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3D PRINTED MATERIALS FOR HIGH TORQUE APPLICATIONS: CHALLENGES AND POTENTIAL

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ABSTRACT: Metals are significant materials used in high torque applications such as drive shafts. In recent years, 3D printing has gained much popularity in manufacturing of engineering parts for industrial applications. However, there has not been any investigation into the use of 3D printing for manufacturing of materials for high torque applications. This paper presents a review on using 3D printing for parts used in high torque applications, such as drive shaft. Current state-of-the-art in drive shaft design and fabrication was discussed. Requirements of a 3D printed drive shaft are presented. Finally, the challenges and potential of using 3D printing to produce high torque bearing parts are discussed.

Keywords – High torque, Rapid Prototyping, Additive Manufacturing, 3D printing, fibre printing

INTRODUCTION

High torque applications are defined as applications that are required to deliver torque higher than 1000Nm (Cho & Choi, 1997; Sopanen, Ruuskanen, Nerg, & Pyrhönen, 2011). Drive shafts are the most commonly known parts for high torque applications. Drive shafts have been developed in various fields such as automotive (cars), aerospace (helicopters), heat transfer (cooling towers) and etc. (Shokrieh, Hasani, & Lessard, 2004). In automotive industry, a drive shaft transmits power from the engine to the differential gear of a rear wheel drive vehicle. A typical torque capability of an automotive drive shaft should be no lesser than 3500 Nm (Kim, Kim, & Kim, 2004).

Drive shafts are usually made of solid or hollow tube of conventional materials such as steel or aluminum. Sometimes, long drive shafts are required in certain applications. The most important benefit of long shafts is that they reduce the number of bearing supports required, and therefore greatly shrink the maintenance costs and the weight of the driveline (Montagnier & Hochard, 2013). The design process is more complex, however, because the shaft has to cross a critical speed, and dynamic instabilities due to rotating damping can occur in this regime (Montagnier & Hochard, 2013).
Conventional materials are unsuitable for manufacturing long drive shaft in one-piece as the natural frequency will go too low into the operating rotational frequency range. This is due to the fact that as the natural frequency is inversely proportional to the square of the length and proportional to the square root of the specific modulus (Nasr, El-Zoghby, Maalawi, Azzam, & Badr, 2015). Hence, multiple-piece drive shaft comprising joints that connect different parts of the shaft are used instead.

However, the use of multiple-piece drive shaft adds on weight and reduces the fuel efficiency. To further improve the strength-to-weight property of the drive shaft, composite drive shafts have been developed taking advantage of the high stiffness-to-weight ratio of the composite. Long single-piece drive shaft can be made using carbon fibre/epoxy. A composite drive shaft offers excellent vibration damping, cabin comfort, reduction of wear on drive train components and increases tire traction (Sivakandhan & Prabhu, 2014). In addition, the use of single torque tube reduces assembly time, inventory cost, maintenance, and part complexity (Sivakandhan & Prabhu, 2014). However, the fabrication process of composite shaft is labor intensive via manual layup method. Another type of commonly used method which is the filament winding (Talib, Ali, Badie, Lah, & Golestaneh, 2010) only allows simple parts to be produced and would have difficulty manufacturing intricate structures.

An ideal drive shaft structure should be in single piece long structure reduce assembly and at the same time to reduce the unnecessary weight of the joints. The use of material with high strength to weight ratio is also important for producing lightweight shaft. Furthermore, on-demand fabrication may sometimes be needed to replace a faulty drive shaft as it eliminates the need of storing large replacement parts. Intricate composite structure is also hard to be manufacture using conventional manufacturing techniques. These requirement call for advanced manufacturing technique and new material opportunities.

3D printing is a group of fabrication techniques which fabricates parts layer by layer directly from digital design (S. L. Sing, An, Yeong, & Wiria, 2015). 3D printing techniques have the advantage of manufacturing parts without the need for tooling, thus reducing the time of manufacturing (Chua, Yeong, & Leong, 2005). On the other hand, the layer-by-layer method enables the fabrication of intricate inner structures which are difficult using conventional manufacturing methods. 3D printing has now evolved to print various kinds of materials, ranging from plastic materials (Y. L. Y. Yap, W. Y., 2014), hydrogels (Tan & Yeong, 2014), ceramics (Zhao, 2014), to high strength metals (Loh et al., 2015; S. Sing, Yeong, Wiria, & Tay, 2016; S. L. Sing et al., 2015; S. L. Sing, Yeong, & Wiria, 2016), generating various applications in aerospace and biomedical (J. M. Lee, Zhang, & Yeong, 2016; Yeong, Chua, Leong, Chandrasekaran, & Lee, 2005). Recent development also sees the printing of composite materials in particular carbon fibre printing. Carbon fibre printing allows intricate shape to be manufactured. Properties of 3D printed materials such as compressive (C. Lee, Kim, Kim, & Ahn, 2007; Y. L. L. Yap, Y. M.; Zhou, H. F.; et al., 2014), tensile (Vandenbroucke & Kruth, 2007), and flexural (Bellini & Güçeri, 2003) strengths have been well studied. However, there is only limited research on the torsional properties of the 3D printed materials. In this paper, the challenges and potential of 3D printed materials for high torque applications will be highlighted.

**CHALLENGES**

There are some challenges that need to be addressed in order to realize 3D printing of one-piece long composite shafts. They are discussed in detail below.
Build size and speed- Shafts normally are long (can be as long as 1.5m)(Rastogi, 2004). With the current start-of-the-art metal printing techniques such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), the longest printable part is just 600mm based on the largest machine available. Although the 3D printing is easily scalable, it will take a long time to build a long shaft in the layer-by-layer method using single laser beam. Multiple beams printing method in the future can shorten the printing time.

Porosity- porosity is the due to the presence of voids as a result of lack of solid material in the portions of the part(Bland & Aboulkhair, 2015). Porosity is not desirable especially for high torque applications as it reduces the fatigue property of the printed parts(Edwards, O’Conner, & Ramulu, 2013). However, porosity is common in 3D printed parts. High density parts have been obtained for metals such as AlSi10Mg (Aboulkhair, Everitt, Ashcroft, & Tuck, 2014), cobalt chromium and Titanium-6Aluminium-4Vanadium (S. L. Sing et al., 2015). In carbon fibre printing, the porosity of the printed part was shown to be larger than the conventional compression molded part(Tekinalp et al., 2014). This shows more research needs to be done to reduce the porosity of the 3D printed parts.

Anisotropic property- It is well-known that 3D printed parts exhibit anisotropic properties which need to be considered when designing the parts(Ahn, Montero, Odell, Roundy, & Wright, 2002). Study conducted by Rickenbacher et al. shows that the Young’s modulus of IN738LC part in the across layer direction is only 70% of that of the layer wise direction(Rickenbacher, Etter, Hövel, & Wegener, 2013). Another study by Spierings et al. also shows that the ultimate tensile strength of 316L steel in the across layer direction is 15% lower to that of the layer wise direction(Spierings, Herres, & Levy, 2011). Although the effect of anisotropic is well characterized in tensile and compressive behavior, it is still not known how the anisotropic property of the 3D printed materials would affect the torsional behavior of the printed parts. More research is needed to evaluate the torsional properties of 3D printed materials.

Robotic- For fibre printing, fibres are laid in the layer wise direction which could lead to severe anisotropy of the printed parts. The introduction of advanced robotics allows the creation of more axes printing machines that enable conformal printing of carbon fibre and hence realizing the true 3D printing. Arevo Labs came up with the six-axis FDM 3D printing machine. The robotic arm controls a high-performance carbon-fiber reinforced thermoplastic filament deposition nozzle with state-of-the-art thermal management technology(“Arevo Labs Introduces First-of-its-Kind Robotic Additive Manufacturing Platform for 3D Printing Composite Parts,” 2015).

POTENTIAL

Integral rotor- 3D printing allows the research in the direction of integral rotors (shaft-disc-blade system). 3D printing allows the fabrication of multi-parts linkages and joints directly from digital designs which eliminates the need for assembly(Cali et al., 2012). Besides the fact that such systems being large owing to their size and complex geometry, pose the common issues associated with the very large degree of freedom, there are important issues specific to composite rotors(Gupta, 2015).

Metal matrix composite (MMC) - The attention of research on composite rotors thus far has been on epoxy based composite shafts, and little focus has been given towards MMC shafts. In near future, the uses of MMC shafts in numerous systems involving high temperatures such as gas turbine, are anticipated to surge. Apart from MMC, other types like ceramic or glass matrix based, or carbon-
carbon composites (Li, Matsuyama, & Sakai, 1999) for high temperature applications will also be considered. These materials have been demonstrated to be processed successfully via 3D printing. 3D printing techniques such as selective laser melting, selective laser sintering and Laser Engineered Net Shaping (LENS) have been shown to be able to produce metal matrix composites (Kumar & Kruth, 2010).

**Smart material**- 3D printing of smart materials has also been a research focus recently. 3D printing of Shape Memory Polymer (SMP) (Ge, Qi, & Dunn, 2013), piezoelectric materials (Bandyopadhyay et al., 1998) has been demonstrated. The introduction of 3D printing of smart materials to the field of drive shaft allows the creation of “smart drive shaft” which allows the real-time health monitoring of drive shaft (Frankenstein, Hentschel, Pridoehl, & Schubert, 2005). It is especially useful for composite drive shafts. Greater application of smart materials such as shape memory alloy (SMA), magnetorheological fluids (MRF), piezoelectric fibres/patches etc. to composite rotors, will receive the attention of researchers.

This table below gives a summary of the 3D printing technologies that can be used to realize the 3D printed composite shaft.

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<th>Technologies related to high torque applications</th>
<th>3D printing method</th>
<th>Materials</th>
<th>Remark</th>
<th>Reference</th>
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<tr>
<td>Long metal cylinder</td>
<td>Powder–bed fusion (SLM)</td>
<td>Titanium alloy, Steel 316L</td>
<td>High strength materials</td>
<td>(S. Sing et al., 2016; S. L. Sing et al., 2015; S. L. Si et al., 2016)</td>
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<tr>
<td>Carbon fibre printing</td>
<td>Fused deposition method</td>
<td>Carbon fibre and ABS plastic</td>
<td>High strength-to-weight ratio composite material</td>
<td>(Ning, Cong, Qiu, Wei, &amp; Wang, 2015)</td>
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<td>Printing of multiple parts in single build</td>
<td>Direct energy deposition (SLS)</td>
<td>-</td>
<td>Eliminate assembly work</td>
<td>(Calì et al., 2012)</td>
</tr>
<tr>
<td>Smart material</td>
<td>Inkjet printing</td>
<td>Polymer ink</td>
<td>printing of glassy shape memory polymer fibers in an elastomeric matrix</td>
<td>(Ge et al., 2013)</td>
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**CONCLUSION**

3D printing has the potential in terms of printing intricate structures, on-demand fabrication, and composite printing. However, more research are needed to advance the process chains in 3D printing for high torque application. This includes simulation, new material, new robotic technique and mechanical testing of real physical 3D printed shaft.
REFERENCES


