Material Selection, Simulation and Validation for Cop Coils High Voltage Spark Plug Boots Insulators

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Abstract. The following research presents the study and selection of an alternative composite material to manufacture electrical insulation devices for the high voltage circuit of Otto cycle internal combustion engines, better known as gasoline engines. High voltage insulators are generally made of materials such as rubber or silicone, whose material, when subjected to high temperatures, suffers technical degradation, causing electric power leaks and engine power losses. The purpose of this study is to suggest a composite material, with which only these insulating bodies can be manufactured. To do this, multicriteria selection techniques are used while the results are validated by virtual simulation of thermal character and normed experimental tests.

Keywords: Automotive vehicle · Temperature · Composite material · Electric power · Electronic circuit

1 Introduction

The selection of materials is one of the most important stages when designing a product. From the point of view of engineering design, the selection of materials is the process that aims to identify the appropriate materials for manufacturing processes [1].

Multi-criteria decision making (MCDM) methods for selecting materials are considered one of the design strategies implemented to achieve product efficiency [2, 3]. Because each product is different, each one may require numerous functions that could not be satisfied using a single material for all of them [4, 5]. A design that incorporates the selection of multiple materials is a viable alternative to achieve the functional requirements of a product. According to [1, 6]. The implementation of multiple materials in the design of the product leads to a greater performance of the product in terms of functionality, manufacturing capacity, costs, and aesthetics. For Caliskan, H. [7] MCDM methods are based on the comparative study of candidate materials: since they are techniques that help defining the characteristics of what is sought, a list of candidate materials must be established in order to determine what the main function will be and later select a single one. According to Aly et al. [8] selecting an appropriate

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material to manufacture a product generally involves a comparative evaluation of several criteria and attributes of the material, which are important when offering it as a service. This means that the comparison between materials is key when determining a material as suitable. On the other hand, it is necessary to validate the results of the MCDM. The design simulation helps manufacturers verify and validate the intended use of a product in the development phase, as well as its manufacturing capacity [9, 10]. Generally, the term "simulation" is used as a generic term for computer-aided engineering (CAE) [11, 12]. Several design simulations approaches have become standard components of product development in different sectors and continue to gain in importance, as this economical, fast, affordable and easy-to-use design simulation software allows users to cope with new technologies and applications.

Simulation models are sets of mathematical equations that represent the response of the system in a physical domain of interest. The complexity of mathematics depends on the availability of the data and varies according to the application and the design stage [11]. These simulations can cover aspects such as structural behavior, acoustics, system dynamics, resistance to shocks, thermal and flow analysis, stress analysis, fuel economy, the development of controls and much more [12].

However, none of the mentioned articles uses the MCDM methods with laboratory simulation and experimentation to enhance the design phase and corroborate the results. The purpose of this paper was to perform a MCDM of a spark plug boot (SPB). After the MCDM selection process, a thermal origin simulation was performed using the NX Nastram Software in the thermal simulation module. Finally, the results of the simulation were verified by submitting several specimens of SPB constructed with the material selected and considered optimal to laboratory tests of thermal and dielectric nature.

2 Materials and Methods

The materials and methods include the operation of the piece, the properties of materials used in the study, the explanation of the MCDM, how simulation was performed, and the thermogravimetry test. Hereunder, each of them will be explained.

2.1 Piece Performance

Automotive ignition coils are an essential part of automotive engines. According to Skinner & Lovers [13] they are complex small devices that initiate combustion in an engine. They provide high voltage electric power (34 kV), or spark to ignite the stoichiometric air-fuel mixture.

These devices are known as independent coils (coil on plug, COP). COP coils are composed of two main parts: the body of the coil or high voltage transformer (HVT), which houses the electrical and electronic components responsible for providing high voltage, and the high-tension lead (HTL) that transports energy from the coil to the spark plug. It should be noted that the HTL is removable from the coil. The HTL is covered with an electrical insulator which prevents electrical energy from leaking out of this circuit known as spark plug boot (SPB). The SPB high-voltage insulation undergoes technological degradation of the material, due to the working conditions, causing failures such as excessive slack in the boot in the sector that shelters the upper part of the spark plug or fissures in the material. The result of this degradation is a leakage of electrical energy, which causes the combustion of the stoichiometric mixture in the cylinder where the degradation takes place to be incomplete or null, thus causing failures such as: power losses of the engine (25% approximately), excessive fuel consumption due to the compensations managed by the multi point fuel injection system (MPFI) and high pollutant emissions. For these reasons, it is necessary to replace the insulating SPB. However, in the Ecuadorian market, the spare part cannot be found, but rather the complete COP coil, i.e., the SPB and the HVT coil together. But whenever there is a problem that only affects the SPB, buying the complete COP coil is an unnecessary expense, which has strong economic and environmental consequences (carbon footprint). Therefore, it would be ideal to be able to independently find the SPB [13–19].

2.2 Materials

The choice of materials was made through the preparation of a list with seven polymeric materials, which were evaluated under the following preliminary criteria:

1. having dielectric, thermal, chemical and mechanical qualities, which are necessary to fulfill the indicated function;
2. being easily found in the Ecuadorian market;
3. having a competitive price.

A matrix where the candidate materials and the criteria that will be considered can be seen is built. The materials were assigned the letter M while the criteria were assigned the letter C, as can be seen in Table 1. Only the first six criteria will be considered since criteria 7 and 8, corresponding to the chemical qualities, have the same value in all materials. The materials to be studied are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), polyvinyl chloride (PVC) Polyamide 6- Nylon PA6, copolymer of Ethylene-Tetrafluoroethylene ETFE - Teflon and Polypropylene PP. The choice is based on the references [13, 20–22] that dwell on their properties. In all the criteria, a higher is better, except in the elasticity module.

2.3 Multicriteria Selection Methods and Weighting Method

The multicriteria selection methods used are: VIKOR, PUGH, TOPSIS, PROMETHEE, DOMINIC and COPRAS. Mentioned methods need the criteria with which the selection will be made to have a weight or quantitative value, for which the weighting method known as STATISTICAL VARIATION was applied.

Method of Statistical Variation: It is an objective statistical method that gathers the values of all the variables of a preestablished decision matrix and concatenates them with each other numerically until finding the value that most closely matches the ideal. This will assign a higher weight to the numerically higher criterion [2].

Table 1. Selected materials and their properties

Materials (M)	Dielectric strength V × m (C1)	Work temperature (C2)	Price $ × Kg. (C3)	Coefficient of thermal expansion × 10^{-6} K^{-1} (C4)	Thermal conductivity $Wm^{-1}K^{-1}$ (C5)	Elasticity module GPa (C6)	Resistance to Hydrocarbons (C7)	Resistance to grease and oils (C8)
Polyethylene AD (M1)	22	120	4	100	0.33	0.3	Yes	Yes
Polyethylene BD (M2)	22	90	4	100	0.52	1.2	Yes	Yes
Polystyrene (M3)	20	95	4.25	70	0.17	1.65	Yes	Yes
PVC (M4)	14	75	4	75	0.25	4.0	Yes	Yes
Nylon (M5)	25	160	4	95	0.28	3.0	Yes	Yes
Teflpon (M6)	25	160	4.5	90	0.24	0.8	Yes	Yes
Polypropylene (M7)	30	120	5	100	0.22	1.5	Yes	Yes

VIKOR Method: VIKOR method is the MCDM method originally developed to solve problems of deciding alternatives and criteria. Assuming that compromise is acceptable for conflict resolution, the decision maker wants a solution that is the closest to the ideal, and the alternatives are evaluated according to all established criteria. VIKOR ranks alternatives and determines the solution named compromise that is the closest to the ideal [23].

PUGH Method: For [24], the PUGH method is used to evaluate options in a design process, categorizing and quantifying criteria, material, processes, characteristics, etc. It gives them certain importance in order to create a scale.

TOPSIS Method: The TOPSIS method is used to sort preferences by similarity to ideal solution. TOPSIS is a multiple criteria method to identify solutions from a finite set of alternatives. The basic principle of TOPSIS method is to choose the alternative that has the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. An ideal solution is defined as a collection of scores or values for all attributes considered [25].

PROMETHEE II Method: The PROMETHEE method involves using a list of alternatives and building a series of scales, which can be positive or negative and net, according to the desired characteristics of a certain valuation process. The process is as follows [26].

DOMINIC Method: The Dominic procedure is a qualitative method of material selection, which considers weight factors in the selection criteria. The selection is made with matrices. In the rows, the criteria and the weight factors are included, while the columns contain the candidate materials, identified with a letter. The operative method is described in [27].

COPRAS Method: The COPRAS method is a decision-making method which combines the values of the criteria with the weights of the criteria. Priorities are thus obtained, which are relative, based on the qualities looked for in a material. These positive and negative priorities are evaluated in such a way that performance levels of each material option can be observed, that is, their measurement is a percentage. In this way, a classification of the materials according to their numerical performance can be achieved [2].

2.4 Spearman Correlation Coefficient

Once the results of the MCDM have been obtained, the existence of a correlation between them must be measured, for which a tool such as the Spearman Correlation is used. Values obtained with this method can score from −1.0 to 1.0, going through 0, interpreted as follows: if they approach 1.0, it means that there is a positive correlation; if they approach −0.1, there is a negative correlation; and if the value is 0, there is no correlation. To do this, the results of the MCDM must be analyzed in pairs, making combinations so that they all come together.

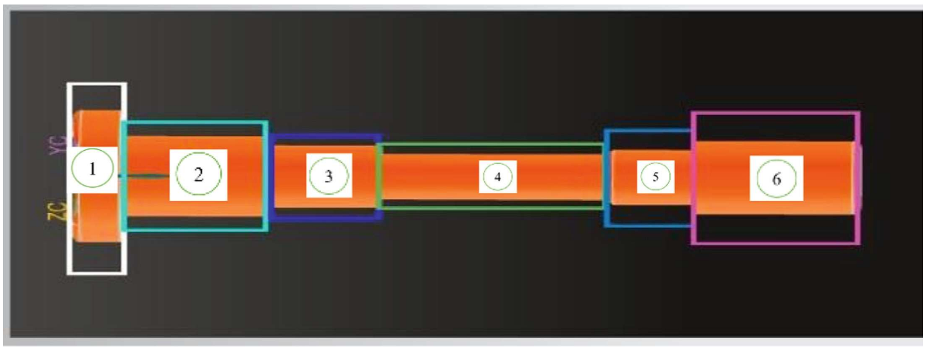


Fig. 1. SPB divided in 6 quadrants

2.5 Simulation

The simulation process shows us how effective could be the winner material in a virtual extreme work.

Procedure: 1. Open a new Fem and Sim environment; 2. Import a 3D CAD model; 3. Load the material from the software library; 4. Mesh the object 5. Set the thermal charge up; 6. Set the thermal restrictions up; 7. Run.

Thermal Simulation: This environment is known as Fem and Sim, which are the virtual places where the simulation will be carried out in the NX software and where a CAD model of the SPB will be loaded. The Fig. 1 shows a specimen of SPB divided in 6 quadrants in order to analyze the temperature effects in each one of them (Table 2).

Table 2. Border conditions for simulation

Material	Load (W)	Temperature °C	Coefficient of Thermal conductivity 23 °C (V m^{-1} K^{-1})	Thermal exposure time From O sec. to 600 s	Computer time by simulation (Min.)
Polyethylene BD	30	160	0.3	Yes	10
Polyethylene AD	30	160	1.2	Yes	12
Polystyrene	30	160	1.65	Yes	14
PVC	30	160	4.0	Yes	15
Nylon	30	160	3.0	Yes	20
Teflon	30	160	0.8	Yes	17
Polypropylene	30	160	1.5	Yes	21

2.6 Thermogravimetry Test

The experimentation process tries to test the thermal characteristics of an SPB prototype built with the material with better results, carried to extreme values, beyond those that the material possesses.

The Thermogravimetric experimental process was carried out in the laboratory of the CIAP Polymer Applied Research Center of the National Polytechnic School of Ecuador. The test was carried out in accordance with the ASTM D3850-12 standard "Rapid Thermal Degradation of Solid Electrical Insulating Materials by Thermogravimetric Methods (TGA)". The test conditions are specified in Table 3.

Table 3. Test conditions

Factors	Characteristics/values
Laboratory:	CIAP/EPN
Norm:	ASTM D3850-12
Equipment:	Thermo balance
Gas:	Nitrogen
Gas flow:	50 ml/min
Crucible:	Platinum

3 Results and Discussion

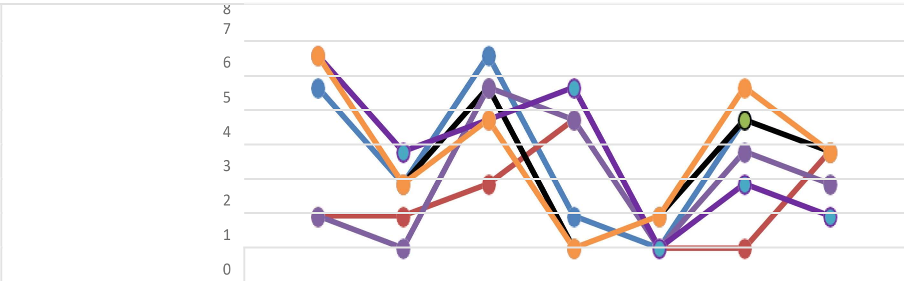
The materials and methods include the results obtained in the MCDM, the results of the simulation in each of the materials, and the thermogravimetry test in the chosen material. Each will be explained below.

3.1 Results of the MCDM

In MCDM the winner material is which reaches the closest position to ZERO. A matrix where the candidate materials can be seen was constructed in Table 1. The next step was to apply the multicriteria methods in order to determine the most suitable material to manufacture the SPB insulators in a technical way. To be able to apply the multi-criteria methods, the criteria with which the selection was going to be carried out must be precisely taken into account: the dielectric strength, the working temperature, the coefficient of thermal expansion, the thermal conductivity, the modulus of elasticity, the resistance to hydrocarbons, the resistance to fats and oils, and the price. Once the criteria were determined, each criterion was to be weighted, that is, it had to be determined which of the criteria was the most important in this selection of materials. According to [2] the weighting factors express the relative importance of each criterion.

3.2 Results of the Statistical Variation Method

Figure 2 shows a statistical comparison of the results, where the best material is the one that holds the first position of the overall ranking the highest number of times. Nylon obtained the first place four times, and the second place twice.



	Polietileno BD	Polietileno AD	Poliestireno	PVC	Nylon	Teflón	Polipropileno
VIKOR	6	3	7	2	1	5	4
PUGH	2	2	3	5	1	1	4
TOPSIS	7	3	6	1	2	5	4
PROMETHEE	2	1	6	5	1	4	3
DOMINIC	7	4	5	6	1	3	2
COPRAS	7	3	5	5	2	6	4

Fig. 2. Comparison of MCDM results

The results of the correlation of results of the MCDM methods appear in Table 4. It is observed that the VIKOR method has a correlation of 0.92 with TOPSIS and 0.85 with COPRAS, which indicates a great correlation. However, it has a low correlation with the PUGH method. In general, the PUGH method has correlations below 0.55.

Table 4. Spearman correlation in MCDM results.

	VIKOR	PUGH	TOPSIS	PROMETHEE	DOMINIC
PUGH	0.071	–	–	–	–
TOPSIS	0.92	−0.17	–	–	–
PROMETHEE	0.5	0.54	0.2	–	–
DOMINIC	0.46	0.42	0.46	0.38	–
COPRAS	0.85	−0.3	0.85	0.85	0.28

3.3 Results of Simulation

In the figure number three it is possible to see every single material, in the hardest conditions of work, with a security factor of 1,6, which means that, the temperature is around sixty percent higher than the regular work temperature. The color scale determines how warm are the several sections of the specimen of SPB. Being the red one the highest temperature (160 °C) and the de blue one the lowest temperature (60 °C) with an orange and yellow scale in between.

The heating points were setting up in the closest areas to the combustion chamber, that is why the warmest quadrants are the number 5 and 6. The materials that reach the red color show that these materials are getting very close to the thermal degradation. In that way the Nylon and Teflon materials are enough away for their degradation in such work conditions.

3.4 Results of the TGA

The results of TGA were carried out on a prototype of SPB made of nylon, which was the best resulting material of the MCDM selection and showed its ideal behavior in virtual simulation. The manufacturing process was manual machining. The geometry used was the same as the simulation, which is that of a SPB equipped in the Suzuki G16B engine used by Grand Vitara vehicles. The results obtained after the TGA thermogravimetric test, to a prototype built with Polyamide 6 (nylon), can be observed graphically in Fig. 14, where the curve of thermal degradation of the material starts from 400 °C approximately, evidencing that the SPB built with nylon will perfectly support the 1630 °C that it will have to face inserted in the cylinder head of an internal combustion engine (Figs. 3 and 4).

Table 5 shows the exact values thrown by the TGA, which warn of a degradation calculated as SPB weight loss from 420 °C.

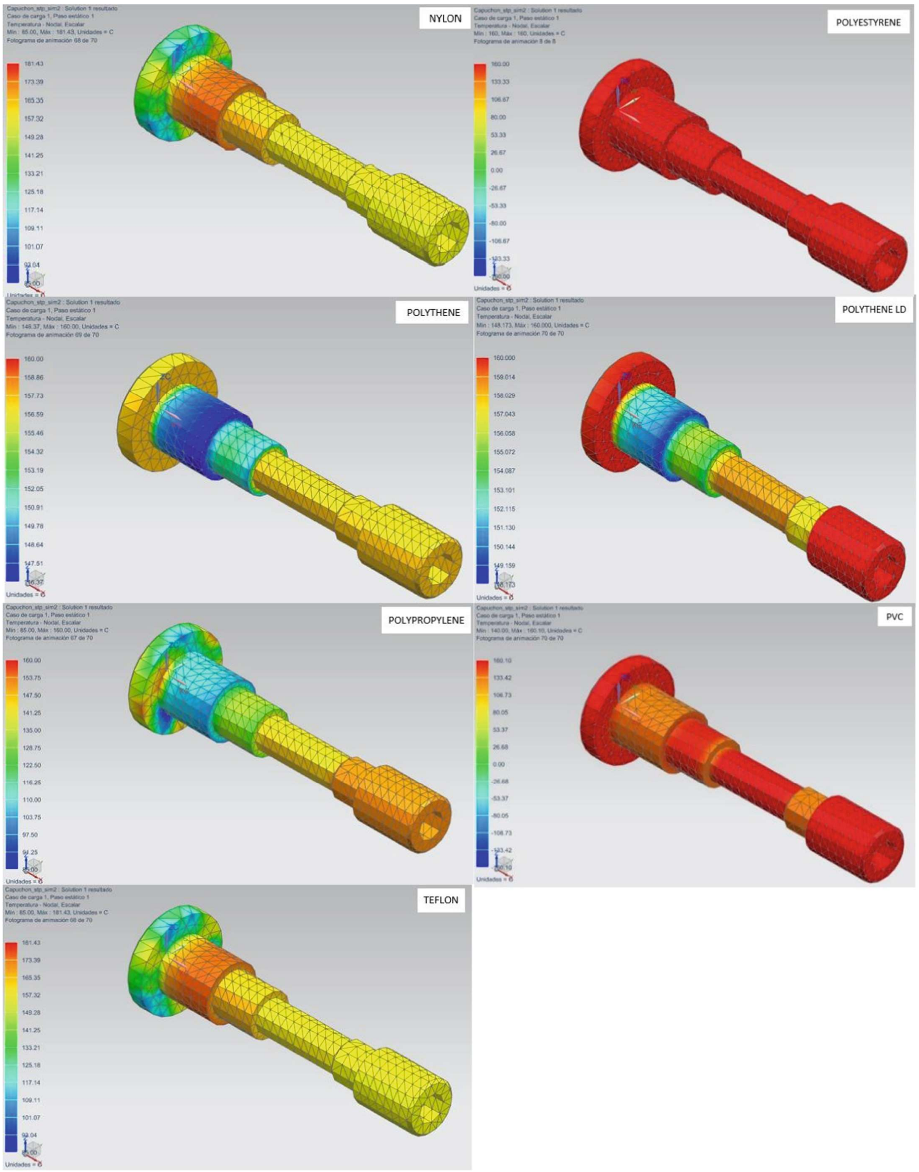


Fig. 3. Comparison of SIMULATION results

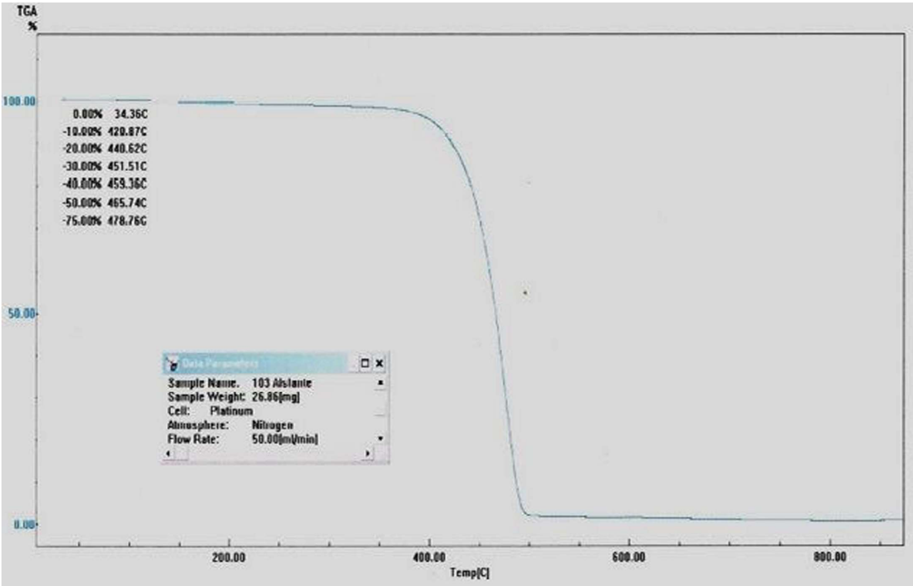


Fig. 4. Results of TGA

Table 5. Thermal degradation values of the SPB constructed with Nylon in the TGA

Lost weight (%)	Temperature
10	420.9
20	440.6
30	451.5
40	459.4
50	465.7
75	478.8

4 Conclusions

The present research was able to select an alternative composite material, to manufacture electrical insulation devices for the high voltage circuit of Otto cycle internal combustion engines. The selection of the material was made using three selection procedures: the application of multicriteria methods, virtual simulation, and experimentation. The use of these three methodologies helped each one validates the previous one and allowed establishing real limits.

It was determined that, of the non-traditional materials used to manufacture SPB studied in this research, the material suggested for constructing high-voltage insulators for COP coils is nylon. It was determined that 4 of the 6 multicriteria selection methods used in this research place nylon as the first option while the other two place it as a second option, representing 66.7% acceptance of nylon as the ideal material to manufacture SPB, according to the MCDM.

Through the virtual simulation process, it was determined that in the same environment where the edge conditions are the same, the thermal behavior of the materials varies significantly, since the quadrants show behavior alterations according to the material. It was established that, in order to comply with the dielectric isolation process of the SPB constructed with nylon, the dimensions are determinant, since the nylon has a low modulus of elasticity in comparison with the silicone. In this way, to be coupled to the geometry of the spark plug and perform the ideal insulation, it needs to have a minimum clearance.

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