The material and process requirements for driving shaft engineering essay

Based on my research, a drive shaft, driving shaft or propeller shaft is a mechanical component for transmitting torque and rotation that usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.

Besides that, drive shafts carrying an important role as carrier of torque in driveline application. They are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. Therefore, they must be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia.

Drive shafts frequently incorporate one or more universal joints or jaw couplings, and sometimes a splinted join or prismatic join to allow for variations in the alignment and distance between the driving and driven components

Based on the functions that has been discussed in previous, I know that the material of drive shaft must be strong enough to bear the stress, light weight which able to reduce the overall automobile weight and thus, increase their inertia at the same time.

For the mechanical properties that required for drive shaft including the ability to minimize the losses in transmission, high tensile strength material, high torsional strength and light weight. Therefore, I would like to suggest that polymer matrix composite is more suitable as a chosen material that can be apply in driveline application.

1. 1 Design Factors

In the progress of my research in driveline application, I found out that marketing considerations are paramount in the motor car industry. There are two factors make this particular application attractive to the industry.

On the one hand, vehicles are solid in the market place on claims of increased comfort, luxury and smoothness of operation. On the other hand, the manufacturer is also seeking to provide the maximum performance with the minimum fuel usage at the same time.

Thus, usually these two requirements are conflicting. For example, a decrease in body panel thickness reduces mass and so increases performance and fuel efficiency, but this change also increases internal noise. Therefore, some automobile industry has spend much modal in doing research and recently, they have an idea which using carbon fiber (polymer matrix composite) in drive shafts which able to contributes to achieving both aims simultaneously.

The factors to be optimized in a shaft after meeting the basic operating requirements just outlined is mass, smoothness of ride and cost. This is because reducing mass is important:

To improve performance of vehicle and reduce fuel consumption.

To reduce un-sprung mass and so improve vehicle handling and ride.

To reduce the residual out of balance forces from rotating parts and so further improve smoothness in use.

2. 0 Material Selection

Based on the research of different type of material of drive shaft or propeller shaft in driveline application, I have chosen polymer matrix composite as the material selection in driveline application.

2. 1 Introduction to Polymer Matrix Composite

Polymer Matrix Composite is the material consisting of polymer matrix combined with a fibrous reinforcing dispersed phase. Polymer matrix composites are very popular due to their low cost and simple fabrication methods.

Use of non-reinforced polymers as structure materials is limited by low level of their mechanical properties such as tensile strength of one of the strongest polymers (epoxy resin) is 20000 psi (140 Mpa). In addition to relatively low strength, polymer materials posses low impact resistance as well.

Besides that, the reinforcement tends to be stiffer and stronger than the matrix providing stiffness and strength. Reinforcement is laid in a particular direction, within the matrix, so that the resulting material will have different properties in different directions. As example, composites have anisotropic properties. This characteristic is exploited to optimize the design and provide high mechanical performance where it is needed.

2. 2 Design of a Composites Shaft

According to A. W. Thompson from Bristol Composite Materials Engineering Ltd, He has mentioned the two typical shafts side by side, one made in steel and the other in composites as shown in Figure 1.

Figure 1 Composite Drive Shaft (Upper) with Steel Shaft

The illustration shows the simplicity of the design made possible by carbon fiber. The combination of high stiffness and low density in the composite enables a longer shaft to be made without reaching a critical whirling speed. The whirling speed of a rotating shaft is the speed at which it becomes unstable and defluxions occurs normal to the axis of rotation. The advantage in whirling speed is such as to enable most two piece steel shaft to be replaced with a single composite part.

Besides that, weight and cost are reduced by dispensing with the central universal joint and the associated bearing. Moreover, N. V. H (Noise, Vibration and Harshness) factors are improved by the consequent isolation of the passenger compartment from drive line vibration following deletion of the centre bearing from underneath the driver’s seat. Further reductions in N. V. H are possible by modification to the orientations of the fibres in the properller shaft tube, which effect longitudinal and radial stiffness.

2. 3 Reason Selecting Polymer Matrix Composite as Material in Driveline Application

The basic attraction of polymer matrix composite materials for driveshaft application is that they make it possible to increase the shaft length, which is otherwise constrained by bending resonance. For many vehicles, a one piece composite shaft may replace a two piece steel shaft which simplifies both the shaft and installation in the vehicle.

Besides that, by using fibre reinforced composites, it is possible to arrange the fibre orientations in the tube so that the bending modulus has a high value (above 100Gpa) whilst the specific gravity is low (below 1. 6). This leads to a favourable specific bending modulus and an enhanced critical speed as well.

Figure 2 Critical Speeds for Automotive Propshaft

According to A. W. Thompson from Bristol Composite Materials Engineering Ltd, the relationship between shaft length and critical speed for tubes suitable for automotive propshaft is illustrated in Figure 2.

The graph shows that, for a particular application where a critical speed of 8000 rev/min is acceptable, the longest shaft possible out of steel is 1250 mm whereas a composite shaft of 1650 mm could be achieved.

Thus, the maximum length for either shaft is reduced depending on the compliance of the end connections. For acceptable NVH (Noise, Vibration and Harshness), there must also be an adequate margin between vibration drivers and bending resonance of the shaft. Nevertheless, it is generally true that a composite shaft can be made longer than a steel shaft and that for automotive platforms where a two-piece steel shaft with centre support bearing is specified a one-piece composite shaft may be acceptable.

This fundamental material property advantage is a powerful technical driver for composite shafts, and substantial weight savings can be achieved. One-piece shafts also simplify the design and engineering of the vehicle floor pan.

Therefore, based on explanation above, it is obviously that I have chosen carbon fiber composite (one type of the polymer matrix composite) as the material for drive shaft and further material properties will be discuss in detail later as well.

2. 3. 1 Material Property of Carbon Fiber Composite (Polymer Matrix Composite)

According to Core Composites, Division of ROM Development Corporation's research, the material properties of Carbon Fiber Composite are as below:

Features

Benefits

Extremely High Stiffness

With a variety of modulus available from standard 33 msi to ultra high modulus pitch over 125 msi carbon fiber has the highest specific modulus of all the commercial reinforcing fibers.

High Tensile Strength

The strongest of all commercial reinforcing fibers in tension. Especially good for the tension skin on composite laminates.

Excellent Corrosion Resistance

Used in reinforcing concrete, carbon has good alkaline resistance as well as resistance to salt water and many other chemical environments.

Excellent Fatigue Properties

Used as a primary reinforcement for fatigue prone products such as helicopter and wind turbine blades as well as offshore power and driveline application.

Excellent Compression Properties

Proper fiber sizing for the resin matrix selected can yield impressive compressive properties but this quality can be quite difficult to measure with standard ASTM test methods and careful test specimen preparation is critical to achieve accurate result.

Low Coefficient of Linear Expansion

Carbon is a good tooling reinforcement for molds that will see temperature and where parts need tight dimensional stability.

2. 3. 2 Composite Shaft Performance

According to the research that done by Tetsuyuki Kyono, Composites Development Center, Toray Composites (America), Inc. about the carbon fiber composites applications for auto industries, they have mentioned about carbon fiber composite drive shaft having crush worthiness. Crash load generated during head collision can be absorbed by newly developed joining technology with no adhesive between carbon fiber composite tube and steel adapter.

This technology can add safety value to passenger cars in addition such as weight and noise reductions. Therefore, the performance data of the composite shaft should be take consideration as one of the main section in choosing the best material to apply in driveline application.

Thus, they have evaluated torque carrying capability as index of shaft performance. One of typical data has been shown in Figure 3. It is noted composite drive shaft performed as expected up to 150â-¦C at static torsional test and showed much better fatigue resistance than steel system shown as target.

Figure 3 Torsional Strength of Drive Shaft for 2000 Nm Class

In Figure 4, residual torque carrying capabilities after exposure to various environments are shown in percentage compare with control data. As shown below has shown the reduction in performance of composite drive shaft is very minimal.

Figure 4 Residual Torsional Strength (%) after Environmental Testing

2. 3. 3 Proving Test

After the obvious laboratory tests above to show static strength and stiffness, fatigues tests are important as well. Carbon fibre has an excellent performance in fatigue and glass fibre is as good as most metals.

A composite shaft has withstood 106 cycles of maximum torque as compared with the 104 cycles typically required of a steel shaft. Shafts were fitted to cars to gain road experience and demonstrate satisfactory operations. Such testing demonstrates that the component really works and meets all the criteria required.

In this application, for instance, road use showed that:

Temperature resistance to underbody environment was satisfactory

Corrosion resistance (example: to salt spray was not a problem)

Creep loading resistance was adequate

Resistance to flying stone damage was not a problem

End attachment strength was adequate

Shock load capability was adequate

Based on the proving test that has been done by A. W. Thompson, we knew that polymer matrix composites is suitable to be taken as material in driveline application such as making drive shaft or propeller shaft as well due to its attractive material properties and more affordable cost as well if compare with others material such as steel.

2. 3. 4 Crash Performance of Composite Propshafts

According to Dr Andrew Pollard, GKN Technology, Wolverhampton, UK, he stat that increasing public interest in safe vehicles is encouraging car manufacturers and their suppliers to design components and systems that will perform well in a crash (2). The propeller shaft in rear- and fourwheel-drive cars is good example of this.

Figure 5 Behaviour of Propeller Shafts in Frontal Crash

In a frontal crash, the propeller shaft transmits forces from the engine/gearbox unit to the rear axle. Many vehicles today have a two-piece propeller shaft that can buckle at the centre bearing in any direction, depending on the joint position at impact. It is therefore virtually impossible to predict the axial force and the energy absorbed by the shaft in a crash.

This is illustrated in Figure 5, contrasted with the behavior of a propeller shaft with a defined axial collapse mode. The target for crash-optimized propeller shafts is to achieve a defined behavior of axial force and displacement during an impact and consequently controlled energy absorption as shown in Figure 5.

3. 0 Manufacturing Process of Carbon Fiber

The process for making carbon fibers is part chemical and part mechanical. The precursor is drawn into long strands or fibers and then heated to a very high temperature with-out allowing it to come in contact with oxygen. Without oxygen, the fiber cannot burn. Instead, the high temperature causes the atoms in the fiber to vibrate violently until most of the non-carbon atoms are expelled. This process is called carbonization and leaves a fiber composed of long, and tightly.

The fibers are coated to protect them from damage during winding or weaving. The coated fibers are wound onto cylinders called bobbins.

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Moreover, the inter-locked chains of carbon atoms with only a few non-carbon atoms remaining.

Here is a typical sequence of operations used to form carbon fibers from polyacrylonitrile.

3. 1 Spinning

First: Acrylonitrile plastic powder is mixed with another plastic, like methyl acrylate or methyl methacrylate, and is reacted with a catalyst in a conventional suspension or solution polymerization process to form a polyacrylonitrile plastic.

Second: The plastic is then spun into fibers using one of several different methods. In some methods, the plastic is mixed with certain chemicals and pumped through tiny jets into a chemical bath or quench chamber where the plastic coagulates and solidifies into fibers. This is similar to the process used to form polyacrylic textile fibers. In other methods, the plastic mixture is heated and pumped through tiny jets into a chamber where the solvents evaporate, leaving a solid fiber. The spinning step is important because the internal atomic structure of the fiber is formed during this process.

Third: The fibers are then washed and stretched to the desired fiber diameter. The stretching helps align the molecules within the fiber and provide the basis for the formation of the tightly bonded carbon crystals after carbonization.

3. 2 Stabilizing

Forth: Before the fibers are carbonized, they need to be chemically altered to convert their linear atomic bonding to a more thermally stable ladder bonding. This is accomplished by heating the fibers in air to about 390-590° F (200-300° C) for 30-120 minutes. This causes the fibers to pick up oxygen molecules from the air and rearrange their atomic bonding pattern. The stabilizing chemical reactions are complex and involve several steps, some of which occur simultaneously. They also generate their own heat, which must be controlled to avoid overheating the fibers. Commercially, the stabilization process uses a variety of equipment and techniques. In some processes, the fibers are drawn through a series of heated chambers. In others, the fibers pass over hot rollers and through beds of loose materials held in suspension by a flow of hot air. Some processes use heated air mixed with certain gases that chemically accelerate the stabilization.

3. 3 Carbonizing

Fifth: Once the fibers are stabilized, they are heated to a temperature of about 1, 830-5, 500° F (1, 000-3, 000° C) for several minutes in a furnace filled with a gas mixture that does not contain oxygen. The lack of oxygen prevents the fibers from burning in the very high temperatures. The gas pressure inside the furnace is kept higher than the outside air pressure and the points where the fibers enter and exit the furnace are sealed to keep oxygen from entering. As the fibers are heated, they begin to lose their non-carbon atoms, plus a few carbon atoms, in the form of various gases including water vapor, ammonia, carbon monoxide, carbon dioxide, hydrogen, nitrogen, and others. As the non-carbon atoms are expelled, the remaining carbon atoms form tightly bonded carbon crystals that are aligned more or less parallel to the long axis of the fiber. In some processes, two furnaces operating at two different temperatures are used to better control the rate de heating during carbonization.

3. 4 Treating the Surface

Sixth: After carbonizing, the fibers have a surface that does not bond well with the epoxies and other materials used in composite materials. To give the fibers better bonding properties, their surface is slightly oxidized. The addition of oxygen atoms to the surface provides better chemical bonding properties and also etches and roughens the surface for better mechanical bonding properties. Oxidation can be achieved by immersing the fibers in various gases such as air, carbon dioxide, or ozone; or in various liquids such as sodium hypochlorite or nitric acid. The fibers can also be coated electrolytically by making the fibers the positive terminal in a bath filled with various electrically conductive materials. The surface treatment process must be carefully controlled to avoid forming tiny surface defects, such as pits, which could cause fiber failure.

3. 5 Sizing

Seventh: After the surface treatment, the fibers are coated to protect them from damage during winding or weaving. This process is called sizing. Coating materials are chosen to be compatible with the adhesive used to form composite materials. Typical coating materials include epoxy, polyester, nylon, urethane, and others.

Eight: The coated fibers are wound onto cylinders called bobbins. The bobbins are loaded into a spinning machine and the fibers are twisted into yarns of various sizes.

3. 6 Quality Control

The very small size of carbon fibers does not allow visual inspection as a quality control method. Instead, producing consistent precursor fibers and closely controlling the manufacturing process used to turn them into carbon fibers controls the quality. Process variables such as time, temperature, gas flow, and chemical composition are closely monitored during each stage of the production.

The carbon fibers, as well as the finished composite materials, are also subject to rigorous testing. Common fiber tests include density, strength, amount of sizing, and others. In 1990, the Suppliers of Advanced Composite Materials Association established standards for carbon fiber testing methods, which are now used throughout the industry.

3. 7 Health and Safety Concerns

There are three areas of concern in the production and handling of carbon fibers: dust inhalation, skin irritation, and the effect of fibers on electrical equipment.

During processing, pieces of carbon fibers can break off and circulate in the air in the form of a fine dust. Industrial health studies have shown that, unlike some asbestos fibers, carbon fibers are too large to be a health hazard when inhaled. They can be an irritant, however, and people working in the area should wear protective masks.

The carbon fibers can also cause skin irritation, especially on the back of hands and wrists. Protective clothing or the use of barrier skin creams is recommended for people in an area where carbon fiber dust is present. The sizing materials used to coat the fibers often contain chemicals that can cause severe skin reactions, which also requires protection.

In addition to being strong, carbon fibers are also good conductors of electricity. As a result, carbon fiber dust can cause arcing and shorts in electrical equipment. If electrical equipment cannot be relocated from the area where carbon dust is present, the equipment is sealed in a cabinet or other enclosure.

4. 0 Fabrication Process of Driveshaft by using Polymer Matrix Composite

According to the project research that done by Alex Santiago from Texas A&M University Kingsville, he has discussed the fabrication process of drive shaft by using polymer matrix composite which is carbon fiber as main material.

As reference, the fabrication process by Alex has been taken for me to understand the hand make drive shaft by using carbon fiber in real life. Thus, the following fabrication process is belonging to Alex from Texas University which is worth to be taken as references in this topic discussion.

There are several things to consider when picking a fabrication method. Time is a major consideration. There is little time for fabrication, so the fabrication process has to be quick. The fiber has to be laid at specific angles to give the shaft certain characteristics. The weave patterns have to be tight and compact. Resin has to be applied evenly. The shaft has to be wound in a way such that the yokes can be easily attached. The easiest fabrication method for creating a hollow tube is filament winding. Filament winding is an automated process in which a filamentary yarn in the form of tow is wetted by resin and uniformly and regularly wound about a rotating mandrel. The filament winder can be programmed to create specific and tightly wound patterns.

To create a composite part on the winder, a winding pattern is needed, along with a mandrel, mold release, fiber, resin and hardener, a way to apply even pressure to the part and a curing procedure. The wind patterns were determined by using Laminate Design software created by Dr. Larry Peel. After entering mechanical properties for the resin and tow, different wind angles and layers were tried in the Laminate Design software until the driveshaft had the desired characteristics. Table 1 gives the wind angle and its purpose.

The tow, resin and hardener, and adhesive are the most critical elements of the shaft. Each structural component must be carefully selected so that the shaft has good mechanical properties. The tow which was used in the Laminate Design Software calculations was chosen because it is strong, light weight, and aerospace quality carbon fiber. Fiber used by the aerospace, although expensive, is rigorously quality controlled. It was decided that this fiber would be uniform, therefore giving the driveshaft uniform properties.

The resin and hardener were chosen for several reasons. First, the resin is tough. The resin also has a high viscosity. High viscosity is desired because, with the wet winding process, is easier to control the amount of resin being applied to the tow. Wet winding will be discussed further in the process section. Another reason for choosing this resin is its elongation at break. At 6% elongation at break, it is known that the resin will not be too brittle and that the wound shaft will have some flex for absorbing the shock between shifting gears. Finally this resin was chosen because of its high pot life. After mixing the resin and hardener, there is a little over two hours before it begins to gel. This is enough time to wind the entire shaft before the resin sets up.

The adhesive was chosen for a few reasons. Foremost, the adhesive also met the criteria for high tensile lap shear strength at room and elevated temperatures. At room temperature the adhesive has lap shear strength of 4, 200 psi. At 250 F the lap shear strength is 2, 300 psi. Also, the adhesive is aerospace grade, ensuring high quality.

Table 1 Wind Angles

4. 1 Mandrels

In order to produce the mandrel of a driveshaft, several derivations should have gone through. Mandrels made of cardboard tubing and solid shafts were considered. These ideas were never fabricated because it would be hard to remove the mandrel from the wound tube. The resin would cause the cardboard mandrel to stick to the shaft making it impossible to remove. A solid shaft of steel or aluminum would be heavy, and expensive to create.

4. 1. 1 Mandrel 1

Firstly, it was decided to create a mandrel made of steel muffler tubing which was split with a plasma cutter into four parts along its length. The idea was to wind the shaft, let it cure, then dismantle the mandrel and remove the tube. Next, two pieces machined out of steel were created and attached to the muffler tubing which allows the mandrel to be spun in the filament winder. One end is chucked into the winder the other end has a live center which spins on a center point. This mandrel did not work because the mandrel pieces could not be bolted to the machined ends in a way that they were square. This was due to the fact that the muffler tubing is cold rolled which means it is pre-stressed. Once the tubing was split into four pieces, each piece bowed.

4. 1. 2 Mandrel 2

A second mandrel was created using muffler tubing which was split into two pieces. This mandrel was square when bolted into place. To keep the tension of the fiber from pulling the gap in the mandrel closed, three round, wooden pucks were evenly spaced through the center of the mandrel.

The second mandrel was used to create a practice drive shaft. The pucks were evenly spaced through the center of the mandrel. Shrink wrap tape, which shrinks and applies pressure when heated, is wrapped around the mandrel over the areas where the pucks are. The tape applies pressure and keeps the pucks in an upright position as shown in Figure 6. Once the pucks were set in place, a few dry runs were made with no resin. One pass of each fiber angle was wound.

Figure 6: Wooden Puck in Mandrel

Once the winding began, it became obvious that there was not enough turn around room. When winding a composite part, there are four defined areas on the part. The entire part consists of the head, the turn around, the useable shaft, and the tail. The winding layout is shown in Figure 6. The wind angle is the angle the fiber makes with the center line of the mandrel. The 45 degree and 15 degree wind angles did not have enough friction to stick to the mandrel in the turnaround areas. The fiber began to slip and bunch up, causing misalignment in the pattern.

Figure 6: Winding Layout

This created a new problem. To keep the fiber from slipping, the turnaround area needed to be lengthened. The mandrel at its current length just fits in the curing oven, making it impossible to lengthen the mandrel. To alleviate this problem, two pieces of pipe, about one foot long each, were threaded into the ends of the machined pieces as shown in Figure 7. Adding the extensions made more turn around area. These threaded pieces can be removed once the shaft is wound and the resin sets up. When the extensions are removed the mandrel can easily be placed in the oven to finish curing.

Figure 7 Mandrel Extensions

The wind patterns were tested again with the extended turn around room. The extensions and the change in diameter kept the fiber from slipping, and allowed for full uniform coverage by the fiber. The test patterns were removed, and resin and hardener were mixed and poured into the resin bath to start a practice shaft. The resin bath applies resin to the fiber before it is wound about the mandrel. The resin bath can be seen in Figure 8. A practice shaft was wound using the setup shown in Table 2. A practice shaft was wound for a few reasons. The practice shaft allowed testing of the wind patterns with the resin and the fiber together. Curing temperature and time could be observed. Dismantling the shaft can be attempted, and the shaft can be inspected for proper resin wet out, roundness, and overall strength.

Table 2 Practice Shaft Wind Pattern Setup

Figure 8 Resin Bath

This was a very difficult process. First, the material that wrapped over the end caps had to be cut back in order to expose the bolts holding it to the mandrel. Once this was accomplished we began removing the bolts. Resin had seeped into the threads of some of the bolts causing them to stick. The head of one bolt was twisted off trying to get it out. This bolt was machined out. Once the caps were removed the shaft did not collapse as expected. The gap were the mandrel had been split had filled in with resin. A tubing cutter was used to cut the shaft into sections and then it was split in half with a band saw. A 2 foot piece was spared and slid off the shaft. The ridge left inside the shaft was 0. 125 inches deep. This created a stress riser that severely reduced the integrity of the shaft. It was obvious that this mandrel was not going to work.

4. 1. 3 Mandrels 3

Improving upon the mistakes on the previous mandrels, a new, one piece, mandrel was made from aluminum tubing. The tubing maintained a 2. 75 inch OD and was readily available. A 16 gauge 2. 75 OD tube was purchased. The tubing is normally made for turbo charger inlet ducting. A test piece was cut from the tube to be used for testing. The test piece was wet sanded with 2000 grit sandpaper. A silicone mold release compound was applied to the test shaft. 90° test patterns were wound onto the piece and cured at 250°F for 15 hours.

We used a higher curing temperature in order to expand the aluminum mandrel while compacting the fiber. After curing was complete, we then placed the test mandrel in the deep freeze that was Ö¾20°F in order to shrink the aluminum tube. The test mandrel was removed from the freezer. The tube was impacted onto a block of wood while holding the fiber. The mandrel came out with no difficulty. This test was successful.

The third mandrel was fitted to the end caps. The end caps were then bolted to the mandrel. Figure 9 shows the final mandrel.

Figure 9 Final Mandrel of Driveshaft

5. 0 Conclusion

As conclusion, the potential for carbon fibre composites (one type of polymer matrix composite) in automotive drive shafts as a means of achieving substantial weight reduction has long been recognized and has been demonstrated in small volume since 1988.

Finally, I think that polymer matrix composites is the most suitable materials which can applied in driveline application and engineers should find cost effective applications on it to bring this applications to fruitful use in future.