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NUMERICAL ANALYSIS OF ALUMINUM COMPOSITE CYLINDRICAL GEARS

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Abstract: Spur gears are the simplest type of gears, which are widely used in modern structures. One of the main tasks of researchers in application areas of gears within the responsible structures, especially in spacecraft propulsion mechanisms, is to obtain compact gear, small size and weight, while maintaining or improving functional characteristics. Therefore there was a need to explore new materials that could be used as a replacement for steel in the manufacturing of gears. A good alternative for steel is hybrid composite with aluminum matrix and various reinforcements, which provides adequate mechanical properties, while reducing the weight of the gear. The paper presents the modeling of gears and analysis of their stress-deformation state using the finite element method. Steel and composite gears made from aluminum matrix with various reinforcements were tested. Results from this study show that the gear made of composite material offers enhanced features compared to metal gears.

Key words: Composite, Deformation, Improvement, Gear, Stress.

1 INTRODUCTION

Through historical development of gear, thanks to technological advances, the use of gear has become big in various industrial fields. Very form of it allows the economical production of gears, with easy maintenance and installation [1]. Gears transmit motion and torque from one shaft to another using a link form, consisting of linked gear teeth [2]. In most cases, the gears are made of iron alloys. Recently, for the production of specific mechanical components are used metal matrix composite materials (MMC) [3]. This is due to their advantages in comparison with polymer composite materials such as light weight, high strength, greater dimensional stability and resistance to corrosion, although the price of MMC composites is very high [4]. One of the areas where MMC materials can be applied is gear transmissions [5].

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Al-SiC composite, as well as other composite, they can be produced by powder metallurgy or by casting with constant mixing and as such, provides improved hardness and tensile strength with a much lighter weight [6-8]. For reinforcement are commonly used carbides, borides, nitrides, oxides and Al_2O_3, *SiC, TiC,* TiO_2, B_4C, TiB_2 [9-11]. For the Al-SiC, as well as for other composite materials, it is necessary to add a bonding agent such as fly ash, in order to increase the bonding of the particles for molten aluminum alloy. In this paper, the focus is on numerical analysis of metal gear to investigate its replacement with gear made from composite material. Purpose is to reduce its weight and increase machine efficiency [12]. Similar procedures were carried out in [13-19].

2 DESIGN OF GEARS

Construction of gears is a combination of science and design. There are various methods for constructing the gear [20-22]. Lewis - formula and Hertz - equation are applied because of various influencing factors. In this study was carried out test on contact gear stress, to determine relation of stress – deformation characteristics [18, 23]. Basic dimension needed for the design of gear through the above-mentioned formulas are shown in Table 1.

Table 1. *Input parameters for design of gear*

Parameters	*Value*
Input strength, P	*10 kW*
Input speed, n_1	*1440 min*$^{-1}$
Module, m	*2.5 mm*
Gear ratio, i	*3.1*
Gear width, b	*30 mm*
No. of drive gear pinion, z_1	*20*

Based on Table 1 value, there were performed their entry into the *Autodesk Inventor®* module. There was conducted testing of gear meshing and checking whether the gears meet the given input parameters. After that testing, gear model goes into the module for structural analysis where the load and appropriate restrictions were put in order to see the results of the Von Misses stress and deformation.

3 FINITE MODELING OF SPUR GEAR

Modeling of gears is made in the software program *CATIA v5®*, and then the model is imported into the module for structural analysis in *Autodesk Inventor®* software. The condition for analysis has been assumed as static. For finite element analysis (*FEA)* of the obtained composite gears, module of elasticity and Poisson's ratio were taken from the corresponding literature [23-29]. Table 2 shows the characteristics of the materials used in the study.

Table 2. *Mechanical properties of materials*

Material	Young module, E	Poisson's ratio, v	Density, ρ	Yield strength, R_e	Tensile strength, R_m
Steel	207 GPa	0.3	7.85 g/cm³	207 MPa	345 MPa
Nylon	225 GPa	0.35	1.13 g/cm³	82 MPa	82 MPa
CFRP	132 GPa	0.39	1.43 g/cm³	300 MPa	577 MPa
Al, SiC 15 %	150 GPa	0.3	2.79 g/cm³	90 MPa	151 MPa
Al, SiC 16%, CNT 1%	93 GPa	0.3	2.79 g/cm³	150 MPa	202 MPa
Al, Al_2O_3 0.5%, TiB_2 0.5%	138 GPa	0.3	2.76 g/cm³	257 MPa	294 MPa
Al, Al_3Ti 2.5%, MgO 3%	85 GPa	0.3	2.76 g/cm³	158 MPa	252 MPa
Al, Al_2O_3 10%	96.2 GPa	0.3	2.76 g/cm³	187 MPa	280 MPa
Al, SiC 10%	81.2 GPa	0.3	2.79 g/cm³	198 MPa	298 MPa
Al-SiC 10%, graphite 1%	81.6 GPa	0.3	2.76 g/cm³	170 MPa	255 MPa

In this case, was performed the comparison of Von Misses stresses and deformations between gears made of steel, nylon, CFRP and gears made of hybrid composite with aluminum matrix. Structural analysis is carried out under a load of 150 N, 300 N, 450 N, 600 N, and 750 N. The forces were posted at tangent side edges of teeth simulating the load that would occur if the gear is engaged with the other gear. Based on this condition, there was obtained the value of Von Misses stress and deformation of gears.

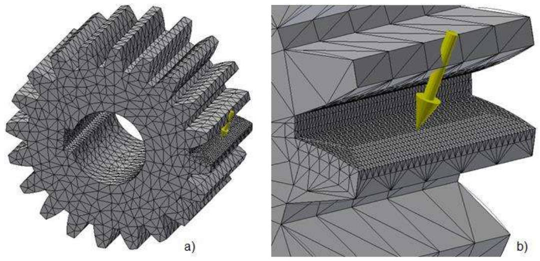

Figure 1. *The gears with a mesh under appropriate load (a) and the appearance of fragmented mesh on the required parts (b)*

Figure 1 show the layout of the mesh on the gear and the place where the mesh is fragmented. Mesh consists of 27414 elements and 42254 nodes. The mesh is fragmented around the place of acting force and on the place where the gear is connected to the shaft through wedge. It was set under the assumption that on these places will be the biggest stress values.

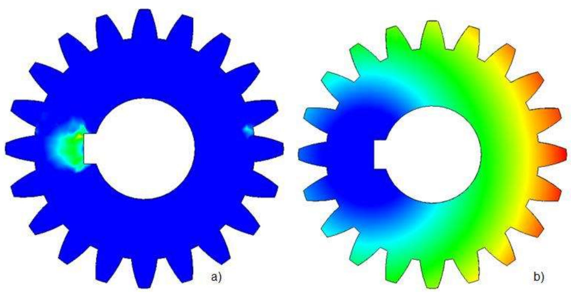

Figure 2. *Von Mises stress (a) and deformation of gear under load (b)*

According to Figure 2 (a), it can be concluded that the value of maximum stress appear at the site of tooth root and the point where gear join with shaft. Figure 2 (b) shows the deformations of gear. Lowest deformation is on the place where gear connect with shaft, and the greatest is on the place where second gear act on the surface of first gear. Figure 3 shows the layout of the stress state at the root of tooth, and also the point where the gear connect with shaft with wedge.

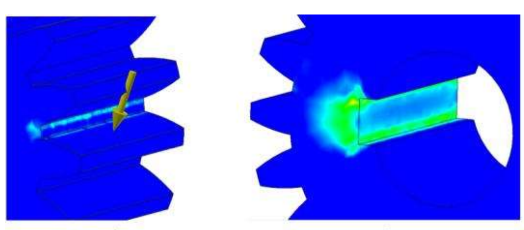

Figure 3. *Von Misses stress in the root of gear toot (a) and on a place where gear connect with shaft (b)*

Table 3 show the obtained values of Von Misses stress and deformations of gears made from various material.

Table 3. *Value of Von Misses stress and deformation of gear by various materials*

Material		Load (N)				
		150 N	300 N	450 N	600 N	750 N
Steel	Stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.01041	0.02082	0.03124	0.04165	0.05206
Nylon	Stress (MPa)	32.33	64.66	96.99	129.3	161.6
	deformation (mm)	0.7318	1.464	2.195	2.927	3.659
CFRP	stress (MPa)	30.92	61.85	92.77	123.7	154.6
	deformation (mm)	0.01577	0.03153	0.0473	0.06306	0.07883
Al, SiC 15%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.01458	0.02915	0.04373	0.05831	0.07289
Al, Al_2O_3 0,5 %, TiB_2 0.5%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.01573	0.03146	0.04716	0.06292	0.07866
Al, Al_3T_i 2.5%, MgO 2.5%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.02572	0.05145	0.07717	0.1029	0.1286
Al, SiC 16%, CNT 1%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.02351	0.04702	0.07054	0.09405	0.1176
Al, Al_2O_3 10%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.02273	0.04546	0.06819	0.09092	0.1136
Al, SiC 10%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.02693	0.05386	0.08079	0.1077	0.1346
Al, SiC 10%, graphite 1%	stress (MPa)	33.83	67.67	101.5	135.3	169.2
	deformation (mm)	0.0268	0.05359	0.08039	0.1072	0.134

After the obtained values of Von Misses stress of gears, it can be said that all other materials of which is gear made except nylon and CFRP have the same stress value with same load because it is a linear structural analysis. Within this analysis, on the value of stress affect force, area and the Poisson's ratio. Nylon and CFRP for the same load of gears have different stress values for various values of Poisson's ratio. In Figure 4 are graphically displayed Von Misses stress deviations between these materials at different loads.

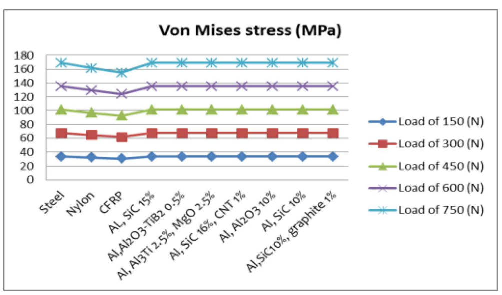

Figure 4. Gear *stress dependence from the value of load and type of materials*

In this analysis, materials of gear are examines in the area of elasticity, so it is necessary to compare the obtained values of stress for load of 150 N to 750 N with the values of yield strength of given material. By comparing these values, there can be obtained maximum force for given materials at a time when the material moves from the elasticity to plastic area. Table 4 shows the values of deformation under maximum gear load. These values were obtained at yield stress of material or at a stress when the material passes from elastic to plastic deformation.

Table 4. *Value of max Load and deformation of gears on* yield strength of *materials*

Material	Yield strength, R_e	Load, F	Deformation
Steel	207 MPa	930 N	0.06386 mm
Nylon	82 MPa	385 N	1.878 mm
CFRP	300 MPa	1450 N	0.1524 mm
Al, SiC 15%	90 MPa	400 N	0.03887 mm
Al, SiC 16%, CNT 1%	150 MPa	665 N	0.06463 mm
Al, Al_2O_3, TiB_2 0.5%	257 MPa	1140 N	0.1196 mm
Al, Al_3T_i 2.5%, MgO 2.5%	158 MPa	703 N	0.12 mm
Al, Al_2O_3 10%	187 MPa	830 N	0.1258 mm
Al, SiC 10%	198 MPa	880 N	0.155 mm
Al, SiC 10%, graphite 1%	170 MPa	752 N	0.138 mm

Based on the results in Table 4 it can be concluded that because of different yield stress, come up with different values of maximum load gear. In Table 3, the gear is subjected to a load up to 750 N, but the results in Table 4 show that gear made from some materials have much smaller allowed force. Figure 5 shows the results of the maximum gear load.

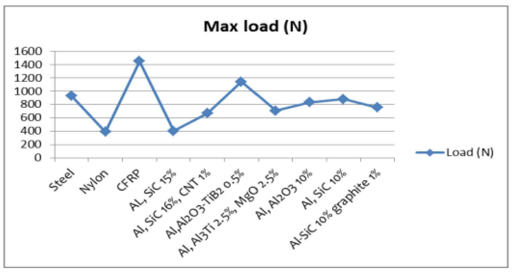

Figure 5. *Maximum gear load on yield strength of materials*

Based on Figure 5 and results in Table 4 it can be concluded that the gear made of CFRP can withstand maximum load of 1450 N, because this material has the highest value of the yield strength. Besides him also Al, Al_2O_3, TiB_2 0.5% showed good characteristics because they can withstand a load of 1140 N. The weakest of all tested materials as nylon and AlSiC that could withstand only load of 385 N and 400 N. Minimum deformation of all the gear has a steel gear and after it gear made of AlSiC and Al, SiC 16%, CNT 1%. Gears build from these materials have two to three times less maximum load than the gear made of CFRP, which has a slightly lower deformation than steel. Figure 6 shows the schema of gear deformations due to all loads. All values of gear deformations were observed in the zone of material elasticity.

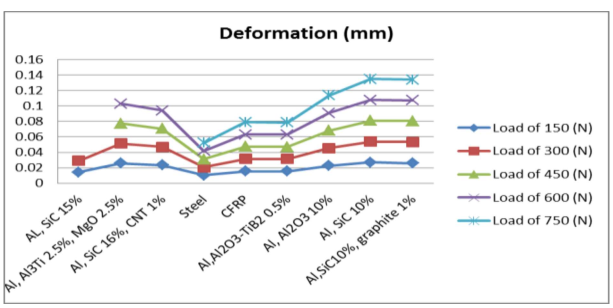

Figure 6. *Gear deformation due to all loads*

Results of deformations of Figure 6 shows that the gear made from alloy AlSiC with 15% content of SiC has the least deformation and that have a maximum load of 400 N, and it can be used as a substitute only for small loads. Unlike him, gear made from CFRP has a slightly larger deformation than the gear of the AlSiC but generally has the best ratio of max load and deformation. Most of the materials from which gear can be made have approximate results of deformation at the same given load. The results of gear deformation show that all materials except nylon meet the necessary requirements for making gear of them. In table 5 are given the value of the gear mass of the same geometrical parameters made from various materials.

Table 5. *Gear mass from various materials*

Material	Steel	Nylon	*CFRP*	*Al, S_iC* 15%	*Al,Al_2O_3, TiB_2* 0.5%	*Al, Al_3T_i* 2.5%, *MgO* 2.5%	*Al, SiC* 16%, *CNT* 1%	*Al, Al_2O_3* 10%	*Al, S_iC* 10%	*Al, S_iC 10%*, graphite 1%
Mass (kg)	0.38	0.05	0.07	0.13	0.13	0.13	0.13	0.13	0.13	0.13

Based on the value of weight in Table 5 it can be concluded that the gear made of nylon and CFRP has a 7 and 5 times less weight compared to steel gear. Mass of composite gear with aluminum matrix 3 times is less compared to the gear of steel. Based on these values it can be said that the composite gears are considerably lighter than steel gears.

4 CONCLUSION

This paper studies the results of stresses and deformations in testing gear made from different materials. The aim of the research is to investigate the possible composite materials that could replace steel as a material for gears. The main objective of the study is that the results generate a new composite gear less weight, and his mechanical properties, stress and deformation remain within acceptable limits. After the FEA analysis of gear model, there was performed comparing the gear value of Von Misses stresses and deformations made from steel and composite materials. Gear materials which were used for comparison is nylon 6/6, CFRP and hybrid composites aluminum based with nanoparticle of SiC, Al_2O_3, TiB_2, MgO, CNT. On the model of gear was performed static load under different influences of forces in the range to 150 - 750 N. Result of the analysis led to the following conclusions:

- Gear made from composite materials with aluminium matrix have similar deformation like steel gear,
- As the best substitute for steel gear has proven gear from CFRP,
- Composite gear has a 3 to 7 time less mass then steel gear,
- Composite gears can withstand a higher load than steel,
- Gear made from CFRP have the least value of Von Misses stresses in comparison to gears from other materials,

Based on these results it can be concluded that the composite materials in large numbers of characteristics overcome steel, and in the future expect a lot more applications not only in gears, but also in other elements of mechanical structures.

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NOMENCLATURE

Variables:

b gear width, mm
E Young module, GPa
F load, N
i gear ratio, -
m module, mm
n_1 input speed, min^{-1}
P input strength, kW
R_e Yield strength, MPa
R_m Tensile strength, MPa
z_1 number of drive gear pinion, -

Greek symbols

v Poisson's ratio
ρ density, g/cm^3

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