Application and Performance Analysis of Carbon Fibber Composites in Deep Sea Oil and Gas Development

Xiaohui Wang¹, *, Xueying Xie², Chunyan Song¹ and Xin Yuan²

¹Technical Test Centre of Sinopec Shengli OilField, Dongying 257000, China
²Testing and Evaluation Research Co., Ltd. of Sinopec Shengli OilField, Dongying 257000, China

*Corresponding author: wxhui583@sinopecgroup.com

Abstract. With the drastic reduction of China's land and shallow sea oil and natural gas resources, offshore oil and gas field exploration has gradually developed into the deep sea of 1500-300 m. Traditional steel materials are no longer applicable, and fibre composite materials have become the most exploited in subsea oilfields. One of the good materials is widely used in all aspects of deep-sea oil field equipment, providing a reliable guarantee for the development of deep-sea oil and gas fields. Based on this research background, the paper discusses the characteristics of carbon fibre composite materials (light weight, high specific strength, high specific modulus, fatigue resistance, corrosion resistance, and small thermal expansion coefficient), and discusses its application in the field of subsea oilfields.

Keywords: Carbon fibre composite materials, deep sea oil and gas, deep sea oil and gas pipeline repair.

1. Introduction
Oil and natural gas are precious energy and chemical raw materials, the "blood" of the modern economy, and one of the most important energy sources today. It is closely related to people's clothing, food, housing and transportation. It is a standard for measuring the comprehensive strength of a country. It can affect the development of a country or region, directly affect the stability of the national economy, and can even lead to the political and economic stability of a country or region. The drilling and exploitation of oil gradually extends from land to ocean, and the ocean also extends from shallow sea to deep sea to meet market demand. The land and ocean environments are very different, especially the corrosion of mining facilities by seawater is quite serious, which greatly shortens the service life and increases the mining cost. Most of the land mining equipment is mainly steel, but the use of steel in the deep sea has encountered many technical difficulties, such as seawater corrosion, etc., hope to use carbon fibre composite material (CFRP) or carbon fibre and glass fibre composite material (CF/GFRP), carbon fibre and aromatic Polyester composite material (CF/KFRP) to solve these problems. The application of CFRP in the field of subsea oilfields mainly highlights the characteristics of its five aspects [1].
2. Characteristics and applications of carbon fibre composite materials

2.1. Characteristics of carbon fibre composites

2.1.1. Light weight. The density of carbon fibre is about 1.76~1.80g/cm³, the density of the composite material made is between 1.50~1.60g/cm³, and the steel material is about 7.87g/cm³. Obviously, CFRP is much lighter than steel.

2.1.2. High specific strength and high specific modulus. The specific strength of CFRP is about 7 to 12 times that of steel, and the specific modulus is about 3 to 5 times. Therefore, CFRP can be used to make various products that are light, strong and rigid.

2.1.3. High fatigue resistance. CFRP has high fatigue resistance, is significantly better than steel, and has a long service life. Especially the reciprocating movement of the sucker rod, the pressure of the seawater outside the pipe and the pressure inside the pipe are unbalanced, causing fatigue of the material, resulting in fatigue fracture. Using CFRP sucker rod can solve this problem.

2.1.4. Corrosion resistance. CFRP has strong acid and alkali resistance, corrosion resistance to various environments, and no rust. Its service life in seawater is much longer than that of steel parts.

2.1.5. Excellent thermal performance. The thermal expansion coefficient of CFRP is small, the axial thermal expansion coefficient is about -0.1×10⁻⁶/℃, and the vertical thermal expansion coefficient is about +35×10⁻⁶/℃. It is not brittle in cold environment, and dimensionally stable in hot environment. The heat resistance of CFRP depends largely on the matrix resin. In terms of the heat resistance of carbon fibre, it can be used for a long time in the air below 300℃.

2.1.6. High stretch and high strength. From the mechanical properties, carbon fibre is generally divided into the following grades. Such as T300 grade carbon fibre, tensile strength is 3530MPa, elastic modulus is 230GPa; T700 grade carbon fibre, tensile strength is 4900MPa; T800 grade carbon fibre, tensile strength reaches 5490MPa, elastic modulus reaches 294GPa; T1000 is ultra-high strength carbon fibre, the tensile strength reached 6370MPa. Table 1 is a typical carbon fibre series and its mechanical properties.

| Grade | Tensile Strength/MPa | Elastic Modulus/GPa | density/ (g/cm³) | Specific strength/10⁷cm | Specific modulus/10⁹cm |
|-------|---------------------|--------------------|-----------------|------------------------|-----------------------|
| T300  | 3530                | 230                | 1.76            | 2.01                   | 1.31                  |
| T700  | 4900                | 230                | 1.8             | 2.72                   | 1.28                  |
| T800  | 5490                | 294                | 1.81            | 3.03                   | 1.62                  |
| T1000 | 6370                | 294                | 1.8             | 3.54                   | 1.62                  |

As can be seen from Table 1, carbon fibre has high tensile strength and high elastic modulus, combined with lower density, making its specific strength and specific modulus unique among many structural materials. These comprehensive properties make CFRP one of the best materials for the development of subsea oil fields. In particular, the development of deep-sea oil fields will play a greater role.

2.2. Application analysis

The application of CFRP in the deep-sea (900-3,000m) oil field has attracted much attention. It is hoped that high-strength, high-modulus and light-weight CFRP will replace steel products in order to reduce the quality of the tension-leg platform and the tension legs. The load of the supporting structure.
For example, in the 1,200m deep sea oil field in the Gulf of Mexico, the lift pipe is made of CF/GFRP hybrid composite material, which is light in weight. Compared with steel pipes, the weight is reduced by 45kg/m, and the weight of 1,200m can be reduced by 54t. The weight effect is very significant, which can greatly reduce the size and investment of the buoyancy body. For deep-sea oil fields, the tether for anchoring the platform to the seabed and the riser connecting the wellhead to the platform are important components. If it is made of steel, the quality is heavy, and the floating size of the large platform is required, which will definitely increase the investment. If manufactured with CFRP, its own mass reduction effect and mass reduction effect are very significant. For example, a 1,500m deep sea operating platform uses steel cables (tether) of approximately 6,500t and CFRP cables (Compteter) of only 1,000t. At the same time, the former can only reach a depth of about 1,500m, while the latter can be used in a deep-sea oil field of 3,000m. In addition, the composite cable can be wound on a mandrel with a diameter of 4.4m, which is very convenient for transportation and operation. Figure 1 is a composite cable.

Figure 1. Deep sea oil and gas production composite cable.

3. Reinforcement of carbon fibre composite materials in oil and gas transportation pipelines

3.1. Maintenance and reinforcement of long-distance crude oil pipeline

3.1.1. Damage to long-distance crude oil pipelines. The gradual exposure of the anticorrosion layer of the long oil pipeline has caused problems such as aging of the anticorrosion layer, corrosion of the pipe body, and even pipeline leakage, or forced to stop operation. With the production of crude oil with high water content in the eastern region, the corrosion rate of crude oil pipelines is accelerated. At present, many long-distance pipelines in China, such as the Zhongluo Line, Luning Line, and Grating Line, are severely corroded. There are also many oil transportations companies and oil fields that have many pipelines that are severely corroded and urgently need to be repaired. For example, Daqing Oilfield has nearly 300,400km of pipelines that require major repairs or replacements due to corrosion every year. Pipeline transportation has low cost, high efficiency, short construction period, less land occupation, safety and no pollution. It has become one of the main transportation methods of oil and gas and other fluids in the world. However, metal pipes often suffer from chemical or electrochemical corrosion under the influence of the surrounding environment. In severe cases, they lead to corrosion perforation and leakage, causing fires and explosions, threatening personal safety and causing environmental pollution. In addition, man-made damage will occur during the pipeline operation. According to foreign data reports, the two main causes of pipeline damage due to corrosion and human interference [2].

3.1.2. Maintenance and reinforcement of long-distance crude oil pipelines. When defects such as metal loss and perforation occur on the pipe body or when the pipe covering layer is peeled or damaged in some way, from the perspective of safety and economy, the defective pipe needs to be
reinforced and repaired. The impact of corrosion on pipeline damage and damage cannot be completely avoided, and many gathering pipelines, long-distance pipelines, and urban pipeline networks constructed in early my country have reached the design life, and the corrosion situation is serious. If these defective pipes are not dealt with in a timely and effective manner, it may cause security accidents and economic losses. Statistics show that China’s ground pipelines are replaced every year due to external corrosion, and the replacement rate has reached 2.5%, resulting in economic losses of up to 500 million yuan. Foreign countries, such as the 1977 US oil pipeline line, this is Alaska’s A pipeline with a length of 1287km and a cost of 8 billion US dollars has 826 holes perforated 12 years later under the action of external corrosion, and the cost of repairing it has reached 1.5 billion US dollars. After the pipeline is found to be corroded, the treatment of the pipeline is usually the following four methods: pipeline corrosion reinforcement, abandoned pipelines, continued operation at low pressure, and replacement of pipelines. Reinforcement of pipelines is mainly due to its economic efficiency. In actual engineering, corrosion pipelines that use replacement and repair methods are used in the entire corrosion pipeline the proportion is less than 1/20. Therefore, the most common on-site engineering treatment method is to reinforce corroded pipelines. Reinforcing and repairing corroded pipelines has social benefits and good economy. In recent years, the reinforcement technology of external corroded pipelines has been Became the main content of foreign oil and gas company research.

3.2. Long-distance crude oil pipeline reinforcement technology

3.2.1. Calculation of the thickness of the reinforcement layer. The parameters of carbon fibre reinforced layer, according to the US ASME 2006 PCC. 2 Calculate the design standard of pipeline repair, the specific formula is as follows:

(1) The reinforcement thickness is shown in (1). Among them, \( t_{\text{repair}} \) represents the reinforcement thickness; \( T \) represents the wall thickness of the pipeline; \( t_s \) represents the remaining wall thickness of the pipeline; \( E_c \) represents the Young's modulus of the carbon fibre composite material; \( \varepsilon_c \) represents the maximum elongation of the carbon fibre composite material; \( \sigma_b \) represents the tensile strength of the pipeline material; \( \sigma_y \) Represents the yield strength of the pipe material.

\[
\begin{align*}
t_{\text{repair}} &= \frac{\sigma_y - t_s \sigma_b}{E_c \varepsilon_c} \tag{1}
\end{align*}
\]

(2) The number of reinforcing layers of carbon fibre composite material is shown in formula (2). Among them: \( N_H \) represents the number of reinforcement layers; \( t_{\text{ply}} \) represents the thickness of a single layer of reinforcement layers.

\[
N_H = \text{int} \left( \frac{t_{\text{repair}}}{t_{\text{ply}}} \right) + 1 \tag{2}
\]

(3) The reinforcement width is shown in equation (3). \( L \) represents the reinforcement width; \( D \) represents the pipe diameter; \( L \) represents the axial length of the defect. The thickness of the reinforcement layer for welding reinforcement only needs to consider the choice of the same material and the same thickness of the metal material as the original pipeline from the perspective of the convenience of prefabrication and the corrosion allowance. The thickness of the reinforcement layer for the reinforcement of the clamp only needs to be greater than or equal to the thickness of the original pipeline, but it is necessary to ensure that the clamp and the pipe body are closely combined.
\[ L_c = 4\sqrt{Dh} + L \]  \hspace{1cm} (3)

3.2.2. Performance analysis after pipeline reinforcement. The composite material has excellent tensile strength and elastic modulus, and the mechanical parameters such as tensile strength and elastic modulus are close to the numerical values of the steel, so it is an ideal material suitable for pipeline reinforcement. Composite material repair technology uses filling resin to first fill the pipeline defects, and then use special adhesive to wrap the fiber material around the pipeline that needs to be reinforced to form a fiber composite reinforcement layer. After curing, the reinforcement layer is integrated with the pipeline, replacing the pipeline material to carry the pressure in the pipeline, so as to achieve the purpose of recovering or even exceeding the design operating pressure of the pipeline.

After the reinforcement, the deformation of the pipeline at the welding contact point of the outer wall of the pipeline is directly transmitted to the reinforcement layer, so that the reinforcement layer bears part of the pressure of the pipeline; for the spiral welded pipeline, the corrosion area and the reinforcement layer exist due to the protrusion of the spiral weld The gap makes the deformation of the corrosion area unable to be transmitted to the reinforcement layer, and the stress is very small, almost zero. In the scheme of using welded casing reinforcement, the spiral weld is properly ground, and the gap between the casing and the pipe body is filled with epoxy resin with strong adhesion and force transmission, which will greatly improve the casing the actual effect of reinforcement.

After the reinforcement, the deformation of the corrosion of the outer wall of the pipeline is directly transmitted to the fixture, so that the fixture can bear part of the pressure of the pipeline: to ensure that the strength of the pipeline after reinforcement meets the requirements, the fixture and the pipe must be guaranteed, the road fits closely.

3.3. Repair and application of carbon fibre composite materials in deep-sea oil and gas pipelines

3.3.1. Performance of carbon fibre composite materials. The repair materials involved in the carbon fibre composite repair technology mainly include special resin, special filling putty and carbon fibre cloth. Table 2 and Table 3 give the main technical indicators of the pipeline defect repair carbon fibre composite material.

| Test items | Index requirements | standard test |
|------------|--------------------|---------------|
| Cured resin | Application period (25°C)/min | 30-90 | GB/T12007.7 |
| | Gel time (25°C)/min | 50-120 | GB/T12007.7 |
| | Tensile strength/MPa | ≥40 | GB/T2567 |
| | Impact strength/J | ≥3 | SY/T0315 |
| | Adhesion/level | ≤2 | SY/T0315 |
| | Curing time (25°C)/h | 0.8-2 | GB/T14074 |
| | Mass fraction 10% HCl (room temperature, 7d) | | |
| | Mass fraction 10% NaOH (Room temperature, 7d) | coating | GB/T1763 |
| | Mass fraction 10% NaCl (room temperature, 7d) | | |
| | Filler fineness/μm | ≤100 | ASTMD1210 |
| | Compressive strength/MPa | ≥50 | GB/T2567 |
| Chemical resistance | | | |
| Fill the putty | | | |
Table 3. Performance index of carbon fibre composite materials.

| Test items                         | Performance requirements | Applicable standards |
|------------------------------------|--------------------------|----------------------|
| Carbon fiber wire                  |                          |                      |
| Tensile strength/MPa              | ≥ 2 500                  | GB/T 3362            |
| Cloth density/(g·m-2)             | ≥ 200                    | HB 7736.3            |
| Single layer tensile strength/MPa | ≥ 900                    | GB/T 3354            |
| Single layer tensile modulus/GPa  | ≥ 150                    | GB/T 3354            |
| Elongation at break/%             | 1 - 5                    | GB/T 3354            |
| Carbon fiber composite material    |                          |                      |
| Bonding shear strength with steel/MPa | ≥ 15                | SY 0041              |
| Bonding strength with anti-corrosion layer/(N·cm-1) | ≥ 10            | SY/T 0413            |
| Adhesion to steel / grade         | ≤ 2                      | SY/T 0315            |
| Impact strength/J                 | ≥ 10                     | SY/T 0315            |
| Cathode peeling (65℃, 28d)/mm     | ≤ 3                      | SY/T 0037            |

3.3.2. Scope of application of carbon fibre composite repair technology. According to ASME PCC-2, carbon fibre composite repair technology can be applied to the following aspects: (1) Repair and reinforcement of corrosion, cracks, mechanical damage, weld defects, etc. with a defect level of less than 80% of the pipe wall thickness. (2) Temporary reinforcement and single-point reinforcement of internally corroded pipelines can also be used for defect reinforcement of the whole pipeline section. (3) Increase the safety factor of the pipeline and enhance the pipeline when the pipeline increases the operating pressure. (4) Repair of defects of irregular pipe fittings such as elbows and tees. (5) Leak repair of oil and gas pipelines.

3.4. Application process of carbon fibre composite reinforcement technology in oil pipeline maintenance

When applying carbon fibre composite reinforcement technology in oil pipeline maintenance, a scientific technology application process must be adopted to ensure the quality of the technology application and the operation state of the oil pipeline. When the carbon fibre composite reinforcement technology is applied in oil pipeline maintenance, the technical process is shown in Figure 2.

Figure 2. Repair flow chart of carbon fibre composite material reinforcement technology oil pipeline.

1) Treatment of damaged pipelines. When applying carbon fibre composite reinforcement technology during oil pipeline maintenance, the main technical application process is to process the damaged oil pipeline to lay the foundation for the technical application. The main processing content
includes 3 parts: 1. Clean the damaged oil pipeline, remove the impurities on the outer surface of the oil pipeline, and then remove the original anti-corrosion layer of the pipeline to ensure that the outer wall of the damaged oil pipeline is clean. 2. Treat the rust on the surface of the damaged pipeline to avoid the problem of rust causing the maintenance quality to decline. Use electric rust removal tools to clean the rust on the surface of the pipeline one by one, only to achieve the rust removal standard of St3 level, can we ensure that the carbon fibre composite reinforcement technology will not be affected by rust during maintenance. 3. Clean the surface of the pipeline with detergent, and then dry it to ensure the dryness of the damaged pipeline.

2) Filled with resin. The second technical process when the carbon fibre composite reinforcement technology is applied in the maintenance of oil pipelines is to fill the filling resin in the damaged pipeline position, such as the depression of the damaged oil pipeline, it needs to be filled with the filling resin. Until the damaged position of the oil pipeline recovers flat. During the filling process of the levelling resin, the flatness of the levelling resin must be ensured to avoid gaps in the winding of the carbon fibre composite material due to uneven filling, resulting in a drop in the bearing pressure of the oil pipeline maintenance section and affecting the working state of the oil pipeline, So that there are hidden dangers in the oil transportation process.

3) Carbon fibre cover. After the cured resin of the damaged oil pipeline is initially cured, carbon fibre composite material should be used to wind the cured filled resin and ensure that the carbon fibre composite material completely covers the damaged oil pipeline to ensure the quality of maintenance. The problem of inadequate coverage will lead to insufficient sealing of the damaged oil pipeline and a reduction in the bearing pressure, which will have a huge impact on the operation state of the pipeline. When winding carbon fibre composite materials, we must scientifically control the winding thickness according to the damage. In general, the winding thickness of carbon fibre composite materials must be controlled at more than 8mm to fully guarantee the quality of maintenance.

4) Antiseptic treatment. After the treatment of the reinforced area of the damaged oil pipeline is completed, strict anti-corrosion treatment should be performed on the reinforced area to avoid secondary damage due to corrosion problems in the reinforced area. Therefore, it is necessary to implement anti-corrosion treatment on the reinforced area to ensure that the reinforced area of the carbon fibre composite material will not reduce the sealing performance due to corrosion problems. After anti-corrosion treatment in the reinforced area, backfill the oil pipeline [3].

4. Application and analysis of carbon fibre composite materials

Traditional offshore oil and gas field production equipment is mostly made of steel, including mooring lines for anchoring the offshore platform to the seabed and tube and mooring lines connecting the subsea wellhead to the platform. As the depth of deep-sea oil and gas exploration and production continues to increase, the quality of the steel pipe rope mooring force forces the floating size of the offshore platform to increase, which brings a variety of cost consumption. In addition, the steel is easily corroded by seawater immersion, and the working life is short, generally only 2 to 3 years, so periodic production inspection and maintenance of the pipe cable are required. Taking the pipeline cables out of the deep sea, repairing them according to the requirements, and then reinstalling them, not only costs maintenance costs, but also causes the project to stop production. In particular, it is more difficult and costly to perform such maintenance under harsh deep-sea environmental conditions. In comparison, CFRP has the characteristics of light weight, high strength, good flexibility, fatigue resistance, corrosion resistance and long service life. Its specific strength and specific modulus are 10 times and 5 times that of steel, respectively, and it is very suitable for application in the deep sea. Oil and gas field environment [4].

Another application form of carbon fibre pultruded rod is to replace the steel or polyester anchor cable with carbon fibre tether to fix the mobile deep-sea drilling system, especially the fixed oil tanker or mobile underwater structural parts. Tether to fix the drilling system. The polyester anchor cable is composed of polyethylene terephthalate PET fibre stranded (Strand) and untwisted (Parallel) forms. Polyester fibre rope can be used as an anchor cable because of its good mechanical properties and
thermal stability, but it has poor hygroscopicity and is not suitable for long-term use in marine environments. From the comparison of the specific strength and specific modulus (specific stiffness) performance of several commercial anchor cable materials shown in Table 3, it can be seen that the specific strength of polyester fibre stranded cable (about 0.32 GPa/SG) is better than untwisted cable (about 0.24 GPa/SG), but the specific stiffness of both is very low. Nevertheless, the specific strength of both is better than steel tether (about 0.1-0.14 GPa/SG), so polyester tether can be used to replace steel cable. In addition, the specific strength and specific modulus of ultra-high molecular weight polyethylene fibre cable and aramid fibre cable are about 0.6-0.7 GPa/SG and 20-60 GPa/SG, which are obviously better than polyester fibre cable. The specific strength of the carbon fibre pultruded rod is about 1.2 GPa/SG, and the specific modulus is about 90 GPa/SG, which is obviously superior to all the above synthetic fibre tethers. Therefore, the carbon fibre pultrusion reinforced rod as the main load-bearing member of the anchoring cable has a significant comprehensive performance advantage [5].

Table 4. Comparison of specific strength and specific strength performance of carbon fibre pultruded rods and commonly used anchor cable materials.

| Performance/Material     | Steel stranded wire | Polyester cable | Aramid tether | UHMWPE cable | Pultruded carbon fibre reinforced rod |
|--------------------------|---------------------|-----------------|---------------|--------------|---------------------------------------|
| Specific strength (GPa/SG) | 0.14                | 0.32            | 0.46-0.6      | 0.58-0.65    | 1.2                                   |
| Specific strength (GPa/SG) | 7-20                | 3-5             | 22-60         | 20-30        | 90                                    |
| Hygroscopicity           | Easy to rust        | Difference      | Moisture resistance | Moisture resistance |

Another important advantage of CFRP cable is its fatigue resistance and low notch sensitivity. The carbon fibre pultrusion reinforced rod bundle is subjected to dynamic alternating high stress loads in the tether. Even if micro-cracks occur in local overload, the composite material is insensitive to the propagation of micro-cracks, and the damage propagation is terminated in the high-toughness resin. This advantage makes CFRP much safer than metal materials. In addition, each CFRP reinforcing rod is an independent structure, and any damage will end in this rod itself, and will not be transmitted to other rods. Therefore, this type of bundle rod cable has the most optimized design layout when bearing the tensile load, and also exerts the advantages of high tensile strength of carbon fibre, which improves the reliability. Fig. 3 is a schematic diagram of the structure of a CFRP tether, and Fig. 4 is a CFRP tether under construction. CFRP mooring cables are light-weight, save installation costs, and require almost no maintenance. They are ideal mooring cables for large oil production platforms and oil and gas production equipment in deep water areas [6].
5. Conclusion
Land oil is drying up, and the development of deep-sea oil and gas fields is now an inevitable trend. Carbon fibre composite materials play an important role in deep sea oil and gas exploitation. In order to ensure stable and continuous work in deeper seas, the potential largest market for carbon fibre applications is driving the development of the carbon fibre industry. The seven major carbon fibre manufacturers have announced plans to expand production by 78% in the next 3-5 years, marking a large-scale expansion of the application of CFRP in industrial areas where metal materials have limitations. The gap between the use of carbon fibre composite materials in the deep-sea oil field in China and that in foreign countries is decreasing. In order to meet the high pressure, light weight and corrosion resistance requirements of deep-sea oil and gas exploitation in China, future research and development efforts will continue to increase to achieve high performance Localization of pipes.

References
[1] Maierhofer, C. R. Llig, M., Gower, M., Lodeiro, M., Baker, G., & Monte, C., et al. Evaluation of different techniques of active thermography for quantification of artificial defects in fibre-reinforced composites using thermal and phase contrast data analysis. International Journal of Thermophysics, 39 (5) (2018) 61.
[2] Li, Y. L. Zhao, X. L., Singh, R. K. R., & Al-Saadi, S. Tests on seawater and sea sand concrete-filled cfrp, bfrp and stainless-steel tubular stub columns., 108 (11) (2016) 163-184.
[3] Javidan, F. Heidarpour, A., Zhao, X. L., & Al-Mahaidi, R. 12.22: seismic performance of high capacity hybrid beam-columns: comprising of high strength steel tubes subjected to lateral cyclic loading. Cepapers, 1 (2) (2017) 3661-3670.
[4] Sato, Y. Tsukamoto, M., Matsuoka, F., Yamashita, K., & Masuno, S. Effect on several gas ambiances for cfrp processing with nanosecond laser. Ieej Transactions on Fundamentals & Materials, 135 (10) (2015) 569-574.
[5] Atthapreyangkul, A. & Prusty, B. G. Experimental and numerical analysis on the geometrical parameters towards the maximum sea of cfrp components. Composite Structures, 164 (3) (2017) 229-236.
[6] Agrawal, S. Singh, K. K., & Sarkar, P. K. Comparative investigation on the wear and friction behaviors of carbon fibre reinforced polymer composites under dry sliding, oil lubrication and inert gas environment. Materials Today Proceedings, 5 (1) (2018) 1250-1256.