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Physics of Baseball Bats - An Analysis

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Abstract. An analysis of the physics of baseball bats is presented in this study. The analysis compares the performance of aluminum and wooden baseball bats. Novel experimental approaches to indirectly quantify the performance of these bats have been implemented. The analysis also considers various aspects of baseball including the physical dimensions of the baseball fields, ball exit speed ratio, moment of inertia, trampoline effect, coefficient of restitution and youth baseball. In youth baseball, the baseball bats used are more effective relative to the physical dimensions of the baseball fields. The novelty, in this study, focuses on the investigation of bat and ball collision with the ball immersed in liquid nitrogen. The results seem to suggest that the energy transfer between aluminum bat and liquid nitrogen immersed ball is better than that of wooden bat and immersed ball.

Keywords: Baseball, ball exit speed ratio, moment of inertia, trampoline effect, coefficient of restitution

1. Introduction

The sport of Baseball has seen tremendous improvements in the quality, reliability and integrity of baseball bats. These improvements have not only increased the performance of the bats to be able to hit a pitched ball, but also in the durability of the bats.

During the 1850's, when the sport of baseball was still young [1], there were not many regulations on the types of bats that were allowed to be used. This led to experimentation which eventually led to regulations on the diameter of the barrel of the bat to be at 2.5 inches and a maximum length of 42 inches. After two decades, the name, Louisville Slugger, became one of the finest baseball bats to come into existence. The 1870's was also the time when the 2.5 inch diameter restriction on the bat was lifted and set to a new maximum of 2.75 inches. These restrictions on the diameter of the baseball bats are still in use to this day.

The next major development for the bats came in 1924 when a patent was issued to William Shroyer for the first aluminum baseball bat [2]. However, it was not until 1970's when Worth Inc. started to manufacture the first batch of aluminum bats that were put into practice by Major League Baseball (MLB) [1]. Towards the end of the decade, Easton Inc. [3] introduced a higher grade aluminum bat. Eventually, this led to significant improvements, from double walled aluminum bats to titanium bats, and, more recently, composite bats. These improvements were so vast compared to the maple and white ash wooden bats that were in use by the MLB, that the MLB refused to allow the aluminum bats into the sport [4].

The incentive for limiting bat performance was to guarantee fairness between batters. However, in recent years, the use of aluminum bats in youth baseball has become a contentious issue. Initially, aluminum bats served as alternatives to wooden bats since they would not be damaged so easily, thus effectively cutting costs for the youth teams [5]. The aluminum bats are usually said to have a significant trampoline effect, a larger sweet spot and can be swung at a faster rate. An inherent property of the aluminum bat is the trampoline effect in which the barrel of the bat stores less and releases most of its energy into the ball, much like a spring. The trampoline effect results in a faster batted-ball speed compared to a wooden bat of similar proportions. Along with the trampoline effect, another property of aluminum bats is that they usually have a lower swing weight or moment of inertia, MOI. Thus, the aluminum bats can be swung faster than their wooden counterparts of similar weight. The aluminum bats also have a larger sweet spot, which is the area on the bat wherein the baseballs come off the bat at a faster speed [6]. For the youth, the aluminum bats allow for a certain amount of leniency when hitting the ball; the bats can be swung faster and can hit harder as well.

The argument begins with the assertion that the aluminum bats demonstrate batted ball speeds which are considerably greater than those hit by wooden bats. As a result, numerous states and towns, in the United States, are introducing ordinances into their local governments banning the use of aluminum bats [5]. The purpose of this research is to design and implement an experiment in which the result would be a visual proof of how much energy is lost to the batted ball from both aluminum and wooden bats. Thus, from the loss of energy due to the batted ball, it is possible to calculate the speed at which the ball travels through the air. In a comprehensive field test study, this research analyzes the amount of force that was imparted onto the baseball through the use of two types of baseball bats. Also, through the analysis of contemporary literature along with the current performance standards, this research delves into the various aspects of the bat and ball collision.

2. Theoretical Background

There are several important factors when comparing wooden and aluminum baseball bats. This research will analyze the ball exit speed ratio, moment of inertia and youth baseball as well as the information gathered from the experiment that was conducted to draw conclusions regarding the effectiveness of the various types of baseball bats. This research will also consider the differences between both the collegiate level baseball fields as well as the little league fields.

2.1. Different Fields

In recent years, there have been an increasing number of incidents in which pitchers on the baseball field are being hurt by the direct hits that the batter makes. There is, however, a significant difference between both the collegiate level fields and little league fields, which would be the distance between the pitcher and the batter.

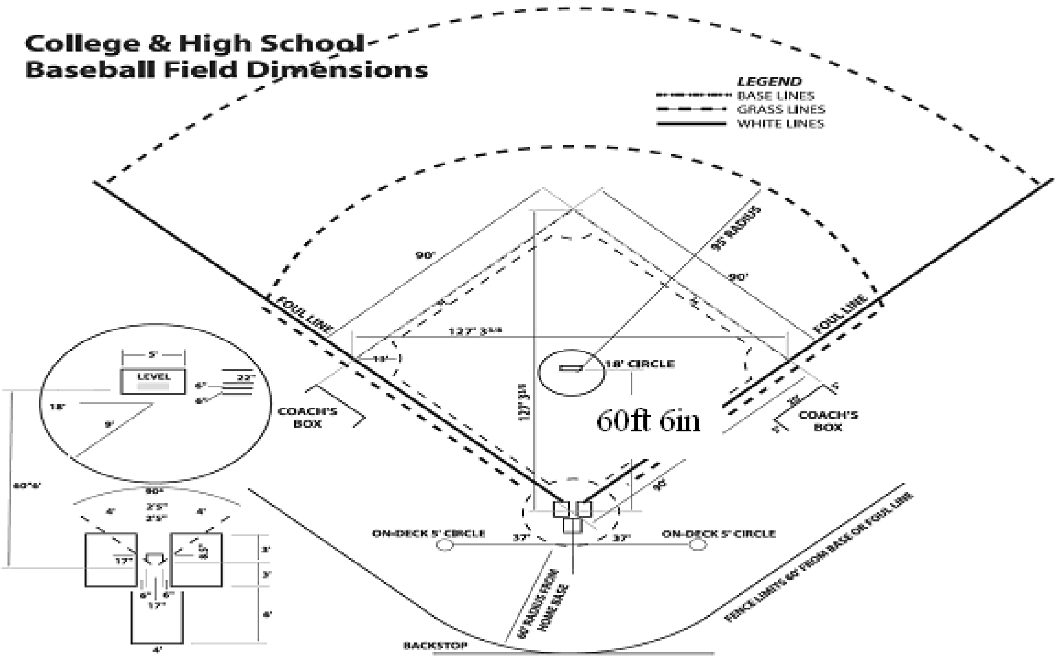

Fig. 1 College & High School Baseball Field Dimensions [7].

As can be seen from Figure 1 [7], in the collegiate level field, the distance between the pitcher and batter is 60.6 ft whereas, in Figure 2 [7], the Little League field, the distance between the two locations is 46ft. This difference in distance is important for calculating the various aspects of the speed of the ball while exiting or after collision with the baseball bat.

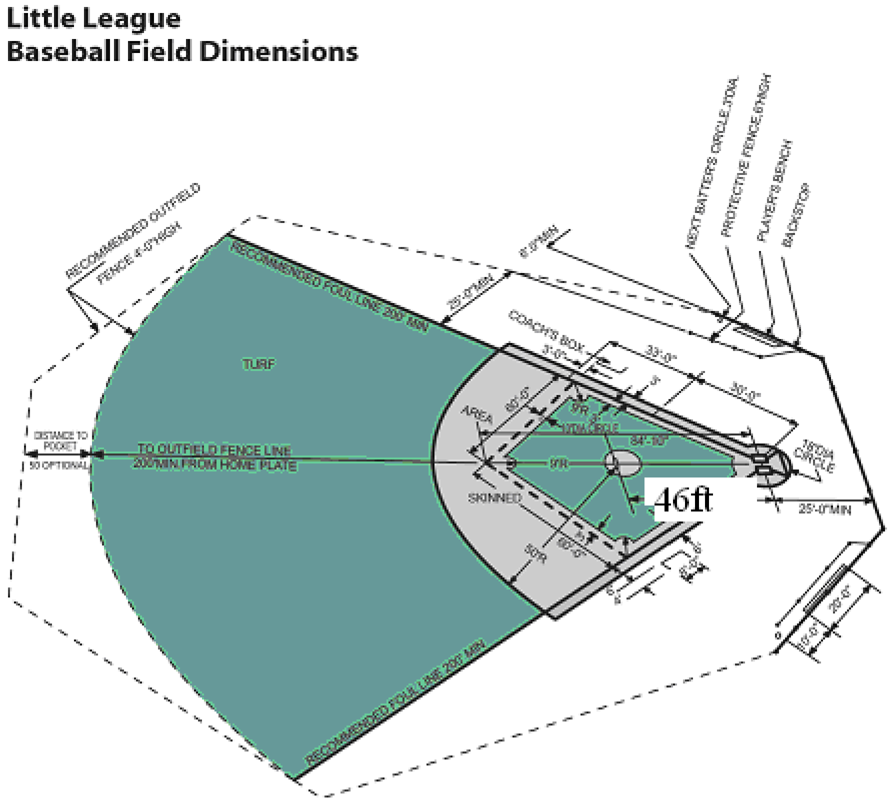

Fig. 2 Little League Baseball Field Dimensions [7].

2.2. Ball Exit Speed Ratio (BESR)

In 2005, the National Collegiate Athletic Association (NCAA) placed a standard for testing baseball bat performance [8]. The NCAA prescribed a few key factors that determine the speed at which a ball exits a collision with a baseball bat. One of these factors is called Ball Exit Speed Ratio (BESR). This ratio permits to analyze the bat-ball collision using theoretical models. In Figure 3 [8], Vpitch is the speed of the ball due to the pitcher just before the point of collision. Vbat is the speed of the bat before the moment of collision and Vball exit is the speed of the ball after the moment of collision which is also known as batted ball speed (BBS). The ball exit speed is quite essential for calculating the projected field speed of the ball.

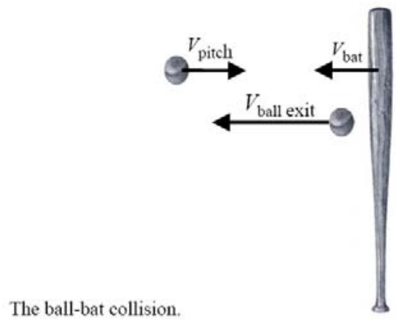

Fig. 3 The ball-bat collision [8].

The ball exit speed ratio (BESR) is a number which facilitates in calculating the Vball exit if both Vbat and Vpitch are given as shown in equation 1 [8]:

$$\text{Vball exit} = (\text{BESR} + \tfrac{1}{2}\,\text{Vbat}) + (\text{BESR} - \tfrac{1}{2}\,\text{Vpitch}) \quad \text{(Eq.1)}$$

$$\text{BESR} = \text{Vball exit} / (\text{Vbat} + \text{Vpitch}) \quad \text{(Eq.2)}$$

In equation 2 [8], note that BESR is the ratio of the speed of the ball while exiting the site of collision Vball exit to the combined initial speeds of both the baseball and the Vbat and Vpitch.

For all lab BESR calculations, a 70-mph pitch speed is used, and the swing speed is 66 mph. This is the standard that was used for calculating the BESR ratios originally by the NCAA. Figure 4 [8] is a graph which displays the maximum allowed BESR for a baseball bat according to the NCAA; however, this data utilizes a pitching speed of 80mph.

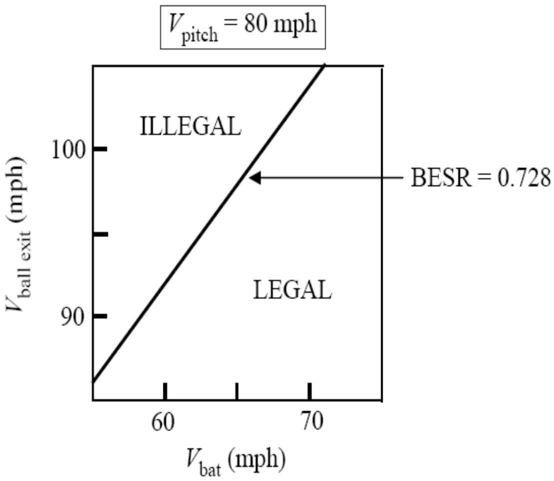

Fig. 4 Maximum allowed BESR for a baseball bat according to the NCAA [8].

In the Little League, the maximum length of the baseball bat is 32 inches, which when referenced on the NCAA Certification Protocol [9] corresponds to the maximum BESR of 0.716 rather than the 0.728 BESR maximum found earlier in Figure 4 [8]. Also, according to the NCAA Certification Protocol, the Moment of Inertia (MOI) for a ball that is batted by a 32 inch bat at a distance of 6 inches from the end of the bat is 7630 oz-in2. However, when referencing the length of a bat that must maintain a maximum BESR of 0.728, the corresponding length of 34 inches is allowed for the bat. At this length of 34 inches, the MOI for the bat is 9530 oz-in2.

This results in the difference in the MOI to be equal to 1900 oz-in2. This difference is critical and thus plays a significant role not only in determining the effectiveness of the baseball bats but also when measuring the effectiveness of the bats on the different field dimensions. The different field dimensions play an important role since the smaller field has less distance between the batter and the pitcher. The MOI should be less on such a field due to the restrictions placed by the NCAA on bat length for Little League players.

2.3. Trampoline Effect

The bat and ball collision can be simplified to demonstrate the basic physics of the trampoline effect [10]. The trampoline effect refers to elasticity in the baseball bat such that it acts as a trampoline. It is also referred to as a spring-like effect due to the degree to which the baseball bat is depressed, and then springs back into shape when striking a ball. As a baseball hits a wooden bat, the ball is nearly compressed by half of its original diameter. This makes the ball lose approximately 75% of its initial energy to internal frictional forces. However, this is not the case in an aluminum bat, in which the barrel of the bat is hollow. This allows the bat to behave like a spring, and thus, during the collision, the baseball loses much less of its initial energy due to internal frictional forces.

According to Mustone [11], the trampoline effect also causes the baseball to deform less, which is significant because the baseball is not a good energy storage device. When impacted with the solid wood bats, the baseball deforms more, thus dissipating some of the collision energy. By using newer metal alloys that have higher yield-strength, the trampoline effect can increase the exit velocity of a baseball. Also, the aluminum bat, behaving like a spring, stores up energy from the impact and thus while the ball is leaving the impact zone, the bat in its tendency to act like a spring, imparts force onto the ball.

The Crisco-Greenwald [12] study compares batted ball speeds for balls hit with a wooden bat and the highest performing metal bat. Figure 5 [12] shows that, for a given swing speed, the aluminum bat can potentially hit the ball 5-7 mph faster than the wooden bat. This can be explained if the metal bat has a trampoline effect which returns more of the energy to the ball. Thus, the study offers some evidence of an enhancement in performance for metal bats due to the elastic property of the bat.

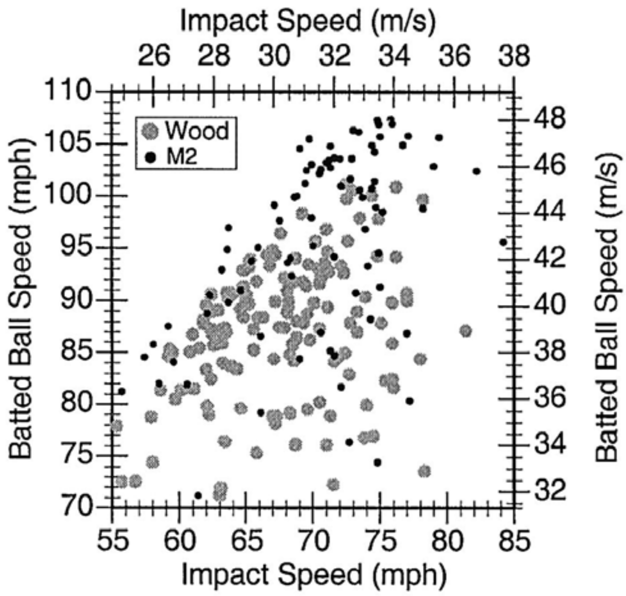

Fig. 5 Batted ball speed versus bat impact speed for a wooden bat and an aluminum bat (black) [12].

A direct comparison of both wooden and aluminum bats in terms of Vball exit and the distance of impact from the knob of the bat is shown in Figure 6 [13]. There is a 3.6% increase between the aluminum and wooden baseball bats in relation to their Vball exit. However, the aluminum bat has a higher Coefficient of Restitution (COR) that gives it 10% Vball exit which then totals to approximately 13.6% increase in the Vball exit which is highly significant. The COR is the amount that the bat will compress when hit by the ball. The COR would be negligible for a wooden bat, since if the bat were to be compressed, the bat would shatter [13]. However, this is not the case with an aluminum bat. Depending on the thickness of the barrel, the aluminum bat has variable amounts of COR. The thicker the wall or the more number of walls present in the aluminum bat, the lesser the COR. However, if the wall of the bat is thinner, the COR will be higher. There is a minimum of 10% difference in the COR between aluminum and wooden bats regardless of the thickness of the barrel of the aluminum bats.

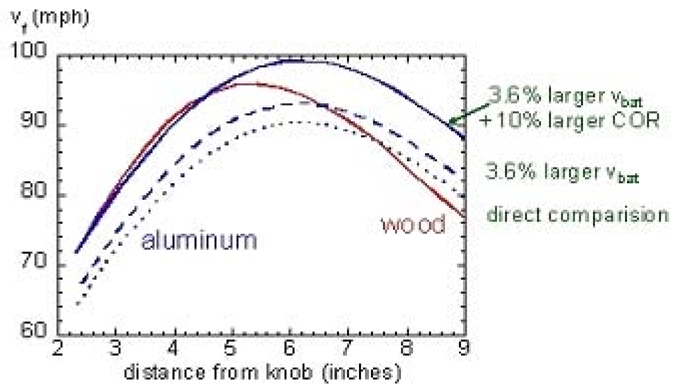

Fig. 6 A direct comparison of both wooden and aluminum bats in terms of Vball exit and the distance of impact from the knob of the bat. The trampoline effect favors aluminum. [13]

There are two types of trampoline effects. Bending modes are those that create a miniature trampoline effect in wooden bats, whereas Shell modes are those that cause the trampoline effect in aluminum bats. According to Nathan [13], the bending modes of wooden bats act much like a rapid impulse which stores less energy, and this amount of energy is put into vibrations across the bat. However, the shell modes of the aluminum bat store more energy due to thinner barrel and therefore most of the energy is restored into the ball as shown in Figure 7 [13].

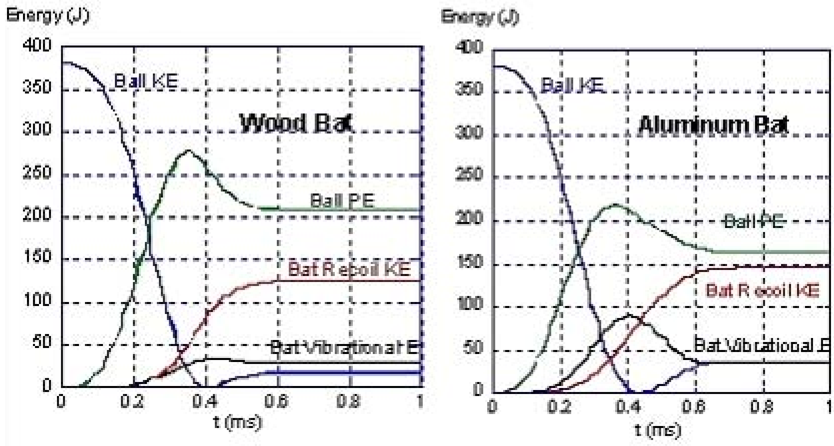

Fig. 7 Tracking the energy versus Time during bat and ball collision for wooden and aluminum baseball bats [13].

2.4. Youth Baseball

When considering the accuracy of previous literature regarding the differences between BESR and MOI on adult bats, the research is on point; however, the literature neglects to study youth baseball bats. According to tests conducted by the University of Massachusetts at Lowell [5], the NCAA standard placed on youth baseball is not efficient since it does not take into consideration the actuality of the theoretical calculations.

The NCAA standards for the maximum length of 34 inches and weight of 32 oz, correlates well with the data that calculates the BESR using these values. However, youth baseball bats vary greatly with both length and weight, and thus they do not correlate well with the NCAA standards for BESR values.

Table 1- Comparison of wood and aluminum bats having similar Moments of Inertia and Ball Exit Speed Ratios [5].

Bat ID	Length cm (in.)	Weight g (oz.)	MOI kg-cm² (oz-in²)	Sweet Spot Location cm (in.)	Calculated Swing Speed km/h (mph)	BESR	BBS km/h (mph)	Type	Barrel Diameter cm (in.)
JJ044	80.963 (31.875)	513.3 (18.105)	910 (4975)	17.8 (7.0)	67.6 (42.0)	0.678	93.2 (57.9)	nonwood	5.72 (2.25)
JJ022	73.500 (28.938)	606.7 (21.400)	917 (5013)	15.2 (6.0)	61.0 (37.9)	0.679	86.4 (53.7)	wood	5.72 (2.25)
JJ054	78.740 (31.000)	633.5 (22.345)	1152 (6297)	16.5 (6.5)	63.1 (39.2)	0.677	90.3 (56.1)	wood	5.72 (2.25)

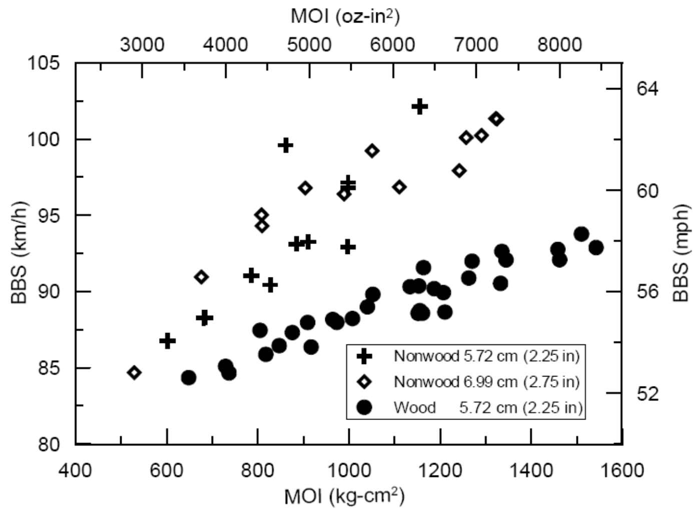

Fig. 8 NCAA Ball Exit Speed Ratio versus Moment of Inertia [5].

As exemplified in Table 1 [5], a 5.72-cm (2.25-in.) barrel aluminum bat and a 5.72-cm (2.25-in.) barrel wood bat can have the same MOI but can differ in length by up to 10.16 cm (4 in.). Even if the two bats have precisely the same NCAA BESR as well as MOI, they can vary in ball-exit speed by several mph. The reason for this discrepancy in ball-exit speed is the difference between the lengths of the bats. The longer aluminum bats share a similar sweet spot, but move further away from the handle due to the extra length of the bat. This results in a higher bat speed at the point of impact due to the change in MOI [5].

Another study performed looks at the BBS against the MOI. The data correlates well with the fact that a bat with a larger MOI will result in a larger BBS.[5] However, the graph also demonstrates that a bat with similar MOI on a wooden bat results in a smaller increase in BBS compared to the BBS obtained from an aluminum bat. This is shown in Figure 8 [5].

3. Experimental Approach

The experimental procedure, in this study, was as follows: Aluminum based multi-wall bats and wooden bats, that were compatible with MLB standards, were chosen for the experiments. A new pack of 24 baseballs were chosen in order to be able to compare performance of the bats and the balls. Two National Collegiate Athletes Association (NCAA) baseball players from New Jersey Institute of Technology participated in the experiment. In order to make a fair analysis of the experiment, the baseball players were asked to choose at least one of each type of bat, so that the collected data of the batted ball was independent of the physical characteristics of the players. In order to remove the effects of the motion of the ball in the air due to the pitcher, the baseballs were placed on a baseball tee. This would eliminate the effects of the initial speed of the ball and, thus, force the baseball players to hit the ball from an almost consistent height and distance, thus reducing a few variables except for the human element.

Liquid nitrogen is usually at a temperature of -196°C which is cold enough for cryogenics. Each of the baseballs were immersed for 7 minutes in a container of liquid nitrogen. After a duration of 7 minutes, the baseballs were placed onto the baseball tee using heavy duty leather gloves. When the balls were placed on the baseball tees, the baseballs were carefully placed in such a way that the laces of the ball would not make contact with the bat. This would ensure that the ball would make maximum contact with the bat and thus show more clearly the impact of the bat on the ball.

3.1. Baseballs

The baseballs used were new NMB Official League practice and recreational baseballs. Each ball has a synthetic leather cover, a solid cork and rubber center. Each of the baseballs were of official size and weighed 5.25 oz or 148.84 grams.

4. Results

Table 2- Experimental results of batted liquid nitrogen immersed baseballs.

Type	Mass of Ball after impact (grams)	Circumference of Largest Ring	Number of Rings	Number of Cracks	Length of Crack 1	Length of Crack 2	Length of Crack 3
Wood	144.6	12.8	6	13	35.5	29.1	19.5
Aluminum	144.25	13.3	9	14	38.4	29.9	20.9

In order to maintain a standard for the measurements, the experimental data was averaged for each bat respectively. The baseballs that were immersed in liquid nitrogen facilitated the ability to assess the energy transfer between the bat at room temperature and the ball at liquid nitrogen temperature. Due to the thermodynamic non-equilibrium situation, the impact of the bat on the ball was visible. This resulted in rings and cracks all along the surface of the ball. The data that was then collected took into consideration the mass of the balls before and after the collision. There was a marked decrease in the mass of the baseballs after impact. However, there was larger decrease in the baseballs hit by the aluminum bat.

The baseballs that were hit by both types of baseball bats showed both concentric rings around the site of impact as well as radiating cracks from the site of impact. In Table 2, the data collected includes the measurements of the largest ring for each ball and the number of rings on the ball. The number of cracks that were present were counted and the lengths of the three longest cracks on the baseball were measured.

5. Discussion

The experiment that was conducted in the above study allowed insight into the collision of the baseball bat and the baseball. There was a slight difference in the masses of the baseballs after the impact from the wooden and aluminum bats. Due to these results, the mass that was lost due to the collision was the material that broke away from the ball after the impact. The material that was lost was mostly leather and pieces of thread from the ball.

The data gathered in Table 2 shows that, due to the increase in the number and length of the radiating cracks and the number and length of the concentric rings, the aluminum bats imparted more energy to the baseballs thus increasing the damage to the baseballs.

A study that has been performed by the Baseball Research Center examined temperature dependence of the coefficient of restitution of baseballs. Part of their study focused on storing the baseball in a refrigerator which cooled the baseballs to 25°F to emulate cold playing conditions [14]. When the baseballs were tested, they showed a change in COR by 3% lower than the same baseball placed at the benchmark temperature of 70°F as observed in Figure 9 [14].

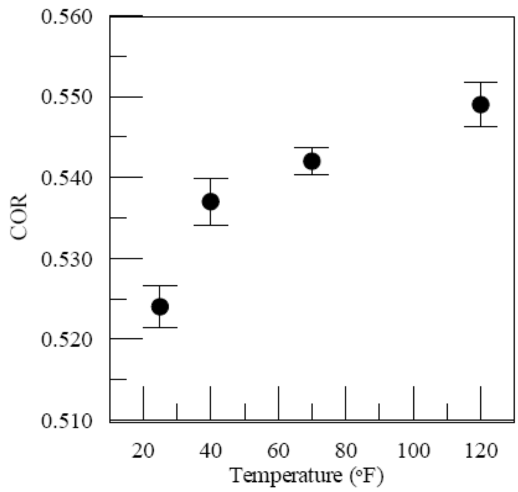

Fig. 9 Average COR values for 12 baseballs tested at four temperatures using a test speed of 60 mph [14].

The argument is that, by freezing the ball in liquid nitrogen, the effect of spring constant associated with the ball, K, is being amplified [10]. In other words, the general impression is that the spring, associated with the ball (due to the effects of the bat), is non-linear (due to the effects of the bat) and liquid nitrogen essentially assists in enhancing the impact of the bat on the ball. A detailed investigation of the literature did not reveal significant studies of the effects of aluminum and wooden bats on liquid nitrogen immersed balls.

6. Conclusions

The liquid nitrogen experiment visibly demonstrates the energy transfer from the aluminum and wooden bats to the ball. This study also analyzed the information regarding the BESR, BBS and MOI of various baseball bats, and the results of the trampoline effect and COR. Using the information provided in the literature as well as the experiments that were conducted, the aluminum bats are much more effective in terms of hitting the ball with more force thus resulting in a longer distance traversed by the ball than that by a wooden bat.

To the best of our knowledge, this is the first study in the literature on the comparison of the performance of aluminum and wooden bats on hitting liquid nitrogen immersed balls. Conceptually, liquid nitrogen “freezes” the baseball with the result that, the baseball becomes comparatively compact. The expectation is that the bats should permit the compact ball to expand when hit.

7. Acknowledgements

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Science Center is acknowledged with thanks.

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