Enhancing Load Capacity of Plastic Gears Via the Application of Woven Composite Blankets

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ABSTRACT

In this work, the application of a woven composite fabric covering the surface of the fillets of the teeth of plastic gears is proposed to increase their loading capacity. Tip-relief is also applied to avoid severe edge contacts and peaks of high contact stresses as well as to achieve a smooth load transfer between consecutive pairs of contacting teeth. The investigation is carried out using the finite element method (IGD/ANSYS). A five-tooth model is applied for the gears, and nylon and carbon/nylon are adopted as materials. The evolution of the maximum contact stresses as well as maximum bending stresses is evaluated over two cycles of meshing for both the pure plastic (nylon) gears and the gears with the composite blanket (carbon/nylon). The results indicate that, for the case considered, covering the fillets of the gears with composite blankets reduces the bending stresses in the plastic material at the fillet region but does not consistently alleviate the contact stresses, and subjects the composite blankets to high level of stresses. However, in general, for the specific case studied, the set of gears safely tolerated double the torque recommended by VDI 2545 standard and consequently may be a viable method for increasing the load capacity of plastic gears.

INTRODUCTION

Due to their lightweight and ease of manufacturing, plastic gears are finding a wider role in many industrial applications. Plastic gears are lighter than their metallic counter ones, can be easily manufactured, have more internal damping capacity, and require no or very little lubrication [1]. However, they provide less loading capacity than metallic gears. In addition, because of the relative flexibility of plastic gears, they experience larger deformations, compared to metallic ones, and consequently are prone to edge contacts, which are associated with high contact stresses that lead to the failure of the gear drive. Two approaches that have been applied to metallic gears to mitigate edge-contacts are the application of parabolic-crowned profiles and the application of tip-relief profile modifications (Figure 1).

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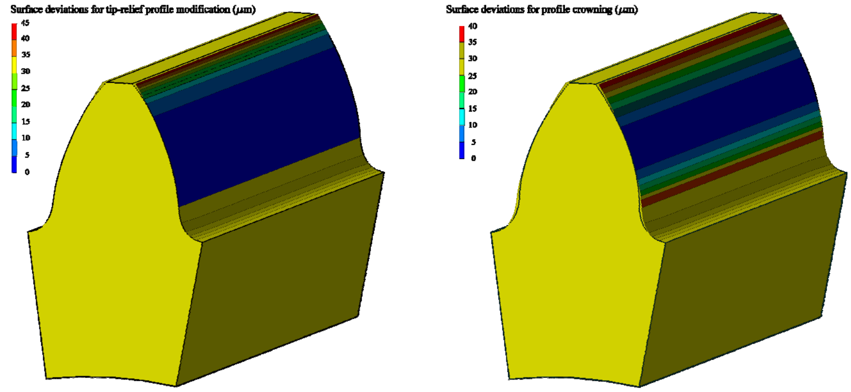

Figure 1**.** Tip-relief (left) and profile crowning (right) modifications of the gear tooth surfaces.

It should be pointed out that almost all of the research work with fiber reinforced plastic gears was based on the use of short fibers injection molding. This method, in general, experiences difficulties controlling the fiber orientation, which is a crucial factor in controlling the mechanical properties of the gears. Short fibers also exhibit stress concentration at the tips of the fibers, which reduces the strength of the composite laminate compared to continuous fibers laminates. Masaya *et al.* [2] showed that gears made of carbon-reinforced polyamide in general, and polyamide 12 in particular, exhibit excellent wear and noiseless properties. Senthilvelan and Gnanamoorthy [3] developed a selective short carbon fiber reinforced Nylon 66 spur gear using multi-shot injection molding process. Two different geometries, circular and spline shaped hubs were used for developing the selective reinforced gears. A selective reinforced gear with spline hub exhibited superior fatigue life compared with the selective reinforced gear with circular hub. Short glass fiber orientation in nylon 66 injection molded spur gear unit were inspected and correlated with the results of mold flow simulation. The predicted fiber orientation in molded gears using simulation technique coincides well with the actual fiber orientation near the injection point, weld line and tooth profile region [4]. A finite element analysis of glass short-fiber reinforced polyamide 66 was performed by Mohammad and Zhong [5]. They observed that the reinforced gears experienced higher maximum stresses than those of the corresponding isotropic unreinforced polyamide and steel gears. Marimutha *et al.* [6] evaluated the bi-directional and unidirectional bending fatigue performance of injection molded unreinforced polyamide 66, and carbon fiber reinforced polyamide 66 gears using a servo-motor-driven test rig developed in-house. The carbon fiber reinforced polyamide gears exhibited higher bending load carrying capability and fatigue life than unreinforced gears due to the superior thermomechanical properties. Kousalya [7] conducted a finite element analysis using ANSYS of steel, cast iron and short fiber carbon reinforced nylon spur gears, and concluded that the use of composite gears for limited load application is recommended.

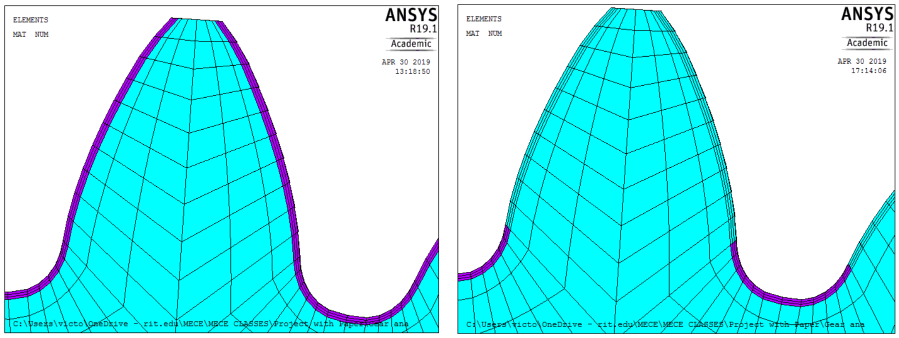

Figure 2. All-surface (left) vs. fillet-only (right) composite blanket.

In an attempt to increase the loading capacity of plastic gears, the authors have previously applied parabolic-crowned profiles to the gear tooth surfaces and covered the whole surface of the gear teeth (Figure 2-left) with a blanket of woven composite materials [8]. A comprehensive stress analysis was conducted, with emphasis at the two main areas of high stresses in gears: at the surface where contact between gear tooth surfaces occur, and at the fillet of the teeth where the maximum bending stresses take place. The mentioned research work demonstrated that the approach successfully reduced bending stresses at the fillet of the gear teeth for a specific pair of plastic gears and for a specific loading scenario. However, the approach did not reduce the contact stresses along the active surface of the gear teeth, and made the composite laminate blanket at the surfaces, where the contact takes place, vulnerable to interfacial failure. To overcome these shortcomings, in this work, only the fillet area of the gear tooth surfaces has been covered with composite blankets and the main tooth surface profile has been left unmodified (Figure 2-right) to keep the contact ratio as high as possible. In addition, an optimal tip-relief modification has been obtained and applied to the plastic gear tooth surfaces to allow for a smooth process of loading and unloading of the gear teeth. The application of an optimal tip-relief mitigates the effect of edge-contacts without compromising the bending strength of gear teeth at the fillet, and keeping the gear tooth surfaces unmodified allows for an increased contact ratio. In addition, not covering the tooth surfaces with the composite blanket renders the risk of interfacial failure irrelevant.

A comprehensive numerical isothermal 3D static analysis has been conducted to investigate the effect of the tip-relief profile modification and the application of the composite blanket at the fillet of the gear teeth on the stresses at the critical areas of the teeth (contact surface and fillets). A pair of spur nylon gears is the subject of our study. The number of teeth for the pinion and the wheel are 23 and 85, respectively, with pressure angle of 20° and module of 1.375 mm. The profile shift coefficients considered for pinion and wheel are of 0.3707 and 0.0287, respectively. The addendum coefficient is 1.0, the dedendum coefficient is 1.25 and the edge radius coefficient of the cutting tool is 0.38. The face-widths for the pinion and wheel are 20.02 and 19.33 mm, respectively. In accordance with VDI 2545, this gear set tolerates an applied torque of 4 N·m. However, for the analyses to be performed henceforth, a torque of 8 N·m has been considered in order to evaluate the proposed approaches directed to increase the load capacity of plastic gears in general. The study is performed using the finite element (FE) method. The geometry and the mesh of the gears are generated using the IGD software [9], and the stress analysis is conducted using ANSYS. Figure 3 shows the typical mesh used for the analysis. A five-tooth model for both pinion and gear is considered. A preliminary analysis indicated that five teeth per gear are sufficient to obtain good stress results (converging) and to mitigate the effect of the boundaries at the model sides. For the composite-blanket analysis, a carbon/nylon composite is chosen. The nylon matrix is a natural choice since it is the material of the core of the gears, and carbon fiber is selected for its superior specific strength and stiffness. It also adheres well with nylon, has a high thermal conductivity, and consequently it would effectively dissipate the frictional heat generated at contacts.

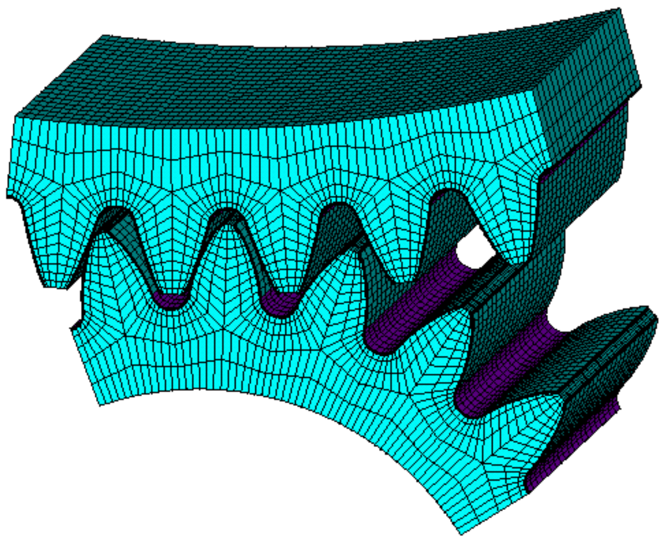

Figure 3. Finite element model with five pairs of contacting teeth.

TABLE 1. MATERIAL PROPERTIES.

	Stiffness		Strength	
Nylon	E	2 GPa	σ_u	70 MPa
	ν	0.41		
Carbon /Nylon	E_1	52 GPa	F_{1t}	400 MPa
	E_3	20 GPa	F_{1c}	300 MPa
	G_{12}	2.3 GPa	F_{3t}	50 MPa
	G_{23}	2.4 GPa	F_{3c}	100 MPa
	ν_{12}	0.04	F_4	20 MPa
	ν_{23}	0.7	F_6	20 MPa

The material properties of both nylon and carbon/nylon fabric adopted in the analysis are presented in Table 1. The properties of the composite woven material are for an assumed fiber volume fraction of 0.4.

The FE stress analysis is conducted for both pure nylon gears, and gears with composite fabrics (carbon/nylon) blanketing the fillet areas of the teeth. First, the analysis of the pure plastic is performed to examine the effect of the tip-relief on the contact and bending stresses. Then, the effect of the woven composite fillet-blanket on the stresses is presented.

TIP-RELIEF MODIFICATION

The effect of the tip-relief profile modification on contact stresses (von-Mises) for the case of pure plastic gears is studied and presented here. The tip-relief is a micro-geometry modification that removes gear tooth material towards the top of the tooth in a geometric progression that depends on the type of tip-relief applied. A parabolic tip-relief is considered for this work. Two parameters control the tip-relief profile modification: datum length and amount of tip-relief. The datum length is the radial distance from the addendum radius in which the tip-relief starts and the amount of tip-relief is the maximum modification (or material removal) applied at the addendum radius.

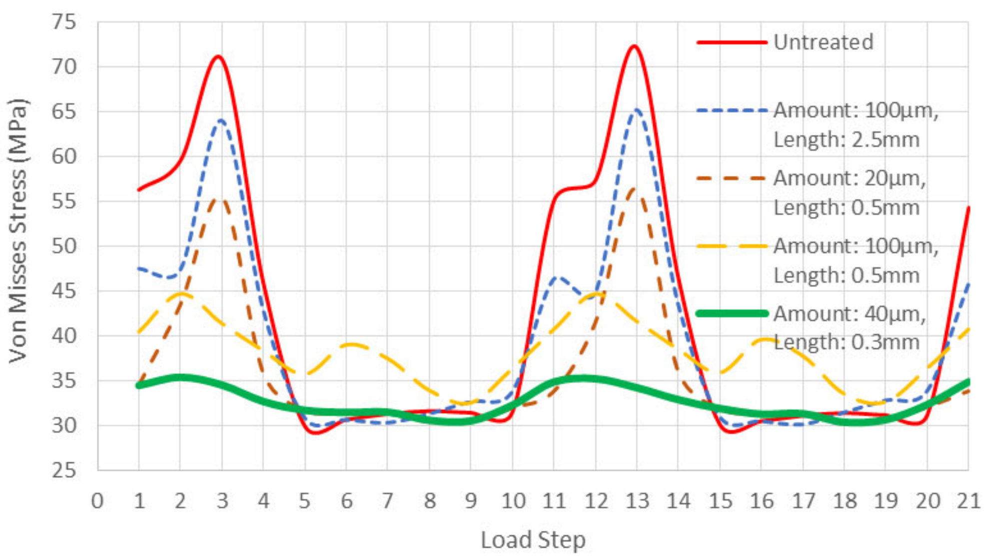

Figure 4. Effect of tip-relief profile modification on contact stresses.

Figure 4 shows the evolution of the maximum von-Mises stress at the contact surfaces along 21 contact positions distributed over two cycles of meshing of the gear set. The stresses are presented for different combination of the tip-relief parameters, including the case of unmodified tooth surfaces. When the gear tooth surfaces are left unmodified, the contact stresses experience a sharp peak at contact positions 3 and 13. It is noticed that these elevated stresses occur whenever the tip of a gear contacts the surface of the mating gear; that is, whenever edge-contact occurs. Applying a tip-relief profile modification mitigates the effect of the edge-contact and consequently reduces the elevated stresses associated with it. It appears that there are "optimum" values for the tip-relief parameters, which levels out the contact stresses over the entire cycle of meshing the most. For the case under consideration, the "optimum" values of the parameters are approximately 0.3 mm for the datum length and 40 µm for the tip-relief amount. It should be pointed out that similar to the case of parabolic-crowned modification [8], the tip-relief profile modification did not significantly affect the maximum bending stress at the fillets.

COMPOSITE BLANKET EFFECT

The effect of the application of the composite blanket at the fillets of the gears for the optimal tip-relief case on the maximum contact and bending stress has been studied. Samples of the obtained results are shown in Figures 5 to 7.

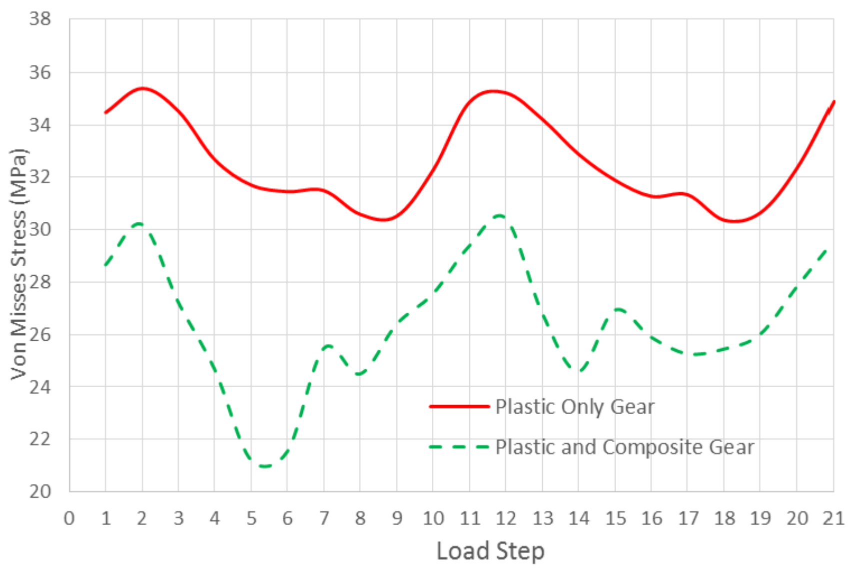

Figure 5. Evolution of maximum bending stresses at the fillet region in the fillet plastic sub-blanket material.

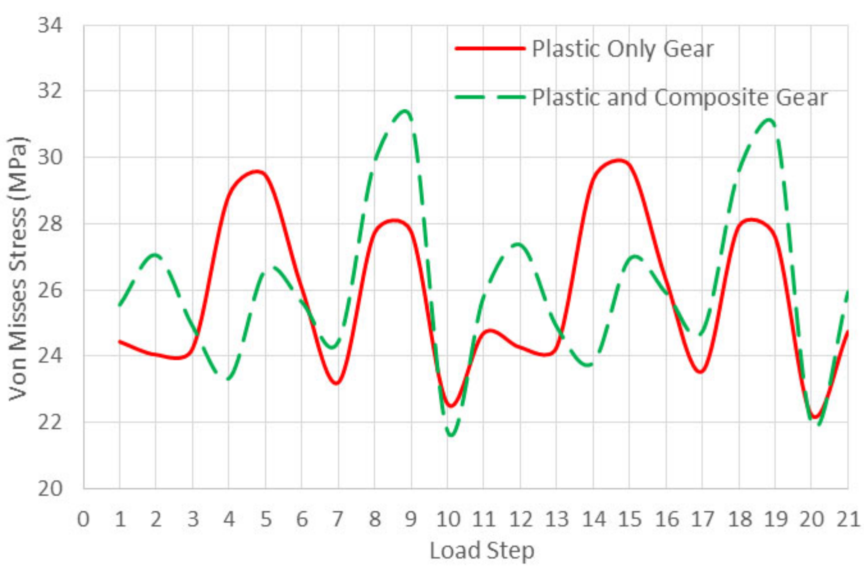

Figure 6. Evolution of maximum contact stresses for two cycles of meshing.

Figures 5 and 6 display the evolution of the maximum von-Mises stress at the fillet and contact surface, respectively, along 21 contact positions distributed over two cycles of meshing of the gear set. The results are displayed for the pure plastic case (solid line) and the case when the composite blankets are applied at the fillets (dashed line). Clearly, the application of the composite blankets reduces the stresses and protects the plastic at the fillet (Figure 5). However, for the contact surfaces (Figure 6), the results are inconclusive: the stress level does not show a significant change and increases or decreases depending on the contact position point. Those fluctuations of the stresses can be reduced by increasing the number of elements of the finite element model in profile direction.

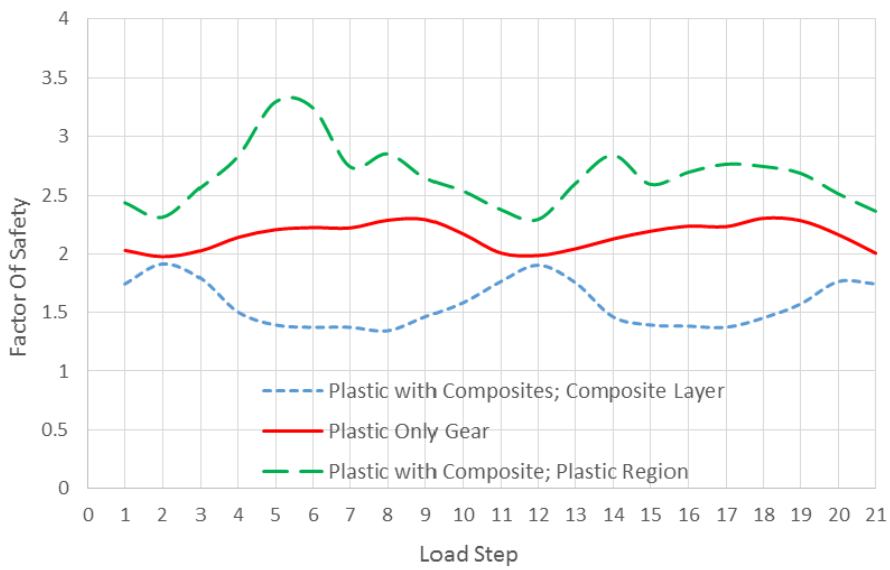

Figure 7. Factor of safety at the fillet region.

The factors of safety corresponding to the maximum von Mises stresses in the fillet plastic material (Figure 5) for both cases of pure plastic gears (solid line) and gears with the composite blankets (dashed line) are presented in Figure 7. The evolution of the maximum Tsai-Wu strength ratio over two cycles of meshing is also presented as factor of safety for the composite layer in Figure 7. The factor of safety for the plastic is calculated by dividing the ultimate stress (Table 1) by the von Mises stress. It can be inferred that while the composite blanket applied at the fillet reduces the stress in the plastic material at the fillet region, and consequently increases its factor of safety (dashed line versus solid line), the composite blanket itself suffers a high level of stress and consequently experiences a lower factor of safety (dotted line) and becomes more vulnerable to failure. However, the proposed design with woven composite blankets at the fillet region is still safe when double the nominal torque of plastic gears is considered.

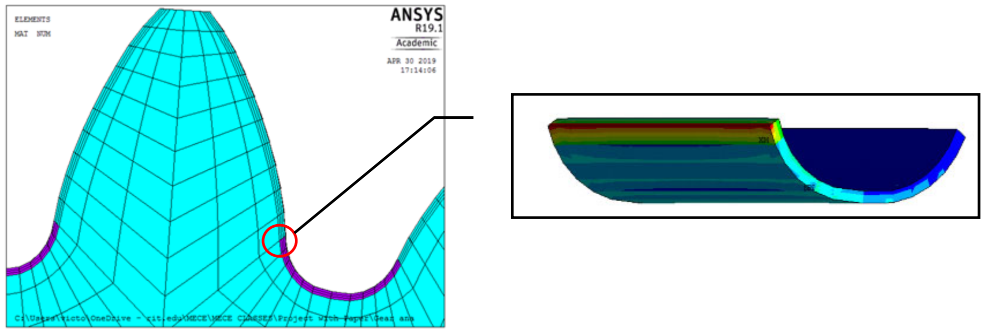

Figure 8. Stress singularity at the sharp edges of the interface of the composite blanket and the plastic material.

It should be pointed out that a stress singularity occurs at the sharp corner of the intersection between the interfaces of the composite blanket and the plastic material (Figure 8). According to the St. Venant's principle, this singularity has been ignored in this work. Further investigation in this regard must be conducted in future work [10].

CONCLUSION

In an attempt to increase the loading capacity of plastic gears, the application of a woven composite fabric covering the surface of the fillets of plastic gears in conjunction with a tip-relief profile modification is proposed. A thorough isothermal 3D static analysis for a specific nylon gear has been conducted and the following conclusions are drawn:

- The tip-relief profile modification can mitigate the high contact stresses caused by edge-contacts and consequently reduce the maximum contact stresses over the entire cycle of meshing of the gear set.
- The application of the composite blanket reduces the bending stresses and protects the sub-surface plastic material at the fillet region; however, there will be no improvement in the maximum contact stresses with respect to plastic gears without composite blankets.
- The composite blanket protects the plastic material at the fillet region at its own expense; the composite material experiences a higher level of stresses and becomes more vulnerable to failure.
- Further work is needed to investigate the stress singularity manifested at the sharp corners of the interfaces between the composite blanket and the plastic material.
- In general, for the specific gear set and case studied, the suggested tip-relief profile modification together with the application of woven composite blankets at the fillet doubled the recommended applied torque by the VDI 2545 standard, and consequently may be viewed as a viable method for increasing the load capacity of plastic gears

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