Development of Integrated Technology of FRP Gear Manufacturing

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Gears are integral part of mechanisms and machines. The development of new composite materials impulse to increase of specific weight and load-carrying ability of gears. Current trend can be supplied with fiber reinforced materials (FRP) whose specific weight strength could by five times higher than of hardened steel. Those the mechanical properties of FRP wheel can substantially be influenced by technological heredity than metallic one. That is why the influence of technological steps should be taken into account during FRP wheels manufacture. The purpose of current research is to develop integrated technique of FRP wheels manufacture. Consequently in current experimental research the cooperation of load-carrying ability of non metallic and metallic wheels was provided. Different techniques were used for optimization of reinforcement fiber geometry when FRP wheels manufacture. Operating procedure of wheel manufacture contents computer simulation of forming, and properties programming helped to provide quality and load-carrying ability of the wheels.

Keywords: Machining: Polymer gear; Fiber orientation; CFRP; Gear metrology

1 Introduction

In recent decades, composite materials are widely used in aircraft industry, automobile structure and energy. The main reason for the application of the new materials is achievement of improved dynamic behaviour of new machines. While the static stiffness of current solutions is usually sufficient, the dynamic behaviour suffers due to large density of cast iron and steel. Usage of FRP materials could be one possible way to reduce noise and vibration level of power transmission gears [6].

Using composite materials for tooth gear production has a big field for improvement their parameters such as noise quality, which avoids the unpleasant-sounding frequencies. He found that strength of a tooth with a reinforced fiber angle of 45° is lowest when the load is applied to the tooth tip while a critical tangency point of 15° occurs from the tooth root fillet on the tooth tip side. To increase tooth strength are in some studies suggested considering the stress concentration factor of the tooth root fillet in design systems [1].

Theoretical and experimental research which carried out on the models proved that assumed applications of polyoxymethylene (POM) and glass fibre polyoxymethy- lene POMGF25 plastics for the making of hydraulic elements possible. Authors concluded that nowadays for strength reasons, plastic systems can work at the working pressure that doesn’t exceed 4MPa. Their advantages are:

simple design, silent performance, low weight, and a simple and low-cost production method [8] [2].

Study to compare steel or cast iron to CFRP spindle rams. It was found that damping ratio evaluated from the free vibrations in FRP samples was several times higher than the damping ratio of the steel one. In the case of the assembly with connection interfaces, the evaluated damping ratio was increased by 70 % in comparison with the reference steel spindle ram. The weight of spindle rams was reduced by 41% by replacing steel with composite [3].

It was found that the commonly used methods for prediction elastic prosperities of wheels produce wide variations. It was proposed to use a rue of mixtures equations for better approximation of tooth behavior. To increase accuracy of tooth deflection the imaging technique at the number of positions in the gear should be used [7] [4].

Review of different novel composite applications was realised according to [5]. Among them composite double arm type robot hands, CFRP rotating boring bar, composite one-piece propeller shaft. Authors concluded that usage of hybrid connection of metal and composite parts in on detail could significantly (5 times) increase stiffness of above mentioned parts [10].

The concept of integrated technology includes not only heat treatment and machining of gears of CFRP, but the whole range of design features CFRP properties, including, but not limited to, computer designing of fiber arrangement in detail, the bearing capacity of the structure optimization of gear and programming properties of the final product.

However the stiffness of the designed component is not sufficient enough yet. The efficiency of gears from CFRP mechanical transmission depends not only on their geometric design, but from the design CFRP in a particular product, the technology of manufacturing and finishing [9].

Therefore, the aim of this work is to develop an integrated technology of manufacturing gear mechanical transmission with the use of a small mass of carbon fiber composite materials.

2 Analysis of production process

Quality of wheel gears depends on degree of matrix and fiber interaction and integration of technological steps during there manufacture. Empirically it is well known that technological heredity in the manufacture of the wheel gears form FRP much stronger impact on the quality of the finished product than the manufacture of metal one.

Indeed, if the carrying capacity of the metal wheel gears is determined by the chemical composition of the starting material (fiber) finish operations forming geometry and surface properties of teeth, the performance of FRP wheel gears depends on the filament placement, orientation, density, location, and their adhesion to the matrix. Therefore, processing procedure of the FRP wheel gears manufacture should comprise additional steps of integrating together "programming" properties of the workpiece material, and machining surfaces of teeth to achieve a high mutual bracing (Fig. 1)

Programmming of FRP wheel gear properties involves selection of spesific parameters of laying fibers which will ensure its higher load capacity and durability. This step should base on finite element analisys of gear in order to define zones of stress concentration and direction of the principal stresses. For involute gears the most dangerous zone will be the base of the tooth and the tooth flank. In the base of the tooth FRP must resist bending, on the tooth flank side - bending and crumpling. As will be shown below the apparent orientation of the fibers in the tooth, does not provide the full potential of FRP wheel gear strength and therefore, further research are required in this regard. To increase consistency of CFRP wheel gears machnical and running ability the processing procedure of there manufacture was designed (Fig. 1).

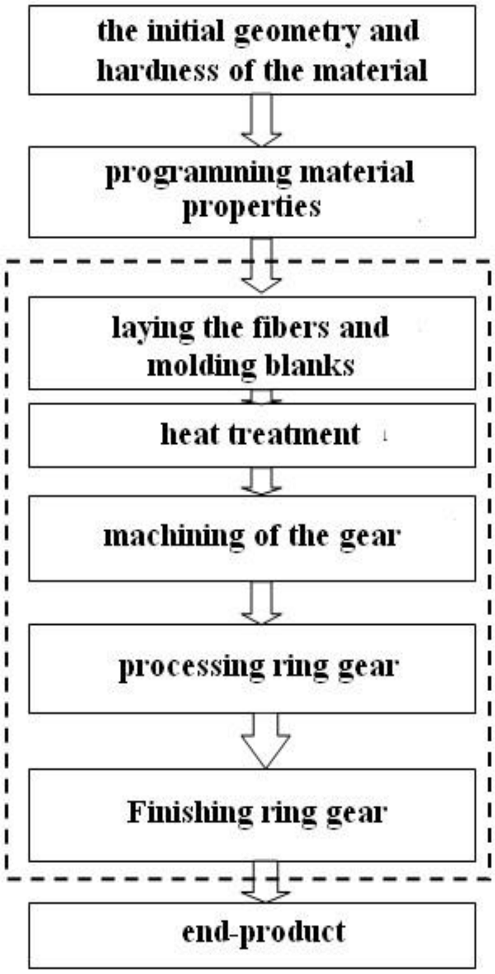

Fig. 1 Processing procedure of CFRP wheel gears manufacture

During next step of processing procedure, the information about the desired scheme of fiber placement should be used for forming gears. As result of this step we can get wheel gears manufactured in compliance with 8-9 degree of accuracy. More accurate wheel prevents shrinkage wheel buckling and leashes of workpiece occurring during forming and heat treatment.

Heat treatment step is needed for hardening of the matrix which increases it mechnical properties. Accuracy enhancement of FRP wheel gears could be achived during machining on gear machinery. However, the implementation of these production steps is complicated with low durability of cutting tool due to high intensity of abrasive wear when cutting high-strength reinforcing fibers in FRP.

It should be mentioned that due to low temperature needed forFRP wheel gear production manufacturing process of there fabrication is more efficient than metal one.

Unfortunately, in the current manufacturing technology of FRP wheel gears "programming" step does not imply FRP properties due to subsequent machining operations, resulting in significant layers of reinforcing fibers are often cut. That reduces the loading capacity of wheel gear. It can be seen from the feature experiment.

Tab. 1 *Specific mass strength cooperation*

Material			*E*, GPa	*Yr*, MPa	p, kg/m^3	Specific mass strength, MPa/(kg/m^3)
C/3	Steel 1044, 180 HB		205	540	7850	0.068
10	Steel 1044,400 HB			1200		0.15
Fiber reinforced plastic	Epoxy resin Lorit 285		50	85	1250	0.068
	Carbon fiber ЛУ-П-01 (unidirectional)		250-270	2000	1500	1.33
	CFRP	Tension longitudinal to fiber direction	115-MO	1250	1400	0.89
		Compression longitudinal fiber direc-tion		600		0.42
		Compression transverse fiber direction	80	150		0.11
		Tension transverse fiber direction		35		0.025
Plastic	POM		20	140	1000	0.14
	Fluoropolymer 20		11	26	2000	0.013
	Polyamide 612		8.0-9.5	160	1020	0.16

3 Experimental setup

Experimental research was realized using following materials Polyamide 612, POM, Fluoropolymer 20, CFRP and steel 1044 (180 HB). Wheel gears were manufactured with the same geometry for all materials: Tooth height - 2 mm. number of teeth - 30, width of tooth - 10 mm. the degree of accuracy - 8. Gear was designed especially for the purpose of the experiment to compare different operational characteristics of selected materials. All manufactured gear wheels were with the same dimensions with 30 teeth with diameter 155mm.

CFRP wheel of gears was produced using vacuum formation method. After fiber placing in form it was placed in vacuum bag Securlon L-500Y, air was pumped with vacuum pump 2HBP-5M out and form was filled with epoxy resin Lorit 285. The vacuum bag was sealed with sealant tape AT 199 (Fig. 2).

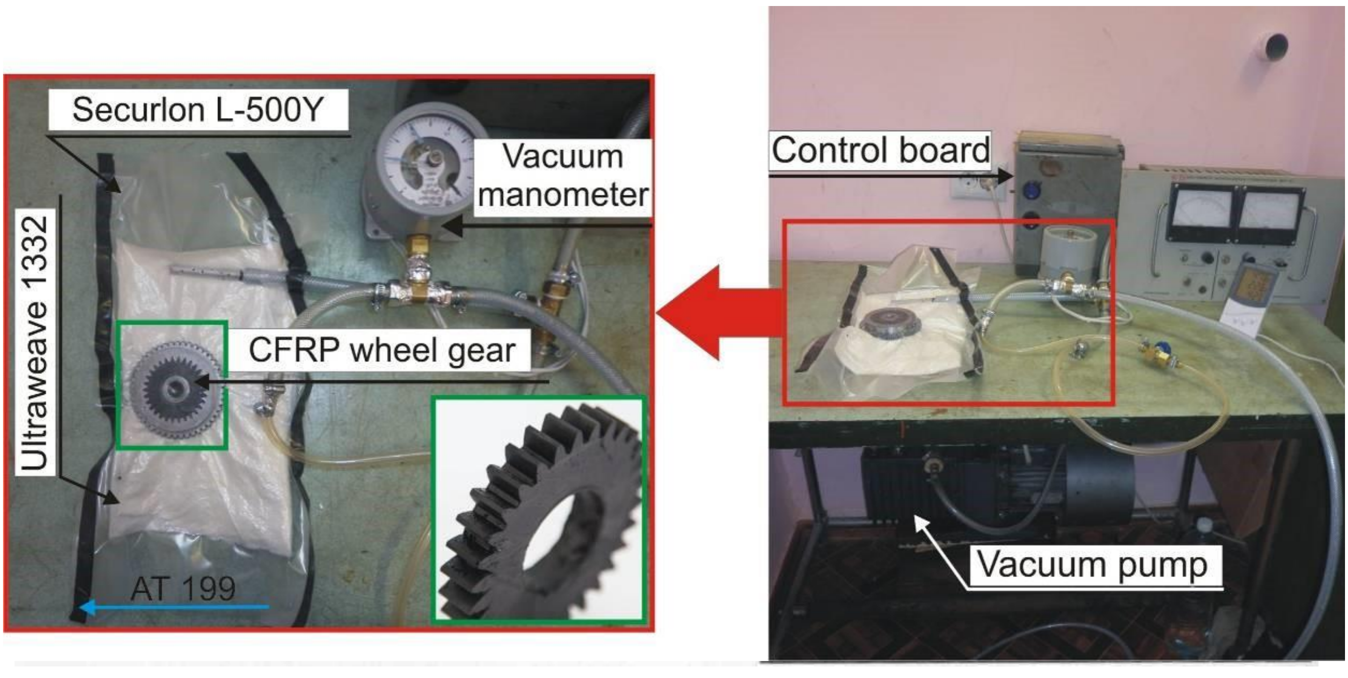

Fig. 2 *Scheme of CFRP wheel gear vacuum formation*

Thermal treatment was done during 8 hours at 80°C, followed by heating up to 120°C during 4 hours.

CFRP gearwheel was produced in two ways. First sample was produced from cylindrical workpiece with feature turning and gear shaping.

Second was formed as a wheel gear with defined geometry and mechanical properties. Unlike the first sample the second one was formed without fiber damage after machining.

Polyamide 612, POM, Fluoropolymer 20, CFRP and steel 1044 (180 HB) wheel gears were produced with gear shaping. The tests were conducted by stepwise static loading torque.

The test facility is a single-stage gearbox (Fig. 3). The gear shafts are mounted in bearings. On the driving shaft has been fixed and the steel gear catch, which was loaded with applying torque. On the driven shaft installed test gear wheel that is fixed against rotation gear sector. Loading was performed up to destruction of the teeth by gradually adding cargo.

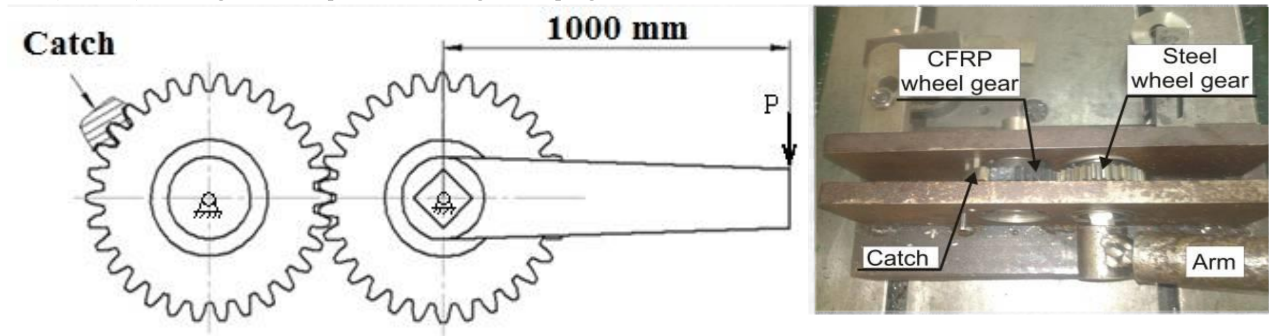

Fig. 3 *Schematic of wheel gear load*

Tab. 2 *Wheel gear properties*

Material	*Yr*, MPa	*E*, GPa	Roughness *Ra*, pm	Extreme deviation of tooth spacing *Fp*ₜ, pm	Deviation of base tangent length *Fc*, pm	Degree of accuracy in according GOST 1643- 81 DIN 3962
Fluoropolymer 20 (HB 58)	26	1.2	1.18	30	20	8
POM (HB 177)	140	2.6	1.45	50	70	9
Polyamide 612 (HB 134)	160	8.0-9.5	1.82	30	20	8
(HB 114)		1.5-2	9.46	140	80	10
CFRP (random fiber orientation) (HB 180)	35-150	8-10	1.6	110	60	9
CFRP (random fiber orientation) (HB 144)	35-150	8-10	1.7	16	20	8
CFRP (ordering fiber orientation) (HB 219)	60-1200	US-140	1.4	80	70	9
CFRP (ordering fiber orientation) (HB 219)	600-1200	115-MO	0.8	10	10	6

4 Results and discussion

Tests have shown that the greatest load capacity of all the non-metallic gears was measured in POM wheel gears, but still it was at half the load capacity of the steel gear. CFRP gears load capacity showed about half the load capacity of the POM, but there destruction occurred without significant plastic deformation. As the load capacity without plastic deformation POM, polyamide, and CFRP were almost at the same level 100 N-m. At the same time the load capacity of the steel gear was 410 N-m, i.e, 4 times larger. At the same time specific mass carrying capacity of above mentioned wheel gears equal to 0,071 N-m /(kg/m^3), and steel one 0,051 N-m / (kg / m^3), i.e. 30% less.

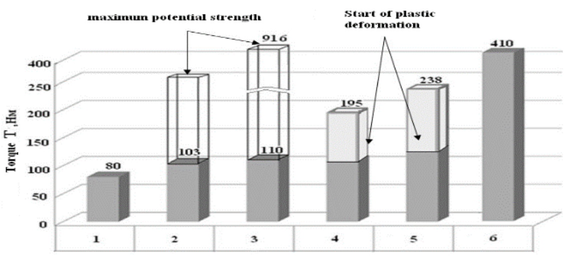

Fig. 4. - *Distractive torque of wheel gears for different wheel gears: 1 – Fluoropolymer 20; 2 – machined CFRP; 3 – vacuum formed CFRP; 4 – POM; 5 – Polyamide 612; 6 – Steel 1044 (180 HB)*

It was noticed that carrying capacity of non thermal treated CFRP wheel gears was 10% greater than the treated one. This indicates the necessity of "programming" properties of CFRP considering subsequent machining. The potential strength of the CFRP explicit underutilized (Fig. 4).

Assume that tooth decay in the experiment was a tensile transverse to the fiber direction - the worst embodiment arrangement of reinforcements in the body of the tooth. Then the load capacity at the optimal placement of filaments when all fibers will only accept tensile can be achieved.

$$T_{max}=\frac{X_T}{Y_T}T_{exp} \quad (1)$$

where, Texp - experimentally measured torque, N-m;

XT - Longitudinal tensile strength, MPa;

YT - Transverse tensile strength, MPa; then,

$$T_{max}=\frac{1250}{150}110=916\_N\cdot m \quad (2)$$

The possibility of increasing the maximum torque for machined and vacuum formed CFRP shows the thin line in Fig. 4. It can be seen that the potential load capacity of CFRP gears is two times higher than steel one, simultaneously the specific potential load capacity - more than 10 times larger. Obviously this is a theoretical limit, but at the same time it is clear that CFRP gear has a large potential for increasing load capacity, which has not yet been exhausted.

5 Conclusions

Studies have specified that inheritance process in the manufacture of CFRP gears significantly stronger than wheels made of metal. Therefore, the production process of CFRP gears manufacture should take into account the effect of the steps as the moulding blanks and their machining.

This can be achieved by integrating between a "programming" the material properties of the workpiece and CFRP wheel gear tooth surfaces machining in order to provide a high geometrical accuracy in a single process. Considering optimization of fiber reinforcement scheme as a production step what makes possible to take into account the need for fibers orientation in the direction of the greatest loads and minimize damage during subsequent machining of the wheels with a high degree of accuracy.

The load capacity of CFRP gears is comparable with load capacity of other non-metallic materials, but only CFRP gear has a large reserve for increasing the load capacity by optimizing the fibers orientation schemes and manufacturing technology that has not yet been exhausted.

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