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Experimental study of the evolution of composite baseball bat performance

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Abstract

As composite bats are used in the field, microdamage can be developed in the form of microcracks in the matrix, fibre breakage and ply delamination, thereby reducing the barrel stiffness and increasing the resulting batted-ball speed. To replicate this microdamage with field-use phenomenon in the lab, an accelerated break in (ABI) process is employed by rolling the bats in a press. In this research, a representative set of composite bats was subjected to repeated rolling and performance testing to explore the evolution of bat performance with ABI. This paper will explain the ABI process and discuss changes in bat performance and barrel stiffness as a result of rolling for a representative set of composite baseball bats.

Keywords: Baseball; Bats; Composite; Hoop Frequency; Batted-Ball Speed; Performance; Rolling; Accelerated Break-In

1. Introduction

Baseball bats fall within three material classifications; solid wood, hollow metal or composite. While there are a few “solid” composite baseball bats, the majority of composite baseball bats are hollow. For wood baseball bats, northern white ash and hard maple comprise the majority, and damage during use presents itself in the form of a crack or split in the wood. When such a crack or split occurs, the wood bat is removed from service. Hollow metal baseball bats are made from aluminium-alloy tubes. The tubes span a range of aluminium alloys, and the bat failure mode will be deformation of the thin-walled barrel in the form of dents and/or cracks or possibly a crack in the handle. Composite baseball bats are typically made using filament-winding, braiding or layering of woven fabrics made with fibreglass and possibly carbon yarns reinforcing a thermoset or thermoplastic matrix. With repeated baseball impacts, microdamage will develop in composite bats in the form of microcracks, fibre breakage and delaminations. Eventually ultimate failure will occur in the form of gross cracking of the bat as a result of the coalescing and propagation of the microcracks to form macrocracks and the gross breaking of fibres and delaminations. As a result of these progressive microdamages, the barrel stiffness can progressively drop and correspondingly there will be a progressive drop in the first hoop frequency between the first hit on the bat, and through use, until the bat ultimately becomes unusable due to gross breaking.

It is now well-known in the baseball-science community that the efficiency of the bat-ball collision is a function of the hoop frequency of the bat barrel in a hollow (metal or composite) baseball bat. Based on a study by Sutton *et al* [1], it was found that the optimal hoop frequency occurs around 1250 Hz. This ~1250 Hz is as measured on a

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free-free bat. The hoop frequency that occurs on field while the baseball is in contact with the bat may be slightly lower due to the added mass of the baseball. For hollow bats tuned with such a hoop frequency, the batted-ball speed (BBS) is measurably greater than that off a wood bat. As this hoop frequency increases, the BBS of the hollow bat converges to that of a wood bat.

Because wood bats have been used in baseball for 100+ years, wood-bat performance is used as the reference level for BBS. Amateur baseball organizations, e.g. NCAA and NFHS (National Federation of High Schools), have used wood bats as the reference for acceptable batted-ball speeds. Thus, a baseball bat company will typically design bats to have a hoop frequency of ~2000 Hz or greater so the bat will perform under batted-ball performance limits set by the respective governing bodies of amateur baseball. However, due to the progressive failure of a composite baseball bat, the hoop frequency of a bat can slowly drop over its useful life as damage is incurred in the barrel. Because the performance increases as the hoop frequency decreases, the bat which was originally designed to perform at or just below a performance limit can then perform slightly or even well above the set limit. Thus, a credible methodology for completing accelerated break-in (ABI) in the lab is needed as a means to simulate this evolution in barrel stiffness and to track the bat performance through its useful life.

2. Accelerated Break-In Process

To determine the maximum performance of a composite baseball bat, the performance change over the useful life of the bat must be tracked. For in-lab investigation, it would be very time consuming to test a bat throughout its useful life using the high-speed air cannon that is used for performance testing. One alternative is to use a durability machine that can put many hits on the bat in a short time and between every n hits test the bat in the high-speed air cannon machine. This durability-machine method was explored by Drane and Sherwood [2] in 2008. For the few composite bats tested in that study, they saw little change in performance through use and that the composite bats were not durable. Both these conclusions may have been a consequence of the test employed and not necessarily representative of the maximum performances that could be achieved.

An alternative to a ball-impact break-in procedure (hitting balls until a performance increase occurs either on the field or in a durability machine) is an artificial or accelerated break-in. The ABI process has been researched for softball bats by Cruz [3] who examined a variety of ways that players altered composite softball bats. The methods included weighting, shaving, natural break-in and accelerated break-in methods. The accelerated break-in methods included hitting the bat with a hammer, compressing the barrel in a vice and bat rolling. The rolling machines all use a prescribed displacement on a pair of rollers to act like a vice on the bat barrel. Microdamage was induced in the barrel as the bat was pulled through the rollers. Today there are several companies that sell machines as well as rolling services.

The displacement controlled method of rolling is the method most commonly used and is accomplished by compressing the barrel of a bat between two rollers typically by screwing the top roller down a specified distance and then rolling the bat barrel through the two rollers. An example roller setup is shown in Fig 1. During the displacement control method the effective applied force will change due to the variations in the diameter of the bat as the bat moves axially through the rollers.

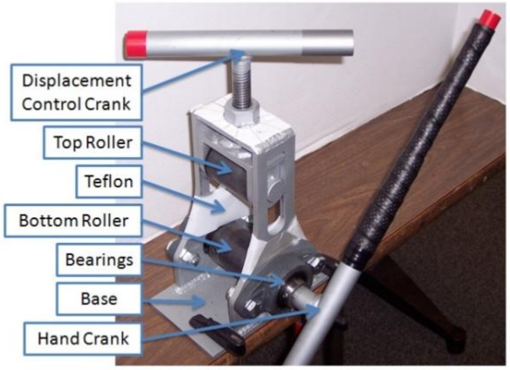

Fig 1. Typical displacement controlled bat roller.

It is important to closely monitor the amount of displacement experienced by the barrel so as to avoid overshooting the amount of damage induced in the bat. To ensure that the bat is not compressed too much during the initial rolling process, a lower displacement {~0.1-in. (0.25 cm) compression on the 6-in. (15.2-cm) location of the barrel (as measured from the tip of the barrel)} is used and then slowly increased in ~0.0125-in. (0.032-cm) increments. During the rolling process, the stiffness of the barrel is monitored carefully by compression testing the barrel after every set of rolling and performance testing. Compression testing is accomplished by putting the bat in a device with a digital displacement indicator and a load cell. A prescribed displacement is applied to the barrel, and the corresponding force is recorded. The bat is compressed at four positions around the circumference of the barrel. The compression force is concluded by averaging the four force values. The objective is to see a minimum decrease in the compression force of 5%. Once the target stiffness reduction (5% or more) is reached, the bat is ready for another performance test to be conducted.

3. Testing Program

All performance tests were completed using a high-speed air cannon test as described in the NCAA Baseball Bat Certification protocol [4]. Prior to each performance test, a modal test was completed to measure the first hoop frequency of the bat. This modal test was done using an impact hammer, two accelerometers attached with wax 90^{o} from each other on the barrel and a data acquisition system. After the first performance test was conducted, the compression and hoop-frequency values were again measured. The bat was then rolled using the displacement-control method to achieve the 5% or greater drop in compression. The compression and hoop frequencies were again checked before conducting another performance test. Then, the process of measure hoop and compression, roll to target drop in compression, performance test, and measure hoop and compression was completed. For this research each set of these steps is classified as a cycle. The test cycles are repeated until there is a significant drop in the maximum performance or the bat is so damaged that it has seen its useful life.

Currently the NCAA sets a performance limit using the ball exit speed ratio (BESR) metric as given in Eqn 1.

$$BESR = \frac{V_{rebound} - \delta V}{V_{inbound} - \delta V} + 0.5 \qquad (1)$$

where: $\delta v = 136mph - V_{contact}$ $(\delta v = 60.8\, m/s - V_{contact})$

and where $V_{rebound}$ is the velocity of the baseball coming off the bat in the BESR test, and $V_{inbound}$ is the inbound velocity of the baseball in the BESR test. The bat velocity at which the baseball makes contact with the barrel of the bat is $V_{contact}$. This velocity is based upon the impact location on the barrel of the bat.

The BESR is the metric that was used in this research to describe if there was a significant drop in performance. A drop in BESR of 0.014 or greater was concluded to be significant. This 0.014 value corresponds to a 2 mi/hr (3.2 km/hr) drop in batted-ball speed.

The NCAA BESR certification protocol closely follows the ASTM standards for determining high-speed bat performance and the moment of inertia of a bat [4, 5]. This process tests a bat by using a high-speed air cannon to "pitch" baseballs at a speed of ~136 mi/hr (218.9 km/hr) at a stationary bat. The bat handle is clamped in a fixture and allowed to rotate freely about a pivot point which is 6 in. (15.24 cm) from the base of the knob. The inbound and rebound velocities are measured using a series of light gates. The BESR is calculated using these velocity data. Performance testing involves impacting multiple locations along the barrel to scan for and to isolate the 'sweet spot' (most efficient or highest performing location on the barrel).

The projected field performance of the bat was calculated in BBS because it puts performance into a dimensional quantity (mi/hr or km/hr) that has physical meaning, i.e. speed of the ball coming off the bat. This BBS calculation is accomplished with Equation 2 which is the relationship between BESR (previously calculated by Equation 1) and BBS which was shown by Drane [6].

$$BBS = V_{pitch}\left(\frac{V_{rebound}}{V_{inbound}}\right) + V_{bat}\left(\frac{V_{rebound}}{V_{inbound}} + 1\right) \tag{2}$$

where V_{pitch} is the velocity of the pitch of the baseball and V_{bat} is the velocity of the bat at the impact location based upon a swing speed model [7].

4. Results

For this research, the evolution of the performance of a bat was tracked from the first hit on the bat to the last hit. Rather than report the data results for all hits on the bat, the data are reported as the maximum performance observed for a test "cycle" as previously described.

Fig 2a shows eight different bats of various lengths and manufacturers used in this study and their BBS evolution over the number of cycles that each bat was tested. Each of the eight bats was tested until the performance peaked then dropped significantly or the bat became unable to be targeted for valid hits due to extensive cracking or barrel separation. Each of the bats has a distinctive line on the graph so the trend can be followed for each individual bat. As depicted in Fig 2a, most of the bats showed an increase in BBS from their initial performance cycle and peaked typically at the third cycle before showing a significant performance decline. There was one bat (Bat ID ABI8) that showed a maximum performance at Cycle 2 and then a decrease in performance. This bat likely had lower durability, i.e. more susceptible to damage, than the other bats used in the study, and thus, the bat required less breaking in to reach its peak performance. There was only one bat (Bat ID ABI5) tested in this study that did not show any increase in performance before the performance decreased and the bat eventually became unable to be tested due to the barrel separating from the handle. The reason that this particular bat had a slight decrease in performance and then failure without seeing an increase in performance can be attributed to the relatively high stiffness of the barrel as reflected in the relatively high hoop frequency.

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Fig 2b shows the 1st hoop frequency of the barrel of the bat versus the batted-ball speed performance of the bat. In general, the hoop frequency dropped for each subsequent cycle (Table 1). The barrel of the bat that did not show a performance increase before failure (ID ABI5) had the highest 1st hoop frequency than any other bat that was tested, and this would be a result of the barrel being stiffest due to a relatively thick wall. The data in Fig 2b show that there is a distinctive increase in performance as the 1st hoop frequency of the barrel decreases.

In Fig 2b, there are three outliers to the trend of increased performance with decreasing 1st hoop frequency. These three data points were taken from bats that were at (or close to) the very end of their useful life and experienced extensive barrel degradation or even separation during the performance test. This extensive degradation can explain the irregular results. Due to gross cracking in some areas of the bat, modal testing is not likely to capture the frequency characteristics of the whole bat but a bat that is being fragmented into two or more pieces. This interpretation is also apparent when looking at the frequency response function (FRF) of a bat that had incurred significant damage. The peaks of the hoop modes were no longer nice crisp peaks, and the two FRFs that should overlay for hoop frequencies when two accelerometers are placed 90° out of phase no longer overlaid nicely as they do on a new bat out of the wrapper.

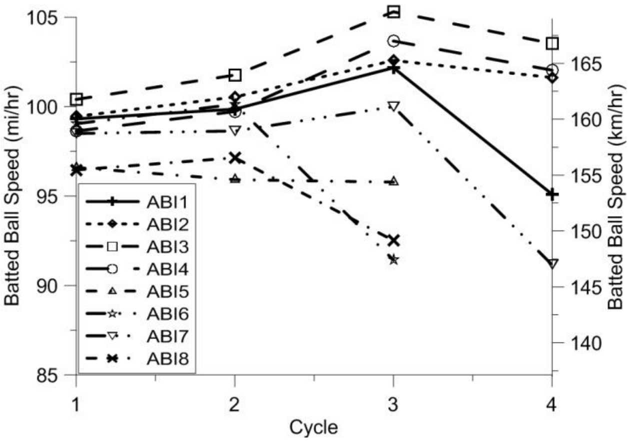

Fig 2a. Evolution of batted ball speeds during an ABI test.

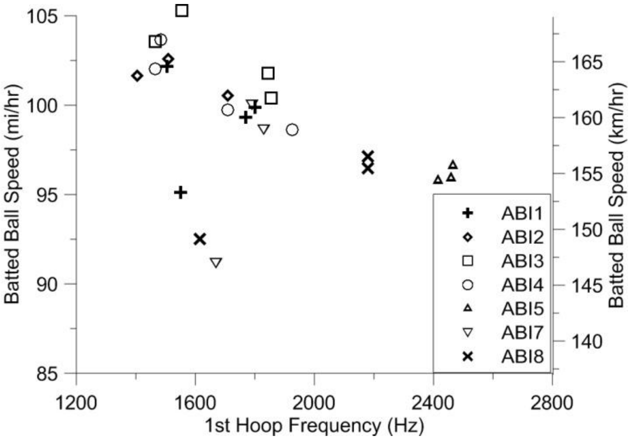

Fig 2b. Batted ball speeds vs. 1st hoop frequency.

Table 1. Hoop frequency as a function of cycles

Bat ID	Hoop Frequency (Hz)			
	Cycle 1	Cycle 2	Cycle 3	Cycle 4
ABI1	1770	1800	1505	1550
ABI2	-	1710	1510	1405
ABI3	1855	1845	1555	1465
ABI4	1925	1710	1485	1465
ABI5	2465	2460	2415	-
ABI6	-	-	-	-
ABI7	-	1830	1790	1670
ABI8	2180	2180	1615	-

To further show that the decrease in the 1st hoop frequency correlates with the increase in performance, the percent change in BBS and the percent change in 1st hoop frequency from new to max performance were calculated. The percent changes in BBS and hoop frequency were then plotted in Figs 3a and 3b, respectively, for side-by-side comparison. As can be seen in Fig 3a, the only bat that had a negative change was Bat ID ABI5. Bat IDs ABI1-ABI4 had the highest percent increase in performance from their original performance with the highest being just over 5%. Bat IDs ABI6-ABI8 had relatively lower percent increases being around 1%. Fig 3b shows the bats in the same order for ease of comparison. These values are all negative because they are a decrease in the 1st hoop frequency and thus a negative percent change. The first four bats (Bat IDs ABI1-ABI4) had the greatest percent drop in 1st hoop frequency in good correlation to the increase in performance shown in Fig 3a. Note that the bat that had a drop in performance (Bat ID ABI5) had a very small drop in hoop frequency before failure occurred. Also note that there was no initial 1st hoop frequency data recorded for Bat ID ABI6 due to an error in procedure, and thus the bat was omitted from the percent change in hoop frequency. The remaining two bats (Bat IDs ABI7 and ABI8) had a relatively smaller percent decrease in 1st hoop frequency which correlates to the smaller percent increase in BBS shown in Fig 3a. These data show that there is a direct correlation between a decrease in the 1st hoop frequency to an increase in performance (BBS).

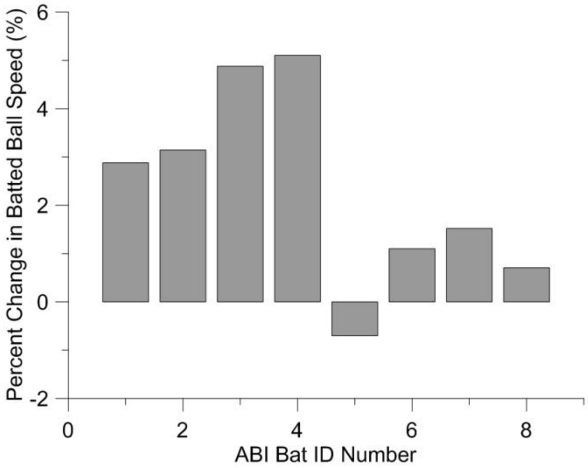

Fig 3a. Percent change in batted ball speed.

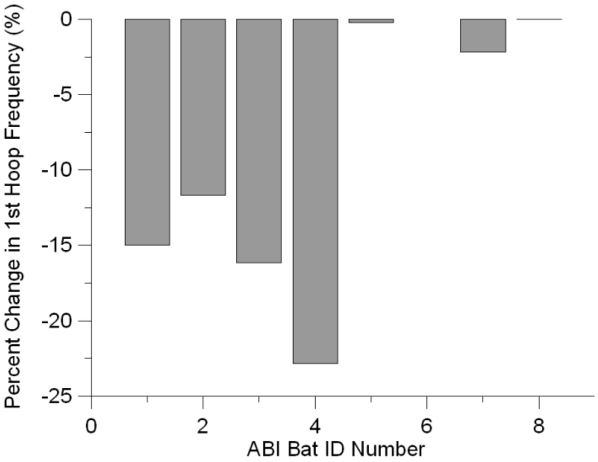

Fig 3b. Percent change in 1st hoop frequency.

5. Conclusion

A set of baseball bats was selected to be subjected to an artificial and accelerated break-in procedure to simulate the effects of game use on commercially available composite baseball bats using a constant displacement rolling method. The data show that many of the composite baseball bats did exhibit an increase in performance as the barrel is broken in using the ABI procedure before the baseball bats become unusable. It was also observed that a 1st hoop frequency of a bat barrel close to ~1500 Hz correlated to a relatively high BBS performance. In addition to the correlation between the hoop frequency of a bat barrel to performance, the data showed a strong correlation of 1st hoop frequency percent decrease to a BBS performance percent increase.

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