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Performance Analysis of the Flywheel Assembly Design Using SolidWorks Modeling and Simulation Capabilities

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Abstract

The flywheel energy storage system (FESS) has been rediscovered a few years ago, it is a rotary system allowing the storage and restoration of kinetic energy which has an inertia wheel. The current paper investigates an assembly design of the flywheel for durable, maintainable and optimal performance. The designed model is based on a geometrical configuration which was already studied in a previous research. Using SolidWorks modelling and simulation capabilities, the model was designed and investigated with different combination of materials. A total of 16 combinations has been tested at high speed and then analyzed in order to optimize the effect of materials on the efficiency of the flywheel and particularly on the specific energy and stress Von-Mises stress. This research shows that a good geometric design of the flywheel and selection of combination of two materials can improve its energy storage capacity. Maximum specific energy of 55,764.538 J/Kg, is observed in the flywheel of combined material which is about 13% higher than flywheel of a single material.

Keywords

Flywheel, Simulation, Modelling, Energy Storage, High Mechanical Strength

1. Introduction

Flywheels used as mechanical energy storage system, are a form of rotational kinetic energy. It consists of a mass, most of the time a hollow or solid cylinder (but other shapes are possible). The mass rotates around an axis, usually fixed, and enclosed in a protective enclosure. It is connected to an electric motor/generator (**Figure 1**) which converts kinetic energy into electricity and vice versa [1].

The storage of energy is based on a series of complementary technologies, in particular that of materials with a very high mechanical strength of the revolving part [2]. However, some authors concluded that the geometric effects remarkably on the flywheel performance by studying up to 44 different most common geometries [3] [4]. An optimal design is also created to maximize the total energy stored by taking account of the effects of the material sequence and the thermal stresses induced by hardening the thickness of each composite rim are regarded as a variable of design [5].

In the design of the flywheel, there is still a place for research, especially when the performance is the objective first. The operating conditions impose a rather narrow margin of limitations of storage of energy, even a small quantity of improvements can contribute to total success.

The flywheel has developed especially in recent years, as current research works on the development and engineering of materials for manufacturing flywheel so that they can resist for high rotational speeds without breaking and have a high efficiency to give us a high specific energy [6].

This paper aims to investigate the performance of an assembly design of the flywheel, based on the most influential parameters mentioned in previous studies. The flywheel assembly has been tested with different combination of materials. Overall, the objective of the problem is formulated in terms of specific energy value and its maximization by the selection of the best combinations of materials which may very well bring about rapid but crucial improvements in the advanced areas of research requiring the use of the flywheel.

2. Flywheel Modelling & Simulation

2.1. Design and Modeling

The dominant factors in determining the flywheel performance are the weight and the strength of the material used. In the present study, an assembly design of

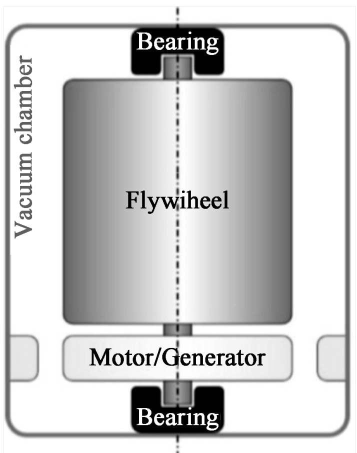

Figure 1. The main components of (FESS).

the flywheel has been performed based on a better geometric configuration which has already been studied, in comparison to others configurations, in a previous article [4]. However, the studied flywheel design contains of a mechanical assembly of two pieces that forms the rotor, namely disc and ring (**Figure 2**), instead of the one-piece in the classical design.

The geometry parameters are given in **Table 1** and illustrated in **Figure 3**.

In fact, it has been reported that the increase in the rim width and the rim height have a remarkable effect on the specific energy accumulated by the flywheel. Although, an increasing in the thickness of the disc, lead to a decrease in the specific energy. However, the maximum mechanical stress that occurs in the flywheel is concentrated in the thickness of the disc.

According to that, the aim of the assembly design is to separate the rotor into two parts in which each part would be able to meeting the performance expectations. In other words, increasing the energy storage capacity by the ring and offering a better tensile strength by the disc, during rotation.

2.2. Simulation and Analysis

In order, to investigate the performance of the new design of the flywheel, the

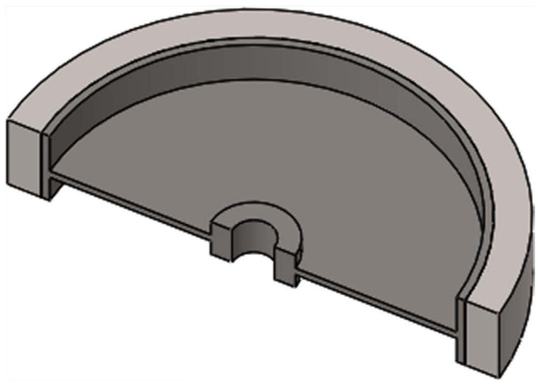

Figure 2. Assembly 3D view of disc and ring models.

Table 1. Geometry parameters of flywheel.

Designation	Hr	Wr	Gh	Dh	Dr	Td	Hh	Wd
Geometry parameter	Ring Height	Ring Width	Hub Gap	Hub Diameter	Ring Diameter	Disc Thickness	Hub Height	Disc Width
Value (mm)	20	3.5	5	20	100	2	10	1.5

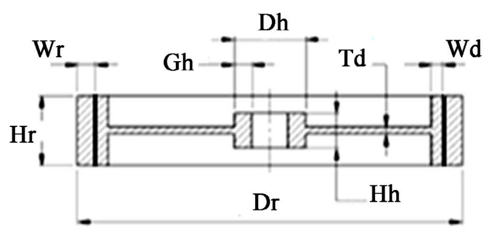

Figure 3. Section view of flywheel.

model was designed with 3D CAD and investigated by using 4 different materials (Table 2).

Considering that the flywheel rotates at a high speed of 70,000 rpm, which correspond to an angular velocity (ω) of 7330.38 rad/s, a total of 16 functional tests of model with different combinations of material for the disc and the ring, has been performed.

For each test and by using the capabilities of *Evaluate* tool in SolidWorks, the flywheel mass (m) and the moment of inertia (I) have been defined.

The kinetic energy (E_k) stored in the flywheel and the specific energy (E_{spec}), were calculated with the formulas below [7]:

$$E_k = 0.5 \cdot I \cdot \omega^2$$

where, I: is the moment of inertia.

$$E_{spec} = Ec/m$$

Von-Mises stress values were obtained after running the simulation study in SolidWorks. This latter has predefined some of the used materials in the material selection tab, but for the missing material properties, the data were manually entering from Table 2. A static analysis is created for the flywheel with boundary and load conditions. Using the fixture advisor tab, fixed geometry is applied in the inner hole circumference of the flywheel, as well as centrifugal loading is carried out in this analysis. The meshing phase of design analysis is carried out by Smart Meshing in SolidWorks which automatically determines the perfect shape of meshing for the given model for analysis.

After running the simulation study and waiting patiently for SolidWorks solver to complete the analysis. The desired result will be obtained on the work screen. The red area obtained shows the maximum values of Von-Mises stress.

The present study was conducted such that highlights the variation of the mechanical stresses that the flywheel is exposed to, with the changing of the flywheel material.

SolidWorks Simulation is powerful Finite Element Analysis (FEA) software, which allowed determining the maximum stresses in the flywheel model with each combinations of material. Therefore, a centrifugal force was applied with a rotational speed, without penetration between assemblies.

Table 2. Mechanical propriety of the flywheel materials.

Materials	Symbol material	Density (Kg/m^3)	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
Steel 4340	St	7850	710	1110	205
Ti-3Al-8V-6Cr-4Mo-4Zr	Ti	4820	1034.24	1220	104
Aluminum alloy 1060	Al	2700	27.57	68.93	69
E-glass fiber	G-f	2600	1900	1900	72

The geometry parameter values, the mass, the moment of inertia, the kinetic and specific energy and the maximum of Von-Mises stress values are given in Table 3.

3. Results and Discussion

3.1. Total Mass

From Table 3 and Figure 4, results that, the total mass of the flywheel, depends on the density of materials used for the disc and the ring. It increases/decreases proportionally with the increases/decreases of the density of either or both materials.

It's clear that the mass of the flywheel is more and more important, when using one or both materials of a high density as Steel 4340 and Titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr, and specifically for the ring of a larger volume, in which the total mass reach 347 g.

3.2. Specific Energy

The kinetic energy and the specific energy vary depending on the total mass of the flywheel. Figure 5 shows that the specific energy exhibit a large alternating variation compared to the kinetic energy. It's clear that this variation does not

Table 3. Calculated parameters of flywheel as functions of the material combination.

Material		Mass	Inertia	Kinetic Energy	Specific Energy	Von-Mises Stress
Ring	Disc	(Kg)	(Kg/mm^2)	(J)	(J/Kg)	(MPa)
Al	G-f	0.117	214.306	5708.325	48,789.102	345.9
	Al	0.119	217.411	5841.237	49,086.028	354.3
	Ti	0.168	283.244	7609.989	45,297.556	530.5
	St	0.238	377.335	10,137.957	42,596.456	796.8
G-f	G-f	0.115	209.359	5624.902	48,912.193	336.2
	Al	0.117	212.464	5757.814	49,212.090	344.5
	Ti	0.166	278.297	7477.077	45,042.633	519.8
	St	0.236	372.388	10,005.044	42,394.255	786.1
St	G-f	0.226	469.076	12,602.786	55,764.538	726
	Al	0.228	472.181	12,686.208	55,641.265	707
	Ti	0.277	538.014	14,454.961	52,183.973	684.7
	St	0.347	632.105	16,982.928	48,942.155	1028
Ti	G-f	0.162	319.182	8575.545	52,935.463	432.7
	Al	0.164	322.288	8658.995	52,798.748	442.7
	Ti	0.213	388.12	10,427.720	48,956.432	632.5
	St	0.283	482.211	12,955.687	45,779.813	925.3

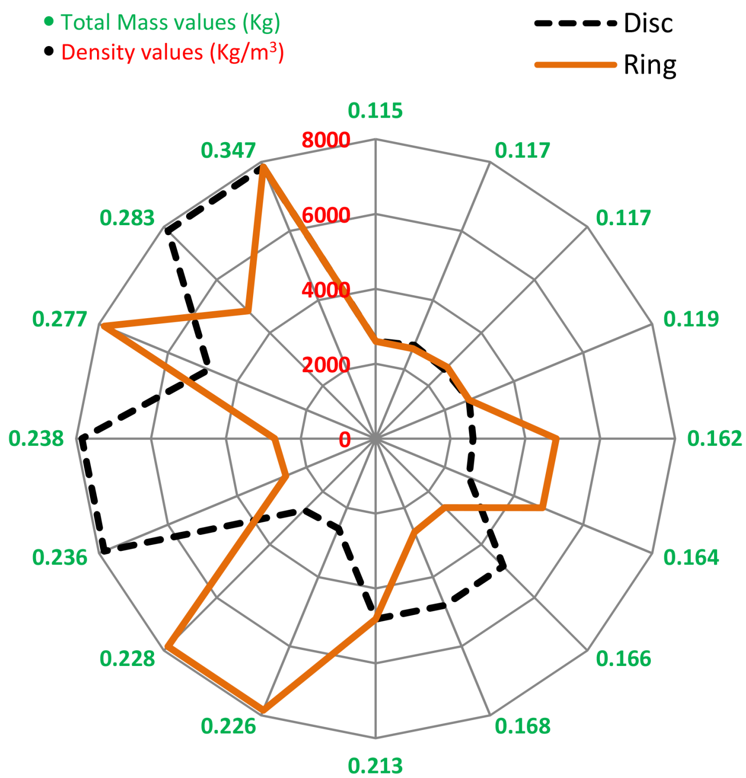

Figure 4. Radar chart of total mass variation as a function of densities.

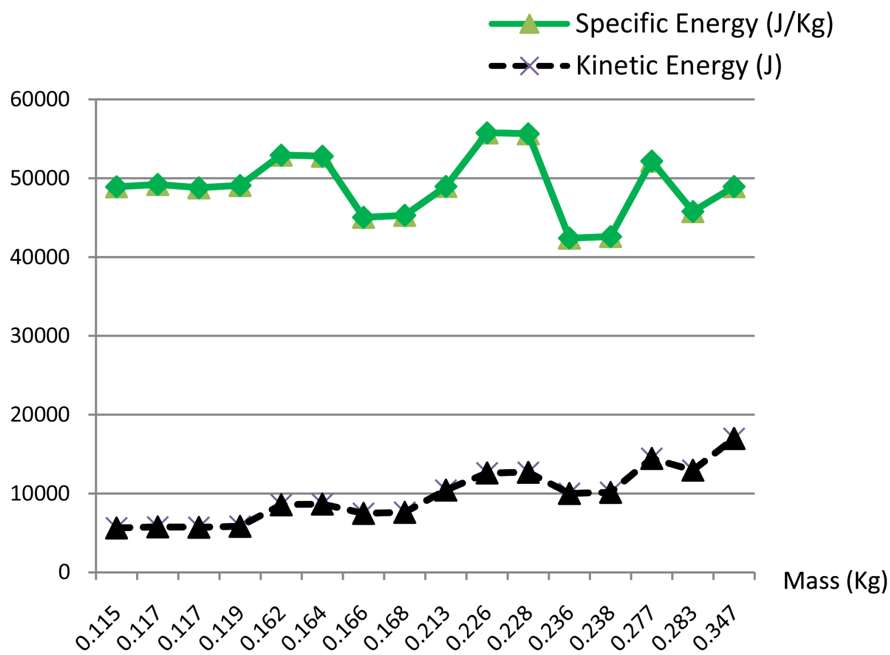

Figure 5. Specific energy variation as a function of total mass.

depend on the total mass specifically, but it depends on both variations of the mass of the disc and the ring, and as a consequence on their densities (**Figure 6**).

Figure 6 exposes the variation of the specific energy as a function of the densities of both materials of the disc and the ring. The radar chart visualization of

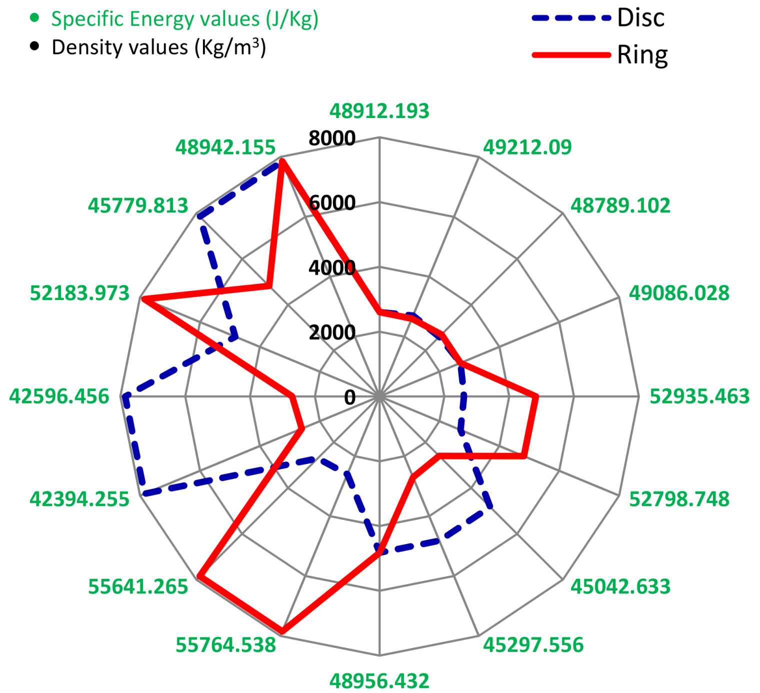

Figure 6. Radar chart of specific energy variation as a function of densities.

Table 4. Specification of material of flywheel for high performance.

Parts	Adequate material	Specification
Ring	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)	High density
	Steel 4340	
Disc	Aluminum alloy 1060	Low density
	Fiber E-glass	

the result shows that the increase of the ring density has a significant effect in increasing in the specific energy. The high values of this latter, are most of the time obtained with a high density of the ring.

However, while the disc density is increasing, there is a reduction in the specific energy. On the other hand, it's noticed that when the density of the disc material is larger or the same as the one in the ring, the flywheel registers a low values of the specific energy. The high values of the specific energy which exceeds 52,000 J/Kg, are obtained by flywheels with materials of specification given in **Table 4**.

3.3. Mechanical Stress

The mechanical stress, evaluated by Von-Mises stress criterion, varies depending on the characteristics of the flywheel design materials.

Overall, the increasing of Von-Mises stress is related to the increase of the mass of the flywheel (**Figure 7**), due to the mechanical stress caused by centrifugal force. Even so, the radar graphic representation (**Figure 8**) showed that the

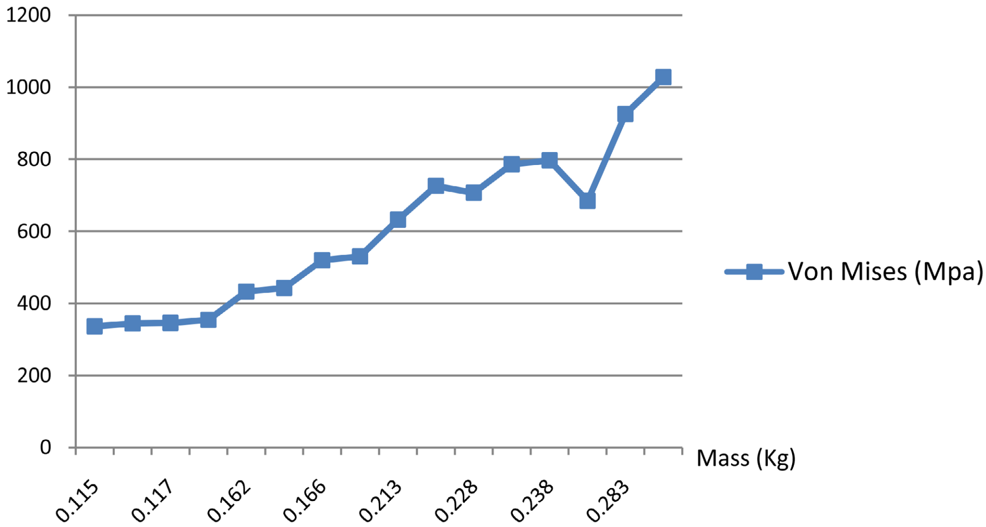

Figure 7. Variation of Von-Mises as a function of the flywheel mass.

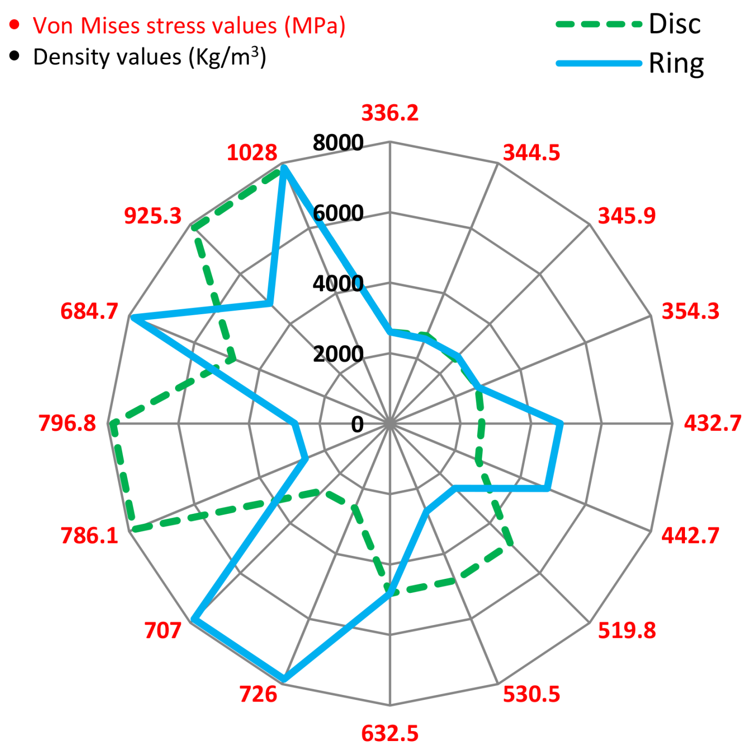

Figure 8. Radar chart of the variation of Von-Mises stress as a function of the densities.

increase of the maximum values of Von-Mises stress, is most of the time specifically caused by the increasing of the mass of the ring and thus of its density.

Figure 9 describes the variation of the maximum values of Von-Mises stress as a function of the flywheel mass and according to the yield strength of the corresponding material of the disc. As noticed, the area of high concentration of stress is located on the disc (Figure 10). At that point, only the materials of sufficiently high yield strength of the disc are available to resist to the centrifugal stresses when applied to the flywheel. When using Titanium alloy or E-glass fiber

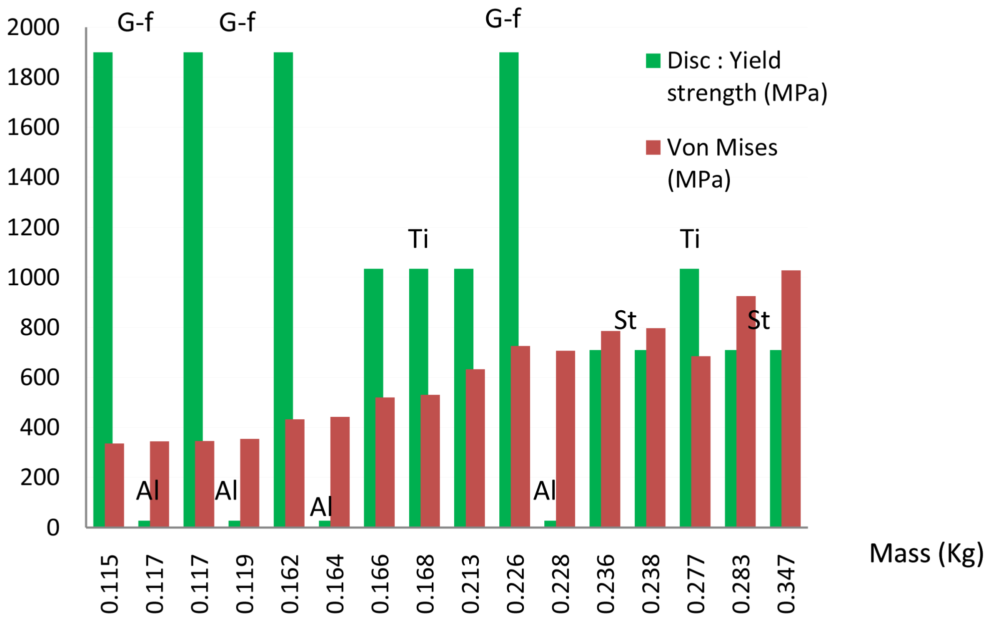

Figure 9. Histogram of the variation of Von-Mises stress against the yield strength of material.

material for the ring, theirs yield strength seems to be larger than the maximum value of Von-Mises stress. However, for the steel 4340 or Aluminum alloy 1060 used as the ring material, the maximum value of Von-Mises stress exceeds theirs yield strength.

3.4. Optimized Model

From analyzing the previous graphs and basing on the criteria of a high specific energy and taking a maximum permissible material stress into account, the optimal models of the flywheel are summarized in the following table (**Table 5**). The rating of optimal models shows that the models consisting of two different materials exhibit a high specific energy compared to models of a single material. This indicates the beneficial effect of the design of separate parts of the flywheel, which will enable the possibility to provide parts with the adequate materials.

4. Conclusions

The results obtained in the present study can be summarized by the following conclusions.

- Instead of only one piece in the classical design. The assembly design of the flywheel of two separate parts (disc and ring) has proven its performance in raising the specific energy, by offering the flexibility to optimize the proprieties of the corresponding material.
- It is observed that improving the performance of the flywheel relates to carefully selecting the right material for the disc and the ring, hence advanced materials with highly specific properties can be beneficial for increasing energy efficiency.
- The major characteristics of the optimal model of the flywheel include:

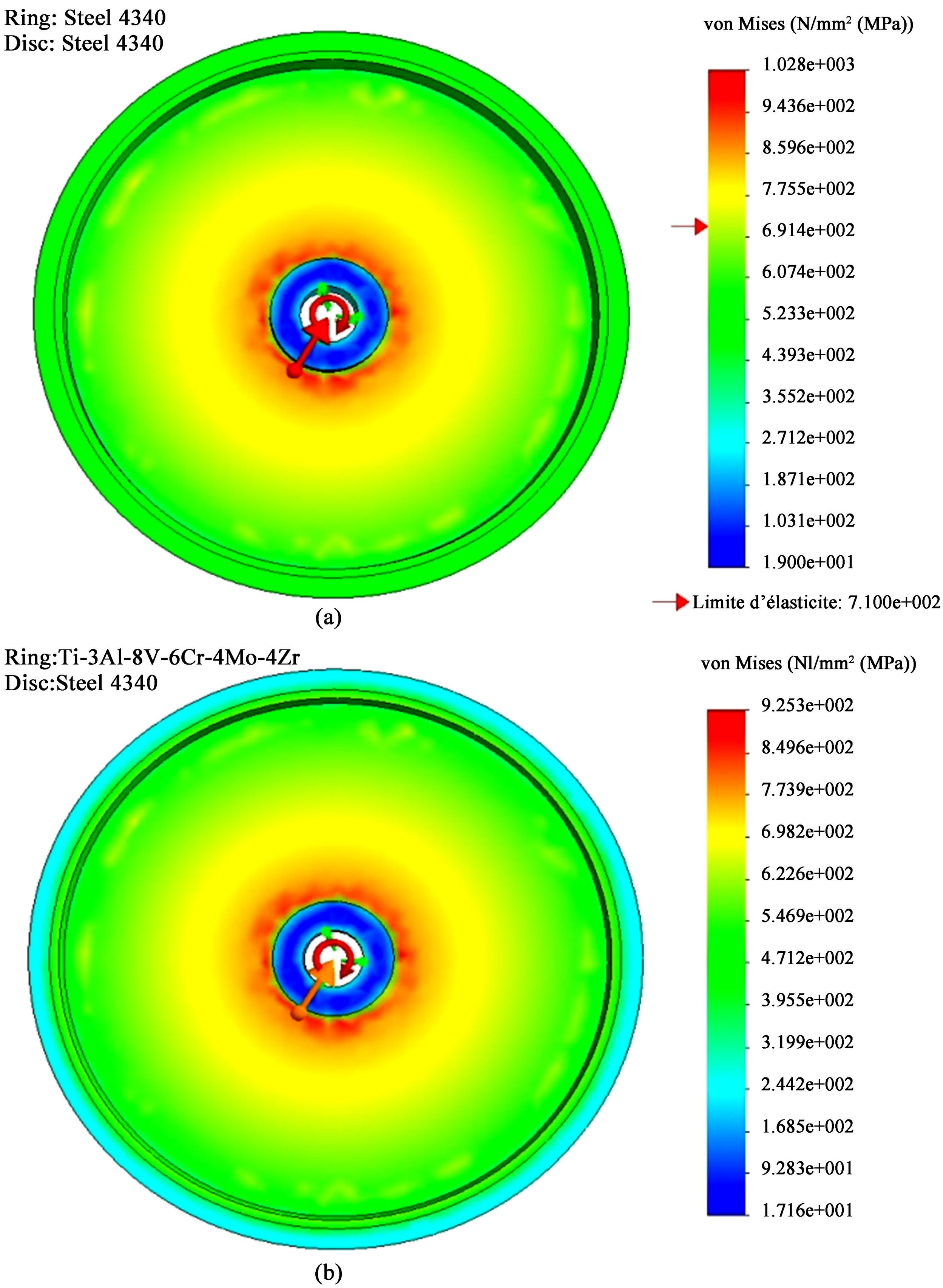

Figure 10. Von-Mises stress distribution.

Table 5. Corresponding materials of the optimal models.

Rank	Material		Specific Energy (J/Kg)	Von Mises Stress (Mpa)
	Ring	Disc		
01	Steel 4340	Fiber E-glass	55764.538	726
02	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)	Fiber E-glass	52935.463	432.7
03	Steel 4340	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)	52183.973	684.7
04	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)		48956.432	632.5
05	Fiber E-glass		48912.193	336.2
06	Aluminum alloy 1060	Fiber E-glass	48789.102	345.9

    - Ring part of a high density material;
    - Disc part of a low density and a high yield strength material.
- Smart design of flywheel geometry and selection of the right material, have a substantial effect on its performance, but determination of the optimum configuration will be the subject of future studies.
- The use of the capabilities of simulation on SolidWorks, can be very helpful to be able to draw meaningful conclusions about the performance of the flywheel based on the corresponding materials.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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