Designing for BALL IMPACTS

Better golf clubs and baseball bats require materials that combine very high flow stresses with low elastic moduli, so that surfaces that impact the ball can be made highly compliant (high deflection/load).

Gary M. Michal* and Mark D. Novak
Dept. of Materials Science & Engineering
Case Western Reserve University
Cleveland, Ohio

A common denominator of the most popular sports is a ball. The ability to make the ball move with a high velocity is almost universally a key element for the players. Imparting a high ball velocity is advantageous for two major reasons: higher ball velocity translates into reduced reaction time for an opponent, and the distance a ball can travel also is directly linked to its launch velocity.

Having a ball carry a great distance is the central feature of arguably the most spectacular events in both the sports of baseball and golf. The home run in baseball and the long drive in golf have in common the soaring flight of the ball. For a ball to travel a long distance it must attain a high velocity. A secondary consideration is the spin of the ball. Ball launch velocity is the primary concern of this article.

How to boost a ball’s launch velocity

Although many a frustrated player has stated emphatically that they could throw the ball farther than they could hit it, the truth is that baseball bats and golf clubs allow a player to achieve much higher ball velocities. Two factors are the basis for the greater ball speed resulting from the use of a bat or club: increasing the radius of rotation and creating a collision.

Rotation radius: Compared with throwing a ball, use of a bat or club increases the length of the radius of rotation between the torso of the player and the point of contact with the ball. For a constant angular velocity, tangential velocity increases linearly with the radius of rotation. A golf driver effectively increases the reach of a player by about 3 ft (1 m). The added length to the radius of rotation allows even a modest golfer to achieve a club head velocity of 80 mph (130 km/h). On average, individuals with equivalent athletic prowess could throw a ball at a speed not much faster than 50 mph (80 km/h).

Collision creation: Games such as jai alai and lacrosse use items of equipment to extend the reach of the players, allowing them to catch the ball and then throw it with a high velocity. However, bats and clubs do not catch or throw the ball. These items of equipment undergo collisions with the ball. Creating a collision is the second way in which bats...
Various alloys and a metallic glass are considered for use in a driver club head.

The remainder of this article will examine how the collisions between sports equipment and balls can be designed to achieve greater ball velocities. First, the basic physics associated with collisions based upon velocities, masses, and a parameter called the coefficient of restitution will be briefly reviewed. This will be followed by a discussion of how the mechanical properties of materials control the efficiency of collisions. Focus will be on the driver club head/golf ball impact, with the bat/baseball collision used for contrast. Finally, a materials selection exercise is outlined for the design of a driver head where the collision performance potentials of selected aluminum, beryllium-copper, and titanium alloys, a precipitation hardening stainless steel, and a metallic glass are evaluated. A metallic glass golf club head is shown in Fig. 1.

**Basic physics of collisions reviewed**

Using conservation of momentum and the coefficient of restitution (CR) parameter, \( e \), the following equation is obtained for the velocity, \( u \), of a ball that has undergone a collision with an object of mass \( M \):

\[
u = \frac{MV(1 + e) + v(M - m)}{M + m}
\]

(Eq. 1)

The ball has a mass represented by \( m \) and initially was traveling toward the striking object at a speed \( v \). The speed of the striking object moving toward the ball before the collision is \( V \).

The coefficient of restitution, \( e \), is defined as the ratio of the relative velocities of two colliding objects after and before their impact (Eq. 2). In this equation, \( U \) is the speed of the striking object after impact with a ball.

\[
e = \frac{u - U}{v + V}
\]

(Eq. 2)

Figure 2 provides graphical illustrations of the relationships among the variables involved with a collision as dictated by Eq. 1. Figure 2(a) applies to the case of a club head of a golf driver striking a golf ball at rest; that is, \( v = 0 \). If the mass of the club head were 10 times that of the golf ball and the collision occurred without any loss of kinetic energy; that is, \( CR = e = unity \), then the launch speed of the golf ball would be 1.82 times the club head speed. In practice, the club head to golf ball mass ratio is commonly 4.3, based on an average driver club head weight of about 7 oz. (200 g), and the CR is 0.69.\(^2\) The result is a launch speed multiplication factor of 1.37.

Figure 2(b) represents the contrasting situation of a pitched baseball traveling at \( v = V \) toward a bat whose impact point is moving at velocity \( V \) toward the ball. In this case, if the bat/ball mass ratio was 10 and the CR was unity, the launch speed of the baseball would be 2.64 times the speed of the impact point on the bat! In practice, the bat/ball mass ratio is about 6 and the CR is about 0.5. The result is a much lower launch speed multiplication factor of approximately 1.57.

![Fig. 2 - Ratio of post-collision ball velocity, \( u \), to pre-collision velocity of striking object, \( V \), for golf club (a) and baseball bat (b). Pre-collision ball velocities, \( v \), are 0 for the golf ball (a) and \( V \) for the baseball (b). Key: \( M \) = mass of striking object; \( m \) = mass of ball; \( CR \) = coefficient of restitution, or \( e \).](image-url)
A perfect elastic sphere would show load being proportional to displacement raised to the $3/2$ power identically upon loading and unloading. The observed loading/unloading hysteresis of the golf ball, Fig. 3(a), represents its anelastic behavior. When a golf ball undergoes compression during impact with a club head, only a fraction of the stored strain energy is recovered as the golf ball regains its shape.

Comparing the golf ball's load/displacement characteristics, Fig. 3(a), with those of a baseball, Fig. 3(b), clearly shows that a baseball is more compliant than a golf ball and also exhibits more pronounced anelastic behavior. (Compliance is defined as $8/P$, or deflection/load.)

A key feature that is more subtle in Fig. 3 is that the fraction of the strain energy that is lost during compression and recovery of shape for both a golf ball and a baseball is a function of the maximum load. As the maximum load increases the fraction of strain energy that can be recovered decreases. Numerical integration of the loading and unloading curves in Fig. 3 allowed the recoverable strain energy fraction to be determined as a function of maximum load for both a golf ball and a baseball. The results are shown in Fig. 4. Lower fractions of recoverable strain energy translate into lower values for the CR for a collision. Figure 4 reveals that to maximize the CR, the maximum load experienced by the ball during the impact must be minimized.

**How material properties affect impacts**

The factors that control the maximum force between colliding objects can be examined using a very simple model of impacting solid cubes. The two cubes have different masses ($m_1$ and $m_2$) and elastic moduli ($E_1$ and $E_2$). Their positions, shapes, and the force between them can be readily calculated as a function of time. The maximum forces generated between two cubes 1 in. (25 mm) on edge impacting flush at 100 mph (160 km/h) as a function of their mass and elastic modulus ratios are displayed in Fig. 5. The mass and elastic modulus of Solid Cube 1 were taken to be those of a golf ball: 1.62 oz (46 g) and 20 ksi (140 MPa), respectively. Figure 5 shows that the maximum force during...
To increase compliance of strong materials use them in the form of thin hollow shells.

Impact increases mildly as the ratio of \( m_2 \) (representing the club head) to \( m_1 \) (representing the ball) increases. The maximum impact force increases more rapidly as the ratio of \( E_2 \) to \( E_1 \) increases. Figure 5 indicates that the key to decreasing the maximum impact force between a ball and a striking object is to reduce the elastic modulus of the striking object! Thus, the striking object needs to be more compliant to lower the maximum impact force and reduce the amount of strain energy lost during the compression and recovery of shape of the ball.

The effective elastic modulus of a golf ball is about three orders of magnitude lower than that of any of the metals that are used to construct club heads for drivers. The effective elastic modulus of a baseball is much lower than even that of a golf ball. An effective value of \( E \) for a baseball is 7 ksi (50 MPa).

The way to drastically increase the compliance of strong materials is to use them in the form of thin hollow shells. Hollow shells are the basis for the design strategies used to improve the ball launch performance characteristics of modern high-tech club heads and bats.

Modeling hollow driver club heads

The last part of this article examines the predictions of a simple design model for the front face of a driver club head. The model treats the face of the driver as a rectangular plate with fixed edges subjected to a load over a small concentric circle of radius \( r_0 \) (in other words, as a membrane constrained at its perimeter, but free to deflect in the direction normal to the club face). The height of the driver face, \( b \), is taken as 1.5 in. (40 mm) and its width is 3 in. (75 mm), or greater. Under such conditions the deflection, \( \delta \), in the center of the club face as a function of the load, \( P \), generated during impact is given by Eq. 3:

\[
\delta = \frac{0.079b^2P}{E \cdot t^3} \quad \text{(Eq. 3)}
\]

The compliance of the driver face (\( \delta /P \)) varies linearly with the reciprocal of the elastic modulus of the material used in its construction, and to the third power of its reciprocal thickness, \( 1/t \). Equation 3 clearly indicates that the face of a driver can be made very compliant if its thickness is reduced to a very low value. However, as the thickness of the face decreases, the maximum stress, \( \sigma \), on its surface increases, as indicated by Eq. 4:

\[
\sigma = \frac{3P}{2\pi \cdot t^2} \left[ (1 + v) \ln \frac{2b}{\pi \cdot r_0} + 0.067 \right] \quad \text{(Eq. 4)}
\]

In this equation, \( v \) is Poisson's ratio for the material used for the club face. Clearly, the club face is not functional if \( \sigma \) exceeds a value near the flow stress, \( \sigma_f \) of the material used in its construction.

With the stress limited by the yield strength of the material, Eq. 4 establishes the minimum thickness of the club face as a function of applied load. The minimum club face thickness defines the maximum compliance for a given material through Eq. 3. The maximum compliance is obtained by a material that maximizes the \( \sigma_f^{1.5}/E \) mechanical property index. Using Eq. 3 and the load/displacement relationship for compression of a golf ball, the lowest value for the maximum force that could be generated when a driver club face traveling at 100 mph (160 km/h) impacts a golf ball was determined for the materials listed in the table.

Comparing candidate club face materials

The maximum impact force values are listed in the table. A club face made of Vitreloy metallic glass produces the lowest maximum impact force, while the aluminum alloy produces the highest maximum impact force. That order of result would be expected based upon the \( \sigma_f^{1.5}/E \) property index values. However, the magnitude of the variations between the property index values and the maximum impact force values among the materials is very different. The property index value for Vitreloy is 6.7 times that of the aluminum alloy, but its maximum impact force is only 17% lower than that of the aluminum alloy. The relative insensitivity of the maximum impact force to the compliance of the club face is due to the compliances of all of the club face materials being much lower than that of the golf ball. For all of the materials tested, the majority of the deformation and buildup of force during impact is dependent upon the properties of the golf ball.

As a point of contrast, the impact force generated for the 100 mph (160 km/h) impact of a 7 oz (200 g) solid block of persimmon hardwood with a golf ball was determined. The impact force is quite similar to those of the hollow metal (membrane design)
Candidate materials for a golf driver club head

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus, E, GPa (10^9 psi)</th>
<th>Poisson’s ratio, ν</th>
<th>Flow stress, σf, MPa (ksi)</th>
<th>Density, g/cm^3 (lb/in.3)</th>
<th>σf/σy, E/σy (psi)</th>
<th>Maximum impact force, lbf (N)</th>
<th>Optimum club face thickness, in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast aluminum alloy 201.0-T6</td>
<td>71 (10)</td>
<td>0.33</td>
<td>435 (63)</td>
<td>2.88 (0.10)</td>
<td>128 (0.02)</td>
<td>3610 (16.1)</td>
<td>0.173 (4.4)</td>
</tr>
<tr>
<td>Cast beryllium-copper</td>
<td>128 (19)</td>
<td>0.30</td>
<td>1035 (150)</td>
<td>8.26 (0.30)</td>
<td>260 (0.04)</td>
<td>3470 (15.4)</td>
<td>0.110 (2.8)</td>
</tr>
<tr>
<td>Cast Ti-6Al-4V</td>
<td>114 (17)</td>
<td>0.34</td>
<td>938 (136)</td>
<td>4.43 (0.16)</td>
<td>252 (0.04)</td>
<td>3480 (15.5)</td>
<td>0.117 (3.0)</td>
</tr>
<tr>
<td>Cast 17-4 PH stainless steel</td>
<td>215 (31)</td>
<td>0.28</td>
<td>1170 (170)</td>
<td>7.70 (0.28)</td>
<td>186 (0.03)</td>
<td>3540 (15.7)</td>
<td>0.103 (2.6)</td>
</tr>
<tr>
<td>Vacuum die cast Vitreloy metallic glass</td>
<td>97 (14)</td>
<td>0.36</td>
<td>1900 (276)</td>
<td>6.10 (0.22)</td>
<td>854 (0.12)</td>
<td>2980 (13.3)</td>
<td>0.079 (2.0)</td>
</tr>
<tr>
<td>Persimmon hardwood</td>
<td>0.9 (0.13)^c 0.19^d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. An amorphous alloy of nominal composition 63Zr-17Ti-12.5C-10Ni-3.5Be, and covered by U.S. Patent No. 5,288,344 (assigned to California Institute of Technology, Pasadena). Vitreloy is known as Liquidmetal when used in heads for golf clubs sold by Liquidmetal Golf, Simi Amorphous Technologies Inc. (ATI), Los Angeles, Calif. ATI has an exclusive worldwide license for the alloy. 2. Tangential direction. 3. Simple average of νT = 0.35 and νL = 0.06, where TR = tangential-radial directions and TL = tangential-longitudinal directions.

Wanted: compliant impact surfaces

In conclusion, collisions between a more massive object and a ball can generate a ball launch velocity that is a multiple of the velocity of the striking object. The size of the multiplying factor is a sensitive function of the amount of energy that is lost during the collision event.

Both golf balls and baseballs are very anelastic bodies. The most significant loss of energy during a collision occurs due to the compression and recovery of shape of the ball. The fraction of the strain energy in the ball that is lost is minimized by reducing the maximum force experienced by the ball during impact. The impact force is lower if the compliance of the striking object is increased.

Improved design of golf clubs, baseball bats, and other ball-impact-based sports equipment requires materials that combine very high flow stresses with low elastic moduli so that their impact surfaces can be made highly compliant. Lower material density has the added advantage of allowing more flexibility in the distribution of weight.

References

For more information: Dr. Michal is chair and LTV Steel Professor of Metallurgy, Dept. of Materials Science & Engineering, Case Western Reserve University, Cleveland, OH 44106 (tel: 216/368-5070, fax: 216/368-4224; e-mail: gmm3@po.cwru.edu). Mr. Novak is a graduate student, Dept. of Materials Science & Engineering, Case Western Reserve University, Cleveland, OH 44106 (tel: 216/368-4819, fax: 216/368-3209; e-mail: mdn@po.cwru.edu).

The authors greatly appreciate discussions regarding the mechanical properties of Vitreloy metallic glass with Thomas Tom, director of advanced technologies, Howmet Research Corp., Whitehall, Mich., and John J. Lewandowski, professor, Dept. of Materials Science & Engineering, Case Western Reserve University, Cleveland, Ohio.