Materials and Tennis: Rackets

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29 June 2004

1. Introduction

One does not have to go too far back in tennis history to notice the radical differences in racket designs and the impact it made on the way the game is being played. Most of us probably still have memories of relentless duels fought between the likes of McEnroe and Borg, with wooden rackets that look more representative of current squash rackets. Deeper investigation into the archives reveals even more radical design changes, including anything ranging from the more pragmatic to the absolute bizarre. It is interesting however that most of the lasting technologies were either directly related to changes in the materials, or to design and manufacturing changes made possible by new materials. Changes in materials effects racket sizes, shapes and weight, which in turn improves stability, comfort and power.

This chapter attempts to show how different materials assisted in changing the way we perceive the game of tennis at present. A brief time line, focussing on remarkable models with a lasting impact on designs is presented, followed by a detailed section on different material properties and the application thereof to benefit designs. The last section describes the current racket manufacturing process as used by most modern tennis factories, highlighting the influences of different materials on manufacturing processes.

2. Influence of materials on racket technology

2.1 Basic material history

A few people might be surprised to know that the first rackets were made of human body parts. According to the first records, dating back as far as the12th century, tennis was first played with the palm of the bare hand, hence the early name "le jue de paume". Subsequently various gloves, bats and paddles were used before the first wooden construction, with strings, was introduced in the 16^{th} century.

In the years following, different types and combinations of wood dominated, until as long as the mid 1900's. Initially, frames were made of a single solid piece of ash wood, soaked in cold water, boiled to make it pliable and bent into the desired shape while still hot. The wood was not cut, but split and shaved along the grain, producing continuous fibre propagation along most of the racket frame, requiring careful selection of suitable wood specimens (Clerici 1976, Robertson 1974, Kuebler 1995).

At first these rackets were very weak in the throat area but failures were reduced by wrapping combinations of canvas, vellum and bindings around the critical areas. Another problem was warping of the frame when exposed to wet conditions, which was improved with hickory and strips of metal reinforcement in the throat. The next advance was in the 1930's, with the development of laminated frames consisting of an arrangement of the layers at different angles, hence achieving directional stiffness. Synthetic cements and formaldehyde were used to bond the odd layered frames, which consisted of up to eleven layers. Additionally more types of wood, like beech, were introduced as alternate layers with ash wood, resulting in a combination of the strengths of both materials.

The introduction of a single leather laminate allowed more geometric freedom and increased strength but was soon replaced in the 1960's with Black Walnut, Vulcan fibre (a resin impregnated in paper) or plastics, like Bakelite. Later glass and graphite fibre laminations were also introduced, increasing frame strength even more (Bodig and Jayne 1982, Kuebler 1995).

In the meanwhile metals have also been making headway in different variations. In early 1920 solid extruded aluminium frames started making their appearance but were substituted with cast magnesium alloys about five years later. It was only in the mid 1960's, when hollow extruded profiles made it the market for both Aluminium and Magnesium alloys and lasted until the late 1980's. The high strength-to-weight ratios of these profiles opened up new opportunities for designers i.e. increased head sizes, which lead to the revolutionary oversized rackets in the early 1970's. Subsequently, aluminium was also used as a cold drawn tube up to the late 1980's and is currently used for low price and some junior racket (Kuebler 1995, Polich 1995).

During the 1970's composites of glassfibre in epoxy were entering the market, which paved the way for what was probably the greatest revolution in tennis rackets to date. Initially glass fibres were mixed with carbon fibres but later evolved in rackets with carbon fibres as the main component. Rackets were hollow, or filled with foam, and the carbon fibres made it possible to obtain stiffer, lighter and longer lasting rackets. From 1980 till the mid 1990's polyamide was also used in frames, either as a thermoplastic injection with carbon fibre reinforcements, or as braided filaments combined with graphite fibres (Haines 1983).

Currently composite rackets consist predominantly of carbon fibres as the main component, complimented with anything from glass, boron, ceramics and Kevlar to titanium and copper fibres, applied in strategic areas to provide the optimal combination of properties. The stiffness-to-weight ratio of these modern materials, as well as the versatile manufacturing process, enables designers to incorporate more effective racket designs with better control, power and vibration characteristics (Easterling 1993, Brody 1995a, Polich 1995).

2.2 Classic and trend setting racket models

During the history of tennis rackets there has been a number of rackets of significant importance, which could be attributed to material developments. In the following section we are attempting to provide a selection of these rackets, while highlighting their significance.

Figure 1

2.2.1 'Scaino' racket

The first racket reported to have a frame and strings, similar to how we know it today was in the mid 1500's. It is often referred to as the 'Scaino' racket since it was described in detail by Scaino, an Italian priest and doctor. Prior to this people were mainly playing with gloves and bats, making it a radical breakthrough for its time. The racket consisted of an almost tear shaped wooden frame, with a diagonal stringing pattern. The racket's head were relatively large and with no throat it was remarkably similar to rackets being used in racquetball today (Kuebler, 1995).

2.2.2 Dunlop Maxply

This wooden racket is often referred to as the most famous racket ever. The Maxply was the first multiply wooden racket to be made, which provided superior strength properties to its predecessors, which consisted only of single bent strips. The racket was constructed from Vermont ash, cherry and hickory layers glued together with water-repellent glue. The handle plates were made of bass-wood and the entire racket was finished off by experienced craftsmen to produce a very elegant product. It was introduced in 1931 and used for almost 50 years, before being beaten off the shelf by more modern constructions made from lighter materials (Kuebler, 1995).

2.2.3 Prince Oversize

In 1974, the development of extruded aluminium profiles allowed Howard Head, former owner of Head Ski Company, to change the design of rackets forever. He invented and patented the first oversize racket, which had a 50 percent larger string area and was claimed to have a four times larger sweet spot. Another advantage, and probably more important, was the 50 percent increase in resistance to twisting in the hand when hitting off-centre shots, resulting in a more stable and less strenuous racket to play with. The racket also had a typical polyamide throat piece, which was much stronger than the construction for wooden rackets. It instantly became a world bestseller and was used until 1988, with its design remaining almost unchanged throughout the entire period (Fisher, 1977, Arthur, 1992, Brody, 1995b).

2.2.4 Wilson T2000

The Wilson T2000, introduced in about 1979, was by far the most popular steel racket ever on the market. The racket had tubular frame with a cross section shape like the number 8. It was plated with chromium and a unique patented steel wire system for threading and attaching the strings. The latter consisted of a bent steel wire creating hoops all along the inner circumference of the head, through which strings are strung. It is turn is attached to the frame by spiral wrapping a thinner wire around it and the frame (Kuebler 1995).

2.2.5 Head Arthur Ashe Competition

This racket is a classic example of a pressed racket, utilising the same technique used for making skis. It was developed in 1979 and consisted of a plastic core, made with a BMC process bonded on both sides by aluminium sheets (Kuebler 1995).

2.2.6 Dunlop Max 200G

In 1980 Dunlop developed a unique injection moulding process, used for their popular Max 200G. The hollow racket frame consisted of Polyamide 66, with carbon fibre reinforcements. To manufacture the hollow frame, a bismuth-tin alloy was used as the core of the frame. The metal has a melting point lower than the polyamide and is melted and removed after moulding. The process was less labour intensive than contemporary processes and produced a racket with very good dampening qualities, which was very popular right through the 1980’s. (Haines et al 1983, Haines 1985, Kuebler 1995)

2.2.7 PDP Staff

The world’s first complete fibreglass racket was introduced by the PDP Sports Company around 1975. Apart from the grommets and foam covered handle, the racket frame was made as a single piece, without any parts and entirely of glass fibre (Kuebler 1995).

2.2.8 Wilson Pro Staff

Towards the 1990’s most manufacturers standardised to carbon fibre composite rackets, manufactured with a bladder-mould process. A lay-up, consisting predominantly of carbon layers oriented in optimal fibre directions, are rolled round and long foil tube, which is pressurised inside the mould to produce a thin-walled racket with optimised strength properties. A more detailed description of the process is provided later in this chapter. One of the first classic rackets to be manufactured in the way is the Wilson Pro Staff, which was introduced in the late 1980’s and is still being used today (Kuebler 1995).

2.2.9 Prince Vortex

Another significant racket based on thermoplastic materials was the Prince Vortex, introduced in 1991. Its hollow frame consisted of Polyamide 6 braided with graphite fibres and the manufacturing process utilised a tubular mould with a pressurised silicone bladder. Besides the higher temperatures, the process was similar to a thermoset matrix racquet (Beercheck 1991, Prince brochure 1993, Kuebler 1995).

2.2.10 Wilson Profile Hammer

Wilson’s next series, the Profile Hammer system, introduced in 1989, took specialised composite designs to the next level. The racket, weighing about 280 g, was based on two major patents; the Profile and Hammer systems, both made possible by a combination of specialised fibres like Kevlar and Boron fibres. The Profile system specified the racket to have a maximum width in the middle of frame, tapering down to the handle and tip of the racket, resulting in the highest stiffness at the point of maximum bending. The idea of the Hammer system is to move the mass to the head of the racket by reducing the weight in the handle, while maintaining overall strength and stiffness. This racket propelled Wilson Company to top of the world market, by being a best seller for three years (Beercheck 1991, Wilson brochure 1992, Wilson 2002, Kuebler 1995).

Figure 2

2.2.11 Head Twin Tube.

In 1996 Head a developed a revolutionary twin tube system, which consists of a polyamide sleeve wrapped around the frame of the racket's head just before moulding, producing a head with a polyamide outer layer. The tube reduces vibrations in the head and can be laser printed with complicated graphics before moulding to apply the graphics. Traditionally detailed graphics comprise a very high percentage of racket costs, since it very labour intensive and time consuming but with this system virtually any graphics can be applied to the racket head at no extra expense. Since the graphics is printed underneath the polyamide it is protected by the layer against abrasion and therefore longer lasting than traditional cosmetics (Head brochure 1996, Head 2002).

2.2.12 Head Titanium

Probably Head's biggest success story up to date was the introduction of Titanium technology in 1998. The racket's throat included an outer weave of carbon fibre and titanium wire, which stiffens the throat and allowed for a large reduction in weight. The Ti.S6 racket, weighing 225 g unstrung, was a world best seller for three consecutive years (Head brochure 2001, Head 2002).

2.2.13 Head Intelligence

A couple of years later, in 2000, Head was the first company to use piezo ceramic fibres in their Intelligence series. The piezo ceramic fibres are moulded into the outer layer of the throat area, on both sides of racket. The polarised ceramic fibres, sandwiched between printed electrodes, convert and dissipate the impact energy capture as electrical energy. Each of the fibre unit is connected to a self-powered circuit board located in the handle, which stores the impact energy and returns the inverted signal back to the throat, fast enough to stiffen the racket frame and dampen up to 50% of the vibrations after impact and increase the power (Head brochure 2001, Head 2002, Crawford 2000b).

2.2.14 Wilson Triad

The Wilson Triad series, introduced in 2001, dampens vibrations by dividing the racket into three parts, hence isolating the handle from the head. The components include; the hoop, comprising of the head with a thin triangular throat piece, the handle terminating in a V-shaped throat piece and a V-shaped elastomer separating the two pieces. The hoop and handle is manufactured separately and bonded to either side of the elastomer with a very strong adhesive. The throat pieces for the hoop and the handles have two common grommet wholes on either side through which four main strings improving the locking between the three components. The system isolates the impact shock and dampens up to 60% of the vibrations (Crawford 2001a, Wilson Brochure 2002, Wilson 2002).

3. Frame materials

During the history of the game various materials have been experimented with, in combination with countless innovations. Notwithstanding, through a natural selection process, which tends to maintain the unique balance between simplicity and functionality, only a few material concepts has had a lasting influence on designs.

As with most other products, the cycle began with wood making the most lasting impact so far on designs. It was only a few hundred years later when manufacturers started experimenting with metals, which itself could never manage to dominate the market before being replaced by composite materials. Today most rackets consist of a carbon fibre based composite frame, combined with various other materials to enhance specific design intend.

3.1 Wood

Today wooden rackets are virtually obsolete, with only a few still available on the market. However, since the beginning of the game, wood has been a dominant material in racket frames for almost 400 years. Wood is a natural composite material, consisting of elongated cells distributed in its own natural resin. It is therefore anisotropic (i.e. much stiffer along the grain) and the composition of the structure is dependent on the type of tree and its growing conditions. These diverse properties are utilised in the development of laminated frames, which could combine the strengths of the different grain directions and wood types. The harder woods, like birch, maple, mahogany, hickory and beech were used to stiffen rackets wile ash or maroti, a softer and more resilient woods, produced more flexible rackets and walnut, sycamore, maple, birch, cedar, mahogany and holly were used as the outer layer for their cosmetic appearance.

Table 1

Wood was gradually phased out by other materials due to a number of disadvantages:

- Instability and warping when moist limited the racket's outdoor life

- Natural defects weaken the material or require expensive quality control
- Low ultimate and fatigue strength cause collapsing under high impact and string tension
- Difficulty to manufacture light-weight and hollow thin-walled frames
- Relatively weak mechanical bonding limited design variations

To improve on the mechanical properties wooden laminates were combined with leather, metals, polyamides and finally composites like glassfibre and graphite until is was eventually replaced completely by composite frames, thus ending the legendary wooden era (Kuebler 1995, Brody 1995a, Polich 1995, Green et al. 1991).

3.2 Metals

During the early nineteenth century metal frames start appearing on the scene but it was not until the end of the 1960’s before it really made a noticeable impression. The major advantage of metals to wood was the higher shear and fatigues strength and the ability to produce complex profiled frames. Initially frames consisted of solid and later hollow extruded profiles, which resulted in even stronger and lighter frame. For the first time an oversized frame could be constructed, which would withstand the high impact forces and string tension. Another major benefit with metals was fixing the throat piece. This was always a weak area in the wooden rackets but could now be made of virtually any suitable material and riveted to the frame, at a very low cost, without considerable weakening (Brody 1995b, Kuebler 1995, Polich 1995).

The only frequent metal alloy used in racket frames is Aluminium 6061, which is subjected to specific heat treatments to produce desired characteristics (Table 2). Aluminium is still used today in low cost racket filling and important position in the market.

Table 2

3.3 Composites

There are numerous types of composite rackets available today, and most of them employ the latest space-age composite materials. Composites either consist of fibres or filaments from very strong materials (graphite, glass, boron, ceramic) or a lamination of various materials with unique properties such as wood, glass, aluminium. The current processes allow improving the properties of the material in flexibility, structural strength, weight and other properties. Moreover, because of the fibrous nature of the material, the direction of the fibres can be oriented to give strength and stiffness in one direction and allow some flexibility in another.

The so-called graphite or carbon racquets consist mainly out of carbon fibre reinforced composites with an epoxy matrix, while glass and aramid fibres are used only to a small extent in some racquets. Additionally thermoplastics are mainly used as a matrix in the form of polyamide.

More information on calculating composite materials properties are beyond the scope of this chapter but can be found in literature, such as Kelly and Mileiko (1983).

3.3.1 Fibres

3.3.1.1 Carbon fibres

The raw material for carbon fibres is a fibre made out of Polyacrylnitril (PAN). The precursor, consisting of 12000 filaments, is commonly used in rackets after undergoing heat and stress treatment. This process, known as pyrolysis, predominantly determines the properties of the final fibre. For instance the temperature and the stretching during this define the Young's modulus and the strength. PAN fibres are a good precursor for carbon fibres, due to its all carbon backbone, which forms a ladder polymer when heated between 200°C and 300°C. The subsequent heat treatment at between 1000°C and

2400°C causes oxidation and dehydrogenation, producing fibres like; high strength (HST), high modulus (HM), and intermediate modulus (IM). The alternative basis for carbon fibres is pitch, resulting in high modulus fibres, which is more cost effective. Since the deformation of a racket is very large as a result of stringing and the impact, the most common fibres used are the HST fibres.

3.3.1.2 Glass fibres

Glass fibres were the first fibres used as reinforcement in rackets. Fibres consist mainly of silicium oxide and are spun from molten glass. The most important type of glass is a so called E-glass, with the “E” representing electric, due to its original used in electrical applications. Compared to carbon the advantages and disadvantages are easy to distinguish; it exhibits high tensile stress but low stiffness and high compression stress combined with a higher density.

3.3.1.3 Aramid fibres

Based on an aromatic polyamide, spun from a solvent, aramid fibres have very good impact behaviour. Their disadvantage is a lack in compression strength, which precludes the broader use of this fibre. In addition to the impact behaviour the low density is another benefit.

3.3.1.4 Boron fibres

These very stiff and very brittle fibres have been used to some extent in the past, but are not used currently in racket designs.

Table 3

3.3.2 Matrix

In order to fabricate fibre reinforced composite articles, it is necessary to impregnate fibres with a matrix. The fibres usually also have a sizing, for better adhesion between the fibre and the matrix.

3.3.2.1 Thermosets

Epoxide resins are the most favoured for use with carbon fibres and in high performance applications, because of their good mechanical properties, low shrinkage and the ability to bond to other materials. All epoxides are characterized by the presence of the epoxides group. This consists of two carbon atoms and one oxygen atom arranged in a 3-membered ring.

Figure 3

The reactivity depends on the position of the group in the molecule and steric factors. The opening of the epoxide ring by a curing agent leads to cross linking and ultimately, the production of a hard, insoluble solid. When fully cured all the epoxide groups should have reacted but this probably does not occur in practice where the epoxy often gets brittle due to the high reaction ratios (Kelly and Mileiko, 1983).

To cure the epoxide it is necessary to use a hardener and possibly accelerator and often heat the constituents, in the correct proportion, for an hour or more between 100°C and 120°C. For 100 parts resin, between 10 and 80 parts of hardener are required. Curing cycles to maximize a given property are usually determined empirically by the resin manufacturers, and will vary not only for different resin types but also for differing desired properties (Kelly and Mileiko, 1983).

3.3.2.2 Thermoplastics

As mentioned earlier, the only thermoplastic materials used racket up to now are polyamides.

Figure 4

Polyamides have good strength and toughness with excellent fatigue resistance. However, they are prone to absorb moisture, ranging from 8-10% for PA6 and PA66 to 2-3% for PA11 and PA12. The PA11 and

PA12 have similar characteristics and a number of advantages including; good stability in temperature, creep and pressure strength, good chemical resistance.

In addition the generally known injection moulding process with PA66, PA6 was also used in the form of fibres, allowing it to be commingled with carbon fibres, forming a kind of a thermoplastic prepreg (Kelly and Mileiko, 1983).

Table 4

The next table provides a comparison between the properties of the most important materials used in racket frames.

Table 5

3.4 Elastomers

In the racquet itself or as an accessory all types of elastomer are used by the different brands, with the main benefit being the dampening. There are two types of rubber; natural rubber which comes from the latex and contents from some trees and others plants, as opposed to synthetic rubber which is an oil by-product. The main characteristic of this material is that it can be stretched to many times its original length and it can bounce back into its original shape without warping. The following table shows contains relevant properties for commonly used elastomers.

Table 6

4. Materials for accessories and special parts

With frame developments pushing the boundaries further every year, accessories are also becoming more sophisticated to help improve performance in any way possible. In these, developments materials often have a very important role to play, with almost any material from metals to elastomers being used.

4.1 The handle

The handle itself is often made of polyurethane foam, injected or glued to the handle after the moulding process. The foam improves vibration dampening and provides a cost effective solution to manufacture rackets with different grip sizes. Many manufactures also incorporate some form of elastomer as the core of the handle, isolating it from the rest of the frame to dampen impacts. The principle is not to have a solid connection between the hand and the frame but rather have the moment transferred through a rather thick absorbing material. In the newer lightweight rackets many of these systems have been omitted though, to save weight. Butt end caps are usually made as injection moulded parts out of various thermoplasts (Head Brochure 1995, Beercheck 1991, Polich 1995).

4.2 The grip

The grip is the interface between the racket and the player and therefore has a very important role as the last frontier to effect a player's perception of an impact. Hence, the purpose is to minimise the shock and vibrations transferred to the players and provide a firm grip, so the racket does not slip in the hand, especially when wet with perspiration. The first wooden rackets had no grip and relied on the shape and surface texture of the handle for a firm grip, while the natural properties of the wood provided the dampening. Often softer strips of woods were attached to the outside of the handle to improve matters. Soon after, leather grips were introduced and although not that popular are still in used today (Kuebler 1995).

Leather grips have mostly been replaced by sophisticated materials like rubbers, polyurethanes and polyesters. Most current grips consist of combinations between these materials, with in many cases a thick textured polyurethane outer layer providing shock absorption and a firm grip. This layer is often perforated to channel the perspiration to a second polyester felt layer, where it is absorbed.

Many players use temporary over-grips made from thin polyurethane. These grips are applied over the normal standard grip, mostly to prevent slipping. The grips are cheaper and can be changed regularly, even between sets to ensure a fresh grip during match situations and to protect the standard grip underneath (Brody 1995b, Head Brochure 2001, Wilson Brochure 2002).

4.3 The grommets

Traditionally, grommets were only holes drilled through the racket frame for connecting the string to the frame but with the development of metal frames it became necessary to have some form of protection for the strings from abrasion against the harder metal frame. Later with the introduction of thin-walled composite frames it became even more important to have grommets, which in this case prevented the strings from cutting through the thin carbon walls, under the high tension. It would also assist in the stringing by providing a guide through the hollow frame. Further functionality was added by using the grommets on the tip of the racket to protect the frame against abrasions when in contact with the ground.

Not too long ago most grommets were still simple round tubes with a tight fit through both the inner and outer frame walls, not allowing too much movement of the string inside the frame during impact. In an attempt to enlarge the string surface, without increasing the head size, various manufactures have been moving to grommets with larger holes on the inside of the frame, allowing the strings to in extend its movement as far as possible to the outside wall. Manufacturers have also utilised grommets to give extra flexion or dampen vibrations to the string bed by adding softer materials or making it designing it so it would act as a spring during impact (Crawford, 2000b, Crawford, 2001b, Wilson Brochure 2002).

These multi-functional grommets require a very tough but flexible material, which can be manufactured to very accurate specifications for a perfect fit into the frame holes. Tolerances on grommets are very tight to ensure they do not fall out and on the other are not too difficult to fix, since it is a manual process. The materials found most suitable for this purpose are polyamides like PA11 or PA6.

5. Current manufacturing process

5.1 Composite rackets

As mentioned before, all high-priced rackets these days are manufactured predominantly from thermoset carbon fibre composites, with other materials strategically placed for optimum performance. This is mainly due to carbon fibres providing the best combination between material strength and manufacturability, with current technology. Except for the small deviations, the manufacturing processes are fundamentally the same for most major brands, even more so since use the same manufacturers in the Fareast. Filament winding is also used to produce racquets, but such racquets are only a small part of the market.

5.1.1 Production of composite rackets

Prepreg

Prepreg (pre-impregnated fibres) are either bought in ready prepared roles, or made in-house by drum winding. The latter process entails winding resin impregnated fibres onto a large drum, producing 0 degree prepreg (fibres have zero degree direction to the long axis of the sheet or the racket), which can be cut into the desired sheet sizes. Although prepreg are manufactured in endless combinations, the basic carbon prepreg used for most rackets are mainly produced with the following specifications, which can be varied for optimum designs:

- Carbon fibre content (grams per square meter)

- Resin content (a percentage of the total mass)

The sheets are cut by hand, or machines, at different angles (0°, 30°, 45°, 60°, 90°) and widths to produce layers with specified fibre angles. Most layers are placed on top of an identical but with the fibres oriented in the opposite direction, producing a layer with fibres aligned symmetric to the long axis.

Lay-up

The lay-up refers to the positioning of the different prepreg layers to form the basic frame. These layers are cut to the correct sizes and then positioned on a flat heated bench to make the prepreg tackier, hence sticking better to the adjacent layers. Although all companies have their own trade secrets and patents distinguishing their lay-up from the others', the basic lay-up for most rackets are very similar, with an example shown in Figure 5.

Figure 5

The basic principles are to use zero degree prepreg for bending stiffness and ±45 degree prepreg for torsional stiffness and anything in between depending on the desired combination. Additionally, most manufacturers add extra material, often glass, at the racket tip for the high impact forces in this region.

The main tube constitutes most of the racket's frame and is prepared first on a flat table and then rolled or folded around a polyamide foil tube, which is pulled over a rod. The rod is then removed, producing a hollow prepreg tube rolled around the foil, which once inside the mould will be filled with air to provide the internal pressure.

The throat piece is prepared separately by wrapping prepreg around anything from sand filled polyamide bags, to rubber pieces or expandable foam. This is necessitated, since there is no easy way to get air pressure inside the throat piece during moulding. The three methods function in one of two ways to create internal pressure; the air or the foam inside the bags expands due to the heat, while the rubber pieces are made fractionally to large for the mould and are therefore compressed when closing the mould. The advantage of the bags of the rubber is the sand can be drilled out after milling reducing the racket weight.

Moulding

Before moulding, all the pieces are assembled on a template to attain the basic racket shape. Simultaneously, the final prepreg pieces are also added to the strategic areas. The main tube is bent around a shape with an inner diameter similar to that of the racket face and the ends are pressed together and wrapped with a prepreg layer to form the handle. The throat piece is then fitted and attached with small supporting prepreg pieces. The air hoses are then connected to both ends of the tube and the finished lay-up placed inside the mould, which is closed and, depending on the prepreg and the desired cycle time, the correct temperature cycle and internal pressure is applied to set the prepreg.

Finishing

Almost half of the racket's manufacturing costs it's finishing and cosmetics after moulding. The first step is to deflash the racket, removing the access resin from the mould seam. It is then cut to the desired length and the foil removed to reduce the racket weight. The rackets are then sanded to roughen up the surface for better lacquer adhesion, followed by the drilling of the grommet holes. Next, small pit holes and minor defects are filled with body putty and sanded for a perfectly smooth surface. The frames are then painted with an electrostatic system, which apply a small electrical charge to the racket thus attracting the lacquer with opposite charge, for better adhesion. Subsequently, the rackets are heated in a ventilation room to harden the lacquer, after which the detailed aesthetics are applied. These are mostly in various forms of printing i.e. silk and tampon printing and the more labour intensive water decals (decorative transfers). The rackets are then ready for all the accessories like the end cap, grip, grommets and strings to be fitted.

Most manufacturers have different quality control points at various stages in the process. Random selections are also made from the finished rackets, which are subject to more stringent testing to ensure high quality. The quality process is discussed in more detail further in this section.

5.2 Aluminium rackets

Aluminium rackets first made their appearance in the 1960's and was later replaced by composite rackets for the high-end market. Composites allow for the manufacture of better performance rackets but with higher material and manufacturing costs. There is still a very significant market for cheaper, low performance rackets though, especially with junior rackets, where performance is not that important. This market is catered for by aluminium rackets, with a radically different manufacturing process from composite rackets.

An aluminium beam extruded with the desired profile, cut to size and annealed to soften the material for bending. It is then bent around a template, which forms it into the basic racket shape, the holes drilled and the frame hardened again with a heat treatment. The rackets are then lacquered by hand and all aesthetics applied, as for composite rackets. Next, the throat piece is simply screwed or riveted into place and the two ends of the tube forced together with a ring at the throat and riveted through the bottom for the handle. The racket handle is then placed into a mould and filled with polyurethane foam for the basic grip shape. The final steps are fitting the accessories, which is similar to the process for composite rackets.

5.3 Racket testing

Although most manufacturers and racquet companies have their own specialised tests, there are also several similar tests used by most. These include:

Non-destructive tests

In most manufacturing processes the mass, balance point and swing weight are monitored at different stages, to pick up problems in the process as early as possible. These properties, as well as the frame stiffness (measured using the standard RA test) are used as basic indicators for manufacturing specifications and are usually measured for randomly selected,or all finished rackets.

A specialised three-point bending test is performed to profile the bending stiffness in the impact direction along the length of the racket face. The face is supported at two locations on both sides of the racket; the first at five and six o'clock and the second 10 and eleven o'clock (referring to the face as an analogue watch). A load contacting both sides of the frame is applied at discrete points along the face. The deflection for all the points are measured and compared for different rackets.

The torsion test is similar to the three-point bending test except for the support which is not at both sides of the face but at alternate sides, i.e. at five and eleven o'clock. It creates torsion in the frame and measuring the deflection provides an indication of the torsional stiffness of the racket.

The tip deformation test applies a two-point load, at one and eleven o'clock on the tip in the direction of the handle, indicating the radial stiffness of the face at the tip of the racket. This is a critical area on the face, experiencing very high loading from the mains during impact. Again the deflection is measured for an applied load.

Destructive tests

A destructive version of all non destructive tests is also performed. During these tests the racket is deformed until it breaks and the ultimate breaking force is measured.

The tip impact test is a dynamic test again for the tip region. For the test the racket is dropped from incrementally increasing heights onto its head until it breaks. The sum of the drop heights up to the failure is used as the indicator of tip's impact resistance.

The tendency of frustrated players to through the racket on the ground and on the net often results in failures at three and nine o'clock on the face, forcing manufacturers to design and test for the condition. The racket is fitted like a swinging pendulum, rotating around the handle and dropped from the horizontal position to collide with solid round edge in the vertical position. The racket can be loaded with weights and, as with the tip impact tests, the weights are increased with every impact until failure. In this case the total weight of all the masses used up to the failure is used as the indication of the resistance to side impacts.

Rackets also needs to be temperature resistant and are therefore subjected to a temperature test. The racket is strung and placed inside an oven at about 80 degrees for approximately 4 hours and then checked for any defects.

Another interesting test is designed to evaluate the grommet strength. A string is threaded through two grommet holes and both end pulled on the inside of the frame until the grommet or the frame wall fails due to the high shear force. The force is measured and the maximum force causing failure is used as an indication of the strength.

Additionally, rackets are also subjected to fatigue tests in various embodiments; including anything from hitting a number of serves to a dynamic version of the tip deformation test.

6. Design criteria

The design criteria for rackets depend very much on the style and quality of the player they are designed for. As a result there are various different kinds of rackets on the market aiming to meet the needs of most users. Criteria include properties like power, control, comfort and mechanical failure. Ideally one would like to have all these properties maximised in all rackets but the optimum results it's often a trade-off between the more important ones, with especially power and control mostly being two opposing properties to design for.

6.1 Power

Probably the first rule of racket design is "for more power use the strings". Strings return about 90 percent of their deformed energy after impact, while the ball alone (when rebounding on a hard surface) only returns about 45 percent of the energy (Brody 1995b). Additionally, the energy in the deformation of the racket frame is not returned to the ball in time to add energy, which means any racket characteristic maximising string deformation during the impact, rather the ball or frame deformation, would increase the power. Relating it to frame parameters, it would include achieving longer strings and a stiffer frame. After the introduction of the oversized rackets in the 1970's rules have been introduced to limit the size of the string bed. The current rules specify maximum dimensions for the string height and width, which is measured to the inside of the frame of the face. Subsequently attempts at maximising the string bed were mostly focused on squaring face shapes, rather than a simple sphere shape. This results in the longest possible length for all the strings but has structural limitations where frames become difficult to manufacture, are not very strong and not pleasing to the eye. Soon more moderate shapes were adapted with more subtle features. In the last decade though, various manufacturers have been playing around with larger grommets to allow the effective size of the string bed to be extended to the outer side of the frame. Another factor affecting power is mass distribution, for which it difficult to achieve and optimum but the principles are straightforward; a lighter racket can be swung faster increasing the speed transferred to the ball, while the heavier racket is swung slower but he increase in mass also cause and increase in ball speed, especially if more of the mass is located at the impact point. Hence, the challenge is to design a racket light enough to be swung at a high speed and for all strokes but still have enough mass behind the ball for an optimum rebound characteristics.

6.2 Control

A smaller head and frame of higher torsional stability usually provide better control because there is less angular deflection of the strings and the frame. A larger angular deflection for an off-center impact will result in the ball coming of the strings at an angle larger than the perfect rebound angle a flat surface would provide. This small difference in angle can cause large error in intended ball placement on the court. A higher resistance to polar rotation cause less twist of the racket in the hand, hence resulting in a more accurate shot. In order to achieve a smaller head which is torsionally stable, additional weight placed on the perimeter of the racket (3 and 9 o'clock). It may be useful to also note at this point that spacing of the strings can also have an affect on the control; more dense strings result in a higher effective sting tension decreasing the angular deflection for better control but also tending to reduce spin, which might be important for some players.

6.3 Comfort

Comfort is a very abstract concept, linked to the player's perception. This is still a very complex and vague area, since different players will have a different perception of the same racket, resulting from various factors. Additionally, players have their own way of describing how they perceive a racket, which makes it very difficult to convert the feedback into concrete design parameters. So far most of the attention has been given to minimise the amplitude of the impact and the resulting vibrations. Stiffer rackets tend to have lower vibration dampening characteristics than the older wooden rackets, which players used to compare to and various additional systems with experimented with to provide additional vibration dampening. The stiffer rackets also have a higher pitched sound, which is usually not preferred by most players, hence the use of string dampeners. Methods to minimise the impact shock include moving the centre of percussion to the face centre and with perimeter weighting. Also related to comfort would be the surface finish used and the grip material used on the handle, which is very much standard for most manufacturers.

6.4 Mechanical failure

Rackets are designed to last as long as possible within demanding restrictions imposed during high performance play. The introduction of carbon fibre materials resulted in a dramatic leap in racket performance and strength. Initial strength problems were mostly related to the junctions between the main racket frame and the throat piece and at the tip of the racket, where it is subject to the largest force from the main strings but most manufacturers have resolved these critical areas with strategically placed reinforcements. The drive for lighter rackets in some markets has forced manufacturers to push their structural designs to the absolute limit, resulting in complex and very specific lay-ups, aimed at impact specific loading conditions. More ways of reducing weight without sacrificing too much in strength were using prepreg with lower resin content, applying fewer lacquer layers and removing the foil and expandable material used to provide the pressure inside the mould. When subjected to abnormal loading during testing though, these rackets can often perform surprisingly weak, since they are not designed to withstand abnormal loading conditions. Critical in this process is therefore proper testing methods to ensure rackets are designed for the correct loading conditions encountered during play.

6.5 Designing for consumer groups

The simple matter of the fact is there is no perfect racket for all players. Players have different levels and styles of play and different racket models are developed to suite as many of the individuals as possible.

Players would mostly start off with a lighter racket with a larger head. Not having the strength and skills of the professional players these players tend to hit more off-centre hits. The larger head compensates for this, allowing the player to make better contact with the ball and so assist in a steeper learning curve and hence more enjoyment of the game. It also provides torsional stability during the off-centre hits, which save the player a lot of energy and the larger heads means more power giving the player more of an advantage at these early stages.

The next mayor category is the club player, who plays regularly for recreation. Being in the development stages of their game they would tend to move to rackets with smaller head sizes for more control and a specific swing weight determined by the individual’s style of play. Base line players, who tend to have a longer swing, would tend to go for rackets with a higher swing weight, while volley players will go for a lighter more manoeuvrable racket. Rackets designed for that range of players have a wide variety of swing weights to fit every players needs.

The next step are the tour players, who are so well conditioned they would rather sacrifice power for the ultimate control, resulting in the exact placement of the ball to win the point. These rackets have a much smaller head and are substantially heavier than beginner rackets. Players at this level can also swing a heavy racket much faster for longer, hence creating more power themselves and not relying on the racket’s lighter weight. Some top professionals have been claimed to play with rackets almost twice as heavy as the beginner rackets! These rackets are usually custom weighted with lead tape for the individuals.

These different criteria for groups of players often lead to manufacturers marketing rackets under categories such as beginner, “intermediate” and tour series, with each series having a selection of swing weights to choose from. Most manufacturers also have racket selection systems to assist players in the choice (Easterling 1993).

7. Future trends

What will be the next technology in tennis, revolutionising the sport again like the examples mentioned in this chapter? This is the question every brand tries to answer on a regular basis when the new products are developed or presented at a trade show. The most important issue here was, still is and will very likely also be; the use of new materials or the use of a construction principle, which allows the use of advantageous materials. Criteria like power, control or comfort have not been designed to a maximum yet. Everyone is willing to get the latest racquet, which will help him win the next game. If this is a more powerful or more controllable racquet, is up to the player.

An area for increasing research is the relation between the racquet and injuries like a tennis elbow. Although everyone has been aware of the problem and have been designing rackets to it, the truth is very little is known about what really causes tennis elbow. The ITF started a congress for the future of the game in 2001, which is an excellent basis for promoting information and discussing new tennis developments and would hopefully lead to finding all the tight answers to develop the perfect racket.

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Figure 1: Remarkable rackets up to the 1980’s. Images from Kuebler (1995)

Figure 2: Remarkable rackets from the 1980’s to 2002.

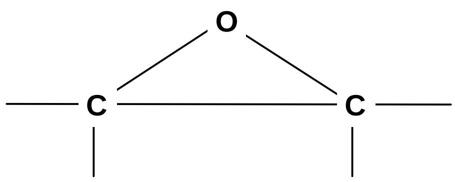


Figure 3: The epoxide group.

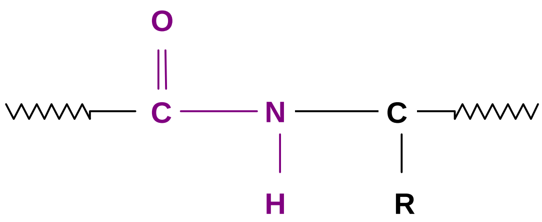


Figure 4: The amide group.

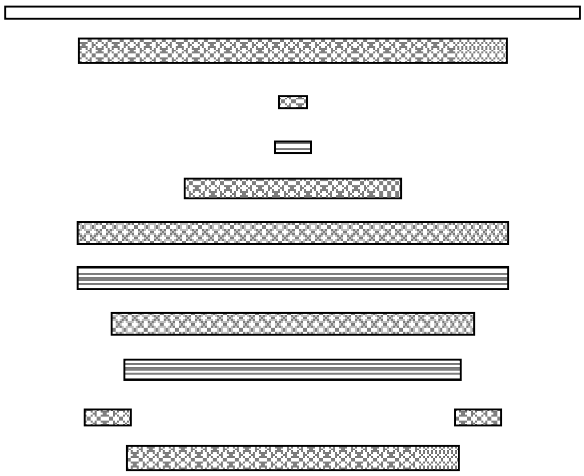
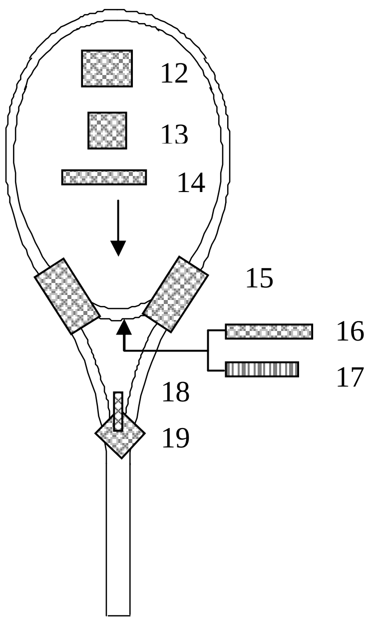
Pre-preg layers	Parts	Material	Fibre angle
 The main tube	1	PA Foil	-
	2	Glass	±20°
	3	Carbon	±30°
	4	Carbon	0
	5	Glass	0
	6	Carbon	±30°
	7	Carbon	0
	8	Carbon	±30°
	9	Carbon	0
	10	Glass	±30°
	11	Carbon	±30°
 The throat piece and reinforcements	12	Carbon	±30°
	13	Carbon	±30°
	14	Carbon	±30°
	15	Glass	±20°
	16	Carbon	±30°
	17	Carbon	90°
	18	Glass	±30°°
	19	Glass	±30°

Figure 5: A typical lay-up for a composite racket.

Table 1: Mechanical properties of various wood types

Wood type	Specific gravity	Modulus of rupture GPa	Flexural modulus GPa	Shear strength (parallel to grain) MPa
Ash black	0.49	0.087	11.0	10.8
Ash white	0.60	0.103	12.0	13.2
Hickory pecan	0.66	0.094	11.9	14.3
Maple red	0.54	0.092	11.3	12.8
Oak, Red Willow	0.69	0.100	13.1	11.4
Sycamore	0.49	0.069	9.8	10.1
Cedar Incense	0.37	0.055	7.2	6.1
Beech	0.64	0.103	11.9	13.9
Birch yellow	0.62	0.114	13.9	13.0
Walnut black	0.55	0.101	11.6	9.4

Note: All properties are typical for woods grown in America with 12% moisture content. Taken from Green et al. (1999), Bodig and Jayne (1982)

Table 2: Properties of Aluminium 6061 with different heat treatments.

Treatment	Yield strength (MPa)	Tensile strength (MPa)
Annealing (0)	55	125
Matured hardening (T4)	145	240
Returned hardening (T6)	275	310

Note: Taken from eFunda (2002)

Table 3: Filament properties for common composite materials.

Material	Density $x10^3$ Kgm^{-3}	Long tensile mod. GPa	Long tensile str. MPa	Trans.tensile mod. GPa	Shear modulus GPa	Compression strength MPa	Strain at fail. %	Major Possion's ratio	Diameter μm	Long. coeff. of thermal exp. $x10^{-6}$ °C^{-1}
E glass	2.54	70	3100	70	28.7	1750	2.5-3.0	0.22	10.0	5
Carbon										
VHM	2.0	517	1860				0.38	0.25	8.4	-1
HM	1.9	350	2000	12.1	13.7		0.5	0.28	11	-0.5
HT	1.78	230	2900	20.4	24.0		1.3	0.26	8.0	0.5
A	1.76	215	2400				1.27	0.26	8.5	1.0
Aramid	1.45		2800	5.38	2.0*	250*	2.0-3.0	0.34*	12.0	-2.0
Boron	2.63	420	3400	420	180	2300	0.7	0.13		2.8

Note: *VHM=very high modulus; HM=high modulus; HT=high tensile (strength);*indicates results for a 60% composite. All figures are approximate and derived from manufacturers' data, taken from Kelly and Mileiko (1983)

Table 4: Material properties of common polyamides.

Property	PA 6	PA 6-GF30	PA-CF30	PA 66	PA11
Density, g/cm^3	1.13	1.36	1,28	1,14	1.04
Yield till breakage,N/mm^2	40	100	240	65	50
Elongation till breakage, %	200	4-5	1,5	150	500
Young's modulus, MPa	1400	5000	16000	2000	1000
Bending strength, MPa	50	130	330	50	70
Maximum temperature of use °C					
briefly	140-180	180-220	180-220	170-200	140-150
continuously	80-100	100-130	110	80-120	70-80
Melt temperature °C	220	220	220	255	185

Note: Taken from Kelly and Mileiko (1983) and eFunda (2002)

Table 5: Comparing the properties for a range of materials used in racket frames.

Material	Density g/cm^3	Tensile strength GPa	Young's modulus GPa	Specific tensile strength	Specific Young's modulus
HST-Epoxy	1,5	1,9	130	1,27	87
HM-Epoxy	1,6	1,2	210	0,94	119
E-Glass Epoxy	2,0	1,0	42	0,5	21
Aramid Epoxy	1,4	1,8	77	1,3	56
Nylon (PA 6)	1.13	0,04	1,4	-	-
Steel	7,8	1,0	210	0,13	27
Titanium	4,5	1,0	110	0,21	25
Aluminium	2,8	0,5	75	0,17	26

Note: Taken from Kelly and Mileiko (1983) and eFunda (2002)

Table 6: Material properties of Elastomers.

Property	NR Natural rubber (cis-Polyisoprene)	SBR Butastyrene (GR-S)	IR Synthetic (polyisoprene)	CR Cloroprene (neoprene)
Specific gravity (ASTM D 782)	0.93	0.91	0.93	1.25
Tensile Strength, MPa				
Pure Gum (ASTM D 412)	17-24	1-2	17-24	21-28
Black (ASTM D 412)	24-31	17-24	24-31	21-28
Elongation, %				
Pure Gum (ASTM D 412)	750-850	400-600	…	800-900
Black (ASTM D 412)	550-650	500-600	300-700	500-600
Recommended temperature Range, °C	-51 – 82	-51 – 82	-51 – 82	-40 – 116
Hardness (durometer)	A30-90	A40-90	A40-80	A20-95

Note: Taken from Perry and Green (1997)