

# Effects of Thread Dimensions of Functionally Graded Dental Implants on Stress Distribution

Kaman M. O. and Celik N.

**Abstract**—In this study, stress distributions on dental implants made of functionally graded biomaterials (FGBM) are investigated numerically. The implant body is considered to be subjected to axial compression loads. Numerical problem is assumed to be 2D, and ANSYS commercial software is used for the analysis. The cross section of the implant thread varies as varying the height ( $H$ ) and the width ( $t$ ) of the thread. According to thread dimensions of implant and material properties of FGBM, equivalent stress distribution on the implant is determined and presented with contour plots along with the maximum equivalent stress values. As a result, with increasing material gradient parameter ( $n$ ), the equivalent stress decreases, but the minimum stress distribution increases. Maximum stress values decrease with decreasing implant radius ( $r$ ). Maximum von Mises stresses increase with decreasing  $H$  when  $t$  is constant. On the other hand, the stress values are not affected by variation of  $t$  in the case of  $H = \text{constant}$ .

**Keywords**—Functionally graded biomaterials, dental implant finite element method.

## I. INTRODUCTION

IDEAL biomaterials for use in dental implants need to simultaneously satisfy many requirements such as biocompatibility, strength, fatigue durability, nontoxicity, corrosion resistance, and sometimes aesthetics [1]. Conventional dental implant with a single composition and uniform structure cannot meet all of these requirements. Hydroxyapatite (HAP), the principal component of bone and teeth, exhibits excellent compatibility with bone, but its mechanical strength and reliability are too low for an artificial implant to be made of pure HAP [2]. The development of a novel class of dental implants with graded microstructure and material properties was thus motivated in the late 1990s. The most commonly used functionally graded biomaterial (FGBM) dental implants are a mixture of HAP and biocompatible metal titanium (Ti), denoted as Ti/HAP, with a continuous gradient in the material composition [2]. In addition to this, there are different functionally graded materials such as Ti/Co, Ti/ZrO<sub>2</sub> [3, 4]. Mechanical properties of FGBM change along the height of implant. This variation can be written as follows

$$V_m = \left(\frac{y}{h}\right)^n, V_c = 1 - V_m, 0 \leq y \leq h \quad (1)$$

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where  $h$  is height of implant,  $n$  is material gradient parameter,  $V_m$  is volume fraction of bio-metal Titanium and  $V_c$  is volume fraction of bio-ceramic HAP (Fig.1). In this situation, material properties can be found as follows:

$$E = E_m V_m + E_c V_c \quad (2)$$

$$\nu = \nu_m V_m + \nu_c V_c \quad (3)$$

$$\rho = \rho_m V_m + \rho_c V_c \quad (4)$$

where  $E$ ,  $\nu$  and  $\rho$  respectively denote the Young modulus, Poisson's ratio and density [2]. Furthermore, the subscripts  $m$  and  $c$  respectively symbolize the metal and ceramic materials.

For prediction of the stress distribution on implant systems, numerical studies on mechanical behavior of implant structures have increased with the development of finite element method in addition to the FGBM. Wang et al. [5] investigated the thermal-mechanical performance of HAP/Ti functionally graded dental implants with the three-dimensional finite element method. The stresses induced by occlusal force for the present HAP/Ti FG implants were calculated to compare to the corresponding stresses for the Ti dental implant. Thermal-mechanical effect of temperature variation due to daily oral activity was also studied. The implant performance was evaluated against the maximum von Mises stress. Enab [6] used finite element analysis to predict knee implant biomechanical behavior under various loading conditions. Two-dimensional finite element models were developed which include the artificial knee and portions of the surrounding biological materials to investigate the required design as a functionally graded material tibia tray.

Heida [7] designed an implant, in the presence of cancellous bone as a thin layer around it, from hydroxyapatite/collagen (HAP/Col) as a FGBM that was developed using the finite element and optimization techniques with using ANSYS package. The investigations shown that the maximum stress in the cortical bone and cancellous bone for the collagen/hydroxyapatite (Col/HAP) functionally graded implant reduced by about 40% and 19%, respectively, compared with titanium dental implants. Lin et al. [8] evaluated bone remodeling when replacing the Ti with a HAP/Col FGBM model. A finite element model was constructed in the buccal-lingual section of a dental implant-bone structure generated from computerized tomography scan images. The remodeling simulation was performed over a 4-years healing period. The FGBM implants showed an improved bone remodeling

outcome. Sadollah and Bahreininejad [9] reported on developing an optimal design of an FGBM dental implant for promoting long-term success. Based upon remodeling results, metaheuristic algorithms such as the genetic algorithms and simulated annealing were adopted to develop a multi-objective optimal design for FGBM implantation design. Lin et al. [10] explored an optimal design of FGBM dental implant for promoting a long-term success by using the computational bone remodeling and design optimization.

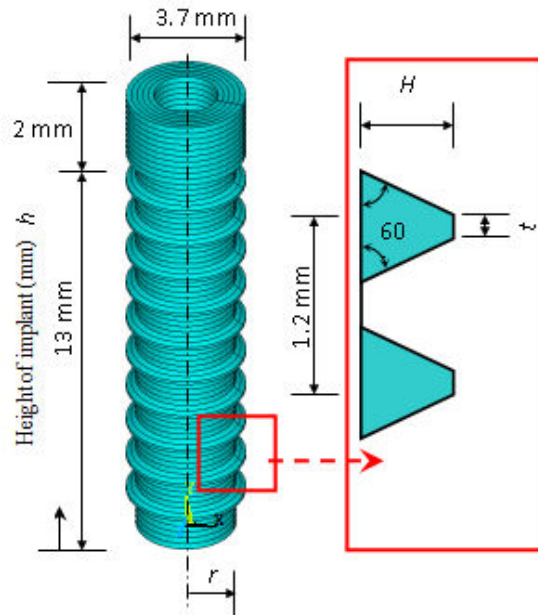
Current study aims to investigate the structural analysis of a FGBM dental implant numerically. Gradient of material properties for FGBM, boundary conditions and two dimensional numerical models were defined with the help of a subroutine prepared by using APDL (ANSYS Parametric Design Language) codes. The loads were applied to the implant normally ( $\theta = 0$  deg). The cross section of the implant thread varied as height  $H$  and width  $t$  (each of them varies as 0.1, 0.2, 0.3 and 0.4 mm). The equivalent stress distribution on the implant was determined and presented with contour plots for different thread dimension and variation of radius along the height of implant.

## II. NUMERICAL ANALYSIS

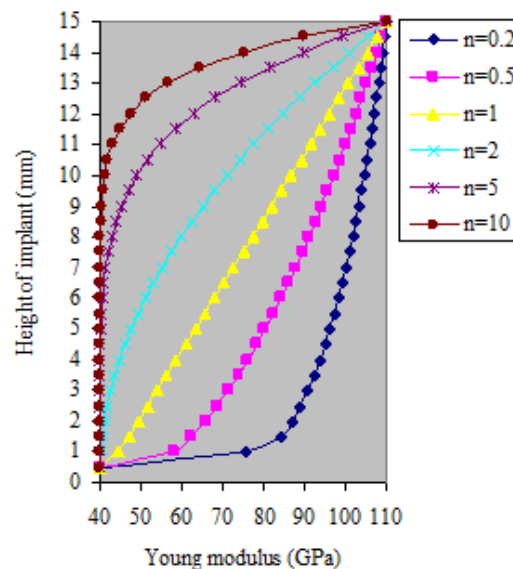
This body of work is an application of computational engineering systems to human body problems, to provide an in-depth fundamental and applications-applicable investigation of dental implants. A number of geometrical parameters are investigated including the height and width of the implant's thread. Fig. 1 indicates the details of the analyzed dental implant and also variation of material properties of FGBM implant. In addition to, the physical model is described in Fig. 2. As seen in the figure, a dental implant with the supporting bone system is the solution domain of the numerical study. Fig. 2 comprises a FGBM implant, a metallic abutment, an internal screw connecting the implant and abutment, and surrounding trabecular bone and cortical bone. The dimensions of the thread of the implant varied as  $H = 0.1, 0.2, 0.3, 0.4$  mm,  $t = 0.1, 0.2, 0.3$  and  $0.4$  mm and  $r = 0.5, 1.0$  and  $1.7$  mm. The analyzed configurations of implant thread are listed in Table I, including the schematic shapes.

The fixed support boundary condition is used at the bottom surface of the cortical bone. The single force of  $F = 100$  N is applied to the center of the abutment with  $\theta = 0$  deg. Perfectly-bonded property is assumed between the implant and the bones (trabecular bone and cortical bone).

Titanium (Ti) is considered as the abutment material. The properties of the implant material and the surrounding structure used in the solution domain are exhibited in Table II. Linear-elastic-isotropic material properties are assumed in the solution.



(a)



(b)

Fig. 1 (a) Dental implant and (b) variation of material properties of FGBM implant with height

The FGBM implant is modeled by using ANSYS finite element software and two dimensional PLANE42 is used as the element type [11]. The element can be used either as a plane element (plane stress or plane strain) or as an axisymmetric element. In this study, the problem is solved assuming axisymmetry case. The element is defined by four nodes having two degrees of freedom at each node; translations in the nodal  $x$ - and  $y$ - directions. The element has plasticity, creep, swelling, stress stiffening, large deflection,

and large strain capabilities. The model consists of 4378 elements and 4558 nodes.

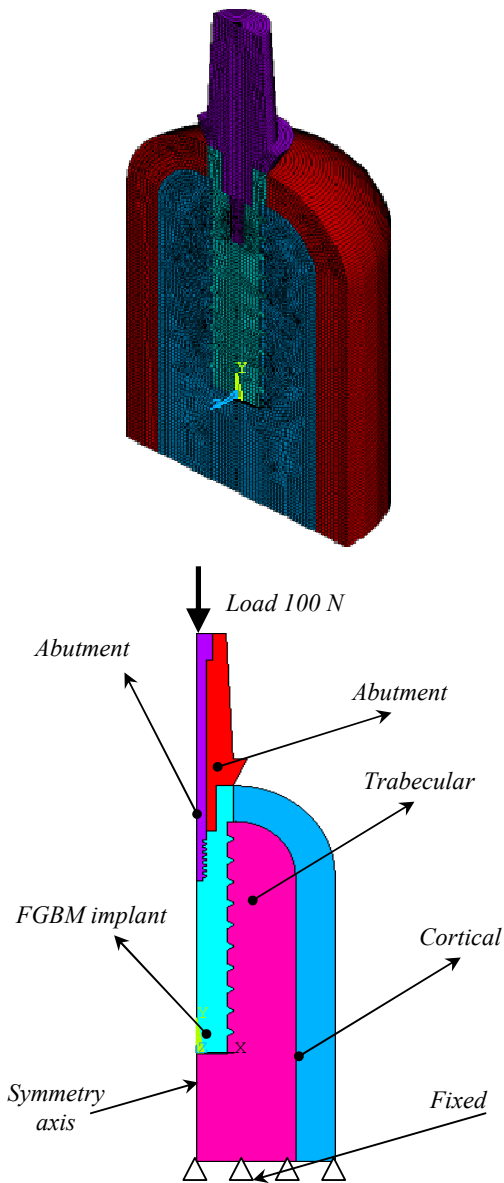


Fig. 2 Two views of axisymmetric finite element model and boundary conditions of FGBM dental implant system

TABLE I  
INFORMATION ABOUT THE MESH STRUCTURE

General assumptions	Case name	t mm	H mm	View of Model
<i>M = 0.446 mm for all models. Variation of implant radius <math>r=0.5, 1.0</math> and <math>1.4</math> mm. Thread model is constant for variation of implant radius=Model 1</i>	Model 1	0.1	0.3	
	Model 2	0.2	0.3	
	Model 3	0.3	0.3	
	Model 4	0.4	0.3	
	Model 5	0.1	0.1	
	Model 6	0.1	0.2	
	Model 7 = Model 1	0.1	0.3	
	Model 8	0.1	0.4	

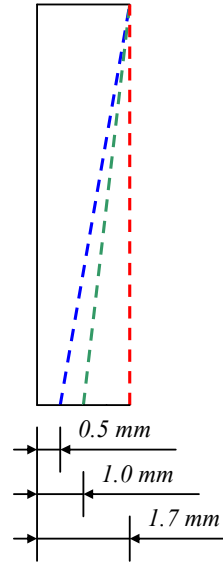


TABLE II  
MATERIAL PROPERTIES OF DENTAL IMPLANT SYSTEM [REF.2]

Material	E (GPa)	$\nu$	$\rho$ (kg.m <sup>-3</sup> )
Abutment	110	0.35	4500
Abutment thread	110	0.35	4500
Cortical bone	14	0.30	1700
Trabecular bone	3	0.30	270
Titanium (Ti)	110	0.35	4500
HAP	40	0.27	3219

Since ANSYS does not offer variation in assigned material properties across elements directly, the material property gradient is applied via a spatial variation in assigned nodal temperatures. As the finite element formulation leads to an interpolation of temperatures within the elements, this results

in a continuous variation in properties [12]. Therefore, gradient of material properties for FGBM is defined as a function of temperature with the help of a subroutine prepared by using APDL codes. Then the Young's modulus is defined as the linear function of temperature and the coefficient of thermal expansion is set to zero to avoid the presence of thermal residual stresses [13]. Hence, it is provided that meaningful property of temperature does not physically remain and variation of material properties  $E$  is defined by using temperature as shown in Fig. 3. The material gradient parameters given in Eq. (1) are considered as  $n = 0, 0.1, 0.2, 0.5, 1, 2$  and  $10$ .

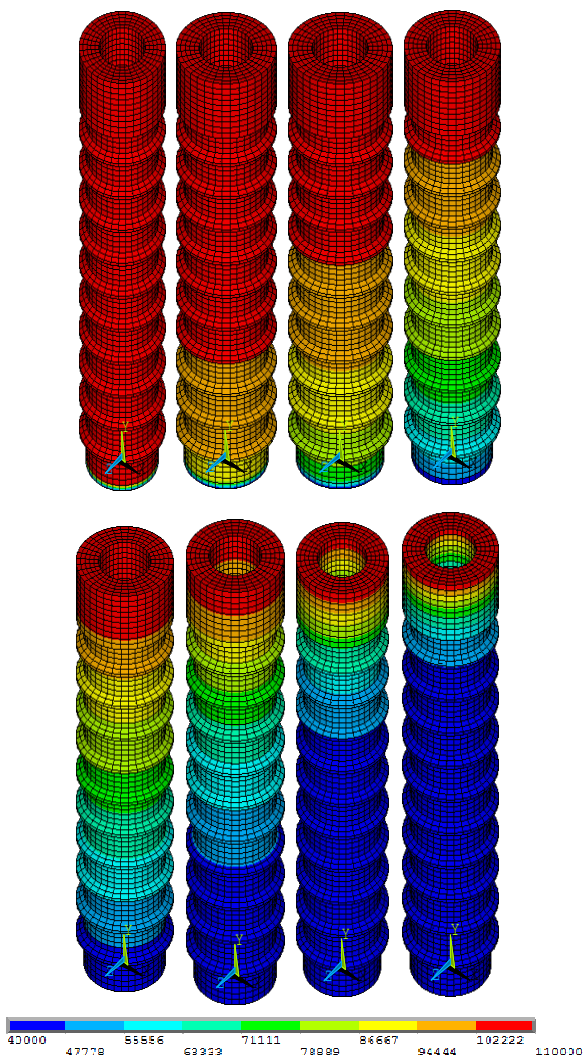


Fig. 3 Variation of Young modulus (MPa) with material gradient parameter  $n$

### III. RESULTS AND DISCUSSIONS

The aim of this section is to determine the numerical stress distribution on a FGBM dental implant system. So, the attention will be directed to the equivalent (von Mises)

stresses. To verify the results, comparison analysis to the reference of Yang and Xiang [2] is carried out. Compared parameters are;  $r = 3.4$  mm,  $H = 0.3$  mm and  $t = 0.1$  mm (Model 1), subjected to compression as shown in Fig. 2.

In the verification analysis, the implant material is 100% Titanium for  $n = 0$ . The material properties are same with the ones presented in Table II. The results are shown with contour plots as seen in Fig. 4. There is negligible difference between present study and the cited reference.

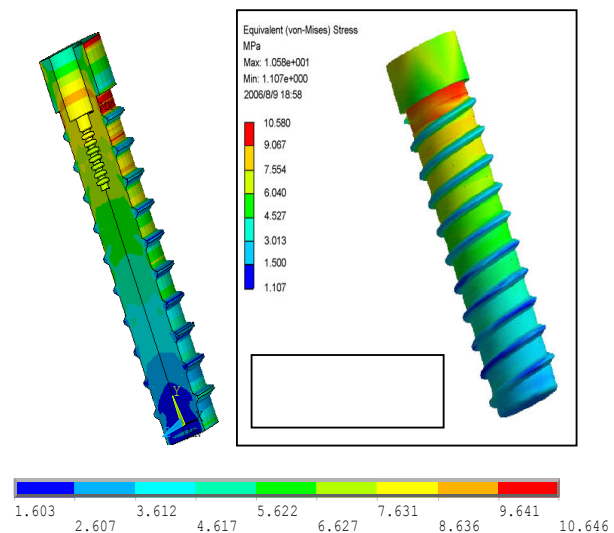


Fig. 4 von Mises stress (MPa) distribution on FGBM implant, for  $n = 0$

The von Mises stress distributions on Model 1 ( $r = 3.4$  mm) for different material gradient parameter  $n$  are given Fig. 5. The figure shows that, equivalent stress decreases with increasing  $n$ . Additionally, the minimum stress zone ( $\sim 3$  MPa) at the bottom of implant increases with increasing gradient parameter. However, the increment rate is quite low for maximum value of equivalent stress (Fig. 6).

Although the maximum values are slightly affected by the  $n$ , the location where the maximum equivalent stresses appear is strongly varying depending on  $n$ . As seen in Fig. 5, maximum equivalent stress locations differ from case to case. For instance; maximum equivalent stress occurs at the top of the implant edge for the case;  $n = 0.5, 1, 2, 5$  and  $10$ , while the maximum value is observed at the top of the thread for the case  $n = 0, 0.1$  and  $0.2$ .

It is evident in Fig. 7 that, the maximum von Mises stress values on trabecular bone are smaller than FGBM implant ( $\sim 1.35$  MPa for  $n = 0$ ) and increasing of  $n$  slightly increases maximum stress value. Variation of the maximum von Mises stress on FGBM implant for different thread dimensions for  $n = 0.5$  and  $r = 3.4$  mm is given Fig. 8. The maximum von Mises stresses increase with decreasing  $H$  when  $t$  is constant. However, the stress values are not affected by variation of  $t$  when  $H$  is constant. When the compressive surface area of the thread, which is affected by the load, increases the stress

distributes onto whole screw and therefore, the values of maximum equivalent stress decrease. Location of maximum stress on FGBM implant does not change with the variation of thread dimensions. It is always obtained at the top of the implant.

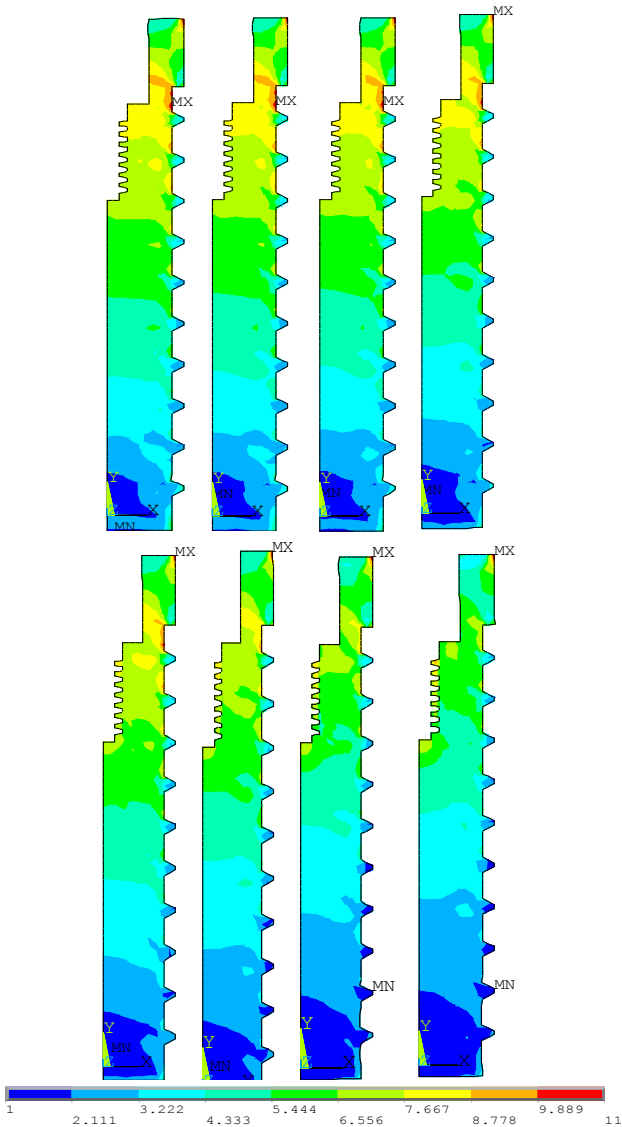


Fig. 5 von Mises stress (MPa) distribution on FGBM implant for different material gradient parameter  $n$

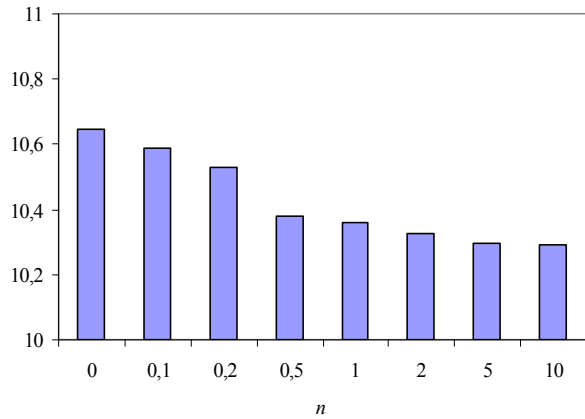


Fig. 6 Maximum von Mises stresses (MPa) on FGBM implant for different material gradient parameter  $n$

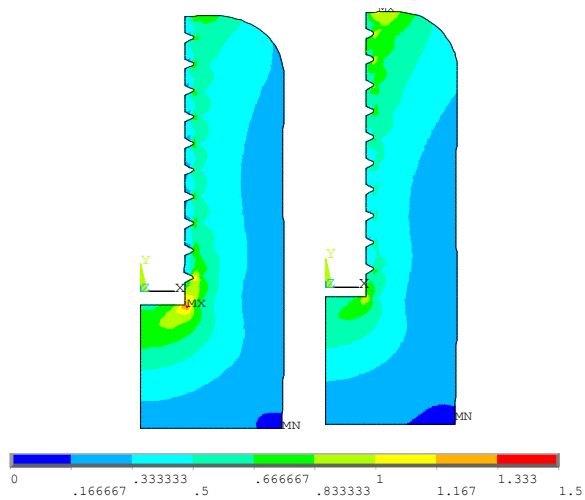


Fig. 7 Maximum von Mises stresses (MPa) on trabecular bone for  $n = 0$  and  $n = 10$

Variation of the maximum von Mises stress values on FGBM implant for different implant radius  $r = 0.5, 1.0$  and  $1.7$  mm and  $n = 0.5$  is given in Fig. 9. Two different model approaches are used to find the effect of variation of implant radius throughout the height; (i)  $H$  (not constant),  $H = 0.3$  mm at the top of the thread,  $H = 2.0$  mm at the bottom of the thread, and  $t = 0.1$  mm (constant), (ii)  $H = 0.3$  mm (constant),  $t = 0.1$  mm (constant). There is no effect of these two approaches on maximum stress value. Maximum stress values decrease with decreasing implant radius. But this attenuation is very small and it can be neglected for the two approaches. Additionally, minimum stress zone ( $< \sim 3$  MPa) at the bottom of implant body increases with increasing implant diameter.

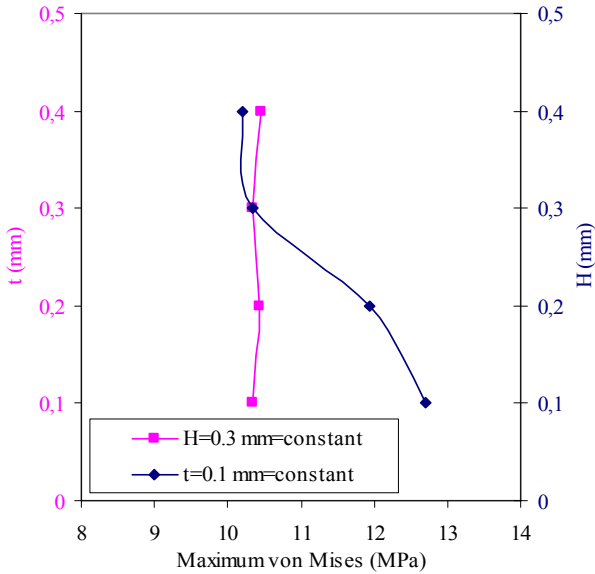


Fig. 8 Variation of maximum von Mises stresses (MPa) on FGBM implant for varied thread dimensions  $n = 0.5$ ,  $r = 3.4$  mm

IV. CONCLUSIONS

In this study, stress distributions on dental implants made of FGBM are investigated, numerically. Problem is examined as a two dimensional axisymmetric and ANSYS, 12.1 package program is used in the solution. Analysis parameters are selected as  $n$ ; material gradient parameter of FGBM,  $H$ ; weight of implant thread,  $t$ ; height of implant thread and  $r$ : radius of implant. Obtained results can be summarized as follows

- Equivalent stress decreases with increasing  $n$  and minimum stress distribution increases with increasing gradient parameter.
- The maximum von Mises stresses increase with decreasing  $H$  when  $t$  is constant. But stress values don't affect from variation of  $t$  when  $H$  is constant.
- Maximum stress values decrease with decreasing implant radius. But this attenuation is very small and it can be neglected.

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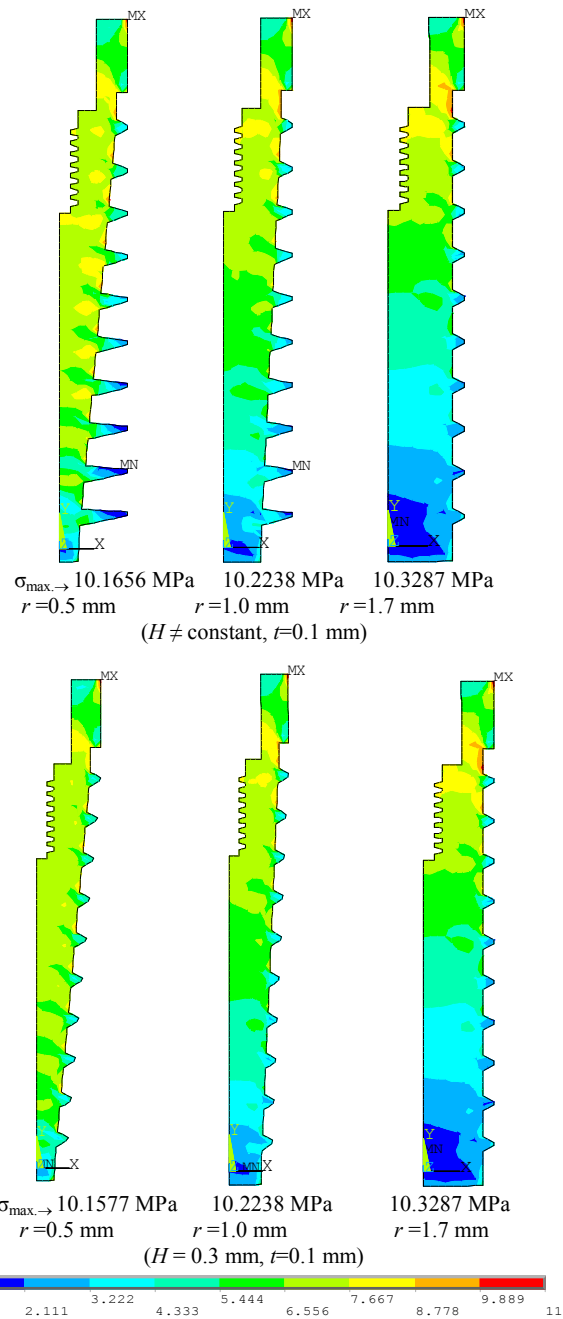


Fig. 9 Variation of the maximum von Mises stresses (MPa) on FGBM implant for different implant radius for  $n = 0.5$

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**Nevin Celik** was educated in Firat University with a broad background in the fluid mechanics and heat transfer. She carried out various experimental works during her MS and PhD educations. She had done numerical analysis by using ANSYS-CFX while she was a visitor Post Doctoral Fellow in the University of Minnesota. She studied with Professor E.M. Sparrow during her visit. Major works of Celik are related to various cases of air jet. She has also worked on some specific heat transfer problems, such as; energy-energy analysis and bio-heat transfer. Permanently she lives in Turkey and teaches at Dep. of Mechatronic Eng. at Firat University. The courses that she teaches are Fluid Dynamics, Thermodynamics and Heat Transfer, Numerical Analysis.