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MATERIALS SELECTION FOR CARBON NANOTUBE COMPOSITES IN POWER TRANSMISSION

Nowadays designers and producers implement non-metallic gears in power transmissions because of their better mechanical properties, like high elastic modulus, tensile strength and high wear resistance. In order to examine these properties we need to get familiarized with the most common materials used to make composites, like POM, PEEK, PA 6, PA 6/6, UHMWPE and one of newest materials in this area – carbon nanotubes (CNTs). This paper describes how to select the best materials in order to create the composite we need for the necessary applications. The article also gives information about the polymers and a comparison between them and CNTs.

Keywords: *polymers; carbon nanotubes; composites; gears.*

Materials selection for polymer and cnt gears. Following the discussion [1] of the works and results of Samy Yousef et. al. [2] and A. Kapelevich et. al. [3] we made an assumption, based on their investigations of the wear resistances of Polyoxymethylene (POM) spur, helical, bevel and worm gears and also the investigation of optimizing the manufacturing processes of polymer gears. In order to have benefits like increased safety factors, higher operating pressure angle, higher operating temperature etc., that we must take under consideration the results from their studies and implement them into making new materials for gears, combining polymers, CNTs and an optimized manufacturing method. But before that first we must get familiarized with the most common materials (polymers) for manufacturing of gears.

POLYOXYMETHYLENE (POM): COPOLYMER [4]

Chemical Designation: Polyoxymethylene, acetal, polyacetal, polyformaldehyde

Class: Synthetic polymers, Thermoplastic

Trade Names: BEETLE ACETAL (by BIP Plastics), CELCON (by Hoechst), DELRIN ST (by DuPont), FULTON LNP (by Engineering Plastics), HOSTAFORM (by Hoechst), KEMATAL (by Hoechst), LATAN (by Lati), RTP 805 (by RTP), TENAC-C4510 (by Asahi Chemical), THERMOFIL ACETAL (by Thermofil), ULTRAFORM (by BASF)

Properties:

Max. Operating Temp.	°C	90	Surface hardness	-	RR117
Water absorption	%	0,22	Linear expansion	-	11
Tensile Strength	MPa	73	Flammability UL 94	-	HB
Flexural Modulus	GPa	2,58	Oxygen index	%	15
Elongation at break	%	65	Vol. resist. Ω.cm	-	15
Strain at Yield	%	8	Dielec. Strength	MV/m	20
Notched Izod	kJ/m	0,069	Dielect. const. 1kHz	-	3,7
HDT @ 0,45 MPa	°C	160	Dissipation Fact. 1 KHz	-	0,0015
HDT @ 1,80 MPa	°C	110			
Matl. drying hrs @	°C	3 @ 90	Melt. Temp. range	°C	190–210
Mold shrinkage	%	1,8	Mold temp. range	°C	60-120

Advantages: Excellent rigidity, impact toughness, abrasion resistance, creep resistance and solvent resistance. Good appearance, hydrolytic stability, fatigue endurance and low coefficient of friction. Better creep resistance, thermal stability, resistance to bases and processability than homopolymer. Higher continuous use temperature than homopolymer – about 100°C in air, compared to 80°C.

Disadvantages: High moud shrinkage (approximately 2 %). Post-molding shrinkage of about 0,1 % normally complete within 48hrs. Attacked by acids and bases, very rapid attack by nitric acid. Very poor resistance to UV radiation. Homopolymers have higher tensile strength, flexural strength, fatigue resistance and hardness. Cannot be fire retarded. Explosive decomposition if processed with halogens.

Processing: Blow Molding, Extrusion, Injection Molding, Rotational Molding

Post-processing: Bonding, Machining, Painting, Welding

Applications: Due to low coefficient of friction, commonly used as bearings, gears and conveyor belt limits. Electric kettles and water jugs. Components with snap fits. Chemical pumps. Bathroom scales. Telephone keypads, pulley wheels, housings for domestic appliances, shower heads, fuel expansion tanks. Toys.

Average Price (€/kg): 0,68

We can see that POM is one of the most suitable materials for us to use – it is cheap, it is available everywhere, it has excellent creep resistance, fatigue endurance, low coefficient of and it is also suitable for 3D printing.

POLYARYLETHERETHERKETONE (PEEK) [4]

Chemical Designation: Polyaryletheretherketone

Class: Thermoplastic polymer

Trade Names: CTI PEEK (by Compounding Technology), PEEK (by Goodfellow), RTP 2200 (by RTP), VICTREX PEEK (by Victrex Sales), VICTREX PEEK 450G (by Victrex USA)

Properties:

Max. Operating Temp.	°C	250	Surface hardness	-	RM99
Water absorption	%	0,15	Linear expansion	-	4,8
Tensile Strength	MPa	92	Flammability UL 94	-	V0
Flexural Modulus	GPa	3,70	Oxygen index	%	35
Elongation at break	%	50	Vol. resist. Ω.cm	-	16,7
Strain at Yield	%	4,3	Dielec. Strength	MV/m	19
Notched Izod	kJ/m	0,083	Dielect. const. 1kHz	-	3,2
HDT @ 0,45 MPa	°C	260+	Dissipation Fact. 1 KHz	-	0,0016
HDT @ 1,80 MPa	°C	160			
Matl. drying hrs @	°C	3 @ 150	Melt. Temp. range	°C	350–390
Mold shrinkage	%	1,1	Mold temp. range	°C	120–160

Advantages: Good thermal stability – UL continuous use temperature of 250°C. Good dynamic fatigue resistance. Good chemical resistance. Inherently fire-retardant with low smoke generation. Good tracking resistance.

Disadvantages: Expensive. Difficult to process. Attacked by concentrated acids.

Processing: Compression Molding, Extrusion, Vacuum Forming, Injection Molding, Machining, Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF)

Post-processing: Machining, Painting, Welding

Applications: Wire covering (cable insulation), injection molded engineering products (gears, bearings), film for flexible PCB, resin in fibre prepregs. Used in aerospace applications and radiation environments.

Average Price (€/kg): 3,85

We can see that PEEK is better than POM for its higher operating temperature, but it is also more expensive which limits its widespread use.

POLYAMIDE 6 (PA 6) (NYLON 6) [4]

Chemical Designation: Polyamide

Class: Semi-crystalline polymer

Trade Names: ADELL B (by Adell Plastics), AKULON (M&K) (by DSM), AMILAN NYLON 6 (by Toray Industries), ASHLENE NYLON 6 (by Ashley Polymers), BEETLE NYLON 6 (by BIP Plastics), BUDD CAST 6 (by Budd), CAPRON Allied (by Signal), CAPRON Victrex (by Sales), CELANESE NYLON 6 (by Hoechst), CTI NYLON 6 (by Compounding Technology), DURETHAN B (by Bayer), DURETHAN B (by Albis), GRILON (by EMS-Grilon), GRILON (by Emser Industries), JONYLON NYLON 6 (by BIP Chemicals), LATAMID 6 (by Lati), NIVIONPLAST B (by EniChem), NOVAMID (by Mitsubishi Engineering Plastics), NYLATRON NYLON 6 (by Polymer), NYLON 6 (by Goodfellow), ORGAMIDE by (Elf Atochem), SCHULAMID NYLON 6 (by A. Schulman), SNIAMID (by Nyltech), TECHNYL C (by Rhone-Poulenc), THERMOFIL NYLON 6 (by Thermofil), UBE NYLON 6 (by Ube Industries), ULTRAMID B3S (by BASF), WELLAMID NYLON 6 (by Wellman), ZYTEL 6 (by DuPont)

Properties:

Max. Operating Temp.	°C	80	Surface hardness	-	SD75
Water absorption	%	1,5	Linear expansion	-	10
Tensile Strength	MPa	40	Flammability UL 94	-	HB
Flexural Modulus	GPa	1	Oxygen index	%	22
Elongation at break	%	60	Vol. resist. Ω.cm	-	14
Strain at Yield	%	4,5	Dielec. Strength	MV/m	25
Notched Izod	kJ/m	0,25	Dielect. const. 1kHz	-	8
HDT @ 0,45 MPa	°C	200	Dissipation Fact. 1 KHz	-	0,2
HDT @ 1,80 MPa	°C	80			
Matl. drying hrs @	°C	3 @ 95	Melt. Temp. range	°C	230–280
Mold shrinkage	%	1,2	Mold temp. range	°C	40–60

Advantages: Easier to process than Nylon 6/6. Castable, may be reaction-injection molded. Lower mold shrinkage than Nylon 6/6. Good fatigue resistance. Useful improvement in stiffness can be obtained by inclusion of glass fibres, unlike acetal.

Disadvantages: Highest rate of water absorption and highest equilibrium water content. Lower strength & stiffness than Nylon 6/6. Higher stickslip than Acetal or PBT.

Processing: Compression Molding, Extrusion, Injection Molding, Rotational Molding, Structural Foam Molding, Vacuum Forming

Post-processing: Bonding, Machining, Painting, Welding

Applications: Gears, cams, rollers, bearings, nuts & bolts, power tool housings, electrical connectors, combs, coil formers, fuel tanks for cars, kitchen utensils.

Average Price (€/kg): 0,88

We can see that PA 6 has somewhat worse properties than POM and PEEK but it seems that its higher price is due to its better water absorption, elongation at break (compared to POM) and higher melting temperature (again compared to POM).

POLYAMIDE 6/6 (PA 6/6) (NYLON 6/6) [4]

Chemical Designation: PA 6/6 (Polyamide 6/6) (Nylon 6/6)

Class: semi-crystalline polymer

Trade Names: ADELL A (Adell Plastics), AKULON (S) (DSM), AMILAN NYLON 66 (Toray Industries), ASHLENE NYLON 66 (Ashley Polymers), BEETLE NYLON 66 (BIP Plastics), CELANESE (Hoechst), COMALLOY NYLON 66 (ComAlloy), CTI NYLON 66 (Compounding

Technology), DURETHAN A (Bayer), DURETHAN A (Albis), GRILON T (EMS-Grilon), JONYLON NYLON 66 (BIP Chemicals), LATAMID 66 (Lati), MINLON (DuPont), NYLATRON NYLON 66 (Polymer), NYLON 6/6 (Goodfellow), NYPEL (Allied Signal), SNIAMID (ASN Nyltech), TECHNYL A (Rhone-Poulenc), THERMOFIL NYLON 66 (Thermofil), UBE NYLON 66 (Ube Industries), ULTRAMID A3K (BASF), VYDYNE (6/6) (Monsanto), WELLAMID NYLON 66 (Wellman), ZYTEL 66 (DuPont)

Properties:

Max. Operating Temp.	°C	80	Surface hardness	-	RR90
Water absorption	%	1,2	Linear expansion	-	8
Tensile Strength	MPa	59	Flammability UL 94	-	HB
Flexural Modulus	GPa	1,2	Oxygen index	%	22
Elongation at break	%	60	Vol. resist. Ω.cm	-	15
Strain at Yield	%	4,5	Dielec. Strength	MV/m	25
Notched Izod	kJ/m	0,11	Dielect. const. 1kHz	-	8
HDT @ 0,45 MPa	°C	200	Dissipation Fact. 1 KHz	-	0,2
HDT @ 1,80 MPa	°C	100			
Matl. drying hrs @	°C	3 @ 95	Melt. Temp. range	°C	280–300
Mold shrinkage	%	1,5	Mold temp. range	°C	40–80

Advantages: Good abrasion resistance (better than Nylon 6). Short cycle times. Strongest aliphatic Nylon. Addition of glass fibre improves stiffness considerably (unlike acetal). Better low temperature toughness than Acetal or PBT or Nylon 6. Good fatigue resistance.

Disadvantages: Relatively difficult to process due to exceptionally low melt viscosity. High water absorption (8% saturated) though less than PA 6. Post mold shrinkage. Weathering can cause color change and embrittlement unless suitably stabilized.

Processing: Injection Molding, Rotational Molding

Post-processing: Bonding, Machining, Painting, Welding

Applications: Gears, bearings, cams, nuts, bolts, rivets, castors, wheels, power tool casings, rotationally molded petrol tanks. Under-bonnet applications including rocker box covers, radiator tops, timing chain covers and fan blades.

Average Price (€/kg): 0,91

We can see that there is not a big difference between PA 6 and PA 6/6 so the choice between Nylon 6/6 and Nylon 6 is often made for reasons of availability, price or familiarity rather than any technical superiority. The exception to this is ease of molding, where Nylon 6 dominates.

ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE (UHMWPE)

Chemical Designation: Ultra-High Molecular Weight Polyethylene

Class: semi-crystalline polymer

Trade Names: HOSTALEN GUR (Hoechst), STAMYLAN UH (DSM), UHMW 1900 (Himont), ULTRA WEAR (Polymer)

Properties:

Max. Operating Temp.	°C	55	Surface hardness	-	RR50
Water absorption	%	0,01	Linear expansion	-	13
Tensile Strength	MPa	35	Flammability UL 94	-	HB
Flexural Modulus	GPa	0,5	Oxygen index	%	17
Elongation at break	%	500	Vol. resist. Ω.cm	-	18
Strain at Yield	%	25	Dielec. Strength	MV/m	28

Notched Izod	kJ/m	1,06+	Dielect. const. 1kHz	-	2,3
HDT @ 0,45 MPa	°C	69	Dissipation Fact. 1 KHz	-	0,0002
HDT @ 1,80 MPa	°C	42			
Matl. drying hrs @	°C	N/A	Melt. Temp. range	°C	N/A
Mold shrinkage	%	N/A	Mold temp. range	°C	N/A

Advantages: Outstanding toughness, cut and wear resistance, excellent chemical resistance, good low temperature impact resistance, low coefficient of friction.

Disadvantages: Not melt processable.

Processing: Compression molding, extrusion

Post-processing: Machining

Applications: Can & bottle handling machine parts, moving parts on weaving machines, bearings, gears, artificial joints, chutes and slides for directing particulate solids, edge protection on ice rinks, butchers' chopping boards.

Average Price (€/kg): 2,5

We can say that while having outstanding toughness, wear resistance and low coefficient of friction, UHMWPE is the newest material pre-carbon nanotubes, and although being slightly cheaper than PEEK (2,5 vs. 3,85 €/kg) it's difficulty in processing and post-processing makes it the hardest material to work with among the ones discussed in this article. Also, just like CNTs, it is still not studied well enough, so some experimenting should be done before making composites with this very high-quality polymer, whose biggest problem is the adhesion to fillers.

CARBON NANOTUBES (CNTS) – SINGLE-WALLED (SWCNTS) AND MULTI-WALLED (MWCNTS) [5]

Chemical Designation: Carbon Nanotubes

Class: Allotropes of carbon

Trade Names: TUBALL (by OCSiAl)

Properties:

Max. Operating Temp.	°C	750	Surface hardness	-	-
Water absorption	%	-	Linear expansion	-	-
Tensile Strength	MPa	500/60	Flammability UL 94	-	-
Flexural Modulus	GPa	1000	Oxygen index	%	-
Elongation at break	%	16	Vol. resist.	-	-
Strain at Yield	%	-	Dielec. Strength	MV/m	-
Notched Izod	kJ/m	-	Dielec. Const. 1kHz	-	-
HDT @ 0,45 MPa	°C	-	Dissipation Fact. 1 KHz	-	-
HDT @ 1,80 MPa	°C	-			
Matl. drying hrs @	°C	-	Melt. Temp. range	°C	1700
Mold shrinkage	%	-	Mold temp. range	°C	-

Advantages: Extremely small and lightweight, resources required to produce them are plentiful, resistant to temperature changes (they function almost just as well in extreme cold as they do in extreme heat), have been in the R&D phase for a long time now (most of the kinks have been worked out), as a new technology, investors have been piling into these R&D companies, (which will boost the economy), Self-lubricating.

Disadvantages: Weak under compression, undergo buckling when placed under compressive, torsional, or bending stress, despite all the research, scientists still don't understand exactly how they work, extremely small (difficult to work with), the process of producing CNTs is relatively expensive and health hazardous, expensive to implement this new technology in and replace the older technology, at the rate our technology has been becoming obsolete (it may be a gamble to bet on this technology).

Processing: –

Post-processing: –

Applications: gears, bicycle components

Average Price (€/g): 6,7

We can see that CNTs have the highest operating temperature, tensile strength and Young's modulus, which makes them perfect for gears, but they also have the highest melting temperature, which makes them difficult to manufacture and process, especially when they are very expensive in 2016. One of their key advantages is the fact that they are self-lubricating, which means that when having CNTs we should not deal with any kind of lubricants.

Materials selection methodology. There exist many different methodologies for selection of materials, some of which we have looked at, like M.Zarandi's et. al. [6] and G.Batalha's [7], but they all gravitate around the methodology developed by M.Hough et. al. [8], so we will stick to it:

The selection of a suitable plastic material for a particular application must take account of a number of factors. These are likely to include the following:

- The operating environment experienced by the component, e.g. exposure to extremes of temperature, mechanical forces;
- The primary production method, e.g. molding, extrusion, pultrusion, forming, etc.
- Assembly technique - Must the component be bonded, welded or fastened mechanically?
- The cost of the material;
- Aesthetic and decorative features – Is surface finish important? Must the component be transparent? Will it be painted or plated?

Generally, all of these factors need to be considered simultaneously in order to obtain a material that satisfies each of the requirements to some degree. However, in some cases a material may be selected which has exceptionally good properties in just one or two areas. One such example is provided by Polytetrafluoroethylene (PTFE) or simply Teflon, where its difficulty in processing and low strength and stiffness are tolerated or designed against, in order to utilize its exceptional chemical resistance. When making a materials selection there are usually a number of material requirements that are essential and a further group that are desirable. Essential requirements are likely to be defined by the operating environment, or by the availability of primary production methods, or perhaps by specific end-uses, such as a need for transparency. Desirable properties may be selected on the basis of preference or compromise. A factor such as low material cost may be essential for a bulky, mass produced item, but inconsequential for a small, specialist component. A rational materials selection procedure must accommodate both the essential and the desirable criteria. The first stage must be to identify those materials which demonstrate the essential qualities to the required level. All materials which fail to meet these requirements may be eliminated from further consideration. The second stage is then to order or rank the selected materials with respect to certain other desirable qualities, and thus obtain a short list of candidate materials which is suitable for detailed scrutiny.

Conclusions. We can conclude that CNTs promise a great deal of success in any area, in which they can be implemented. Of course, nothing is perfect, and CNTs make no exception. The problems they have include weakness under compression, they are still not explained completely, the process of manufacturing is expensive and may lead to health problems and of course – the high price. Mixing them with polymers, in this case POM, PEEK, PA 6, PA 6/6 and UHMWPE we should be able to overcome CNT's limitations.

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