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COMPARATIVE ELASTO-PLASTIC ANALYSIS IN A ROTATING DISK MADE OF POLYMER MATERIAL WITH VARIABLE DENSITY PARAMETER

UPOREDNA ELASTOPLASTIČNA ANALIZA ROTIRAJUĆEG DISKA OD POLIMERNOG MATERIJALA SA PROMENLJIVIM PARAMETROM GUSTINE

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Keywords
- stresses
- disk
- deformation
- yielding
- angular speed

Ključne reči
- naponi
- disk
- deformacija
- tečenje
- ugaona brzina

Abstract

This article deals with the study of elasto-plastic analysis in a rotating disk made of polymer material and having variable density parameter. Mathematical modelling is based on stress-strain relation and equilibrium equation.

Analytical solutions are presented for the disk made of polymer material. The effects of different pertinent parameters (i.e., density and angular speed) are considered. The behaviour of stress distribution, density parameter, and angular speed are investigated. From the obtained results, it is noticed that natural rubber material disk requires higher angular speed to yield at the inner surface as compared to the disk of polypropylene material. The natural rubber disk is more convenient than that of polypropylene.

Izvod

U radu se bavimo se elastoplastičnom analizom rotirajućeg diska izrađenog od polimernog materijala sa promenljivim parametrom gustine. Matematičko modeliranje se zasniva na relaciji napon-deformacija i na jednačini ravnoteže.

Data su analitička rešenja za disk od polimernog materijala. Razmatraju se različiti relevantni uticaji parametara (na pr. gustine i ugaone brzine). Proučeno je ponašanje raspodele napona, parametra gustine i ugaone brzine. Prema dobijenim rezultatima, uočava se da je za disk od materijala prirodne gume potrebna veća ugaona brzina za pojavu tečenja na unutrašnjoj površini, u poređenju sa diskom od polipropilena. Disk od prirodne gume je pogodniji u odnosu na polipropilenski.

INTRODUCTION

Rotating disks are extensively used components in many applications in mechanical, aerospace industries, and chemical processing, such as compressors, flywheels, turbo generators, high speed gear engines, compressors, sink fits, steam turbines, pumps, and computer disks, etc. The solutions of disks can be found in a large number of textbooks, /1-6/. Reddy et al. /7 / have investigated the stresses in a rotating anisotropic annular disk with variable thickness and density. Apatay et al. /8/ proposed the solutions of rotating solid and annular disks in terms of hyper-geometric functions for the elastic deformation. Thakur et al. /9-61/ have investigated large numbers of problems of the rotating disk with different parameters by using Seth's transition theory and generalised strain measure. The objective of this research paper is to investigate the comparative elasto-plastic analysis in a rotating disk made of polymer material with variable density parameter by using the concept of generalised strain measure.

MATERIALS

In the present study, we have been using polymers.

Natural rubber is an elastomer which is obtained naturally. It is made by polymerisation of isoprene which has a chemical formula $(C_5H_8)_n$. It is mainly found in countries like Brazil, India, Sri Lanka, Malaysia, etc.

Polypropylene is a rigid and crystalline thermoplastic used widely in everyday objects like packaging trays, household products, battery cases, medical devices, etc. Polypropylene is made from polymerisation of propane monomer (an unsaturated organic compound C_3H_6) by Ziegler-Natta polymerisation or metallocene catalysis polymerisation.

$$\underset{\text{PP Monomer}}{C_3H_6} \xrightarrow[\text{Metallocene catalysis polymerization}]{\text{Ziegler - Natta polymerization}} \underset{\text{Polypropylene}}{(C_3H_6)_n}$$

Based upon polymerisation, polypropylene can form three basic chain structures and depending on the position of the methyl group, i.e., atactic, isotactic, and syndiotactic. Polypropylene belongs to the group of polyolefins and is partially crystalline and non-polar. Polypropylene materials are of isotropic symmetry and Poisson's ratio at room temperature is $\nu = 0.43$, given by /62/.

MATHEMATICAL MODELLING

Let us consider a thin disk of constant density with central bore inner/outer radii as r_i and r_0 and made of polymer materials see Fig. 1.

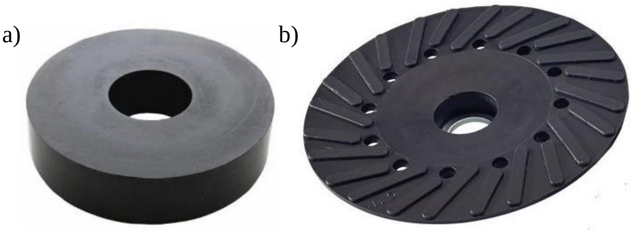

Figure 1. Polymer disk: a) natural rubber; b) polypropylene.

The disk is rotating about its axis with angular velocity ω at the inner surface and the density of disk is taken in the form /48/:

$$\rho = \rho_0 (r/r_0)^{-m}, \qquad (1)$$

where: ρ_0 is constant density at $r = r_0$; and m is the density variation parameter. The stress-strain relation for the elastic isotropic material is given by Thakur et al. /9/:

$$\tau_{rr} = \frac{2\mu}{n}\left[3-2c-\eta^n\{1-c+(2-c)(T+1)^n\}\right],$$

$$\tau_{\theta\theta} = \frac{2\mu}{n}\left[3-2c-\eta^n\{2-c+(1-c)(T+1)^n\}\right],$$

$$\tau_{r\theta} = \tau_{\theta z} = \tau_{zr} = \tau_{zz} = 0, \qquad (2)$$

where: c is the compressibility factor of the material in term of Lame's constant, given by $c = 2\mu/(\lambda + 2\mu)$.

The equation of equilibrium is given:

$$\frac{d}{dr}(r\tau_{rr}) - \tau_{\theta\theta} + \rho\omega^2 r^2 = 0. \qquad (3)$$

Transition points: using Eq.(2) into Eq.(3), we get:

$$(2-c)n\eta^{n+1}T(T+1)^{n-1}\frac{dT}{d\eta} = \frac{n\rho\omega^2 r^2}{2\mu} +$$

$$+T^n\left\{1-(P+1)^n - nT[1-c+(2-c)(T+1)^n]\right\}, \qquad (4)$$

where: $c = 2\mu/(\lambda + 2\mu)$; and $r\eta' = \eta T$. The transition points in Eq.(4) are $T \to \pm\infty$ (elastic to plastic state), and $T \to -1$ (plastic to creep state).

ELASTO-PLASTIC DEFORMATION

The circumferential stress is given by Thakur et al. /9/:

$$\tau_{\theta\theta} = \frac{2\mu}{n}k_1 r^{\nu-1}. \qquad (5)$$

Substituting Eq.(5) into Eq.(3) and using Eq.(1), we get:

$$\tau_{rr} = \frac{k_2}{r} + \left\{\frac{2\mu}{n\nu}\right\}k_1 r^{\nu-1} - \frac{\rho_0\omega^2 r_0^m r^{2-m}}{3-m}. \qquad (6)$$

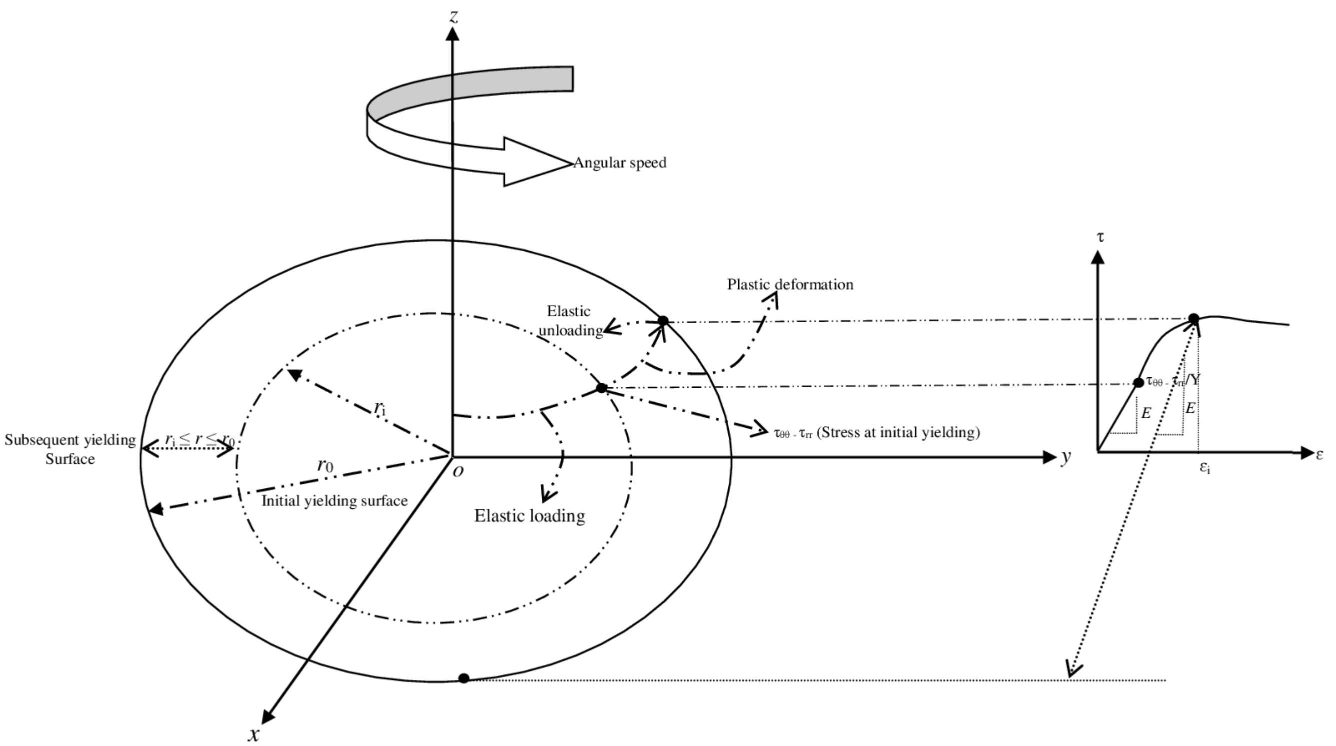

Figure 2. Yielding stress.

Using boundary condition $\tau_{rr} = 0$ at $r = r_i$ and $r = r_0$ in Eq.(6), we get:

$$k_1 = \frac{\rho_0\omega^2 n\nu r_0^m (r_0^{3-m} - r_i^{3-m})}{2\mu(3-m)(r_0^\nu - r_i^\nu)}, \text{ and}$$

$$k_2 = \frac{\rho_0\omega^2 r_0^m}{3-m}\left[r_i^{3-m} - \frac{r_0^{3-m} - r_i^{3-m}}{r_0^\nu - r_i^\nu}r_i^\nu\right].$$

Substituting A and B into Eqs.(5)-(6), we get:

$$\tau_{rr} = \frac{\rho_0\omega^2 r_0^2}{(3-m)R}\left[\frac{1-R_0^{3-m}}{1-R_0^\nu}(R^\nu - R_0^\nu) - R^{3-m} + R_0^{3-m}\right], \qquad (7)$$

$$\tau_{\theta\theta} = \frac{\rho_0\omega^2 r_0^2 \nu(1-R_0^{3-m})R^{\nu-1}}{(3-m)(1-R_0^\nu)}, \qquad (8)$$

where: $R = r/r_0$; and $R_0 = r_i/r_0$.

YIELDING SURFACE

Figure 2 shows the initial yielding surface, the subsequent yielding surface, elastic loading, plastic deformation, and elastic unloading. The initial yielding stresses from Eqs.(7)-(8) are given:

$$\left|\tau_{\theta\theta}-\tau_{rr}\right| = \left|\frac{\Omega_i^2}{(3-m)R}\left[\frac{1-R_0^{3-m}}{1-R_0^{\nu}}\left(R^{\nu}(\nu-1)+R_0^{\nu}\right)-R^{3-m}+ R_0^{3-m}\right]\right| = Y\,. \qquad (9)$$

The following numerical values are taken: $\rho\omega^2 r_0^2 = 20$; $m = 0$, 1.5; $r_i = 1$; $r_0 = 2$; $\nu = 0.5$ and 0.33 (say Poisson's ratios), respectively.

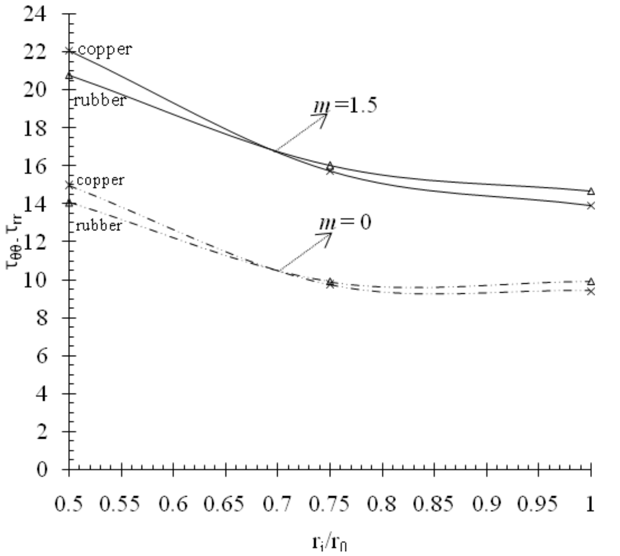

Figure 3. $|\tau_{\theta\theta}-\tau_{rr}|$ vs. radii ratio.

Initial yielding surface: it has been seen from Fig. 3, that $|\tau_{\theta\theta}-\tau_{rr}|$ is maximum at the inner surface ($R = R_0$), therefore yielding of the surface becomes:

$$\left|\tau_{\theta\theta}-\tau_{rr}\right| = \left|\frac{\rho_0\omega_i^2 r_0^2}{(3-m)R_0}\left[\frac{1-R_0^{3-m}}{1-R_0^{\nu}}\nu R_0^{\nu}\right]\right| = Y\,;$$

and angular speed for initial yielding surface are given:

$$\Omega_i^2 = \frac{(3-m)R_0^{1-\nu}(1-R_0^{\nu})}{(1-R_0^{3-m})\nu}\,, \qquad (10)$$

where: $\omega_i = (\Omega_i/r_0)\sqrt{(Y/\rho_0)}$.

Subsequent yielding surface: it has been seen from Fig. 3, that $|\tau_{\theta\theta}-\tau_{rr}|$ is maximum at the outer surface ($R = 1$) and $\nu = 0.5$ for fully-plastic state, therefore yielding of the subsequent surface becomes:

$$\left|\tau_{\theta\theta}-\tau_{rr}\right|_{R=1} = \left|\frac{\rho_0\omega_f^2 r_0^2}{3-m}\left[\frac{1-R_0^{3-m}}{1-\sqrt{R_0}}\left(\sqrt{R_0}-1/2\right)+1-R_0^{3-m}\right]\right|\,;$$

and angular speed for subsequent yielding surface become:

$$\Omega_f^2 = \frac{2(3-m)(1-\sqrt{R_0})}{(1-R_0^{3-m})(2\sqrt{R_0}-1)-R_0^{3-m}}\,. \qquad (11)$$

Stresses for initial yielding surface: using Eq.(10) into Eqs. (7)-(8), we get:

$$\tau_{rr} = \frac{R_0^{1-\nu}(R^{\nu}-R_0^{\nu})}{R} + \frac{(R_0^{3-m}-R^{3-m})(1-R_0^{\nu})R_0^{1-\nu}}{R(1-R_0^{3-m})}\,,$$

$$\tau_{\theta\theta} = R_0^{\nu-1}\nu R^{\nu-1}\,. \qquad (12)$$

Stresses for subsequent yielding surface: using Eq.(11) into Eq.(7)-(8) and taking $\nu = 0.5$ (say fully-plastic), we get:

$$\tau_{rr} = \frac{2(1-\sqrt{R_0})}{\left[(1-R_0^{3-m})(2\sqrt{R_0}-1)-R_0^{3-m}+1\right]}\times \left[\frac{(\sqrt{R}-\sqrt{R_0})(1-R_0^{3-m})}{1-\sqrt{R_0}}-R^{3-m}+R_0^{3-m}\right],$$

$$\tau_{\theta\theta} = \frac{1}{\left[(2\sqrt{R_0}-1)-R_0^{3-m}+1\right]\sqrt{R}}\,. \qquad (13)$$

Validation of results: Eqs.(12)-(13) show similar results after neglecting density parameter as given by Thakur et al. /9/.

RESULTS AND DISCUSSION

To see the collective effect of stress distribution, density and angular speed in a disk made of natural rubber (say $\nu = 0.5$)/polypropylene material ($\nu = 0.43$) /62/, for the initial/subsequent yielding surface based upon the following numerical values have been taken as: $r_i = 1$, $\tau_0 = 2$, and density $m = 0$ and 1.5.

In Fig. 4, curves have been drawn between angular speed versus radii ratio R_0 for initial yielding/subsequent yielding surface and having variable density parameter $m = 0$ and 1.5, respectively. It has been seen that the disk made of natural rubber requires maximum angular speed at the inner surface of the disk in comparison to the polypropylene material. Further, the value of angular speed decreases with increasing density parameter (say $m = 1.5$) at the inner surface of a disk made of natural rubber/polypropylene for initial yielding, but reverse results are obtained for the subsequent yielding surface.

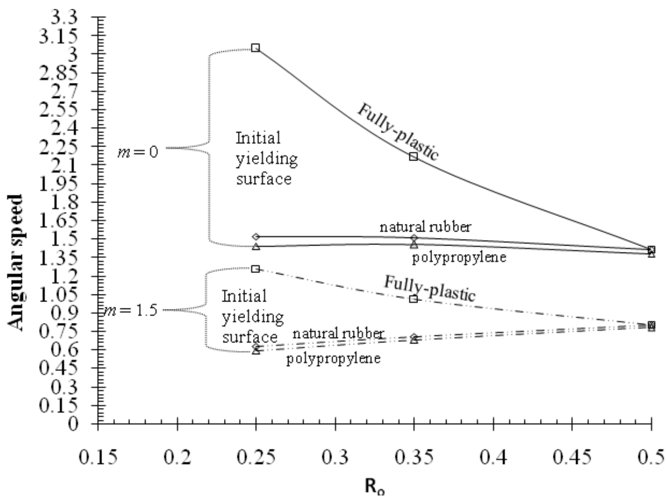

Figure 4. Yielding stress.

According to Fig. 5, curves are drawn between stress distribution versus radius $R = r_i/\tau_0$ with variable density parameter $m = 0$ and 1.5, respectively. It has been seen that the natural rubber disk requires maximum circumferential stress at the inner surface in comparison to the polypropylene disk. With the introduction of the density parameter, the disk made of natural/polypropylene shows significant effects on the circumferential stresses at the inner surface.

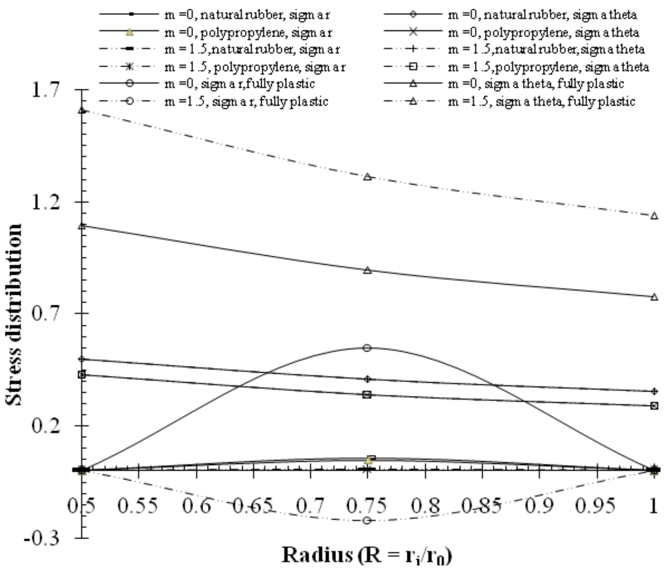

Figure 5. Stress distribution vs. radius.

CONCLUSIONS

The main finding can be concluded as follows:

- The rotating disk made of natural rubber material requires higher angular speed to yield at the internal surface as compared to the disk made of polypropylene material.
- With the addition of variable density parameter at the inner surface of a disk made of natural rubber/polypropylene for initial yielding the value of angular speed decreases, but reverse results are obtained for subsequent yielding surface.
- The hoop stress is maximum at the inner surface of the natural rubber material disk in comparison to the polypropylene disk.
- The disk made of natural rubber is more convenient than that of polypropylene material.

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