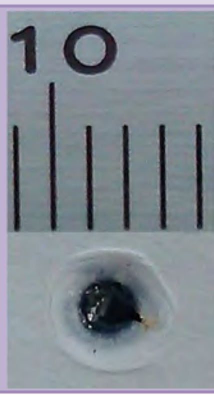


圖 5-1-9 球碰撞前後的恢復係數

二、撞擊單層紙：

圖 5-2-1 不同落下高度去撞擊白紙的圖形

80cm-大撞大-紙片	80cm-大撞小-紙片	80cm-小撞大-紙片	80cm-小撞小-紙片
			
120cm-大撞大-紙片	**120cm-大撞小-紙片**	**120cm-小撞大-紙片**	**120cm-小撞小-紙片**
			
160cm-大撞大-紙片	**160cm-大撞小-紙片**	**160cm-小撞大-紙片**	**160cm-小撞小-紙片**
			

1、觀察圖 5-2-1 可以發現撞擊點被 ”打”出個大洞來，且周圍有燒焦的痕跡。
紙是如何被燒出洞來的？ 難道是撞擊點的中心處燃燒再向外擴散嗎？
但我們觀察撞擊後的鋼球表面，有一個小小紙片殘留黏在上面。
⇒**代表紙片並不是從撞擊點中央往外擴散燒出洞**。

圖 5-2-2

2、鋼球的碰撞會在撞擊點造成瞬間的高溫(請見下方第3點)，但由於撞擊點的中央瞬間壓力很大，故此處可能會缺少氧氣，所以推測中央點反而不易燃燒。
而在撞擊點周圍區域因為鋼球損失大量能量而產生高溫，且得到氧氣共燃，故會形成了環型燒焦的結果。
⇒**至於撞擊中心點部分，由於氧氣不足，所以只有高溫沒有燃燒，故造成材料揮發變薄，形成中心半透明狀** (例如 “160cm-小撞小”)。

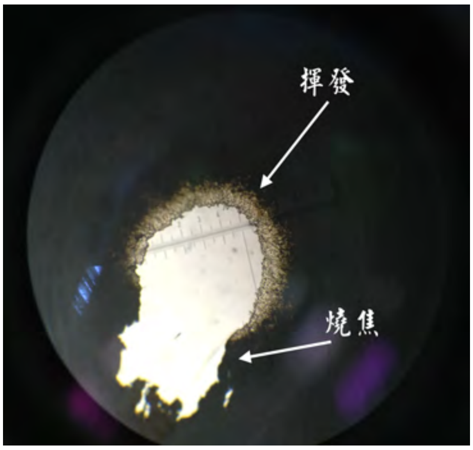


圖 5-2-3 顯微鏡下的紙

3、以下是我們推估球撞擊時的能量損失與造成的溫度：

已知鋼球落下時所造成的壓力 $P=\dfrac{F}{A}=\dfrac{\Delta p}{\Delta t}\times\dfrac{1}{A}$

鋼球的動量變化 $\Delta p = m(\sqrt{2gH_d}+\sqrt{2gH_b})$

假設：m=800 g ， H=100 cm ， g=9.8 m/s^2 ， A= π(0.5mm)^2 ， Δt < 100 μ

$$P>\frac{0.800\times(\sqrt{2\times9.8\times1}+\sqrt{2\times9.8\times0.5})}{1\times10^{-4}}\times\frac{1}{0.0005^2\times3.14}=7.702\times10^{10}(\frac{N}{m^2})=7.702\times10^{5}(atm)$$

而紙的厚度僅約 6.5 微米，故鋼球對紙所造成的功

$$\Delta W=P\times\Delta V=P\times(A\times\Delta d)=(7.702\times10^{10})\times(0.0005^2\times3.14)\times6.5\times10^{-6}=0.3930\ (J)$$

如果這些功轉換成熱經由傳導傳給紙，則： $\Delta W = 0.3930\ (\mathrm{J}) = \sigma A \dfrac{\Delta T}{\Delta d}$

已知：紙的 $\sigma = 0.05$ W/mK ； A= π(0.5mm)^2 ； $\Delta d = 6.5\mu m = 6.5\times10^{-6} m$

當這些熱傳遞給紙表面時，被紙面給吸收，

$$\Delta Q = 0.3930\ (\mathrm{J}) = \Delta m \times s \times \Delta T' = (\frac{4g}{21\times30cm^2}\times0.08\times\frac{1}{2}\times\frac{1}{1000})\times1.4\ \frac{kJ}{kg}\times10^3\times\Delta T'$$

得紙面上升的溫度 $\Delta T' \sim 1000\ °C$ (當然實際溫度應該更低)

這溫度已足以讓紙面燃燒 (燃點約 450℃)

※ $\dfrac{4g}{21\times30cm^2}$ 為 A4 紙的重量/總面積。A= π(0.5mm)^2 為參考鋁箔內圓的面積。

$0.08\times\dfrac{1}{2}$ 為撞擊紙所撞出面積的一半，假想有接近一半面積接收熱能。

4、下是不同高度下所燒出面積的資料：

表 5-2-1 不同落下高度去撞擊白紙的數據

	80cm-大撞大-紙片	80cm-大撞小-紙片	80cm-小撞大-紙片	80cm-小撞小-紙片
面積(cm^2)	0.186181	0.080659	0.087114	0.062836
周長(cm)	1.927056	1.272247	1.291103	1.054856
	120cm-大撞大-紙片	**120cm-大撞小-紙片**	**120cm-小撞大-紙片**	**120cm-小撞小-紙片**
面積(cm^2)	0.239484	0.114295	0.116077	0.059621
周長(cm)	2.175355	1.510482	1.50213	1.045193
	160cm-大撞大-紙片	**160cm-大撞小-紙片**	**160cm-小撞大-紙片**	**160cm-小撞小-紙片**
面積(cm^2)	0.28732	0.13007	0.0605545	0.0257709
周長(cm)	2.3147657	1.5294351	1.015548	0.660978

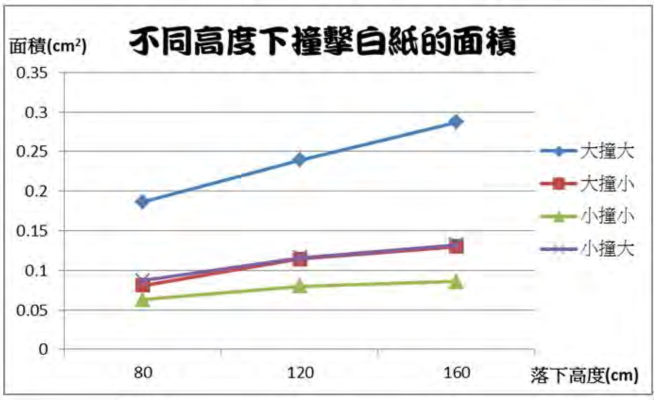


圖 5-2-2 不同高度下的面積比較

(1)由圖 5-2-2 可以看出：大撞大的面積遠高於其他組，而小撞大和大撞小面積幾乎一樣，所以我們推測造成紙面面積大小的**主要原因是接觸面積、次要原因是損失的能量**。

三、撞擊多層鋁箔：以下固定為大撞大，落下高度為 120cm。

鋁箔層數	1	2	4	6	8
內圓面積(cm^2)	0.007311	0.01012	0.01107	0.01572	0.01895
外圓面積(cm^2)	0.1969	0.2016	0.2498	0.2986	0.3663
反彈高度(cm)	27.15	26.50	22.55	18.65	14.89
損失能量(J)	7.27	7.33	7.64	7.95	8.24

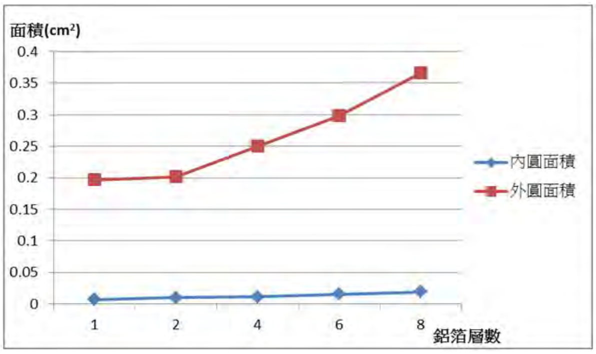


圖 5-3-1 不同層數下的內外圓面積

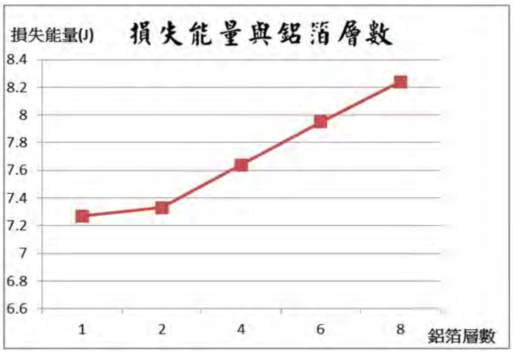


圖 5-3-2 不同層數下所損失的能量關係

1、當鋁箔厚度增加時，內圓面積幾乎呈正比例增加，這符合我們前面推論，**<u>內圓是由球擠壓表面所產生的</u>**。

2、由圖 5-3-1 看的出來：外圓面積則是明顯快速增加，我們猜測是由於接觸時間變長，導致能量傳遞增多所導致。再和圖 5-3-2 比較發現兩者有蠻相像的趨勢。
這似乎符合我們前面的推論，因為這裡撞擊種類相同，故接觸面積應該一樣，主要影響就變成損失的能量了。

3、由前方(第 21.22 頁)的推論得知，撞擊鋁箔瞬間的溫度可能高達數百度甚至千度，這溫度已經超過鋁的熔點(660℃)，所以當多層鋁箔被撞擊後，常常有兩片鋁鉑黏在一起的狀態，我們猜測應該是因為鋁箔受高溫後被熔化再復原後的結果。
(如圖 5-3-3 所示，當多層鋁箔被撞擊後，撞擊處好像黏住一般，我們用彈簧去拉它)

圖 5-3-3　多層鋁箔被撞擊後 ”黏在一起” 的現象

4、為了驗證撞擊鋁箔後是否有達熔點，我們改用厚度接近 6 層鋁箔的銅箔去撞擊，銅的熔點相當高(約 1100℃)，所以理論上我們的撞擊應該不至於會使銅熔化，請見圖 5-3-4，的確看到銅箔只是被撞凹，似乎沒有熔化的現象。

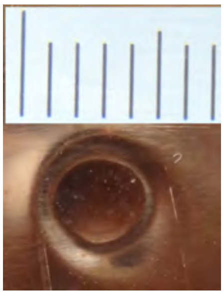


圖 5-3-4 大撞大 120cm 的銅箔

陸、結論

一、就反彈高度而論

1、鉻鋼球從愈高處自由落下，反彈後的高度愈高。

2、反彈高度大小比較：小球撞大球>小球撞小球>大球撞大球>大球撞小球。

二、就面積而論

1、鉻鋼球從愈高處自由落下，撞擊底下鉻鋼球後，中間物(ex：鋁箔)產生的同心圓之內、外圓面積愈大。

2、中間物的厚度愈厚，產生的同心圓之內、外圓面積愈大。

3、產生的同心圓之內圓面積：大球撞大球>大球撞小球>小球撞大球>小球撞小球。

4、產生的同心圓之外圓面積：大球撞大球>大球撞小球>小球撞大球>小球撞小球。

5、當中間物為紙，且高度較低時，內圈可能有未燒破的現象，甚至內圈形成幾近透明的薄膜，但其外圍卻有燒破，只剩細微殘留的絲聯繫內圓與外緣，可見球落下撞擊時，撞擊點缺乏氧氣，無法燒出破洞。而此現象在較低高度時較易發生，至於較高高度時就很少見了。

6、在落下高度、中間物厚度相等情況下，不同材質的中間物，仍會有不同的凹槽面積。

柒、未來展望

1、對於隕石撞地球能有更進一步的預防災害配套及善後措施

2、由此實驗，我們了解到撞擊所產生的能量是很大的，所以在日常生活中，例如窗台花盆擺設，務必要安全固定住，以防其自高處落下，砸到底下行人，造成意外傷亡。

捌、參考資料及其他

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Abstract

Our project is about collision of two steel balls. Since paper is highly accessible, we use paper to conduct our initial experiment. Paper is put on the ball below and the ball above is drawn by electromagnet. The ball above falls vertically, hitting the paper onto the ball below. After the head]-on collision, paper burned or even volatile with a burning smell.

Since paper's burning point is low, we replaced it with aluminum foil whose melting point is higher. After collision, a special pattern—concentric circles with a bright and smooth area in the core was formed on the aluminum. We find the waveform is like energy shock wave passed out from the collision point, so we went on further experiment, which come into four different fallen heights of the ball above, four different thickness of the aluminum foils and different layers of the aluminum foil.

According to the experiments of four different falling heights, we found Energy losses and area of patterns are proportional to the falling heights. From the experiments of four different thicknesses of the aluminum foils, we concluded the wavelike pattern is related to annealing effect and mass transportation. In the experiments of different layers of the aluminum foil, we can obviously see the annealing effect worked on aluminum foil from the cross section. Then, we also conduct the experiments of applying glue to the surface of aluminum foil. We found out that glue acted as buffer, which could effeectively smear the impact from the falling ball.

What we found in these series of experiments can be extended into three applications. The first one is the **buffer system**, in which we apply the concept of glue buffer. The second is **mixed form**: since we know the airplane is really heavy in its weight, the runway in an airport should be firm enough to support the large pressure, but it can also be paved with softer materials to buffer the impact force when an airplane lands on the ground. The third is **effective thickness**: although we 've known that if the thickness of material becomes bigger, the foil will be more able to mitigte the impact from the falling stuff, there exists a critical thickness, which means if it exceeds the limit of the thickness, the buffer effect will not be so significant, and people cannot make the best use of material, either.

I. Introduction

Destruction from shock wave on impact can be devastated. Hardware designs that guide the energy dissipation of shock wave can reduce or limit the damage. Here, we investigate effects of buffer layers in smearing the energy of shock wave while propagating. The impact is simulated by a head-on collision of two steel balls, and the energy dissipation progress of shock wave on aluminum foils resided at the collision point is studied.

II. Experimental Procedures and Equipment

Experimental procedures

1. Use Electromagnet to control the falling of the ball above. (Fig. 1-a)
2. The ball above falls vertically. (Fig. 1-b)
3. The ball hits the aluminum foil which has been put onto the ball below. (Fig. 1-c)
4. The ball above bounces nearly vertically. (Fig. 1-d)

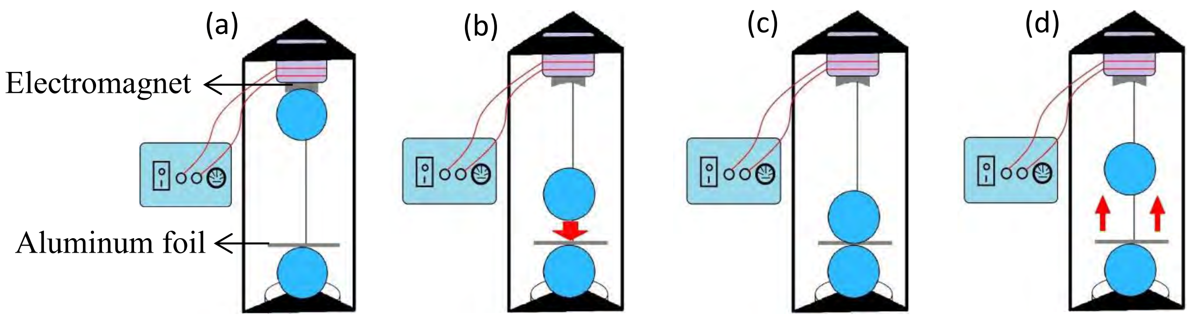


Fig. 1 Experimental schematic diagram

Experimental equipment

Chromium-steel Ball(*2) (Diameter:5cm；Mass:800g)	Electromagnet
	
Holder	High speed camera

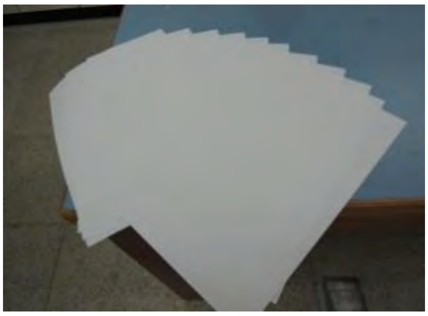
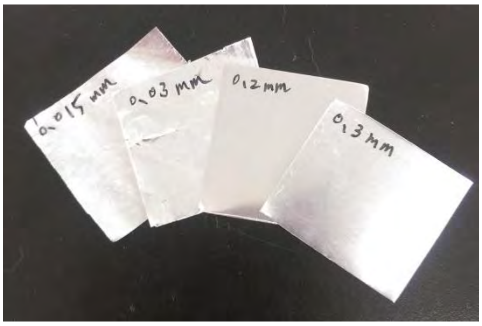
	
Target: Paper	Target: Aluminum foil
	

Fig. 2 Equipment to process the experiment

Microscope	PhotoShop: To figure out the area
	

PMMA: To make the model	Diamond cutter: To slice the PMMA model
	

Fig. 3 Experiment to analyze the data

III. Observations

Paper:

--Since paper is highly accessible, we adopt paper as our first target to conduct our experiment

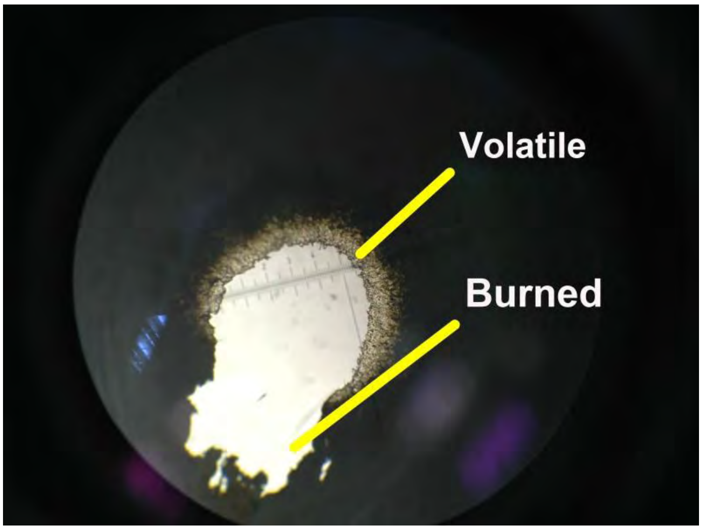


Fig. 4 Paper after the collision

1. The impact point of the collision on the paper burns into a hole.
2. A burning smell produced after collision.

One layer of Aluminum foil:

--The collision produces high temperature, so we try to use aluminum foil as the target.

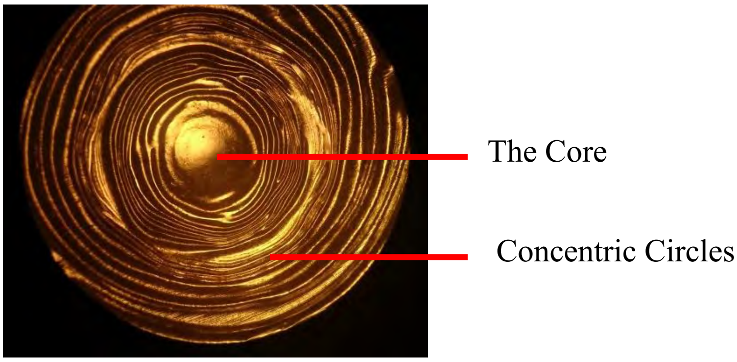


Fig. 5 The Core and Concentric Circles

1. Collision produces concentric circles.
2. In the middle of the concentric circles is an area that is very smooth and bright.

Different layers of Aluminum foil:

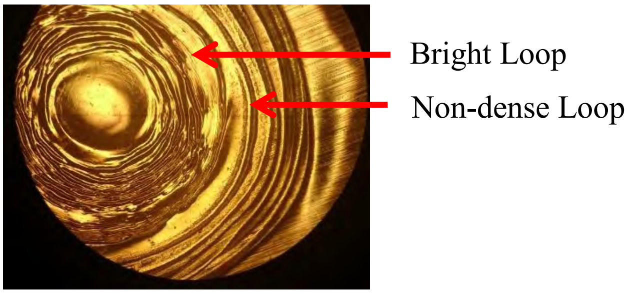


Fig. 6 The pattern of 2 layers

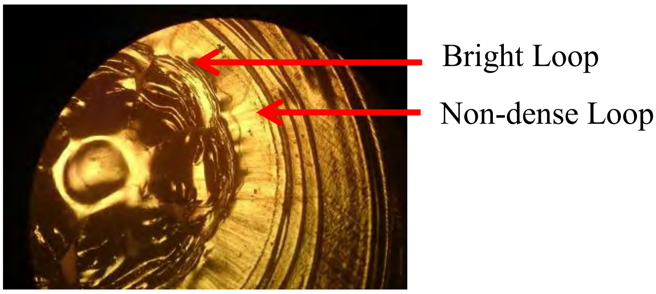


Fig. 7 The pattern of 4 layers

1. After collisions, the impact point stick together and we find that it’s hard to tear apart them.
2. With the increase of the mounts of aluminum foils, there will be bright loops around the core.
3. Amplitude of the shock wave becomes bigger from the core to the outside area.

IV. Objectives

1. Find out what makes the burning of the paper.
2. Calculate the approximate energy and temperature that collision generated.
3. Find out what makes the area of the pattern on the aluminum.

4. Find out the relationship between Energy loss and the area of the pattern on the aluminum.
5. Find out the reasons of the phenomenon form the pattern on the aluminum.
6. Explain the experiment of different layers of aluminum foils.
7. Discuss different patterns on aluminum foils in different layers and find out the reasons behind them.
8. Apply to the Buffer System and the thickness of asphalt used to pave the road.

V. Results and Discussions

Paper—what makes the burning of paper?

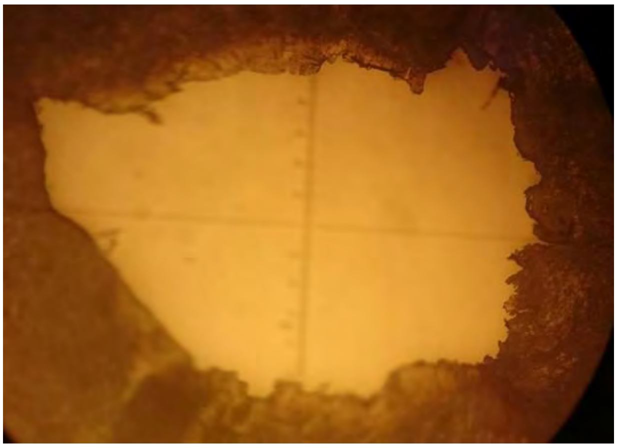


Fig. 8 Paper after the collision (Right: under the microscope)

1. By observing figures, we can find that after the collision, the impact point on the paper burns into a hole. (Fig. 8) What's more, there is also a burning smell. Wandering how does the paper burn into a hole, we observe the surface of the impact point on the steel ball, and find that there is a tiny piece of paper left on the ball. (Fig. 9)

   ⇒It means that the paper isn't burned from the impact point to the outside area.

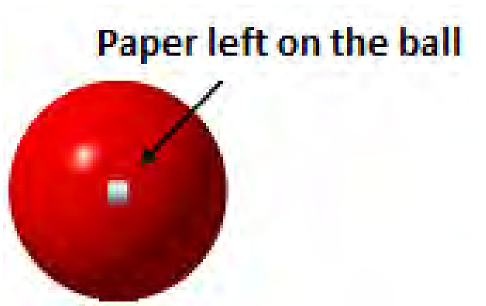


Fig. 9 Schematic diagram of the hit ball

2. Collision of the balls causes high temperature and high pressure. High pressure leads to lack of oxygen at the impact point, so we speculate that it is hard to burn at the impact point.
   ⇒ Due to lack of oxygen, the impact point on the paper doesn't burn. High pressure and high temperature only make the material volatilize and become thinner.
3. The ball loses a great amount of energy after collision, which produces high temperature around the impact point, and the paper gains sufficient oxygen to burn, so it results in a ringed burning.

The loss of the energy and the temperature:

The pressure: $P=\frac{F}{A}=\frac{\Delta p}{\Delta t}\times\frac{1}{A}$

Change of the momentum: $\Delta p=m(\sqrt{2gH_d}+\sqrt{2gH_b})$

Postulate: m=800 g，H=100 cm，g=9.8 m/s^2，A= π(0.5mm)^2，Δt < 200μs

$$P>\frac{0.8\times(\sqrt{2\times9.8\times1}+\sqrt{2\times9.8\times0.5})}{2\times10^{-4}}\times\frac{1}{0.0005^2\times3.14}=3.85\times10^{10}(\frac{N}{m^2})=3.85\times10^{5}(atm)$$

Thickness of the paper:6.5×10^{-3}mm

$$\Delta W=P\times\Delta V=P\times(A\times\Delta d)=(3.85\times10^{10})\times(0.0005^2\times3.14)\times6.5\times10^{-6}=\ 0.196(\text{J})$$

If all the energy converted into heat and conducted to paper:

$$\Delta W=0.196\ (\text{J})=\sigma A\frac{\Delta T}{\Delta d}$$

We have already known:

Paper $\sigma=0.05$ W/mK; A= π(0.5mm); $\Delta d=6.5\mu m=6.5\times10^{-6}m$

If all the heat is conducted to paper, and paper absorbs all of it:

$$\Delta Q=0.196\ (\text{J})=\Delta m\times s\times\Delta T'=(\frac{4g}{21\times30cm^2}\times0.08\times\frac{1}{2}\times\frac{1}{1000})\times1.4\ \frac{kJ}{kg}\times10^3\times\Delta T'$$

$$\Delta T'\cong551.25°C$$

The temperature can be up to 550 (This is higher than the reality) which is higher than the burning point of the paper, 450℃.

Single layer of Aluminum foil

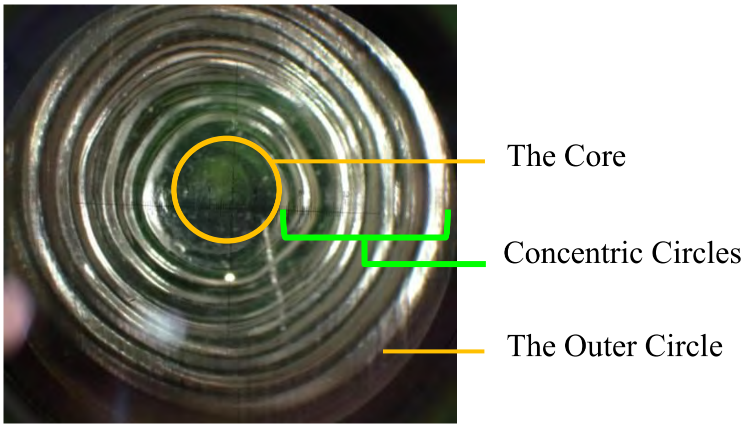


Fig. 10 The definition of the pattern on Aluminum foil (40X)

Area

To find out the factors that influence the area, here, we use two sizes of steel balls:

Big ball (Diameter:5cm ; Mass:800g);

Small ball (Diameter:5cm ; Mass: 800g)

1. **The core**

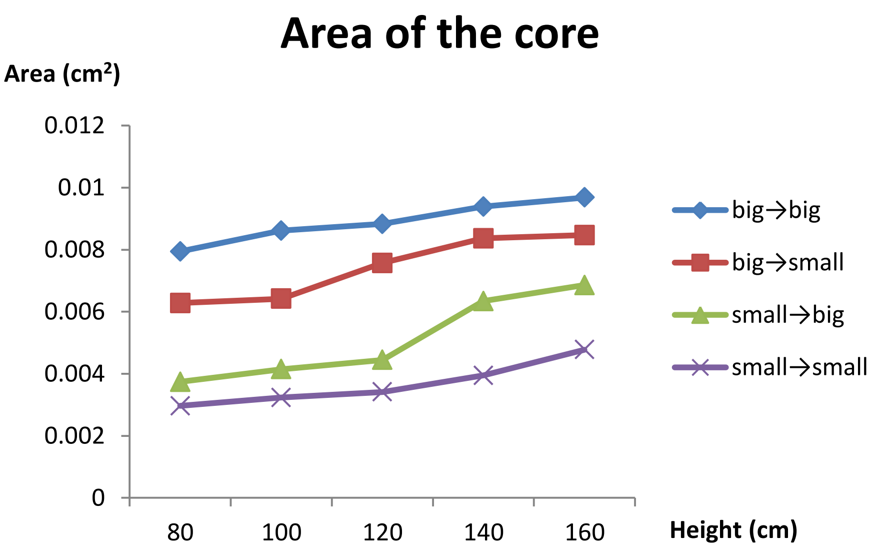


Fig. 11 Area of the Core

Factors that influence the area of the core:

(1) Contact area at the bottom: If the ball below is the bigger one, the area of the core will be larger. (Fig. 12)

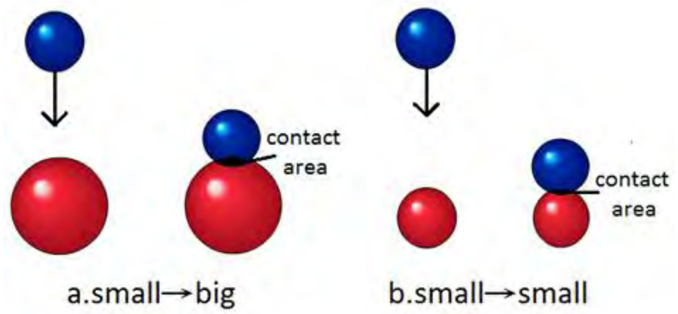


Fig. 12 Different Contact area of collision

(2) Initial kinetic before collision: The higher the falling height is, the bigger the area of the core is.

(3) Contact time: We imagine that the ball is composed of several springs in parallel. (Fig. 13)

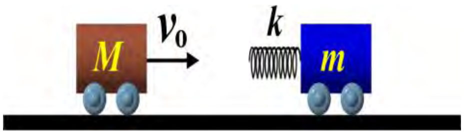


Fig. 13 See the collision of two balls as Simple harmonic motion

$$t=\frac{1}{2}T=\frac{1}{2}(2\pi\sqrt{\frac{\mu}{k}})=\pi\sqrt{\frac{\mu}{k}} \qquad \mu=\frac{Mm}{M+m}$$

	$\mu=\frac{Mm}{M+m}$ **(kg)**	**force constant**	**contact time**
two big balls	$\mu_1=\frac{MM}{M+M}=\frac{M}{2}=0.4$	$k_1=\frac{k_0}{nR_1}\times\frac{1}{2}=\frac{k_0}{2nR_1}$	$t_1=\pi\sqrt{\frac{0.4}{k_0/2n\times2.55}}=\pi\sqrt{\frac{2.04n}{k_0}}$
one big one small	$\mu_2=\frac{Mm}{M+m}=\frac{0.8\times0.11}{0.8+0.11}=0.097$	$k_2=\frac{1}{\frac{nR_1}{k_0}+\frac{nR_2}{k_0}}=\frac{k_0}{nR_1+nR_2}$	$t_2=\pi\sqrt{\frac{0.097}{k_0/n(2.55+1.5)}}=\pi\sqrt{\frac{0.393n}{k_0}}$
two small balls	$\mu_3=\frac{mm}{m+m}=\frac{m}{2}=0.055$	$k_3=\frac{k_0}{nR_2}\times\frac{1}{2}=\frac{k_0}{2nR_2}$	$t_3=\pi\sqrt{\frac{0.055}{k_0/2n\times1.5}}=\pi\sqrt{\frac{0.165n}{k_0}}$

Fig. 14 Comparison of force constant and contact time of different types of collision
(R_1: The diameter of big ball (5cm) ;R_2: The diameter of small ball (3cm))

➔ Comparison of contact time：big hit big > big hit small = small hit big > small hit small

➔ The longer the contact time is, the lager the area of the core is.

2. Outer circles

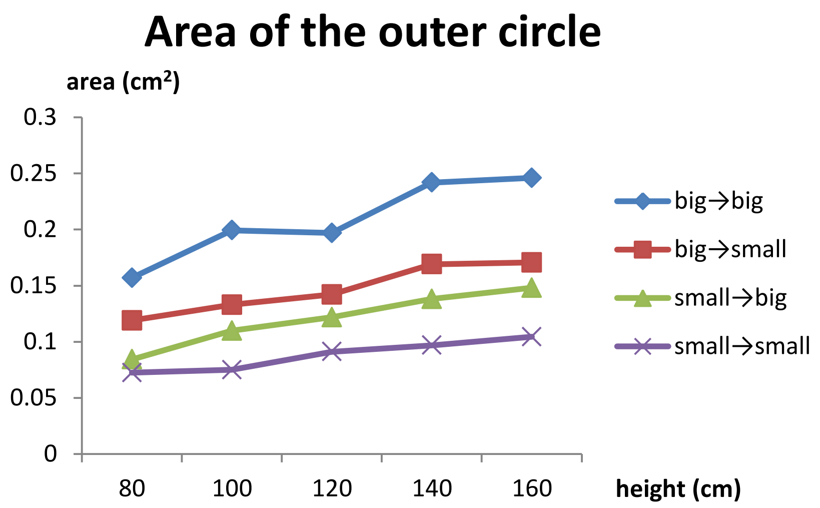


Fig. 15 Area of the outer circle

Factors that influence the area of the outer circles :

(1) The loss of kinetic energy after collision :

If the falling ball is the bigger, the loss of the kinetic energy is larger.

(2) Contact area :

From Fig. 12 , the reason why "big hit big" is larger than "big hit small" is because of contact area .

Height(cm)	Type	Bounding Height(cm)	Coefficient of Restitution	Loss of Energy (J)
160	big→big	45.52	0.53	8.98
	big→small	40.84	0.51	9.34
	small→big	57.93	0.60	1.10
	small→small	52.61	0.57	1.16
140	big→big	37.50	0.52	8.04
	big→small	31.91	0.48	8.47
	small→big	53.09	0.62	0.94
	small→small	50.46	0.60	0.97

120	big→big	27.15	0.48	7.28
	big→small	24.32	0.45	7.50
	small→big	49.74	0.64	0.76
	small→small	44.45	0.61	0.81
100	big→big	21.97	0.47	6.12
	big→small	18.06	0.42	6.42
	small→big	41.78	0.65	0.63
	small→small	39.56	0.63	0.65
80	big→big	17.39	0.47	4.91
	big→small	13.01	0.40	5.25
	small→big	33.66	0.65	0.50
	small→small	27.95	0.59	0.56

Fig. 16 Data of Bounding height, Coefficient of restitution and Loss of energy

(p.s.89°<angle of bounce<91°)

Energy loss and the area of the pattern

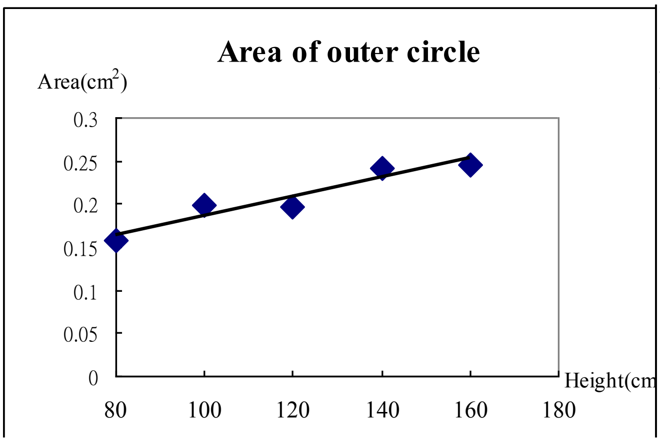


Fig. 17 Scatter diagram of area of outer circle

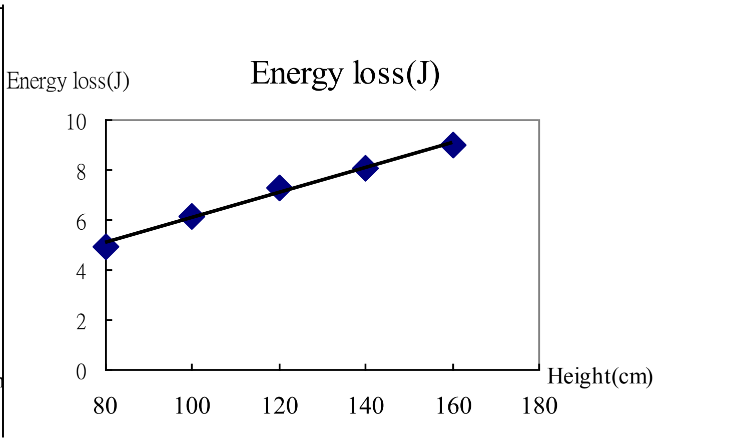


Fig. 18 Scatter diagram of energy loss

Falling height(cm)	Bouncing height(cm)	Energy loss(J)
160	45.52	8.98
140	37.50	8.04
120	27.15	7.28
100	21.97	6.12
80	17.39	4.91

Fig. 19 Data of bouncing height and Energy loss

Energy Dissipation of Propagating Shock Wave

1. According to E=m×g×h, we can calculate the Energy loss.
2. Energy loss of steel ball after collision was calculated from the height lost after bouncing
3. Energy losses and area of patterns are proportional to the falling heights.

   →We infer that the reason of the formation of circular pattern is result from energy loss.

Phenomenon of Mass Transportation

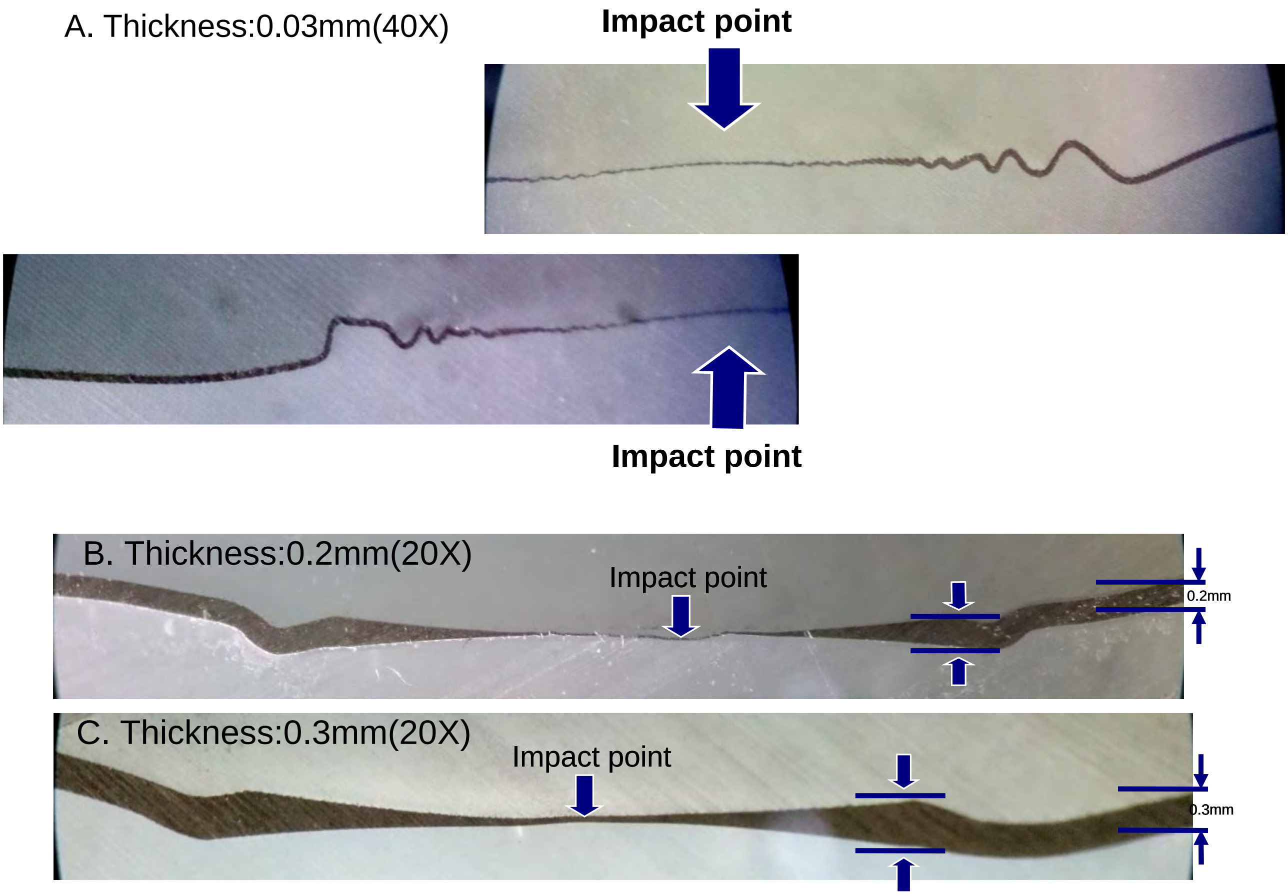


Fig. 20 Lateral views of collision patterns of single layers of Al foil.

1. Impact point is flattened.
2. Aluminum around impact point is thicker than original thickness.
3. Aluminum much farther almost doesn’t rise up its temperature, so it isn’t piled up and remain its original thickness.

Mechanisms

Annealing effect

1. Annealing, in metallurgy and materials science, is a heat treatment that alters the physical and sometimes chemical properties of a material to increase its ductility and to make it more workable. It involves heating a material to above its glass transition temperature, maintaining a suitable temperature, and then cooling. Annealing can induce ductility, soften material, relieve internal stresses, refine the structure by making it homogeneous, and improve cold working properties.
2. This process is performed by heating the material (generally until glowing) for a while and then slowly letting it cool to room temperature in still air. In this fashion, the metal is softened and prepared for further work—such as shaping, stamping, or forming.
3. Annealing occurs by the diffusion of atoms within a solid material, so that the material progresses towards its equilibrium state. Heat increases the rate of diffusion by providing the energy needed to break bonds. The movement of atoms has the effect of redistributing and eradicating the dislocations in metals and (to a lesser extent) in ceramics. This alteration to existing dislocations allows a metal object to deform more easily, increasing its ductility.
4. Hardness decreases and ductility increases, because dislocations are eliminated and the metal's crystal lattice is altered. On heating to a specific temperature atoms will migrate within the lattice and the adjusted grain can change the mechanical properties.

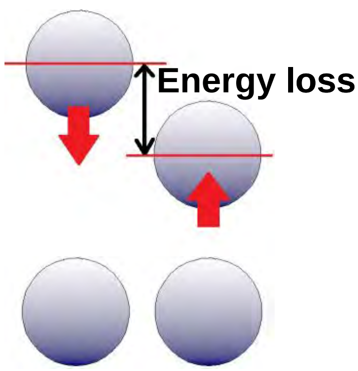


Fig. 21 Fall and Bounce

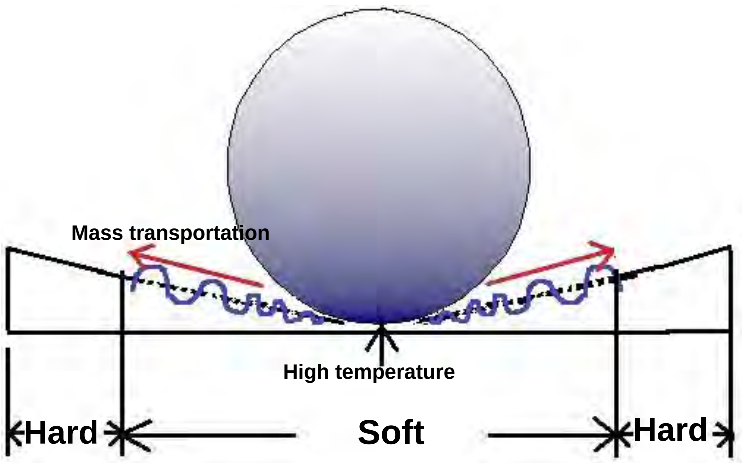


Fig .22 Mass transportation

Energy Dissipation of Propagating Shock Wave

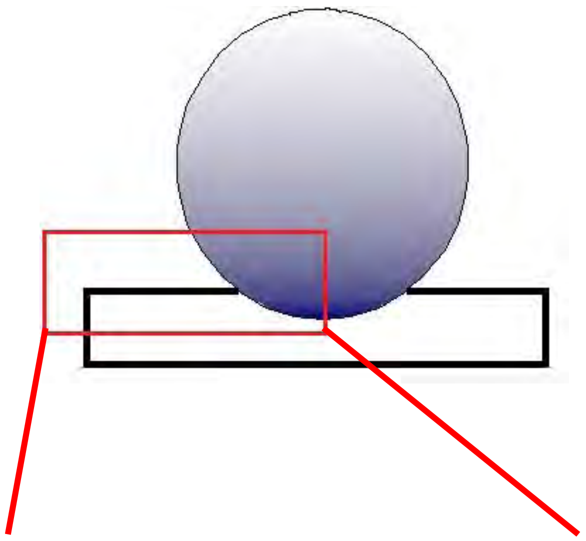
1. Wave like pattern is result from energy loss:

   (1) **Rising of temperature**:

   The ball is heavy and the falling height is high, so the initial energy is tremendous. What's more, the contact area is every small and the contact time during the collision is very short, and these cause the extremely large pressure. According to the formula $\Delta W = P \times \Delta V = P \times (A \times \Delta d) = (7.702 \times 10^{10}) \times (0.0005^2 \times 3.14) \times 6.5 \times 10^{-6} = 0.3930\ (J)$, as well as we count the contact area and the foil thickness, the large pressure cause the enormous energy, which converts into heat. Indeed, after the collision, the balls are really higher than before. Thus, we believe that some of the energy loses to rise up temperature.

   (2) **Mass transportation**:

   High temperature softens the aluminum foil. The impact pushes the material outward, thus generates shock waves and mass transportation. Material piles up to form a wave like pattern at the soft/hard interface that continuously propagates outward along with the shock wave. The pattern is frozen at lower temperature when impact energy is dissipated via deformation and thermal diffusion.



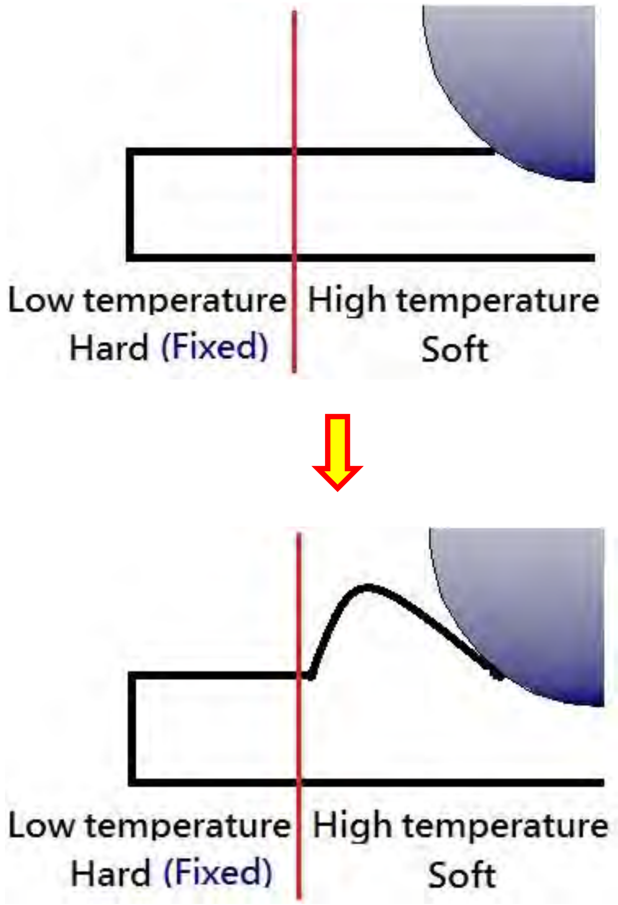


Fig. 25 Squeezing process

2. Why are there several waveforms?

   (1) The farther the distance from the impact point is, the lower the temperature is.

   (2) Observe Fig. T_1>T_2, so the red area is softer than the yellow area, and pile up the material. Likewise, T_2>T_3, so the yellow area is softer than the green area, and pile up the material; T_3>T_4, so the green area is softer than the blue area, and pile up the material.

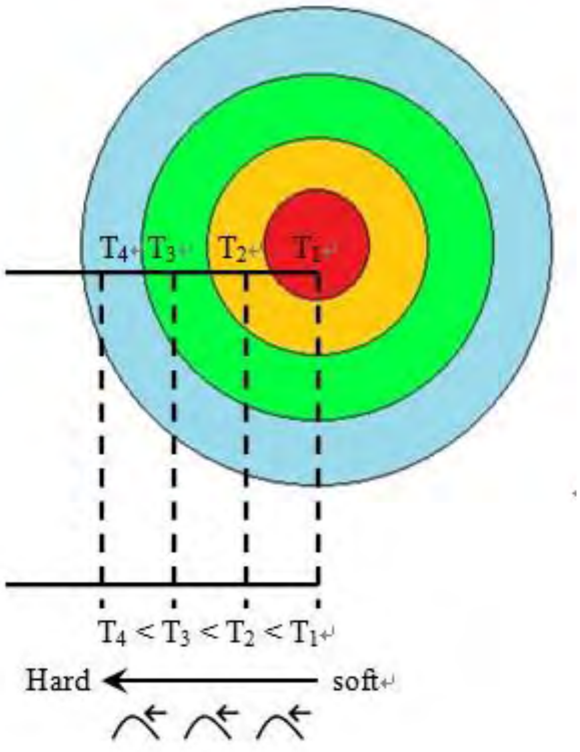


Fig. 24 Schematic diagram of many waveforms

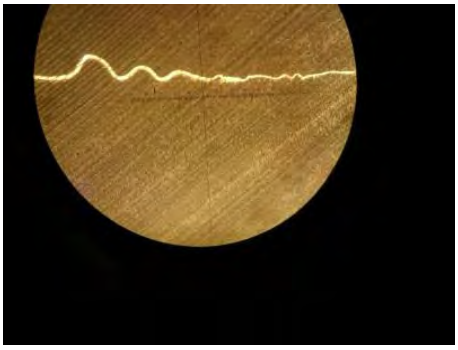
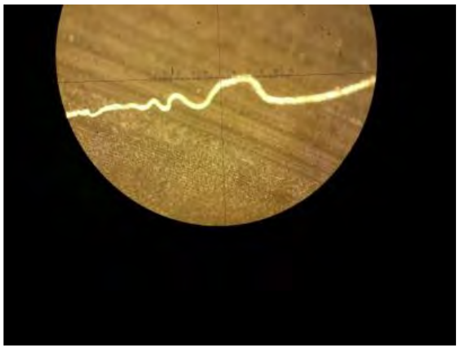
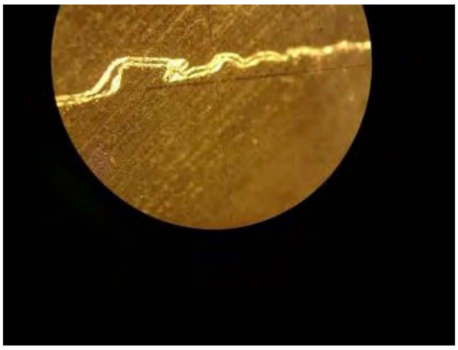
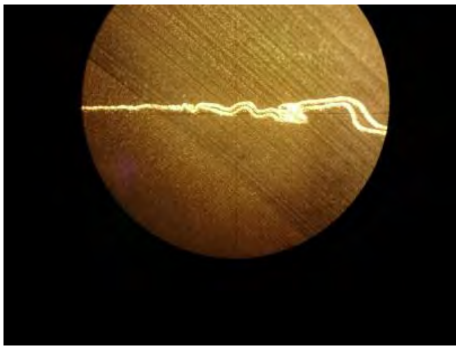
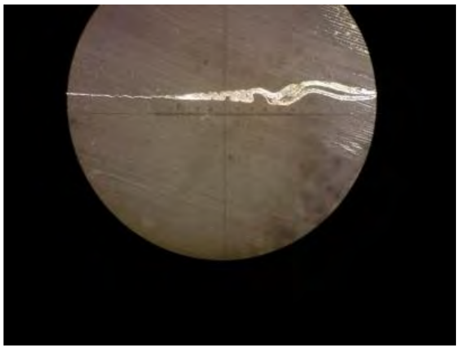
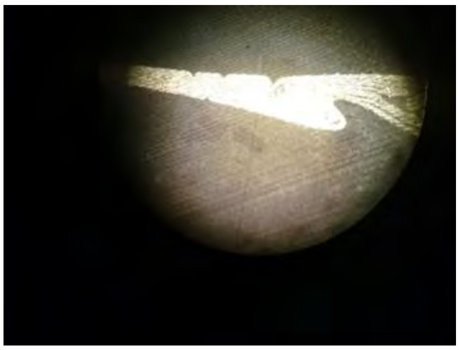
Several layers of Aluminum foil

Cross section

1. Since we have mentioned that the reason why concentric circles are formed is because of extrusion between the two steel balls, we want to see what these circles look like if we make them into models (we use PMMA), and then cut the pattern straight to observe the cross section .

2. At the moment of collision, energy delivered to the aluminum foil is full, so it can be delivered to further places, forming bigger amplitude. However, after a while, energy decreases sharply, so it can only be delivered to neighboring area near the core. As a result, we can see amplitude becomes bigger from the core to the most outside area.

3. By measuring the thickness at the impact point and the wave shape, we discover that the impact point is thinner than it originally is; on the contrary, the thickness of the wave shape become bigger from the core to the outside area. This phenomenon verify what we have mention before; that is, material is extruded during collision, and is transported to outside.

Type / Layers	Left part of Side view	Right part of Side view
1		
2		
4		
8		

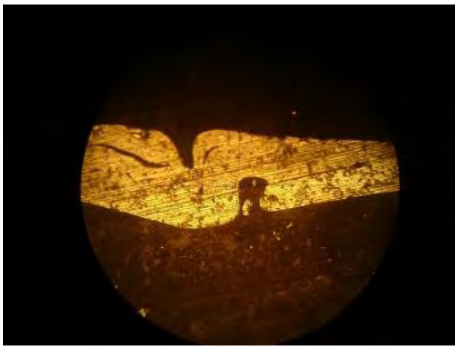
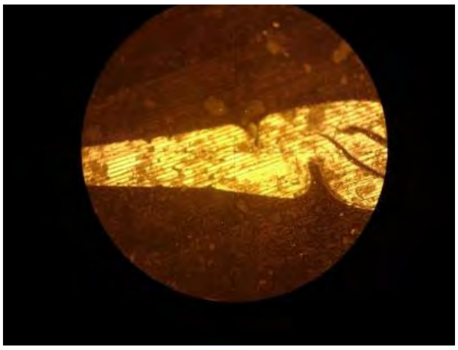
16		

Fig. 25 Comparison of amplitude of different layers of aluminum foils

Top View

After the collision of two balls, we can observe that there are concentric circles around and around on the aluminum foils. And if the layers of aluminum foil increase, patterns differ from one another. Now, we are going to explore further:

1. Different areas on the aluminum foils

(1) The Core

As we have mentioned before, the core looks very bright and smooth. During the contact time, energy is delivered to the surface of the aluminum foil. Due to the collision, it generates high temperature and high pressure, which make the point of collision melt. After it cools down, atoms rearrange, forming an area which is very smooth and bright.

(2) Concentric Circles

Energy passes out in form of shock waves during the contact time, forming concentric circles around the core. We categorize them into two parts, which we call "dense loop" and "non-dense loop". And the two areas appear alternately.

A. Non-dense loop

In this area, waveform is very close to one another. We infer that it is because at the moment of collision, waves pass out with large energy, forming bigger wavelength, which we call non-dense loop.

B. Dense loop and Bright Loop

a. Waves reflex during the progress of passing out. And as we know, energy loses quite a lot, so when the waves reflex, they can only form smaller wavelength, which we call dense loop

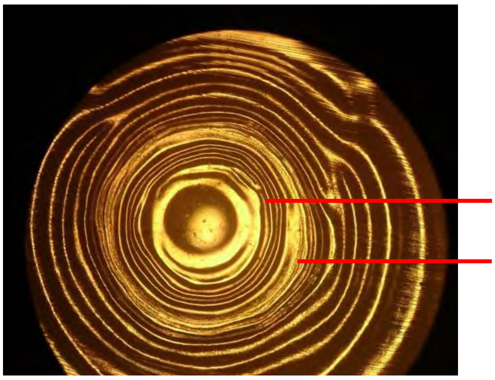


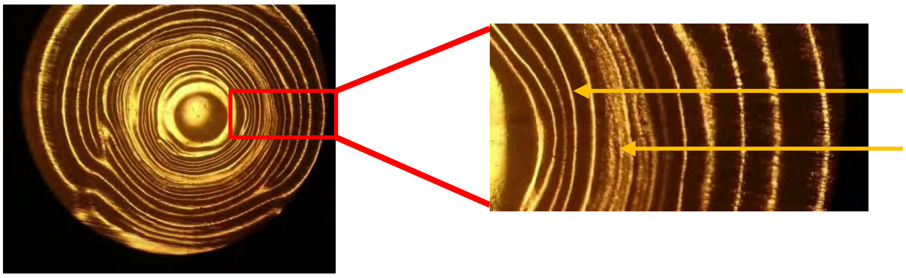
Fig. 26 Dense loop and Non-dense loop (50X)

b. The Energy passes out and reflexes for several times, so the dense loop and non-dense loop appear alternately.

c. If the layers of aluminum foil increase, we can hardly observe the dense loops. Because when waves reflex, energy is absorbed by several layers of aluminum foils, which cannot form obvious waveform, and we call them "bright loop. "

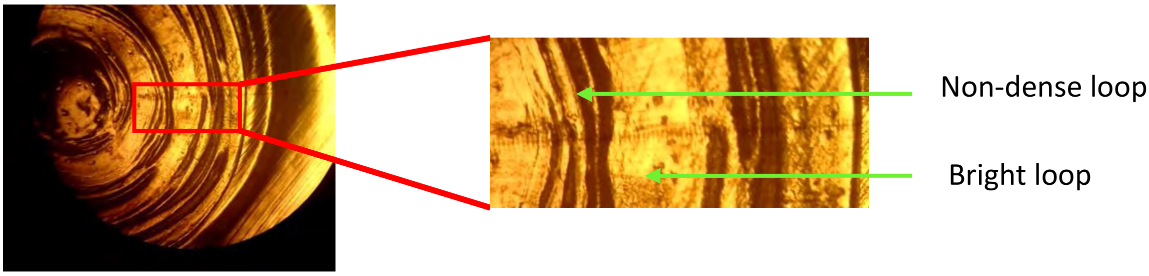
d. Now let's compare the top view patterns of different layers of aluminum foils:

- 1 layer



- 2 layers

- 4 layers



- 8 layers

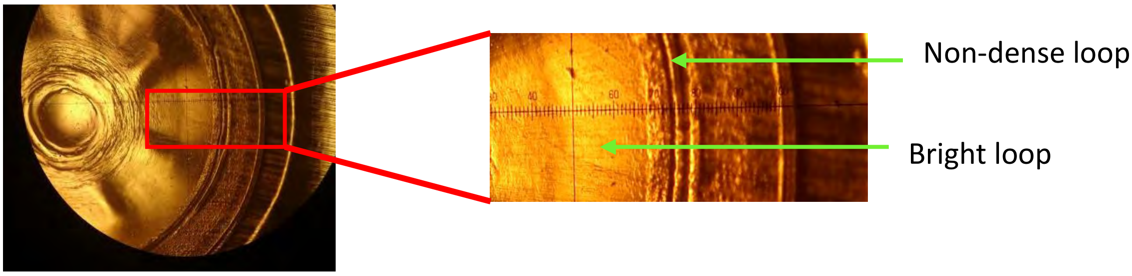
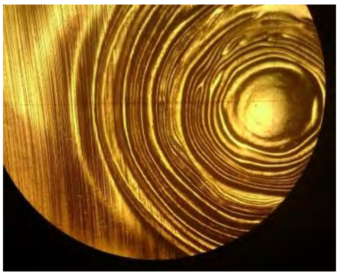
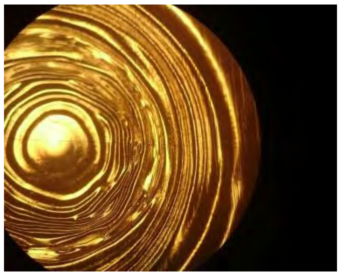
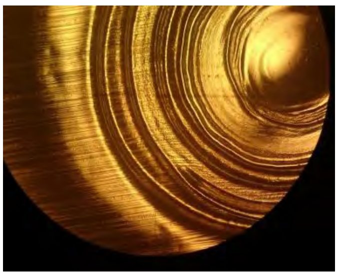
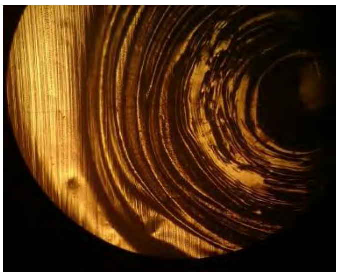
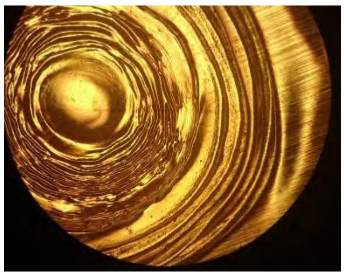


Fig. 27 Comparison of Different layers and heights

Height / layers	**40cm**	**80cm**	**120cm**
1			
2			

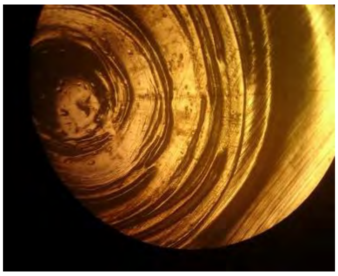
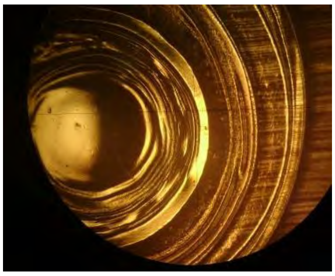
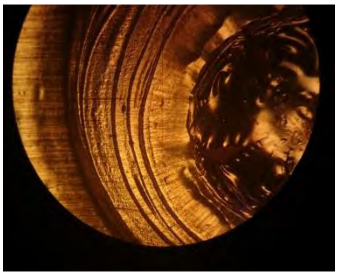
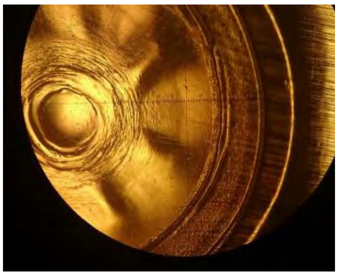
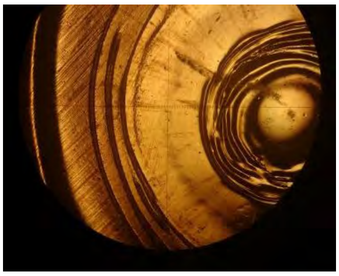
4			
8			

Fig. 28 Comparison of wavelike pattern of different height and layer

VI. Applications

(1) Buffer system:

Air buffer

- Amplitude of the pattern on stacked Al foils is significantly smaller than that on a solid piece of same material thickness.
- The air between Al foils acts as a buffer to reduce vertical displacement, hence the destruction.

(a) Two layers of aluminum foil:
Thickness: 0.03mm

(50X)

(b) Single layers of aluminum foil:
Thickness: 0.03mm

(20X)

Fig. 29 Comparison of patterns on two aluminum foils which are same thickness

Energy Dissipation of Propagating Shock Wave

	2 layers of 0.015 mm foil	1 layer of 0.03 mm foil
Diameter (cm)	0.51	0.5
Area (cm^2)	0.2	0.19

	4 layers of 0.015 mm foil	2 layers of 0.03 mm foil
Diameter (cm)	0.58	0.55
Area (cm^2)	0.25	0.23

Fig. 30 Comparison of foils whose thickness are the same but have different composition

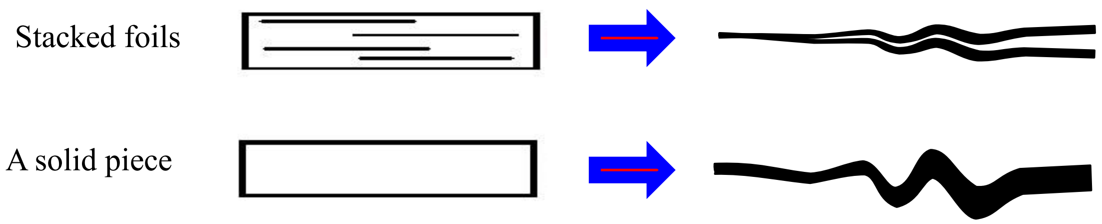


Fig. 31 Amplitude of stacked foils and a solid piece

Glue buffer

- We applied glue to the interlayer between two aluminum foils, and we found out that the amplitude of this type is smaller, which meant the impact of shock wave was smaller. (Fig. 32 $h_1 < h_2$) Therefore, we can infered that glue acted as buffer, and had similar function with air.

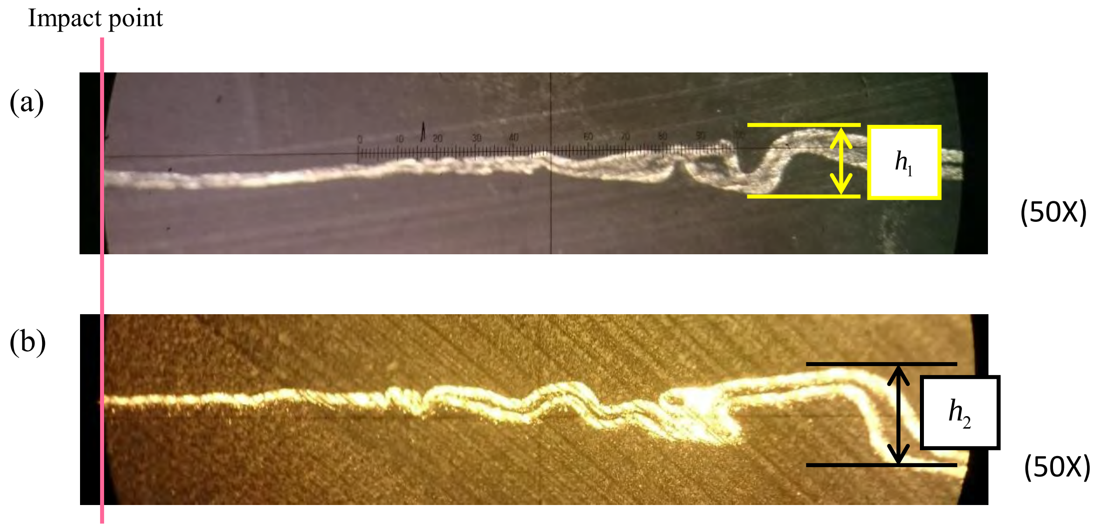


Fig. 32 Cross section patterns of impact for two foils stacked loosely, (a); and adhension by glue, (b).

(2) Mixed form

Since we know the airplane is really heavy in its weight, the runway in an airport should be firm enough to support the large pressure. The runway can be paved with softer materials on the surface, which can buffer the impact force when an airplane lands on the ground.In addition, softer material can easily be repaired when damaged. On the other hand, harder material can be paved under the sofer surface, which can support heavy weight of an airplane when it stays at the airport.(Fig. 33)

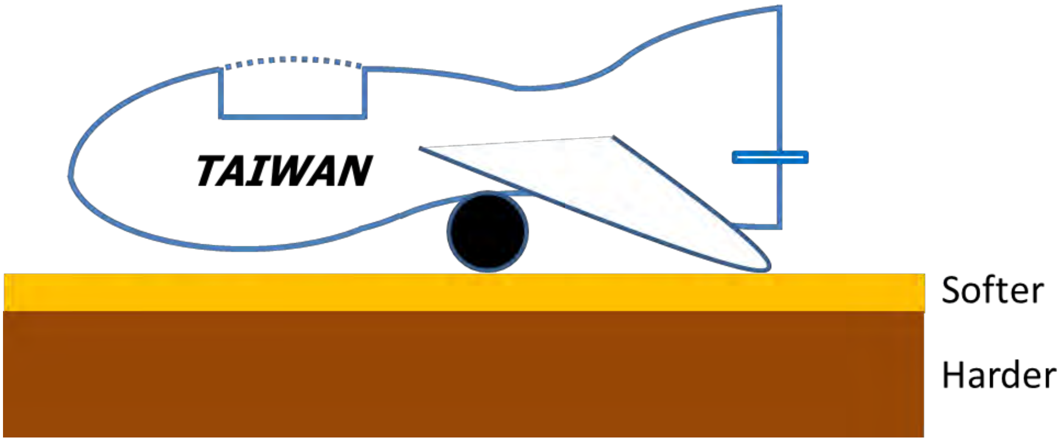
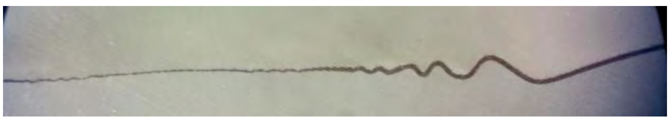


Fig. 33 Softer and harder material paved for the runway

(3) Effective thickness:

- A smaller waveform is generated in a thicker material.
- Interestingly, the deformed thickness does not linearly link to the thickness of the material, showing that there is a critical thickness of the material for effectively absorb the energy generated upon impact.
- In reducing the impact it is of course necessary to increase the thickness of the walls of buildings or asphalt roads, but only up an effective thickness.

A. Thickness:0.03 mm



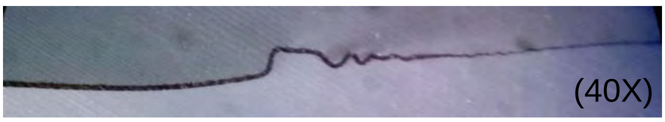


Fig. 34 Lateral views of collision patterns of single layer of aluminum foil

VII. Conclusions

(1) The impact is capable of burning holes through thin papers or generating concentric circular patterns on Al foils.

(2) The impact causes the temperature to raise, that softens the metal for mass displacement and energy propagation.

(3) The collision pushes the material outward, which results in piling up of the materials to form a wave-like pattern.

(4) Air buffer between two metal-layers reduces the displacement but generates a larger deformed area.

(5) A thicker material helps to reduce the amplitude of the displacement on impact, but there is a critical thickness for the material to be effectively demining the displacement.

VIII. References

[1] R. Hessel, A. C. Perinotto, R. A. M. Alfaro, and A. A. Freschia, Am. J. Phys. 743, 176 (2006).
[2] J.A. Greenwood, Proc. Roy. Soc. Lond. A, 453, 1277 (1997).
[3] L. H. van Vlack, Elements of Materials Science and Engineering, Addison-Wesley, 134 (1985).

★ All photos and schematic diagrams by authors

【評語】160038

本作品設計以鉻球作自由落體，撞擊鋁箔膜高速度能量將鋁撞擊後產生孔洞並在鋁平面造成圓形波往外擴散。此實驗說明隕石撞擊地球造成坑洞的現象。

可改進處：

1. 以多層鋁膜證明鋁有熔解，直接證據不足。
2. 造型圓形波往外傳遞，應考慮波之特性波長、頻率、波速、能量可加入總能量。