Structural Optimization of Metallic Toroid using Finite Element Method

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Abstract

This research paper has used a three-dimensional approach that combines Finite Element Analysis, the famous three-factor Design of Experiments by Taguchi, with the third dimension. An idea to optimize a Lithium (Li) and Lead (Pb) based Toroid is presented as they are known hazardous materials. The approach emphasized generating different run orders by a parametric variation of outer diameter, thickness, and base metal on the minimum and maximum specifications. Based on the Design of Experiments, the calculated run orders were modelled and simulated under the specified loading conditions to select the best combination of parameters. The analytical stresses generated in the combinations were compared with the numerical counterparts for model validation. Von-Mises stress and deformation results from the simulation were analyzed to select the optimized design of Toroid structure and the final shape was modelled accordingly. The analytical and numerical stresses also showed good agreement with each other, supporting the validity of the presented approach. The method effectively models such specimens before fabrication, so that all material and geometric aspects can be finalized before risking physical contact with the actual worker.

Keywords: Numerical Analysis, Metallic Materials, Finite Element Analysis, Taguchi, Design of Experiments.

Introduction

Finite Element Analysis (FEA) is the state of the art modelling and simulation-based numerical solution approach, using computer-based softwares such as ANSYS, MATLAB, and Creo Parametric. This has enabled researchers, engineers and scientists to solve various engineering problems in less time using appropriate mathematical models, meshing elements and boundary conditions[1-5].

Various engineering management and quality tools are used daily in various manufacturing and development industries to analyze and improve processes and products. For example, the Design of Experiments (DoE) is a quality tool that enables the user to optimize output by developing different combinations of the inputs at maximum and minimum settings, which helps in optimization by selecting the most suited output at the applied input parameters[6-9].

Metallic materials are the oldest class of materials that have played a significant role in developing engineering and technology for the entire human race. Metals are cost-effective, good conductors, mechanically strong, some also have good corrosion resistance and they also play an essential role in developing composite materials [10-12]. Steel and its alloys, aluminum and its alloys are some common examples that have developed various industries such as automotive and aerospace[13-17].It is important to highlight that all metals are not so friendly i.e., where some metals are beneficial, others have various safety hazards such as Uranium, which is radioactive and can cause cancer and multiple radiation-based diseases if not handled with safety. Similarly, Asbestos, Lithium, Lead are also hazardous metals that are banned for usage internationally due to their toxicity and poisonous effects [18-20].

Nizam et al. [17] has used a numerical approach to assess body implant material hazards and structures. Kamal et al.[20] has numerically analyzed the effects of geo-polymer based binders employed in concrete based applications to reduce degradation risks. Liang et al.[9] has analyzed the damping characteristics of rubber reinforced concrete to reduce the risk associated with structural applications using finite element analysis. Tanwar et al.[12] has evaluated the thermal risks associated with the cooling system of a photonic integrated circuit using a numerical based approach. Jangali et al.[7] has employed finite element analysis to evaluate the thermal and mechanical stresses endured on the cutting tip during the machining of super alloys.

Metallic toroid structures have significant applications in industrial and commercial structures [32, 33]. They started from a common currency coin to corrosion coupons, characterization specimens and even furnace samples [34, 35, 36]. This diverse use can be attributed to their excellent formability, ease of access and cost-effectiveness [21-23]. Furthermore, the compressive stress on a toroid can be mathematically given by the following Equation (1) [24, 25].

$$\delta \text{ (stress)} = (\text{F (Force)}) / (\text{A (Area)}) \qquad (1)$$

A lot of literature is already available on complex metallic as well as composite based toroid structures being evaluated using a computational approach. The general emphasis has been on mechanical design, electro-mechanical analysis or compressive behavior. An industrial gap exists in which augmentation of finite element method, dangerous materials and their qualitative evaluation can be conducted successfully [32, 36, 41]. This research has used the FEA and DoE to optimize the Toroid dimensions as a design parameter to develop a coin made from hazardous metals.

Computational Method

The flow chart proposed for the simulation model is shown in Figure 1.The Computer Aided Design (CAD) model is developed and subjected to the required loading conditions. The model is then discretized into refined elements through meshing and the complete model is sent to the solver for results. After analysis of the results, the parameters are changed as per the calculated run orders.

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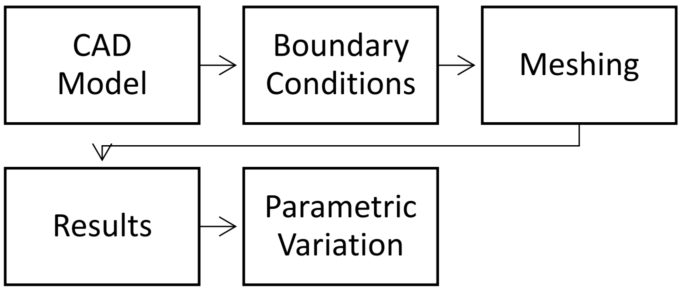

Figure 1. Process flow of Numerical analysis

The two most hazardous base metals selected for the analysis were Lithium and Lead. Table I shows the properties of these materials available in the literature[26, 27]. Table II shows the dimensions of Toroid and Table III represents the dimension range available for design purposes as per available literature [28, 29]. The outer diameter of coin, thickness and base metal used was incorporated as three factors in DoE under high and low settings to generate different run orders on the toroid for simulation in ANSYS workbench 15 static structural module. The run orders are shown in Table IV and Table V indicates the boundary conditions applied since the structure is assumed to sustain a compressive load of 800N [20]. Table VI indicates the meshing criteria, nodes, and elements used in each run order. Figure 2 represents the meshing, while Figure 3 represents the loading conditions applied for each run order. Von-Mises stress distribution and deformation were calculated to compare the behavior of each run order to select the best combination for the toroid.

Table I

Mechanical Properties of Li and Pb[26, 27]

Property	Material	
	Lithium (Li)	**Lead (Pb)**
Density (g/cm^3)	0.53	11.34
Young's Modulus (GPa)	1.9	14
Poisson's ratio	0.36	0.42
Bulk Modulus (GPa)	2.26	29.1
Shear Modulus (GPa)	0.69	4.92

Table II

Toroid dimensions[28, 29]

Parameter	Dimension (mm)
Inner diameter	8
Outer diameter	19
Thickness	4

Table III

Design dimensions[28, 29]

Parameter	Dimension (mm)
Diameter	18~65
Thickness	1.7~3.15

Table IV

Toroid and DOE run orders

Run Order	Outer Dia (mm)	Thickness (mm)	Base Metal
Toroid-Pb	19	4	Pb
Toroid-Li	19	4	Li
1	18	1.7	Pb
2	18	1.7	Li
3	18	3.15	Pb
4	18	3.15	Li
5	65	1.7	Pb
6	65	1.7	Li
7	65	3.15	Pb
8	65	3.15	Li

Table V

Boundary Conditions

Condition	Value
Fixed support end	Z-Axis
Compressive Load	800N (Z-Axis)

Table VI

Meshing Criteria

Run Order	Mesh Type	Nodes	Elements
Toroid-Pb	Hexahedral	6857	3345
Toroid-Li	Hexahedral	6857	3345
1	Hexahedral	4255	2033
2	Hexahedral	4255	2033
3	Hexahedral	5223	2541
4	Hexahedral	5223	2541
5	Hexahedral	5994	2878
6	Hexahedral	5994	2878
7	Hexahedral	4227	2007
8	Hexahedral	4227	2007

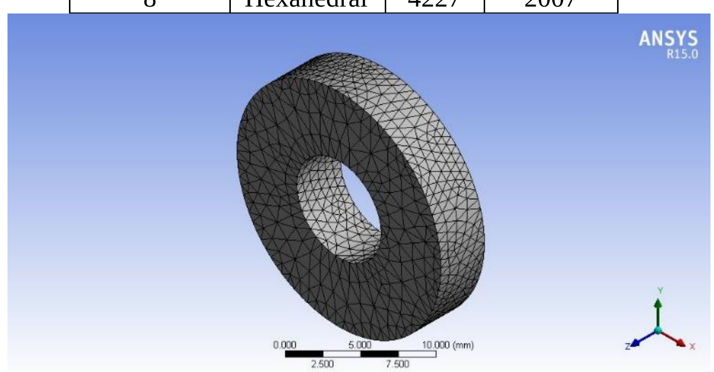

Figure 2. Meshed specimen of toroid model

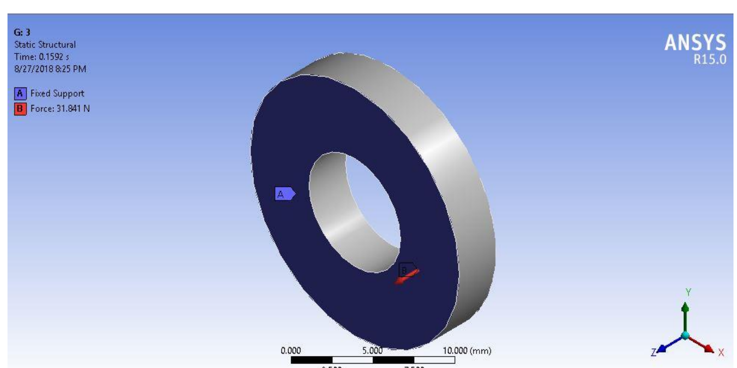

Figure 3. Loading Conditions for compressive load against the toroid model fixed at the bottom

Grid Sensitivity Analysis

It was essential to validate the meshed model before the primary analysis could have been performed. For this purpose, two approaches were employed. In the first approach, a mesh sensitivity analysis was conducted by taking the stress and deformation output values against coarser and finer elements[30, 31]. The respective output values showed no significant variation after a significant increase in the discretized number of elements, as shown in Figures 4 and 5, respectively. In the second approach, once the number of elements was finalized, the analytical stresses were also calculated using Equation (1). Again, the values were observed to be in good agreement as shown in Table VII.

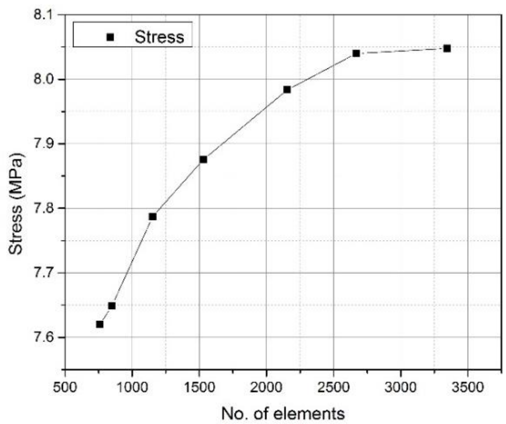

Figure 4. Mesh sensitivity for stress against maximum number of meshing elements

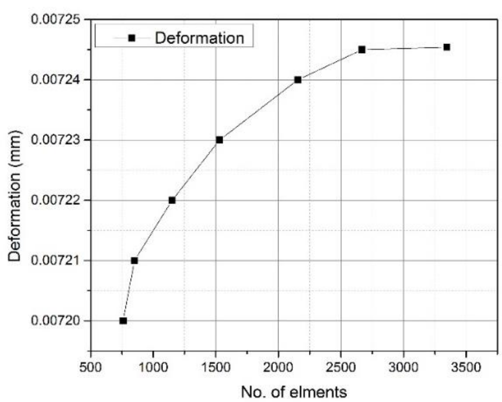

Figure 5. Mesh sensitivity for deformation against maximum number of meshing elements

Results and Discussion

The Von-Mises stress distribution for the model is shown in Figure 6 .It was observed that for all combinations, the stress was distributed on the surface and higher stresses were observed along the outer periphery and the drilled regions of the toroid. This can be attributed to the geometry of the structure in which the outer edge of the toroid acts as an area of stress accumulation. Thus when the compressive stress reaches the outer periphery, it becomes difficult to endure and accumulates [37, 38]. Table VII shows the simulation results quantifying the numerical stress and deformation generated in the models and the analytical stress values. It can be seen that irrespective of the base metal, original toroid samples exhibited higher stress values than most of the DoE combinations. This is because, the original structure of the toroid had the least area to endure stress, hence at the same constant force, the maximum stress was generated [39, 40, 41]. Figure 8 represents a comparative trend between the analytical and numerical stress calculations. It can be seen that the trend for both methods is similar for each run order and the values are in good agreement with each other. It was observed that the maximum stress was generated for order 4 due to the minimum structural area, while the minimum stress was generated for order 5 due to maximum structural area available to accommodate the stress at constant force.

In order to select the best candidate for the coin application, it was decided that logically, the coin should have the lowest stress at applied load. Keeping in view these considerations, order 5 exhibited stunning results since it had the lowest stress compared to all the samples. This is because its area was greater, the thickness was less, and it was composed of Pb, which had higher mechanical properties than other samples, which gave it a better advantage in compressive-load bearing, as shown in Figure 7.

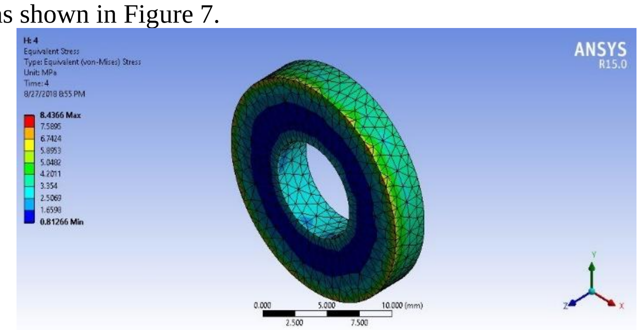

Figure 6. Von-Mises Stress distribution on the toroid structure after processing against compressive load

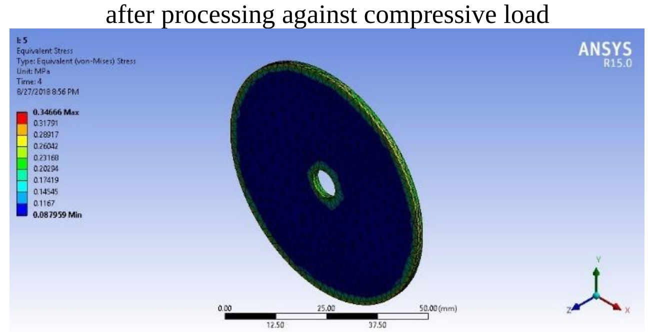

Figure 7. Minimized Von-Mises Stress distribution in optimized design of toroid for coin application

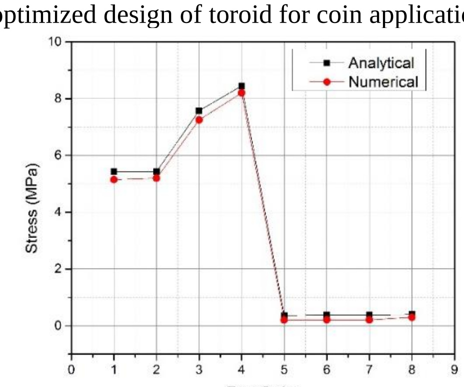

Figure 8. Stress Comparative trend between numerical and analytical results for all run orders

Table VII
Results of applied boundary condition

Run Order	Deformation(mm)	Numerical Stress (MPa)	Analytical Stress (MPa)	Error (%)
Toroid (Pb)	0.00094	8.40	8.42	0.23
Toroid(Li)	0.0072	8.41	8.42	0.12
1	0.0044	5.41	5.43	0.55
2	0.0046	5.75	5.43	0.18
3	0.0063	7.55	7.58	0.39
4	0.00083	8.43	8.45	0.23
5	0.00022	0.34	0.36	0.54
6	0.00028	0.38	0.39	0.26
7	0.00041	0.35	0.38	0.27
8	0.00054	0.39	0.40	0.29

Conclusion

DoE has facilitated in generating good combinations for Toroid design using available literature. FEA has facilitated modelling the generated combinations at the critical boundary conditions and incorporated hazardous metals like Li and Pb for simulation. Pb-based run order 5 exhibited a 96% reduction in stress generated at the same loading conditions as the original Toroid specimen and was hence classified as the optimized design. Different structural and materials hazards have been analyzed using finite element analysis as per the available literature, they have emphasized more on the structural applications, where the material or component is already installed or is in service[5, 7, 9, 17]. It does not reflect the significance of analyzing a material which is radioactive or hazardous to handle, so that one should only process them if they are structurally or functionally attractive. DoE and FEA have greatly simplified converting a thought process into a model without actually handling such hazardous metals, fabricating the actual specimens and preventing safety hazards that would have occurred in practical handling, which has tremendous prospects in protective applications and feasibility studies. By combining Quality tools and Computational Tools, we can develop reliable design combinations without compromising safety hazards.

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