

MATERIALS-INSPIRED INNOVATION FOR ACOUSTIC GUITAR DESIGN

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This paper presents a case study of research leading to a significant innovation in the acoustic guitar sector (1). The acoustic guitar is a result of centuries of design and development with wood, and has evolved into an archetypal and traditional product with a relatively conservative user base. As with many other product sectors, most acoustic guitars are now mass-produced in China, where low labour costs contribute to an average out-of-factory price of just \$20 USD. This paper describes research into a dramatic shift in guitar materials, away from wood fabrication, towards the assembly of industrially moulded thermoplastic components. It is proposed that such a shift in materials can lead to competitive mass-manufacture of acoustic guitars outside of low labour cost countries, whilst invigorating the design of this popular musical instrument. Emphasis is placed on articulating the technical, aesthetic, market, and commercial requirements of a thermoplastic acoustic guitar. The crucial issue of sourcing appropriate forms of advice to aid product design is discussed. Focus is on the guitar soundboard, as the principal sound-generating component of the instrument. Three conclusions are reached, based on the patented soundboard technology that emerged from the research. First, instruments constructed with foamed polycarbonate soundboards can rival the quality of wood counterparts, opening the way for a possible new industry of polymer musical instruments. Second, foamed polycarbonate soundboards have physical material properties surprisingly different to wood yet give equivalent acoustic performance. And third, innovation in this product sector benefits more from designerly ways of knowing and operating and less from scientific discoveries.

INTRODUCTION

The steel-strung acoustic guitar is a close relation to the nylon-strung classical guitar, the design of which developed empirically and most significantly in the nineteenth century by guitar maker Antonio De Torres

(1817-1892). Predecessor instruments resembling guitars were in existence for far longer, thus defining centuries of development with the same basic material: wood. It is probable that the early makers of instruments reviewed the materials available and chose wood because little else existed that could be fashioned into a credible instrument. The present day acoustic guitar has reached a plateau in its development, such that it can be identified as an archetypal product from amongst Thistlewood's (1990) classification of archetypal, historicist and evolutionary product types.

Wood guitars of the highest quality are expensive instruments, as a result of the handcraft skill that professional guitar makers (luthiers) employ to convert timbers into exquisite and unique instruments. In contrast, the overall plan within the mass-produced retail instruments market, in which the vast majority of instrument sales are made, is to standardise construction, increase production capacity and lower costs. The result is that the Far East, Indonesia and Central America are now the world's prime locations for entry-level and mid-range acoustic guitar manufacture. The migration of manufacturing to these countries is principally because of low labour costs, since wood guitar manufacture on a large scale requires substantial manual labour. As a consequence of the migration, manufacturers of traditional instruments based in North America and Europe can be profitable only in the high-end market sector.

This paper reports on research into one strategy for rejuvenating entry-level acoustic guitar manufacture in western economies. This sector of the market is especially important because nearly all players learn on entry-level instruments, but unfortunately the quality of tone and setup is often poor compared to instruments built by luthiers. It is ironic that beginners learn on the hardest to play and poorest quality instruments. This point is echoed in other sectors of the musical instruments industry, most notably violins (Tao, 2007).

It was clear from the outset that changes in design and instrument configuration alone represented an unsatisfactory rejuvenation strategy, since the need for labour-intensive woodworking skills remained. A more fundamental innovation was required, summoning a shift in materials selection away from wood towards alternative materials associated with low cost manufacture and assembly (Norman, 1993). This strategic approach to product design is known as materials-inspired innovation (Fischmeister, 1989). A successful innovation could conceivably dominate the entry-level guitar market in the same manner as the plastic recorder, by addressing one or more of the following points.

Alternative materials supply. The long-term viability of many species of wood for guitar construction is uncertain because of over-forestation and unsustainable demand driven by Far East manufacturers (Jasch, 2007). Alternative materials are needed to counter supply problems with traditional tone woods.

Reduced manufacturing cost. The manufacturing cost and retail price of a guitar can be lowered through the use of lower cost materials, fewer parts (e.g. component consolidation) and simpler construction (e.g. decreased manual labour).

Improved consistency. Acoustic guitar quality is a consequence of design, construction and materials. Manufacturers can directly specify design and construction, whereas wood can only be chosen from amongst the timbers that are available. Wood has an irregular grain structure, comprising

2. Discussion with Dr Mark Lewney, expert in guitar physics, July 2007.

3. Discussion with Alan Marshall, luthier, Northworthy Guitars, May 2008.

regions of fast growth (low density) and slow growth (high density) material. Each piece of wood is different, even if cut from the same tree. Variations in wood affect guitar manufacture, so that in standardised mass-produced instruments, the set-up, playability and tone of two identical brand and model instruments can vary noticeably. It has been reported (2) that even at the Ramirez factory, a maker of very fine classical guitars, retail prices are determined by experts valuing each instrument at the end of the production line, with prices varying by a factor of five (\$2,000 - \$10,000 USD). Acoustic guitars constructed from materials absent of the inconsistencies of wood have potential to be of consistently higher quality.

Resistance to environmental changes. Wood is highly susceptible to dimensional distortions when subjected to changes in temperature and humidity. One luthier has observed expansions of 6mm across the wood grain and 0.1mm along the grain during instrument construction (3). These changes have a negative effect on instrument set-up, and over time can result in instrument cracking. Non-woods have potential to circumvent this problem.

New aesthetic possibilities. Alternative materials provide opportunities for forms and finishes not possible with wood and not yet seen in the acoustic guitar market. A non-wood instrument has potential to attract and inspire a young generation of first-time guitarists not indoctrinated with the (false) conviction that guitars must be constructed from wood.

Greater perseverance. With a high quality instrument, learning the guitar is easier and high levels of competency can be more readily attained.

Against this backdrop, three research questions were posed to direct the instrument research and development (R&D) activities.

- *RQ1.* Can non-wood guitars be developed that rival the quality of wooden guitars?
- *RQ2.* What material specifications lead to successful non-wood guitars?
- *RQ3.* What kind of expertise is needed to achieve materials-inspired innovation for acoustic guitar design?

THE ACOUSTIC GUITAR SOUNDBOARD

It has been known for centuries that the soundboard (the flat figure-of-eight panel over which the strings sit) is the single most important component of an acoustic guitar for influencing sound quality (Siminoff, 2002). The coniferous softwoods alpine spruce, sitka spruce and adirondack spruce (usually sourced from North America) and western red cedar (usually sourced from Europe) are the traditional choices for acoustic guitar soundboards. The most famous empirical investigation of soundboard influence was made by Antonio De Torres, who created a fine sounding guitar with back and sides made from papier-mâché rather than solid wood, thereby demonstrating the lesser influence of these components on sound quality (Romanillos, 1997). Development of a successful non-wood soundboard was the logical starting point for the more ambitious objective of creating an entirely non-wood acoustic guitar.

The function of an acoustic guitar soundboard is to act as an acoustic 'spring' or diaphragm, amplifying the vibration of the guitar strings through displacement of air. For the soundboard to act as a spring, it must

be constructed as a thin plate, typically 2 or 3mm in thickness, and must be equipped with a means of escape for displaced air. This is most commonly in the form of a circular sound hole placed underneath the strings, although guitar makers have successfully experimented with a variety of unconventionally shaped and placed sound holes. The soundboard may be designed either flat or convexly curved prior to the application of string tension, leading to the classification of acoustic guitars as ‘flat top’ or ‘arch/dome top’ models. An advantage with the latter is that the in-built curvature provides increased stiffness with no weight gain, allowing a thinner plate to be used without compromise to structural integrity.

Regardless of material, all acoustic guitar soundboards must satisfy three basic design criteria: structural, acoustic and aesthetic. The designer’s task is to devise a soundboard with freedom to move (to satisfy acoustic criteria), whilst at the same time resisting twisting, bowing and other displacements that can arise from string tension (to satisfy structural criteria). However, an excessively stiff soundboard will resist movement and suffer from poor tone and low volume. Likewise, an overly heavy soundboard will have large inertia, reducing the ease with which it may be set in motion, again having a negative effect on tone and volume. It can therefore be seen that a high stiffness-to-mass ratio is desirable in acoustic guitar soundboards: this property is attributable both to material properties (Young’s Modulus, density) and component geometry (second moment of area, volume). Coniferous softwoods have relatively low density and relatively high stiffness. Assuming structural and acoustic criteria are met, the final requirement is for the soundboard to possess attractive sensorial properties (to satisfy aesthetic criteria). Each of these criteria requires closer inspection.

Structural Criteria

Structural criteria for a soundboard include resistance to deformation, collapse and damage. Good surface hardness, often achieved for wood through the use of supplementary finishing such as lacquer or varnish, is also important for resilience against knocks and scratches. However, the primary structural concern is the tension of the guitar strings, typically

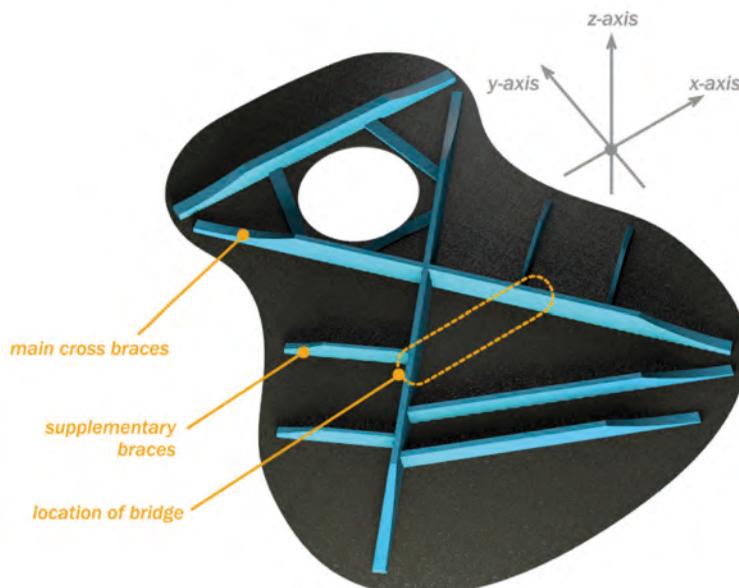


Figure 1. Underside of generic X-braced soundboard showing x-, y- and z-axis stresses.

1000N when tuned to concert pitch. The tension is exerted directly onto the soundboard through the instrument saddle and bridge.

Spruce and cedar soundboard plates are insufficiently stiff and strong to resist string tension. As a result, wood braces are bonded to the underside of the plate, hidden from view, for structural reinforcement and sound modification. Braces are especially important as an insurance against the inherent 'across grain' fragility of wood (commonly 10% of parallel-grain strength). Most manufacturers have adopted variations of an 'X' bracing pattern, developed in the 1930s by The Martin Guitar Company, which is favoured because of its structural efficiency and universal tonal appeal (Figure 1).

With 'X' bracing, the main cross (X) braces provide a combination of longitudinal stiffening (parallel to string tension and the wood grain of the plate, y-axis) and transverse stiffening (perpendicular to string tension and the wood grain of the plate, x-axis). A z-axis component of the string tension is also present on the soundboard because the strings pass across the bridge saddle at an angle, causing a down force. Thus the main cross braces also provide protection against inward bowing caused by z-axis stress. A rule-of-thumb for a 'good' soundboard is that under tension it should be 'on the edge of collapse' with a slight bulge behind the bridge and a slight dip in front, owing to the bridge rotating forward slightly under load. This indicates that there is sufficient flex within the soundboard to deliver good volume, but not so much to adversely affect the playability of the instrument. Many wood soundboards also have a bridge plate located on the underside directly opposite the bridge, to give additional reinforcement. A decorative insert known as a rosette is usually embedded around the sound hole on the outer face, providing additional reinforcement as well as visual enhancement.

The most highly prized timber for soundboards ('AAA grade' or 'master grade') is sourced from high altitude old trees. High altitude conditions slow the tree growth, resulting in timber with very close and straight grain upward of 20 rings per inch (0.79 rings per mm). The closeness and straightness of grain is advantageous for ensuring good resilience under structural loading. However, claims that these properties are also directly attributable to improved tone are less certain.

Acoustic Criteria

Acoustic criteria refer to the timbre, projection (loudness) and playability (response) of a guitar. A crucial point that must not be overlooked is that acoustic properties vary widely across different guitar models. Musicians find a very broad range of tone, projection and playability acceptable from a guitar, linked chiefly to whether these acoustic criteria 'fit' particular types of music (e.g. jazz, folk, rock) or playing styles (e.g. finger picking, strumming). From this standpoint, the idea sometimes forwarded that alternative materials may create generally 'better sounding' guitars is misguided. The rational view is to see alternative materials as a way of (a) equalling or extending the range of acceptable guitar sounds, or (b) potentially surpassing wood instruments for the performance of some types of music or playing styles.

It is well known amongst guitar makers that a change in species of tone wood or a change in bracing pattern can have a dramatic effect on the acoustic characteristics of an instrument. Guitar makers bond supplementary braces to localised regions of the soundboard to alter

acoustic characteristics, rather than to supply significant additional reinforcement (see **Figure 1**). Tapers are usually added to the ends of braces where they approach the soundboard perimeter, in order to avoid overly stiffening the soundboard-sidewall joint and to reduce mass.

Aesthetic Criteria

Aesthetic criteria are determined by the sensorial properties of materials and manufactured products. Wood is a material rich in visual, tactile and olfactory properties and is regarded as a memento of the power, beauty and lifecycle of nature. With these attributes, it is easy to understand how wood has contributed to the romanticism and popular appeal of the acoustic guitar. The traditional use of abalone and other shell pearls as intricate decorative inlays in guitar bodies has further contributed to the high esteem and craftsmanship attached to wood instruments. Non-woods have very different sensorial properties, which must also be attractive to players.

Soundboards from Alternative Materials

The expectation is usually that an ideal soundboard replacement material will retain the superior properties of coniferous softwoods but rectify the weaknesses. Various manufacturers have already adopted alternatives to spruce and cedar. High pressure laminate (HPL) is a common alternative, which can vary in composition from wood veneers bonded to a low-grade wood core (essentially a form of plywood) through to monolithic composites of wood pulp sheet and thermosetting resins similar to Formica®. HPL is used in many entry-level instruments, being relatively cheap to purchase and relatively resistant to changes in humidity and temperature. However, HPL still requires woodworking technology and construction, and so is not really appealing in the context of this paper. Carbon fibre reinforced plastic ('graphite') is also a popular wood replacement, although it is expensive and thus suited only for low production output, high-end instruments (Blackbird, 2008; Composite Acoustics, 2008; Emerald Guitars, 2008; Ovation, 2008; Rainsong, 2008). Soundboard plates fabricated from carbon fibre reinforced plastic are usually sufficiently rigid to negate the need for structural bracing, although bracing for acoustic modification is usually retained. The Martin Guitar Company (2008) offers an 'ALternative-X' guitar featuring an aluminium alloy soundboard, and also an 'SWO' guitar featuring woods and wood composites from reclaimed sources. Other makers have experimented with the use of non-traditional woods including koa, walnut, maple, sapele and cypress as soundboard materials. However, none of these previously used materials adequately fitted the material requirements listed in the introduction to this paper.

Aside from plastic toy guitars, which cannot be considered serious musical instruments, only one manufacturer, Mastro Industries Inc., has developed and marketed an almost entirely polymer acoustic guitar, including a polymer soundboard. Mastro Industries Inc. was founded by Mario Maccaferri (1900-1993), a successful guitarist and luthier who built his professional reputation with the Selmer Company, creating 'gypsy jazz' guitars for artists including Django Rheinhardt. In the 1950s, Mastro launched a range of injection-moulded acoustic guitars made from a specially commissioned grade of Dow Styron plastic (**Figure 2**). The guitars were successors to Mastro's highly successful range of Islander plastic ukuleles, which was launched in 1949 and by the time of its withdrawal in



Figure 2. Dow Styron guitar designed by Mario Maccaferri.

1969 had sold over nine million instruments (Wright, 1995). Unlike the ukuleles however, the plastic guitars were criticised for having a poor sound and were not a market success.

The failure can be attributed to two factors. The first was the limited range and cost of materials and processing technologies available at the time. In the 1950s, plastics technology was in relative infancy. It is reported that Dow took two years testing various formulations of its Styron and Ethocel materials for Maccaferri's instruments, and that the mould tool costs were \$350,000 USD (Wright, 1995). Maccaferri used the best materials and technology available at the time, but they did not prove good enough. The second of the factors was the unenviable task Maccaferri faced in pioneering plastic as an acceptable alternative to wood, in the face of people's scepticism, prejudices and reluctance to break with traditions (Pedgley, 2004).

No company since has attempted the design of a credible mass-market all-polymer acoustic guitar. In the intervening decades however, materials technology and people's acceptance of alternative materials in everyday products has developed considerably, instilling optimism that a materials-inspired innovation in acoustic guitar soundboards could now be achieved.

RESEARCH METHOD

The empirical research was carried out through a mode of enquiry known as 'practice-based' design research, or 'research through designing' (Pedgley and Wormald, 2007; Arts and Humanities Research Council, 2007). Essentially this involves the use of own design practices as a source of research data, for which rigorous methods of capturing and analysing own design activity must be deployed. The aim was to generate chronologically correct documentary evidence of design activity for the soundboard and guitar development, from the project brief through to delivery of the first prototypes. Such an evidence base would be used as the basis for tracking and explaining the origins of design decisions and innovations.

The adopted data collection tool was a diary of designing. This tool was judged suitable through a process of elimination against practical constraints (which tools could be used for a design project spanning months or years?) and data preparation constraints (which tools would generate data amenable to relatively quick processing?). A full

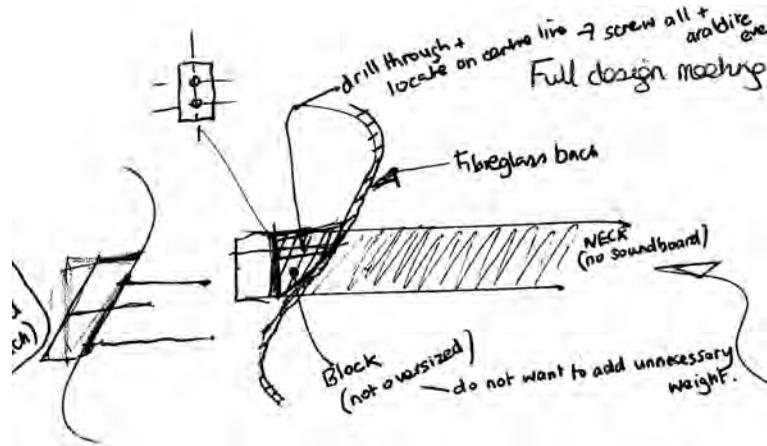


Figure 3. Example sketch extracted from diary of designing portfolio.

methodological account of the diary is published elsewhere, discussing its design, testing and validity (Pedgley, 2007). Briefly, diary entries were made at the end of each project day, giving an account of materials and manufacturing decision-making. A total of 312 separate diary entries were made across the guitar project, which spanned 227 days. Diary entries often made reference to design sketches, physical models and information sources. For example, the following diary entry (number 212) referenced sketch work created for recording some ideas and decisions taken at a meeting (Figure 3).

“Design sketches of prototype 3 manufacture, for me to visualise what Rob Armstrong was explaining to me. I’ll find it easier to make use of this information in the near future when it’s in illustration rather than memory.”

A critical step in devising the research method was to identify useful sources of advice to aid material selection. Tens of thousands of non-wood materials could be contemplated for use in acoustic guitar soundboards, but how should the materials selection begin? An initial approach was taken towards materials science and engineering advice but it was the empirical advice of a luthier that was the origin of the guitar innovation reported in the remainder of this paper.

Materials Science and Engineering Advice

The frequency of sound (pitch) emitted by an object when struck is determined by Young’s Modulus (E) and density (ρ), whilst the timbre (characteristic) and sustain (length) of the sound is determined by a loss coefficient or ‘internal damping’ (Ashby and Johnson, 2002). These are bulk properties of materials used as constants in physics and engineering studies of acoustic guitars (McIntyre et al., 1983; Richardson, 1994). However, the musical properties of manmade materials, and especially of thermosetting and thermoplastic polymers, remain an area of materials science that has received very little attention. Scientific studies have yet to be conducted to fill the gap in understanding that correlates polymer material properties to acoustic phenomena. Consequently very little science or engineering advice was available to support the specific task of designing non-wood acoustic guitars. Furthermore, previous involvement by scientists and engineers in the design of wood acoustic guitars were not well received. The most high profile involvement was by Gibson in the mid 1970s, for the development of their ‘Mark Series’. The instruments failed in the marketplace because they were tonally poor despite being loud.

"There is a relatively recent example of a major guitar-maker taking science on board - and failing to capture musicians with the new guitars. In 1977 Gibson launched the Mark Series acoustic guitars. In the promotional literature for the four new models, the 35, 53, 72 and 81, the company explained how, in the past, improvements to instrument design had come about by trial and error, and luck. 'That's why Gibson chose a new method in its search for a better acoustic guitar - the scientific method'. Gibson's two-year research plan involved three scientists: a professor of acoustical physics, who recorded and analyzed 'voice graphs' of popular guitar designs; a chemical physicist (also director of an institute of molecular biophysics) to oversee structural design; and a professor of acoustics who devised new scientific measuring techniques and an environmental test chamber. But despite all this, the guitars did not prove popular and were soon dropped from the Gibson catalogue. The company returned to their old, proven method of trial and error (and luck), and most players would argue that they returned to making good guitars as a result. Gibson's high-profile failure deterred many makers from the scientific route." (Bacon, 1991)

It was clear that to achieve a successful materials innovation in acoustic guitar soundboards, sources of advice from outside of science and engineering were needed.

Luthier Advice

The view was taken that skilled instrument makers possess the foresight necessary to predict with reasonable accuracy the likely material properties needed of a wood replacement. Such foresight is borne from decades of empirical experience and practical know-how from creating hand built instruments. Luthiers pick the most promising pieces of wood all the time, so helping identify the most promising non-woods was considered reasonably close to routine practice. Although it was unlikely that a luthier's expertise could be accurately defined or made explicit owing to its tacit (non-verbal) dimension (Polanyi, 1983), there was little doubt that such expertise could offer at least some insight into appropriate materials selection and set a good initial direction.

Master guitar maker Rob Armstrong, who was known to have a reputation as an innovator and experimenter, was therefore approached to assist in the R&D activities. He had approaching thirty years professional experience spanning approximately 700 guitars, and very rarely made the same model guitar more than once. His impressive client list included Bert Jansch, Gordon Giltrap, members of Fairport Convention, The Levellers, and the late George Harrison.

The principal method that luthiers use for evaluating the sound quality of tone woods and in creating a soundboard is the 'knuckle wrap test'. This involves gently holding a work piece by its top edge and, with the other hand, knocking it at locations corresponding to nodes of vibration (e.g. and $\frac{1}{4}$ distance from the holding position). Just as members of the public can discern classes of materials (e.g. woods, metals, plastics, ceramics) by recognising tonal characteristics when hit (Djoharian, 1999), so luthiers respond to the subtle material-specific sound and vibration information contained in 'tap tones' when selecting woods and creating a soundboard. Tap tones are evaluated by listening and feeling for velocity of sound (responsiveness) and a characteristic ringing sound with musical content (fundamental, harmonics, transients, partials) (Bourgeois, 1990). The well-published luthier William Cumpiano (1999) gives the following insightful account of the relationship between knuckle wrapping and soundboard development.

“Rather than ‘tuning’ the top, I actually ‘de-tune’ it, working it until the sounds it makes when tapped sound dispersed and indistinct. But just until. If I hear a clear bell-like note when I tap it, that’s telling me that it’s way too, too stiff and I have to bring it down. You hear that clear note best just after it’s freshly (and thus, massively) braced, and it’s waiting for brace carving and shaping with the plane, chisel and sandpaper. The more material you move from the braces and from the top’s actual thickness, the lower in pitch its tapped sound. If you can hear any focused musical tone when you tap a top, it is still too stiff, too massive. Most amateur builders’ first guitars are impossibly massive, because they simply have not developed a sense of proportion that comes with refining their awareness of the precise resilience of the material. My aim, the aim that works for me, is to remove all the material from the top of the guitar that is not needed to support the string tension and its accompanying physical distortion. If you still want to learn about tapping the top until you get a certain note, go to another luthier to explain it to you. I don’t do that. I’m not interested in that, because I know how widely and how unknowably the top’s acoustics changes when you add the rest of the guitar to it.”

Luthiers combine knuckle wrapping with other sensory evaluation methods including counting grain lines, rubbing, candling (inspection of hidden structures under a bright light), ‘finger sawing’, and detecting the ability of the material to pick up ambient vibrations (e.g. from extractor fans and loudspeakers). Thus it can be appreciated that the luthier’s skill is to respond appropriately to sound and vibration feedback by deciding, for example, what combination of complementary materials should be used in an instrument, or what bracing pattern should be used for a given soundboard plate.

RESULTS

Table 1 reports the material selection trail that was left during the project, through a sequence of questions and answers (Q1-9, A1-9). It should be clear from **Table 1** that the selection activity was limited to those materials for which samples could be obtained, and also to the authors’ materials search skills. Although Rob Armstrong’s advice on material composition (A1) was on face value quite simple, it resolved what was potentially a major barrier to progress and proved to be the primary generator for the patented materials innovation that ensued (Pedgley, Armstrong and Norman, 2005). Wood is essentially a porous material and it is this characteristic that Rob placed the highest priority on in the search for alternative materials. Directional fibres and especially prominent stiffness, as exhibited by both carbon fibre composite and wood, were not of concern during the materials selection. From Q3 onwards, materials selection was directed towards foamed polymers because they were known to be low cost, suitable for mass-produced products, and generally possess a homogenous structure. The final selected material was foamed polycarbonate (**Figure 4**)



Figure 4. Rob Armstrong’s sketch indicating an aerated material structure.

Prototype Instruments

A prototype instrument was required to be made in response to A9 of the material selection trail. The prototype was necessary to gauge first impressions of a foamed polycarbonate soundboard when built into an instrument. It was also necessary for highlighting, and providing solutions to, technical matters including levels of stiffness, distribution of mass, adhesive choices, and assembly procedures. For speediness and convenience, the first prototype was a ‘lash-up’, created by retrofitting a

| Question | Answer | Detail |
|----------|--------|---|
| Q1 | | Pedgley: What kind of physical properties should the material have? |
| | A1 | Armstrong: Rob Armstrong draws a thumbnail sketch (Figure 3), indicating desirable physical properties. The principle was to create a lightweight soundboard plate by "...getting air into the material" [Log book entry LB1:18]. |
| Q2 | | Pedgley: What types of non-wood materials can be described as having air within their structure? |
| | A2 | Pedgley: Honeycomb composite materials and foamed varieties of thermoplastic and thermoset polymers. [Log book entry LB1:16] |
| Q3 | | Pedgley: How can foamed polymers suitable for soundboards be identified and evaluated? |
| | A3 | Pedgley: Approach suppliers of off-the-shelf 'cellular', 'microcellular', 'porous', 'foamed' and 'expanded' polymer sheets to provide samples for evaluation. |
| Q4 | | Pedgley: Which of the samples satisfy the structural criteria for soundboards? |
| | A4 | Pedgley: Samples with reasonably high Young's Modulus (> 1000 MPa) are considered suitable and retained for acoustic evaluation. The candidate materials fall within the categories of 'rigid', 'semi-rigid', 'structural' and 'high density' foam sheets. Conventional applications of these materials include: ceiling tiles, modelling and CNC blocks, building insulation, automotive interiors, packaging, exhibition stands, furniture, roofing, signage, displays, point-of-purchase, and merchandising. |
| Q5 | | Pedgley: How do we evaluate the acoustic quality of the remaining samples? |
| | A5 | Armstrong: Employ the knuckle wrap test as described in section 3.2 [Diary entries 73, 80, 94, 198, 207] |
| Q6 | | Pedgley and Norman: Which of the remaining samples is acoustically superior? |
| | A6 | Pedgley and Norman: Foamed polycarbonate is identified through the knuckle wrap test to be acoustically superior: "unlike other polymer sheets (e.g. foamed PVC), it is less bulky and 'rubbery', and has an intrinsic 'ring' when hit. The material is also scratch resistant and has a very pleasing finish." [Diary entry 83] |
| Q7 | | Pedgley and Norman: Does Rob Armstrong agree with the choices made? |
| | A7 | Armstrong: Rob concurs, agreeing that the selected material "would work" [Diary entry 102] and "...was right" [Diary entry 109]. |
| Q8 | | Armstrong: The 5mm material sample is too thick and too small for soundboard construction – was a 3mm sample of suitable dimensions for instrument building available off-the-shelf? |
| | A8 | Pedgley: The local supplier of the material was out of stock, so suitable 3mm material samples were ordered directly from the manufacturer. |
| Q9 | | Pedgley: What approach should be taken to evaluating foamed polycarbonate soundboards? |
| | A9 | Armstrong: It was not possible to predict accurately how well foamed polycarbonate would sound and whether it could resist the structural loading, when built into a guitar. The only way to find out was to make prototype instruments. |

Table 1. Material selection trail for polymer soundboard

foamed polycarbonate soundboard to a Kaman Applause AA33 guitar that featured nylon strings and a HPL soundboard. The AA33 was chosen because it was cheap and had a Lyrachord (glass fibre reinforced plastic) bowl back, so that after retrofitting a foamed polycarbonate soundboard an entirely 'all-polymer' sound box would be achieved.

Wood bracing in a classical 'fan' pattern was used to stiffen the polymer plate, copying the pattern used for the AA33's original soundboard. However, it proved too weak to support the tension of steel strings, and was replaced in a second lash-up with an 'X' bracing pattern. Tonally, the second lash-up demonstrated emphatically that a foamed polycarbonate soundboard could result in a final instrument that was unmistakably 'guitar like' in tone. This represented a major breakthrough in the use of non-woods in acoustic guitar construction. Although the instrument bass response was too overwhelming, owing to the soundboard and bowl back not being a perfect match, to the authors' ears the overall tone was



Figure 5. All-polymer acoustic guitar model FFS2002.

Figure 6. Advanced soundboard with perforated and integrally bent foamed polycarbonate braces.



considerably more characterful and pleasing than that of the unmodified AA33.

In subsequent prototypes, the use of foamed polycarbonate has been refined. Polymer rather than wood bracing has been introduced, and demonstrations have been made showcasing guitars made almost entirely from thermosetting and thermoplastic polymers (**Figure 5**). This developmental work has been carried out under the project name Cool Acoustics (2008).

EVALUATION

A sheet of 3mm foamed polycarbonate is flexible and heavy compared with spruce and cedar, and therefore demands bracing solutions with especially prominent stiffening parallel to the string tension. Cool Acoustics soundboards generally have an 'A' bracing pattern on the advice of Rob Armstrong, with recent developments including perforated and bent foamed polycarbonate braces for improving stiffness with zero weight gain (**Figure 6**).

| Property | Sitka Spruce | White Cedar | Forex® EPC | Palsun® Foam | Aluminum Alloy | CFRP |
|--|-------------------|-------------------|------------------|------------------|------------------|---------------|
| Young's Modulus E (MPa) | 11000 | 6400 | 1200 | 1500 | 69000 | 150000 |
| Density ρ (kgm ⁻³) | 400 | 320 | 650 | 800 | 2700 | 1700 |
| E/ ρ | 27.50 | 20.00 | 1.85 | 1.88 | 25.56 | 88.24 |
| E (% relative to sitka spruce) | 1.00 | 0.58 | 0.11 | 0.14 | 6.27 | 13.64 |
| ρ (% relative to sitka spruce) | 1.00 | 0.80 | 1.63 | 2.00 | 6.75 | 4.25 |
| E/ ρ (% relative to sitka spruce) | 1.00 | 0.73 | 0.07 | 0.07 | 0.93 | 3.21 |
| Fibre reinforcement | Cellulose+ Lignin | Cellulose+ Lignin | None | None | None | Carbon+ Epoxy |
| Directionality | Wood grain | Wood grain | None (isotropic) | None (isotropic) | None (isotropic) | Carbon weave |

Table 2. Properties of guitar soundboard materials (data from various sources)

Unconventional Material Properties

Table 2 gives property data for popular materials used in guitar soundboards, along with data for the commercial grades of foamed polycarbonate (Forex®-EPC, Palsun® Foam) used in Cool Acoustics soundboards.

Earlier in the paper it was established that stiffness-to-mass, represented as E/ρ , is important in acoustic guitar soundboards. However, E/ρ for foamed polycarbonate is dramatically low (7% that of sitka spruce). Furthermore, carbon fibre composite has a E/ρ value of around 300% that of sitka spruce. Following the results of this present research, it can be observed that soundboards with good mudicality can be made over at least a 1:45 range of E/ρ . With such a wide range, it is clear that E/ρ is a poor indicator of the suitability of a given non-wood material for use as an acoustic guitar soundboard. It is also intiguing to note that polymer foams are used most commonly for sound attenuation purposes and not propagation, such as in earplugs, flooring, loudspeaker cabinets, automotive interiors, recording studios, and anechoic chambers. These combined observations lead to the conclusion that other material properties, affecting internal damping of vibrations and tonal colorisation, on a micro structural level, must be far more important in determining the suitability of a non-wood material for use as a soundboard. Properties including hardness, glass transition temperature, chemical composition of the polymer, additives, or particular cellular topography could each be important factors, whether alone or in combination. However, little is currently known about the effect of microstructure even on the sound quality of wood instruments. For example, debates continue over the origin of material superiority attributed to Stradivari violins, with a recent study suggesting density differential between fast and slow growth regions of the violin wood to be important (Stoal and Borman, 2008). It can be speculated that the way a tree was sawn, its location on a slope relative to sun and rain, rapid growth in particular years, effects of bacteria on internal wood structure, or types and thickness of varnish might all be the reason for the superiority of Stradivari instruments, but the evidence so far is sparse.

To further reinforce the need for improved fundamental understanding of the acoustic properties of polymers, another thermoplastic material, foamed polyvinylchloride ($E=1300\text{MPa}$, $\rho=700\text{kgm}^{-3}$, $E/\rho=1.86$), was evaluated by the knuckle wrap test during A6 of the material selection trail,

and was found to be acoustically dead. It exhibited a dull thud with little sustain and accompanying material vibration, despite E and ρ values very close to foamed polycarbonate.

An additional matter that remains disputable is the importance of the anisotropic (directional) nature of wood for soundboard construction. From the innovation reported in this paper, there is no indication that anisotropy in non-wood soundboards is desirable or significant. The method of production of extruded foamed polycarbonate sheets imparts a cosmetic 'directionality', owing to the polymer melt being forced in a single direction through a die, but it does not translate to a differential between longitudinal and transverse mechanical properties. Instruments have been made with the extrusion grain both parallel and transverse to the strings, with no noticeable structural or acoustic differences. Furthermore, a guitar has been constructed using injection-moulded, rather than extruded, foamed polycarbonate sheet. The material had high density ($\rho=1000\text{kgm}^{-3}$) and a turbulent flow structure, owing to its manufacture within a closed mould, but its tone was still excellent.

Acoustic Evaluation

Acoustic damping is the characteristic of a material to attenuate particular frequencies of vibration through the conversion of kinetic energy into deformation of material structures and heat. Carbon fibre reinforced plastic soundboards, for example, exhibit linear damping across the spectrum of audible frequencies, resulting in a very bright and loud sound signature (Decker, 1999) but missing the complex non-linear sustain characteristics of wood, where certain frequencies are attenuated slower than others. The broad opinion from informal listening tests is that foamed polycarbonate soundboards have acoustic properties close to spruce or cedar. The sound quality impressed internationally acclaimed guitarist Gordon Giltrap to write a letter of support and endorsement for an early prototype instrument (1999).

"This instrument does not sound like plastic (whatever that's supposed to sound like) and I believe anyone listening to it will hear a sound usually associated with a good quality acoustic guitar of the wooden variety."

The results of listening tests have also shown that guitars fitted with Cool Acoustics soundboards have a noticeably strong bass response. It is not known yet whether this is attributable to the conservative transverse bracing patterns typically employed or to an inherent acoustic property of foamed polycarbonate. From the instrument designer's perspective, the strong bass response negates the need to (a) devise bracing schemes that promote bass, and (b) opt for large bodied instruments to generate strong bass.

Aesthetic Evaluation

Foamed polycarbonate has an attractive range of sensorial properties, including choices of surface reflectivity (from gloss to matte), surface texture, and pigmentation colour. It is a material well suited to a variety of cold, soft and melt forming processes, although inlays and other embellishments associated with wood construction are not easily reproduced and should be replaced with printing and marking technologies. Indeed, a labour-saving advantage of foamed polycarbonate is that it is usually produced with a closed-cell structure that does not require sealing or secondary finishing. The material has no obvious olfactory properties, although the adhesives used in construction have

odours that are characteristic of industrially manufactured plastics products, thus reinforcing a production aesthetic.

Additional Properties

The following additional properties of foamed polycarbonate are advantageous for its use in soundboards of mass-produced acoustic guitars.

- Thermoplastic polymer, suitable for injection moulding.
- Simple morphology, devoid of fibre reinforcement.
- Absent of across-grain vulnerabilities of wood.
- Permits monolithic soundboard construction with no 'book matched' join between two paired sheets, as is the case for wood.
- Low cost compared to spruce and cedar.
- Excellent service temperature range (-40°C to +120°C).
- Resistant to changes in humidity.
- Good impact strength.
- Recyclable.

ORIGINS OF INNOVATION

Entries into the diary of designing accompanying the innovation showed that 'hands-on' activity was prevalent throughout the innovation path. In other words, innovation was achieved by relying heavily on 'designing and making' and on vocational learning, sometimes also referred to as 'learning by doing'. Such activities are actually a basic human characteristic. A child's early experiences of the material world are through play, where he/she develops personal knowledge by handling, constructing and deconstructing objects, independent of verbal communications (Eggleston, 1998). Learning by doing has long served the professional creation of artefacts, with flint 'napping', welding, glassblowing, and the entire apprenticeship movement being examples.

The foamed polycarbonate soundboard innovation is a present-day example of a technological advance predating its scientific explanation and achieved separately from materials science or engineering knowledge. Other well-known examples are bridges, which predate stress analysis, and steam engines, which predate thermodynamics (Vincenti, 1990). Vocational learning is very normal for designers. They gather project-specific information on a need-to-know basis, by reading and writing knowledge that resides within products: "essentially, we can say that designerly ways of knowing rest on the manipulation of non-verbal codes in the material culture" (Cross, 2006).

It is easy to dismiss designing and making and its associated vocational learning as an illegitimate mode of enquiry for professional or scholarly activity, inferior to scientific methods or scientifically derived findings. This would be a serious oversight in the authors' opinions. The prevalence of learning by doing within this innovation case study demonstrates that vocational skills and know-how are still very relevant as a route to product innovation and for contributing to a knowledge-based economy. The findings also corroborate the argument that design education should uphold a strong vocational element (Norman, 2000).

CONCLUSIONS

The materials-inspired innovation reported in this paper has cast considerable doubts over conventional thinking on materials selection for acoustic guitar soundboards and has demonstrated the legitimacy of designerly ways of knowing and operating in contributing to technological innovation. Conclusions may be drawn for each of the research questions.

- **RQ1.** Soundboards constructed from foamed polycarbonate rival the quality of wood counterparts. With this discovery, a new industry based on polymer musical instruments can be contemplated.
- **RQ2.** Foamed polycarbonate soundboards have material specifications that differ substantially to spruce and cedar. Material selection was inspired by a cellular structure analogy with softwood. The suitability of foamed polycarbonate renders fibre reinforcement, material directionality, and especially high stiffness-to-mass properties as non-essential for soundboard materials.
- **RQ3.** Materials-inspired innovation was driven by expert understanding of technology for guitar design (from a luthier), fused with competence in product design and knowledge of polymer materials and processing (from an industrial designer). The innovation was attributable to designerly knowledge, values and skills and not to applied science. The research usefully illustrates and reinforces that designerly ways of knowing and operating can be used to push the frontiers of product technology, and that the pursuit of technological innovation need not necessarily involve science.

Wooden guitars built by luthiers will always be a tribute to the magnificent skill possessed by their makers. In the face of supply difficulties for tone woods, it seems right that luthiers should be using tone woods in high-end instruments, rather than this valuable resource being depreciated in mass-produced instruments. Through industrial design and the materials-inspired innovation reported in this paper, a new route to product excellence has been opened that circumnavigates the use of precious tone woods. The research team are currently pursuing its commercialisation. Furthermore, scientific research is planned in two areas to advance the technology and provide advice to instrument designers: (a) identification of the material properties that lead to high quality polymer acoustic guitar soundboards, and (b) human sound and visual perception studies in relation to wood and non-wood acoustic guitars.

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AKUSTİK GİTAR TASARIMINDA MALZEMEDEN İLHAM ALAN YENİLİKÇİLİK

Bu makale, akustik gitar sektöründe önemli bir yeniliğe (inovasyona) öncülük eden araştırmaya ait vaka çalışmasını sunmaktadır. Görece tutucu bir kullanıcı kitlesine sahip olan akustik gitar, ahşap ile bütünleşen yüzyıllık tasarım ve gelişmenin sonucu olarak geleneksel bir ürün haline gelmiştir. Diğer birçok ürün sektöründe olduğu gibi, akustik gitarların da pekçoğu Çin'de endüstriyel olarak üretilmekte ve düşük işçilik maliyetleri sayesinde ortalama fabrika çıkış fiyatları sadece 20 ABD dolarını bulmaktadır. Bu makalede, el imalatı ahşaptan uzaklaşıp endüstriyel olarak kalıplanmış termoplastik parça montajına yönelerek, gitar malzemesinde atılan cesur bir adımı anlatan araştırma ele alınmaktadır. Araştırma, böyle bir malzeme değişikliğinin düşük maliyet ile işçi çalıştıran ülkelerin haricinde rekabetçi endüstriyel akustik gitar üretimine de destek vermesini ve bu popüler müzik aletinin tasarımını canlandırmasını öngörmektedir. Araştırmanın anlatımı içerisinde termoplastik akustik gitarın teknik, estetik, pazar ve ticari gereksinimlerine önem verilmiştir; ürün tasarımını geliştirecek uygun tavsiyelerin nasıl derleneceği tartışılmıştır. Bu sırada, enstrümanın sesi üreten temel parçası olan ön paneli üzerine

odaklanılmaktadır. Araştırma, patent alınmış olan gitar ön ses paneli teknolojisiyle desteklenen üç sonuca ulaşmıştır. Birinci sonuç, sünger yapılı polikarbonattan yapılan ön ses panelinin ahşap benzerlerinin kalitesiyle rekabet etmesidir: böyle bir sonuç polimer müzik aletlerine yönelik yeni bir endüstriye yol açma potansiyeline sahiptir. İkinci sonuç, sünger yapılı polikarbonat ses panellerinin fiziksel malzeme özelliklerinin ahşaptan çok farklı olmakla birlikte birbirlerine eşdeğer akustik performans gösterdikleridir. Üçüncü sonuç ise, bu ürün sektöründe yenilikçiliğin daha çok tasarımcı yaklaşımli bilme ve yapmaya dayalı oluşu ve bilimsel buluştan görece daha az destek almış olmasıdır.

