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Review of Design of Hybrid Aluminum/ Composite Drive Shaft for Automobile

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Abstract*— This topic deals with the study of replacement of conventional two-piece steel drive shafts with one-piece automotive hybrid aluminum/composite drive shaft & was developed with a new manufacturing method, in which a carbon fiber epoxy composite layer was co-cured on the inner surface of an aluminum tube rather than wrapping on the outer surface to prevent the composite layer from being damaged by external impact and absorption of moisture. Replacing composite structures with conventional metallic structures has many advantages because of higher specific stiffness and higher specific strength of composite materials. By considering the thermal residual stresses of the interface between the aluminum tube and the composite layer, the optimum stacking sequence is calculated with the help of Finite element analysis. Press fitting method for the joining of the aluminum/composite tube and steel yokes was devised to improve reliability and to reduce manufacturing cost, compared to other joining methods such as adhesively bonded, bolted or riveted and welded joints. The joining of the aluminum -composite tube and steel yoke with improved reliability and optimum manufacturing cost is done by press fitting. In order to increase the torque transmission capacity protrusion shape is provided on the inner surface of steel yoke which will fit on Universal joints.

***Index Terms:* Drive shaft, composite material, Aluminum / composite drive shaft design. Press fitted Joints, Static Torque.**

I. INTRODUCTION

An automotive drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. The torque capability of the drive shaft for passenger cars should be larger than 3500 Nm and the fundamental bending natural frequency should be higher than 9200 rpm [1] to avoid whirling vibration. Since the fundamental bending natural frequency of a one-piece drive shafts made of steel or aluminum is normally lower than 5700 rpm when the length of the drive shaft is around 1.5 m [1], the steel drive shaft is usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. The two-piece steel drive shaft consists of three universal joints, a center supporting bearing and a bracket, which increases the total weight of an automotive vehicle and decreases fuel efficiency

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. Since carbon fiber epoxy composite materials have more than four times specific stiffness (E= ρ) of steel or aluminum materials, it is possible to manufacture composite drive shafts in one-piece without whirling vibration over 9200 rpm[1]. The composite drive shaft has many benefits such as reduced weight and less noise and vibration. However, because of the high material cost of carbon fiber epoxy composite materials, rather cheap aluminum materials may be used partly with composite materials such as in a hybrid type of aluminum/composite drive shaft, in which the aluminum has a role to transmit the required torque, while the carbon fiber epoxy composite increases the bending natural frequency above 9200 rpm.

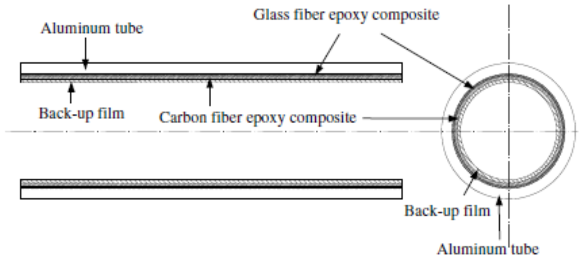

Fig.1: Schematic diagram of the co-cured aluminum/composite drive shaft.

A) Purpose Of The Drive Shaft (Or Propeller Shaft)

The torque that is produced from the engine and transmission must be transferred to the rear wheels to push the vehicle forward and reverse. The drive shaft must provide a smooth, uninterrupted flow of power to the axles. The drive shaft and differential are used to transfer this torque.

B) Functions Of The Drive Shaft

1) First, it must transmit torque from the transmission to the differential gear box. 2) During the operation, it is necessary to transmit maximum low-gear torque developed by the engine. 3) The drive shafts must also be capable of rotating at the very fast speeds required by the vehicle. 4) The drive shaft must also operate through constantly changing angles between the transmission, the differential and the axles. As the rear wheels roll over bumps in the road, the differential and axles move up and down. This movement changes the angle between the transmission and the differential. 5) The length of the drive shaft must also be capable of changing while transmitting torque. Length changes are caused by axle movement due to torque reaction, road deflections, braking loads and so on. A slip joint is used to compensate for this motion. The slip joint is usually made of an internal and external spline.

It is located on the front end of the drive shaft and is connected to the transmission.

C) Different Types Of Shafts

1) Transmission shaft: These shafts transmit power between the source and the machines absorbing power. The counter shafts, line shafts, overhead shafts and all factory shafts are transmission shafts. Since these shafts carry machine parts such as pulleys, gears etc., therefore they are subjected to bending moments in addition to twisting.
2) Machine Shaft: These shafts form an integral part of the machine itself. For example, the crankshaft is an integral part of I.C.engines slider-crank mechanism.
3) Axle: A shaft is called “an axle”, if it is a stationary machine element and is used for the transmission of bending moment only. It simply acts as a support for rotating bodies. 4) Spindle: A shaft is called “a spindle”, if it is a short shaft that imparts motion either to a cutting tool or to a work-piece.Applications:1) Drill press spindles-impart motion to cutting tool (i.e.) drill.2) Lathe spindles-impart motion to work-piece.
5) Ship Propeller Shaft: Transmits power from gearbox to propeller attached on it.
6) Helicopter Tail Rotor Shaft: Transmits power to rail rotor fan.
7) Automobile Drive Shaft: Transmits power from main gearbox to differential gear box

Fig.2: An automobile drive shaft

D) Drive Shaft Arrangement In A Car Model

Conventional two-piece drive shaft arrangement for rear wheel vehicle driving system is shown in fig 3 [2] below.

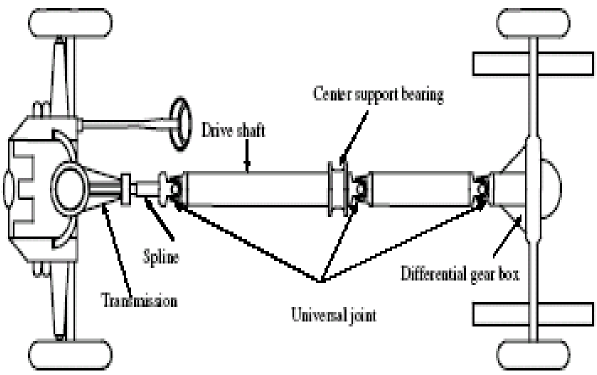

Fig 3: Conventional two-piece drive shaft arrangements for rear wheel driving system

E) Parts Of Drive Shaft And Universal Joint

Parts of drive shaft and universal joint are shown in fig. 4 Parts of drive shaft and universal joints are:
1. U-bolt nut 2. U-bolt washers 3. U-bolt 4. Universal joint journal 5. Lubrication fitting 6. Snap ring.
7. Universal joint sleeve yoke 8. Spline seal 9. Dust cap
10. Drive shaft tube

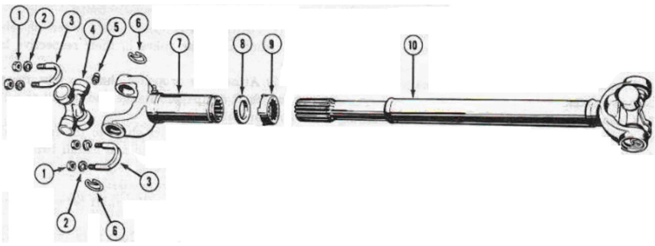

Fig 4: Parts of drive shaft and universal joint

II. THEORY

A) COMPOSITE MATERIAL

A material composed of 2 or more constituents is called composite material.

Composites consist of two or more materials or material phases that are combined to produce a material that has superior properties to those of its individual constituents. The constituents are combined at a macroscopic level and or not soluble in each other. The main difference between composite and an alloy are constituent materials which are insoluble in each other and the individual constituents retain those properties in the case of composites, whereas in alloys, constituent materials are soluble in each other and forms a new material which has different properties from their constituents.

Classification of Composites

- Polymer matrix composites
- Metal matrix composites
- Ceramic Matrix

B) ADVANTAGES OF COMPOSITES

The advantages of composites over the conventional materials are: High strength to weight ratio, high stiffness to weight ratio, high impact resistance, better fatigue resistance, Improved corrosion resistance, Good thermal conductivity, Low Coefficient of thermal expansion. As a result, composite structures may exhibit a better dimensional stability over a wide temperature range, high damping capacity.

C) LIMITATIONS OF COMPOSITES

The limitations of composites are: Mechanical characterization of a composite structure is more complex than that of a metallic structure, the design of fiber reinforced structure is difficult compared to a metallic structure, mainly due to the difference in properties in directions, the fabrication cost of composites is high, rework and repairing are difficult, they do not have a high combination of strength and fracture toughness as compared to metals and they do not necessarily give higher performance in all properties used for material selection.

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D) APPLICATIONS OF COMPOSITES

The common applications of composites are extending day by day. Now a day they are used in medical applications too. The other fields of applications are[8]:

Automotive: Drive shafts, clutch plates, engine blocks, push rods, frames, valve guides, automotive racing brakes, filament–wound fuel tanks, fiber Glass/Epoxy leaf springs for heavy trucks and trailers, rocker arm covers, suspension arms and bearings for steering system, bumpers, body panels and doors.

Space: payload bay doors, remote manipulator arm, high gain antenna, antenna ribs and struts etc. Marine: Propeller vanes, fans & blowers, gear cases, valves & strainers, condenser shells.

Chemical Industries: Composite vessels for liquid natural gas for alternative fuel vehicle, racked bottles for fire service, mountain climbing, underground storage tanks, ducts and stacks etc.

Aircraft: Drive shafts, rudders, elevators, bearings, landing gear doors, panels and floorings of airplanes etc.

Electrical & Electronics: Structures for overhead transmission lines for railways, Power line insulators, Lighting poles, Fiber optics tensile members etc.

Sports Goods: Tennis rackets, Golf club shafts, Fishing rods, Bicycle framework, etc.

E) DEMERITS OF A CONVENTIONAL DRIVE SHAFT

They have less specific modulus and strength and have increased weight. Conventional steel drive shafts are usually manufactured in two pieces to increase the fundamental bending natural frequency because the bending natural frequency of a shaft is inversely proportional to the square of beam length and proportional to the square root of specific modulus. Therefore the steel drive shaft is made in two sections connected by a support structure, bearings and U-joints and hence over all weight of assembly will be more. Its corrosion resistance is less as compared with composite materials and steel drive shafts have less damping capacity.

F) MERITS OF HYBRID ALUMINIUM/COMPOSITE DRIVE SHAFT

They have high specific modulus and strength and reduced weight. A one-piece composite shaft can be manufactured so as to satisfy the vibration requirements. This eliminates all the assembly, connecting the two piece steel shafts and thus minimizes the overall weight, vibrations and the total cost. Due to the weight reduction, fuel consumption will be reduced. They have high damping capacity hence they produce less vibration and noise. They have good corrosion resistance and greater torque capacity than steel shaft. Longer fatigue life than steel shaft. Lower rotating weight transmits more of available power.

III. CASE STUDY

A) DESCRIPTION OF THE PROBLEM

Fig 5: A two-section drive shaft of a truck.

Almost all automobiles (at least those which correspond to design with rear wheel drive and front engine installation) have transmission shafts. The weight reduction of the drive shaft can have a certain role in the general weight reduction of the vehicle and is a highly desirable goal, if it can be achieved without increase in cost and decrease in quality and reliability. It is possible to achieve design of one-piece automotive hybrid aluminum/composite drive shaft with less weight to increase the first natural frequency of the shaft and to decrease the bending stresses using various stacking sequences. By doing the same, we maximize the torque transmission, static torque capability, buckling torque capability and bending natural frequency.

B) DESIGN OF THE ALUMINIUM/COMPOSITE DRIVE SHAFT

The aluminium/composite drive shaft should satisfy three design specifications such as static torque capability, buckling torque capability and bending natural frequency. The major role of the aluminium tube is to sustain an applied torque while the role of the carbon fiber epoxy composite is to increase bending natural frequency. The carbon fiber epoxy prepreg was USN150 manufactured by SK Chemicals (Korea), whose properties are similar to T300/5208. Tables 1 and Table 2 [1][2]shows the mechanical properties of the carbon fiber epoxy composite and the aluminium tube (6061-T6), respectively.

The torque transmitted by the hybrid drive shaft, T is the sum of the torque transmitted by the aluminium tube Tal and that by the composite layer, [1][2]Tco

$$T = T_{al} + T_{co} \quad (1)$$

Considering geometric compatibility and material properties of each material, the torque transmitted by the aluminium tube is calculated as follows [1][2]:

$$T_{al} = \frac{G_{al}.J_{al}}{G_{al}.J_{al} + G_{co}.J_{co}} T \quad (2)$$

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Where G is shear modulus, J is the polar moment of inertia, and subscripts ‘al’ and ‘co’ represent the aluminium tube and the composite layer, respectively.

The shear modulus Gal and the polar moment of inertia of the aluminium tube Jal are much larger than those of the composite layer because only thin layer of unidirectional composite can increase sufficiently the natural frequency of the hybrid drive shaft. Therefore, the torque transmitted by the aluminium tube only is almost same as the torque transmitted by the hybrid aluminium/composite shaft. From now on, the static and buckling torque capabilities of the aluminium/composite shaft will be calculated neglecting the composite layer as follows [1]

$$Tstatic = 2\pi . r_{ave}^2 . t_{al} . S_{s,al} \tag{3}$$

$$T_{buckling} = \frac{\pi\sqrt{2}.E_{al}}{3(1-\nu_{al}^2)^{0.75}} \sqrt{(r_{ave}.t_{al}^5)} \tag{4}$$

Where Tstatic and Tbuckling are the static and buckling torque capabilities of the hybrid aluminium/composite shaft respectively, and r_{ave} is the average radius of the aluminium tube, t_{al} is the thickness of the aluminium tube, S_{sal} is the shear strength of the aluminium, E_{al} is the elastic modulus of aluminium, and ν_{al} is the Poisson’s ratio of aluminium.

Table 1: Mechanical properties of the composite materials [1]

Mechanical properties	**Aluminium**	**Steel**
Tensile modulus, E (GPa)	72	207
Shear modulus, G (GPa)	27	80
Poisson’s ratio, ν	0.33	0.3
Density, ρ (kg/m3)	2700	7600
Yield strength, S_Y (MPa)	270	370
Shear strength, S_S (MPa)	200	-

Table 2: Mechanical properties of the aluminium (6061-T6) and the steel (SM45C) [2]

Material	Unidirectional carbon fiber Epoxy composite (USN150)	Unidirectional glass fiber epoxy composite (UGN150)	Crowfoot satin woven glass fiber epoxy (GEP215)
E_1 (GPa)	131.6	43.3	35.5
E_2, E_3 (GPa)	8.2	14.7	17.2
G_{23} (GPa)	3.5	3.5	3.5
G_{12}, G_{13} (GPa)	4.5	4.4	3.7
ν_{12}, ν_{13}	0.281	0.3	0.22
α_1 ($\times10^{-6}/^0C$)	-0.9	6.3	8.3
α_2, α_3 ($\times10^{-6}/^0C$)	27	19	12.2
S_1^t (MPa)	2000	1050	600
S_1^c (MPa)	-1400	700	700
S_3^t, S_2^c, S_3^c (MPa)	61	65	100
(MPa)	-130	-120	-120
S_{23} (MPa)	40	65	60
S_{13}, S_{12} (MPa)	70	40	40
ρ (kg/m3)	1550	2100	2050
t_{ply} (mm)	0.125	0.12	0.15

The static and buckling torque capabilities of the aluminium/composite shaft are shown in Fig. 6 with respect to the outer diameter $\left(2r_{ave} + t_{al}\right)$ and thickness $\left(t_{al}\right)$ of the aluminium tube. Since the outer diameter of the drive shaft is normally limited to 100 mm for passenger cars, the outer diameter and thickness of the aluminium tube were determined to be 90 mm and 2 mm, respectively.

The fundamental bending natural frequency of drive shafts fn was calculated by the following equation with the simply supported boundary condition on the both ends [1].

$$f_n = \frac{9.869}{L^2} \sqrt{\frac{E_{al} I_{al} + E_{co} I_{co}}{\rho_{al} + \rho_{co}}} \tag{5}$$

Where E is the elastic modulus in the axial direction of drive shaft, I is the sectional moment of inertia, ρ is the mass per unit length, and L is the length of the drive shaft. The aluminum/composite shaft was composed of the aluminum

tube, the glass fiber epoxy composite, the carbon fiber epoxy composite, and the back-up film from outside as shown in Fig. 1. The glass fiber epoxy prepreg was firstly laid-up on the inner surface of the aluminum tube for an insulating material to eliminate galvanic corrosion between the aluminum and carbon fiber epoxy composite. Either a unidirectional glass fiber epoxy prepreg (UGN150, SK Chemicals, Korea) or a crowfoot satin woven glass fiber epoxy prepreg (GEP215, SK Chemicals, Korea), whose warp and weft ratio was 7:3, was selected as the insulating material depending on the stress distribution. The mechanical properties of the glass fiber epoxy composites are shown in Table 1. The stacking angle of the carbon fiber epoxy composites was chosen to be 00 from the shaft axis to maximize the elastic modulus in the axial direction. The bending natural frequency of the aluminum/composite drive shaft was calculated with respect to the stacking number of the carbon fiber epoxy prepregs and the stacking sequence of the glass fiber epoxy composites,

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when the length of the aluminum/composite drive shaft was 1.32 m. As shown in Fig. 7 the bending natural frequency of the aluminum/composite drive shaft increased in accordance with the amount of the carbon fiber epoxy composite. When more than three plies of carbon fiber epoxy prepregs are used, the natural frequency of the aluminum/composite drive shaft is higher than 9200 rpm, regardless of the stacking sequence of the glass fiber epoxy composites[6]. Therefore, in this work, four plies (0.5 mm) of the carbon fiber epoxy prepregs were used for the safety margin of the drive shaft.

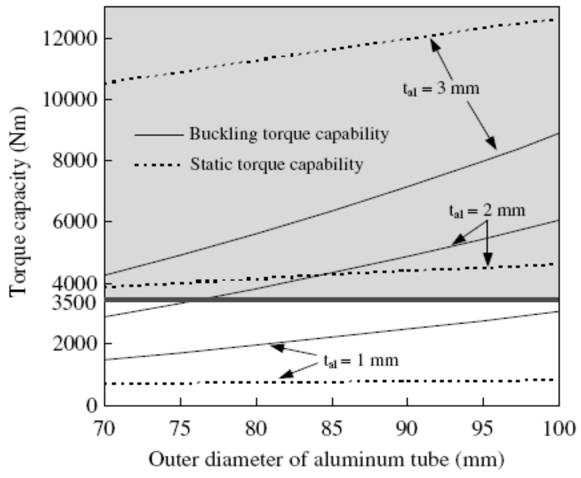

Fig. 6: Torque capability of the aluminium tube with respect to the outer diameter and thickness (tal) of the aluminium tube calculated from Eqs. (3) and (4) (Design torque ≥ 3500 Nm) [2],[4].

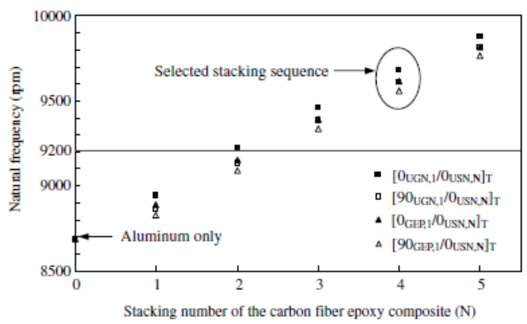

Fig. 7: Bending natural frequency of the aluminum/composite drive shaft with respect to the number of stacked plies of carbon fiber epoxy prepregs (ply thickness = 0.125 mm), and the type and stacking angle of the insulating materials (Design specification ≥ 9200 rpm)[1],[6].

C) SELECTION OF THE GLASS FIBER EPOXY COMPOSITE AS AN INSULATING MATERIAL -

The stacking sequence of the insulating glass fiber epoxy composites was determined considering the thermal residual stress and the failure index of the composite layer under the applied torque. In order to determine the optimum stacking sequence of the insulating glass fiber epoxy composites, the thermal residual stress was calculated with respect to the stacking angle and the insulating material type of the glass fiber epoxy composites by finite element analysis using ABAQUS 6.2 (Hibbitt, Karlsson & Sorensen, USA), commercial software[1]. The aluminum/composite shaft was modeled using the four-node two-dimensional axi-symmetry elements (CGAX4) as shown in Fig. 8[1]. The outer diameter and thickness of the aluminum tube were 90 and 2 mm, respectively. Since bonding thickness between the aluminum tube and the composite layer was very small (5–10μm) when co-cured under the pressure of 0.6 MPa, perfect bonding between the aluminum tube and composite layers was assumed for the finite element analysis.

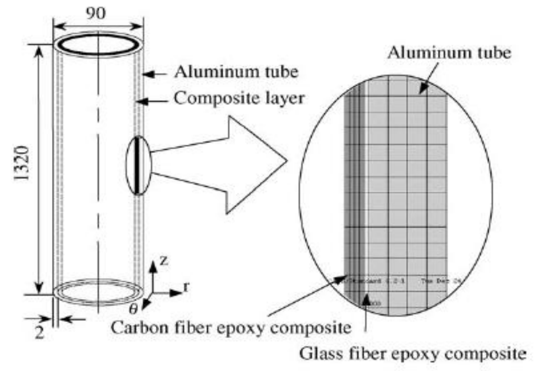

Fig. 8:Finite element model of the aluminum / composite drive shaft (units in mm).

A compressive preloading procedure for eliminating the thermal residual stress in the aluminum tube in the axial direction was included in the analysis step. The thermal residual stress of the aluminum tube in the axial direction was eliminated at room temperature by giving an axial compressive preload -170 MPa on the aluminum tube because it improved the fatigue characteristics of the co-cured aluminum/composite shaft. Five stacking sequences were considered in the analysis as listed in Table 3.

Table 3: Stacking sequence of the glass fiber epoxy composite and the carbon fiber epoxy composite layer stacked on the inner surface of the aluminum tube[1]

Case number	Stacking sequence from the inner surface of the aluminum tube
1	$[0_{USN,4}]_T$ (without the glass fiber epoxy composite)
2	$[0_{UGN,1}/0_{USN,4}]_T$
3	$[90_{UGN,1}/0_{USN,4}]_T$
4	$[0_{GEP,1}/0_{USN,4}]_T$
5	$[90_{GEP,1}/0_{USN,4}]_T$

The carbon fiber epoxy prepregs were stacked in the axial direction for all the cases, while the stacking angle of glass fiber epoxy prepreg was varied. For the stacking sequence of Case 1, only carbon fiber epoxy composite layers were stacked on the inside surface of the aluminum tube without the glass fiber epoxy composite. For the stacking sequences of Cases 2 and 3, unidirectional glass fiber epoxy prepregs were stacked axially or transversely. For the stacking sequences of Cases 4 and 5, crowfoot satin woven glass fiber epoxy prepregs were stacked first, followed by the stacking of carbon fiber epoxy composite layer.

The stacking angles of crowfoot satin woven glass fiber epoxy prepregs for each case were 0^0 and 90^0, respectively. Fig. 8 shows the interlaminar tensile thermal residual stresses σ_r in the composite layer adjacent to the aluminum tube with respect to the stacking sequence. For the Case 1, a tensile peel stress occurred because the coefficient of thermal expansion (CTE) of the carbon fiber epoxy composite in the circumferential

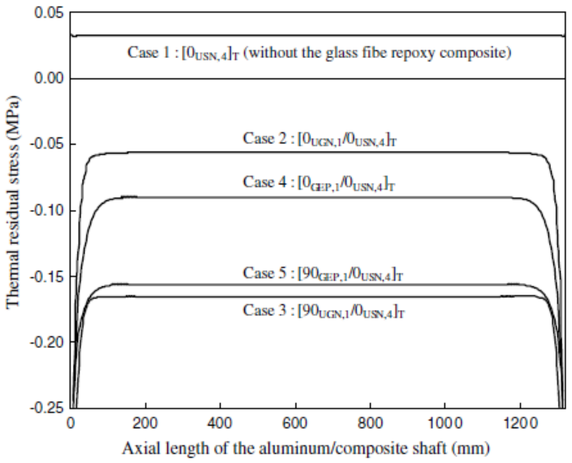

Fig. 8: Interlaminar tensile thermal residual stress distributions in the composite layer in the thickness direction versus the axial length of the aluminum/composite shaft.

direction ($27.0*10^{-6}/^0c$) was larger than that of the aluminum tube ($23.6*10^{-6}/^0c$),which might induce a delamination between the aluminum tube and the composite layer[1],[3]. However, a compressive interlaminar stresses in the thickness direction occurred in all other cases because the CTE of the glass fiber epoxy composites in the circumferential direction were smaller than that of the aluminum tube, which may improve the fatigue strength of the hybrid composite shaft. The stresses in the composite layer were also calculated with respect to the stacking sequence when a maximum buckling torque of 4360 Nm of aluminum tube was applied to the aluminum/composite shaft. In order to assess the failure index of the composite layer under the applied torque with respect to the stacking sequence, the following Tsai– Wu failure index of the composite layer was calculated[1].

$$FI = F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{33}\sigma_3^2 + F_{44}\sigma_4^2 + F_{55}\sigma_5^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 + 2F_{13}\sigma_1\sigma_2 + 2F_{23}\sigma_2\sigma_3$$

Where,

$$F_1 = \frac{1}{S_1^t} + \frac{1}{S_1^c}, \quad F_2 = \frac{1}{S_2^t} + \frac{1}{S_2^c}, \quad F_3 = \frac{1}{S_3^t} + \frac{1}{S_3^c},$$

$$F_{11} = -\frac{1}{S_1^t S_1^c}, \quad F_{22} = -\frac{1}{S_2^t S_2^c}, \quad F_{33} = -\frac{1}{S_3^t S_3^c},$$

$$F_{44} = \frac{1}{S_{23}^2}, \quad F_{55} = \frac{1}{S_{13}^2}, \quad F_{66} = \frac{1}{S_{12}^2},$$

$$F_{12} = -\frac{\sqrt{F_{11}F_{22}}}{2}, \quad F_{23} = -\frac{\sqrt{F_{22}F_{33}}}{2}, \quad F_{13} = -\frac{\sqrt{F_{11}F_{33}}}{2}$$

D) Press Fitted Joint with Protrusions

The press fit joining method between the hybrid aluminum/composite shaft and the steel yokes with protrusions was developed to increase reliability and to reduce manufacturing cost compared to other joining methods. To improve the torque capability of the press fitted joint, the protrusions in the axial direction were generated on the inner surface of the steel yoke as shown in Fig. 9. The protrusions on the inner surface of the steel yoke could engrave grooves on the surface of the aluminum shaft during press fitting process, which made mechanical interlocking between the steel protrusions and the engraved grooves on the surface of the aluminum tube. The protrusions on the inner surface of the steel yoke would be easily formed by broaching or die pressing in mass production, however, in this work an electro discharge machining (EDM) method was used for the prototype manufacturing. The joining between the aluminum tube and the steel yoke was secured more by the press fitting operation, which might reduce manufacturing time and cost eliminating several joining processes. Since the fatigue characteristics of the press fitted joint with protrusions would be affected by the protrusion shape, the optimal protrusion shape was sought.

Fatigue failures of the press fitted joint with protrusions would occur by two reasons: the stress concentration in the protrusions, and the fretting fatigue when torque applied. If the protrusions had sharp edges, the stress concentration would become high, which decreases the fatigue strength. Therefore, the protrusion shape should be smooth enough to reduce stress concentration. The fretting fatigue of contacting surface between the steel protrusions and the grooves on the surface of aluminum tube may be eliminated by giving a compressive stress between the mating surfaces, which prevents the relative motion. The fretting accelerates fatigue crack growth in mechanical components of engineering structures, which causes considerable reduction of the fatigue strength of a press-fitted assembly. It has been known that the fretting fatigue strength reduces much when the amplitude of the slip is higher than 50μ m. Therefore, the slip amplitude between the steel protrusions and the grooves on the surface of the aluminum tube of the press fitted joint by applied torque should be reduced.

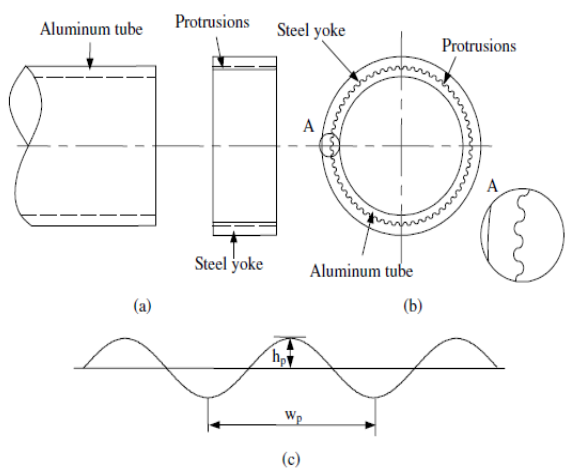

Fig. 9; Schematic diagram of press fitted joining method: (a) disassembled parts; (b) after assembly; (c) sinusoidal shape protrusion with aspect ratio hp/wp

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To reduce the stress concentration in the protrusions, a sinusoidal shape protrusion was selected because of its smoothness and easy representation. In the sinusoidal protrusions shape as shown in Fig 9 hp and wp represent the height and width of the sinusoidal protrusions, respectively.

The slip amplitude of contact surfaces between the protrusions of the steel yoke and the generated grooves on the surface of the aluminum tube under a given magnitude of torque was calculated by finite element analysis using ABAQUS 6.2. Fig. 10 shows the finite element model of the press fitted joint between the aluminum tube and the steel yoke, which are interlocked by the sinusoidal shape protrusions.

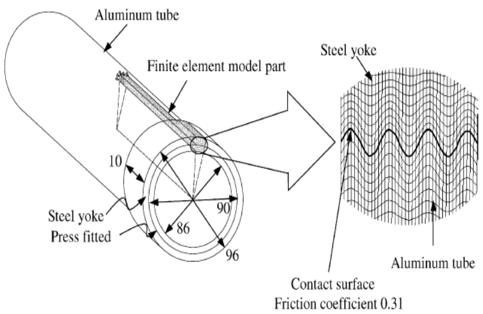


Fig. 10: Finite element model of the press fitted joint with eight-node three-dimensional solid elements for the contact slip analysis (units in mm).

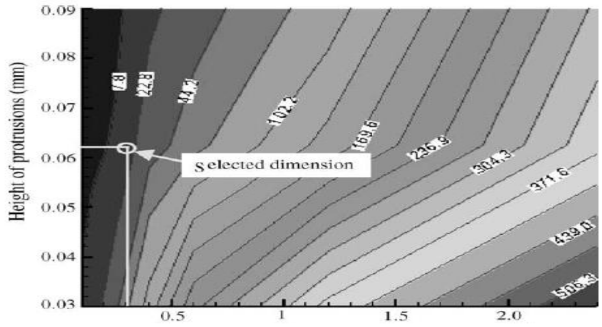
The friction coefficient of 0.31 between the aluminum and the steel was used[1]. The press fitted length of 10 mm was used in the analysis to save computing time although the actual fitting length was larger than this value. The slip amplitude between the aluminum and the steel protrusions was calculated with respect to the height and the width of the sinusoidal protrusions when a torque 4360 Nm was applied to the steel yoke, which was the buckling torque capability of the aluminum tube.

As the height of the protrusions increases, the press force for the press fitting operation increases, which may fail the aluminum/composite drive shaft during the press fitting operation with the steel yokes. Therefore, the width of protrusions of 0.25 mm was selected because the smaller width of protrusion than this value was difficult to be machined by EDM cutting. Then, the height of protrusions was 0.0625 mm.[2] Fig. 11 shows the stress distributions in the protrusions of the aluminium tube under the applied torque of 4360 Nm torque, in which the whole sections of the protrusions in the aluminium tube were yielded.

E) Performance of the Aluminium/Composite Drive Shaft

The static torque capability of the aluminium/composite drive shaft was measured using the specimen of 250 mm length, which was a shortened specimen to be mounted on the torque tester. Fig.12 (a) shows the torque-distortion angle diagram of the shaft with the maximum torque of 4320 Nm. The shaft was buckled at the maximum torque of 4320 Nm as shown in Fig. 12 (b)[2].

The delamination failure of the composites and the failure of protrusions on the press fitted joint were not found until the aluminium tube was buckled. The torque capability of the aluminium/composite drive shaft of 4320 Nm was slightly higher than the design value.



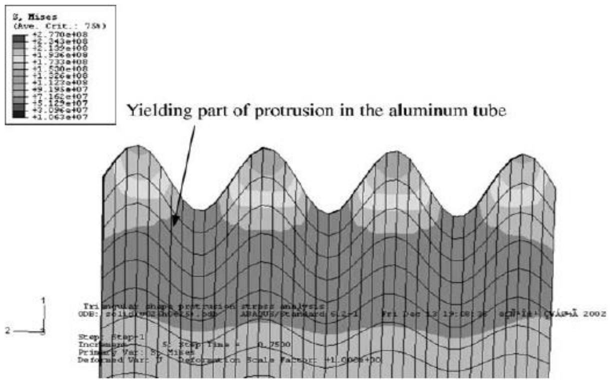
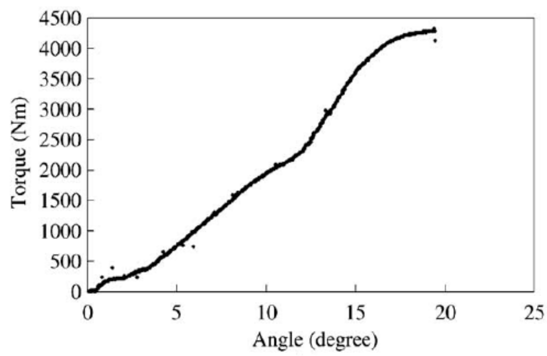
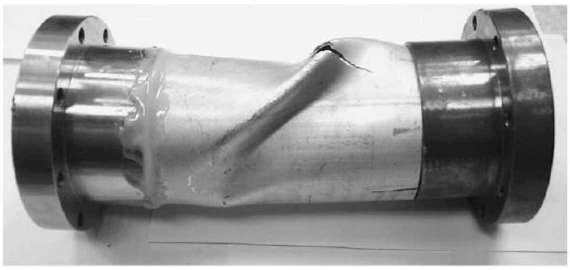


Fig. 11: Stress distributions in the protrusions of the aluminium tube when a torque of 4360 Nm was applied to the press fitted joint whose press fitted length was 10 mm when wp and hp of the protrusions were 0.25 and 0.0625 mm, respectively[1].



(a)



(b)

Fig. 12: Static torque test results of the aluminium/composite drive shaft: (a) torque-distortion angle diagram; (b) buckled specimen after the static torque test.

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IV. CONCLUSION

The hybrid aluminium/composite drive shafts have been designed to replace the steel drive shaft of an automobile.A one-piece hybrid aluminium/composite drive shaft for rear wheel drive automobile has been designed with the objective of minimization of weight of the shaft which was subjected to the constraints such as torque transmission, torsional buckling capacities and natural bending frequency.The mass of the hybrid aluminum/composite drive shaft will be very less compared to the conventional steel drive shaft. The static torque capability and the fundamental natural frequency were 4320 Nm and 9390 rpm, which exceeded the design requirements.

A press fit joining method between the steel yoke with protrusions on its surface and the aluminium tube was developed to increase the reliability of joining and to reduce manufacturing cost.

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