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Mechanical Behavior Variation of an Isotactic Polypropylene Copolymer Subjected to Artificial Aging

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1. Introduction

Most of the injuries suffered by motorcyclists and cyclists on Spanish highways are due to collision with guardrails, particularly with the posts that support these protective devices.

In order to lessen the effect of such accidents, the research group "New Technologies applied on Vehicles and Road Safety" (VEHIVIAL) of the University of Zaragoza is carrying out a series of studies, in collaboration with the company Taexpa S. A.

These studies are developing an innovative a system that will protect motorcyclists and cyclists from crashes against guardrails.

The material chosen for the development of this absorption system is commercial isotactic polypropylene copolymer, due to its great capacity to transform the kinetic energy of the shock into strain energy.

The developed system can be installed on the posts of the highways guardrails, where the polypropylene is affected by the environment, modifying the material mechanical properties.

The isotactic polypropylene is found in almost all of the polypropylene market. It is a crystalline thermoplastic material, so mechanical properties mainly depend on their molecular structure, their crystal structure and the macro-structure induced by the transformation process (Monasse & Haudin, 1995; Rodriguez et al, 2004; Varga, 1992; Fujiyama et al, 2002).

The chapter shows the analysis of the mechanical properties variation of an isotactic polypropylene copolymer, when this material is subjected to artificial aging according to the standard UNE 4892.

The selected material is polypropylene because it is the polymer that has a better impact resistance-price ratio.

2. Materials and experimental techniques

In order to obtain the variation of the mechanical behaviour of polypropylene copolymer under study, experimental and virtual testing techniques have been used.

In the first phase of the developed process a series of samples was subjected to artificial aging in a climatic chamber. The mechanical properties of the original material used and the aged polypropylene were obtained by tensile tests.

Once the mechanical properties of both materials were obtained, a series of numerical calculations by means of the Finite Elements Method (FEM) were made. The results of the numerical tests allow for obtaining the variation of the mechanical behaviour of the material subjected to artificial aging with respect to the original polypropylene.

2.1 Materials

The material used in the study is an isotactic polypropylene copolymer, because it is the polymer that has a better impact resistance-price ratio. To carry out the experimental tests 10 dumbbell-shaped samples of type 1B were mechanized from a square sheet of side 1000 mm and a thickness of 3 mm of this material .These samples were manufactured according to the standard UNE-EN-ISO 527-2.

2.2 Artificial aging of isotactic polypropylene copolymer

The aim of this test is to reproduce the effects that occur when materials are exposed to the environment.

Artificial aging tests of materials were carried out in laboratory under more controlled conditions than in the natural processes of aging. These tests were designed to accelerate the degradation of the polymer and the material failures.

For this, 5 samples were subjected to cyclical periods of UV exposure, followed by periods without radiation. During these cycles, changes in temperature and humidity were carried out according to the standard UNE 4892. This standard is the one governing the artificial aging tests and it was used as a guide in the investigation developed.

The artificial aging cycle applied consists in two hours of UV exposure at a temperature of 30ºC and a relative humidity of 62%, followed by one hour of condensation without radiation at a temperature of 40°C and a relative humidity of 90%. The duration of artificial aging process developed had been 78 hours, which corresponds to 26 cycles.

The equipment used in carrying out the artificial aging process is a climatic chamber Ineltec CC-150, which is located in the premises of the Department of Science and Technology of Materials and Fluids of the University of Zaragoza. The climatic chamber capacity is 125l and the maximum and minimum working temperatures of the machine are 150ºC and 10°C respectively.

Figure 1 shows the inside of the climatic chamber with the samples subjected to artificial aging. Figure 2 shows the position of the samples in the climatic chamber, which were positioned in the irradiation zone of the lamp. This lamp is represented in the figure 2 by an X.

2.3 Tensile test of mechanized samples

Once the samples of isotactic polypropylene copolymer were subjected to the artificial aging process, the next phase in the development process was to obtain and compare the mechanical properties of the aged material and the mechanical properties of the original material.

Fig. 1. Inside the climate chamber with 5 samples

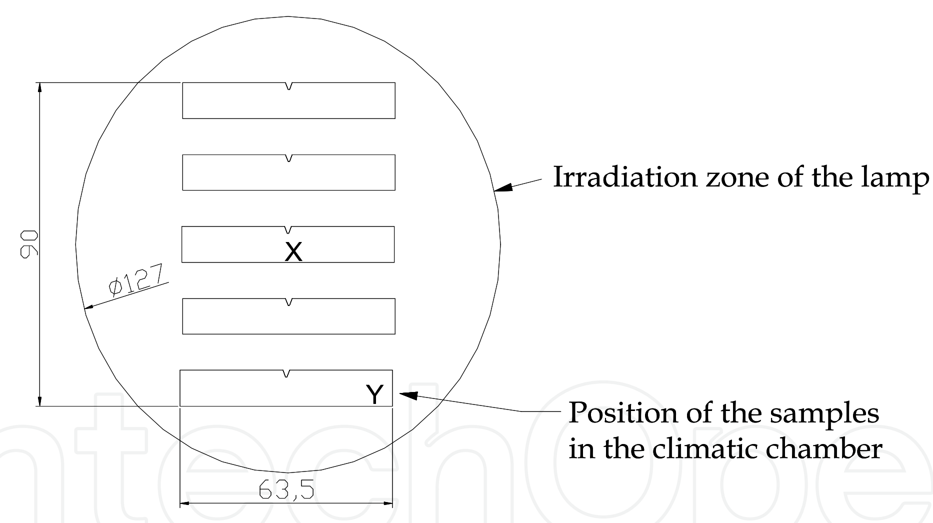

Fig. 2. Position of the samples in the climate chamber

The tensile test is the testing to obtain information of the mechanical properties of materials. The aim of this test is to obtain the elastic modulus, stress-strain curve, yield strength, tensile strength and elongation of a material.

In order to obtain these values, 5 samples with artificial aging (A1-5) and 5 samples without aging process (N1-5) had been tested according to the standard UNE-EN ISO 527 - 1996.

Tensile tests were carried out in an Instron 8032 testing machine at the Department of Mechanical Engineering at the University of Zaragoza. This testing machine has a load capacity of 100kN.

2.4 Numerical analysis by means of the Finite Elements Method (FEM)

The last phase of the study was to obtain the variation of the mechanical behaviour of the material subjected to artificial aging with respect to the original polypropylene in an impact.

The impact analysis in polymers has a number of difficulties (Kalthoff, 1993; Richardson & Wisheart, 1996; Moyre et al, 2000; Read et al, 2001; Tarim et al, 2001; Dean & Wright; 2003; Trudel-Boucher et al, 2003; Jimenez et al, 2004; Aretxabaleta et al, 2004; Aretxabaleta et al, 2004; Aretxabaleta et al, 2005; Davies et al, 2005; Alcock, 2006; Martinez et al, 2008; Aurrekoetxea et al, 2011), which complicate the analysis of such situations. The causes of this complexity have been summarized in the following points:

- The dynamic nature of the problem, including the phenomena of wave propagation Justify, single space (Aita et al, 1992; Bigi,1998)
- The three-dimensionality of the problem, often asymmetric and two-dimensional simplifications being insufficient (Wierzbicki, 1989)
- The behaviour of materials at extreme loads caused by an impacts is almost always non-linear (Krieg & Key, 1976)
- The simulation of material behaviour must be representative of the entire range of strains rates that develop in the impact (Hull, 1985)

The numerical analysis by means of the FEM is a tool to provide solutions to the problems described. This numerical technique has been used and validated in previous studies (Martin et al, 2007). In these previous studies, reliable results were obtained in polypropylene impact.

2.4.1 Application of the FEM

The test to reproduce numerically, by means of the FEM, is the freefall impact of a steel semisphere of diameter 25mm against a square sheet of side 110mm and a thickness of 3mm of polypropylene. This model was validated in previous studies to analyze impact polypropylene sheets. The sheet has been discretized with shell elements of 4 nodes (S4R) and the semi-sphere has been discretized with volumetric elements of 6 or 8 nodes (C3D6 o C3D8R). Figure 3 shows the sheet in green and the semisphere in red. The model consists of 5352 elements and 5568 nodes.

The mechanical properties used in the definition of polypropylene were the averages of the results obtained in tensile tests carried out on the samples subjected to artificial aging and the initial polypropylene samples. The material of the semi-sphere was defined as a linear steel with a Young modulus E = 210GPa, density γ = 7850 kg/m^3 and Poison ratio υ = 0.3.

The methodology applied in the virtual test development has been based on the application of numerical techniques by means of the Finite Element Method (FEM) with the explicit integration of a dynamic equilibrium equation.

Changes in Kinetic energy and strain energy, as well as the displacements in the sheet, are obtained from the simulations for the material with and without artificial aging.

These results provide important information in the optimization process of the developed protection system, because they indicate how the material behaviour changes with the environment, and how it affects the functionality of the energy absorption system developed.

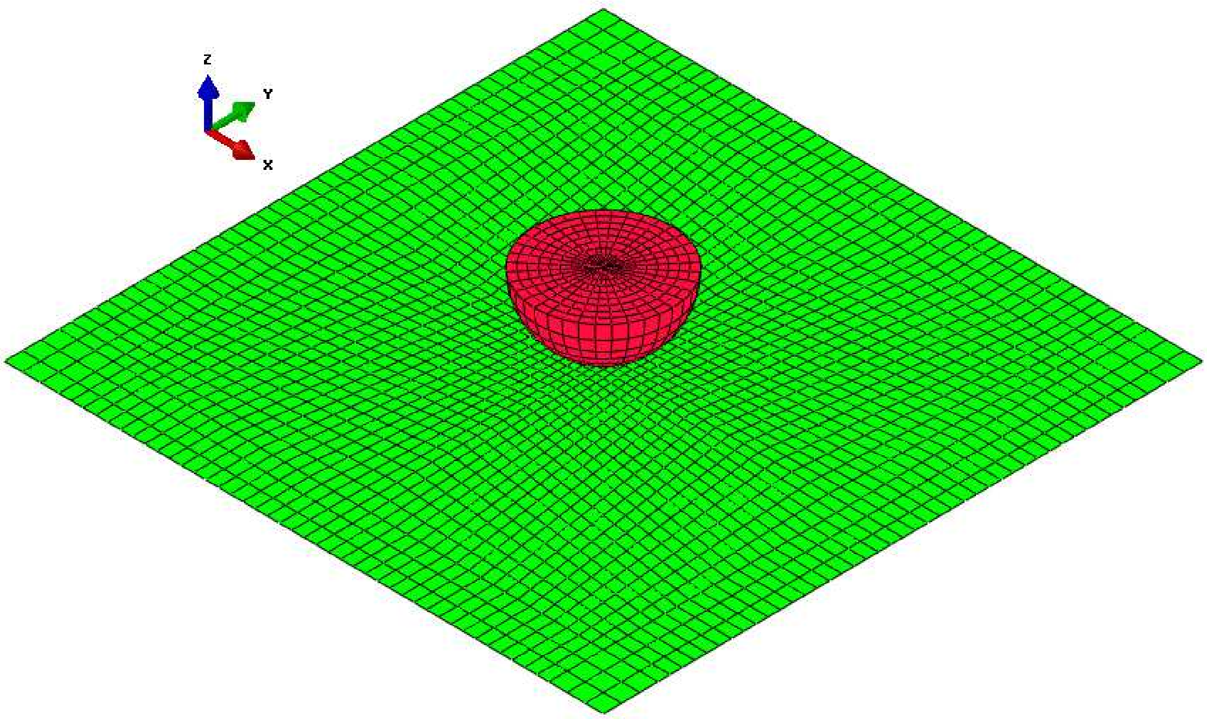

Fig. 3. Finite elements model

2.4.2 Load cases and boundary conditions

The load cases analyzed corresponds to the freefall impact of a steel semi -sphere of 25 mm diameter against a polypropylene sheet of a thickness of 3mm.

In order to obtain greater reliability in the results, three load cases have been analyzed. The difference in load cases is the difference of the height at which the semi-sphere drops.

In order to reduce the computational cost (computation time) of the simulations, the simulation was not carried out on the total trajectory of the semi sphere. Instead, the speed of the semi sphere in the instant previous to the impact was calculated. With this speed and in that position of the semi sphere, the numerical simulation test was initiated. This technique allows for saving the computation time in which the semi-sphere covers the distance from the initial height of the test to the instant previous to the impact with the sheet.

The speed at the instant previous to the impact was obtained by an energy balance, in which at the initial instant of the test, the kinetic energy of the semi sphere is zero (v_1 = 0) and at the instant previous to the impact, the potential energy of the semi sphere is zero (h_2 = 0). Therefore the potential energy of the sphere at the initial instant of the test is transformed into kinetic energy of the semi sphere in the instant previous to the impact. The following equations show the process developed in order to obtain the speed of the semi sphere at the instant previous to the impact against to the polypropylene sheet.

$$EC_1 + EP_1 = EC_2 + EP_2 \quad (1)$$

$$\frac{1}{2} * m_1 * v_1^2 + m_1 * g * h_1 = \frac{1}{2} * m_2 * v_2^2 + m_2 * g * h_2 \quad (2)$$

$$\frac{1}{2} * m_1 * 0 + m_1 * g * h_1 = \frac{1}{2} * m_2 * v_2^2 + m_2 * g * 0 \quad (3)$$

$$m_1 * g * h_1 = \frac{1}{2} * m_2 * v_2^2 \quad (4)$$

$$v_2 = \sqrt{2 * g * h_1} \quad (5)$$

Figure 4 shows a diagram of the starting position and the instant previous to the impact

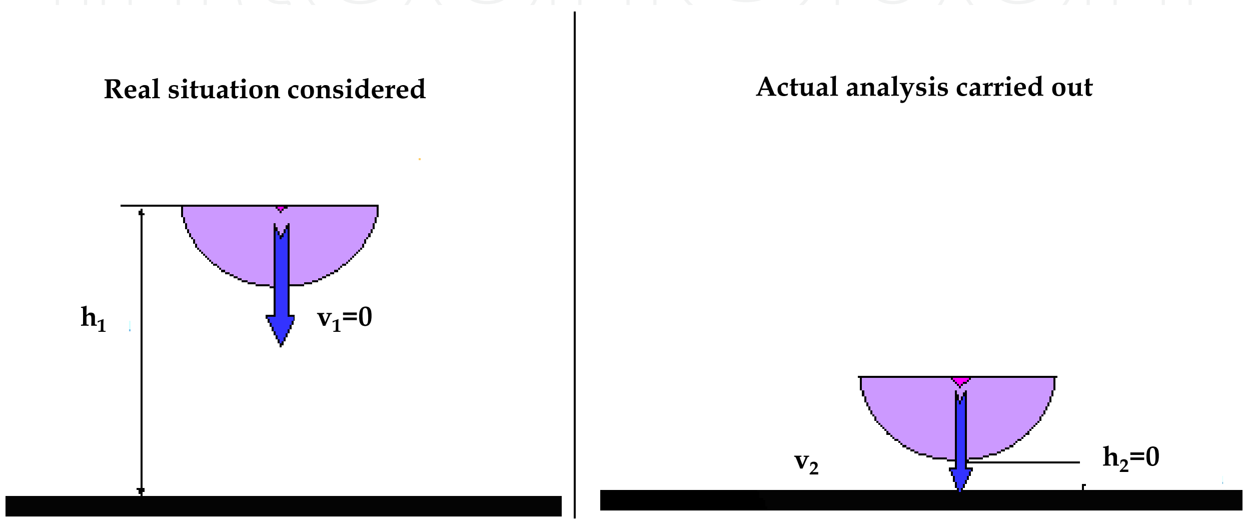

Fig. 4. Diagram of the starting position and the instant previous to the impact

The load cases analyzed are shown in Table 1. The table shows the initial height in the test and the velocity of the semi sphere at the previous instant of the impact.

Load case	Initial height (mm)	Impact velocity (m/s)
1	1,575	5.56
2	790	3.94
3	527	3.21

Table 1. Initial height and impact velocity of the load cases

The imposed boundary conditions reproduce those of a freefall impact test, in which the contour of the sheet is fastened. In virtual testing, rotations and displacements were constrained in nodes located less than 10mm from the edge of the sheet, which are shown in red in Figure 5.

3. Results

Tensile tests carried out on samples of original polypropylene and polypropylene subjected to artificial aging had provided force-displacement curves of the materials, which are shown in figures 6 and 7.

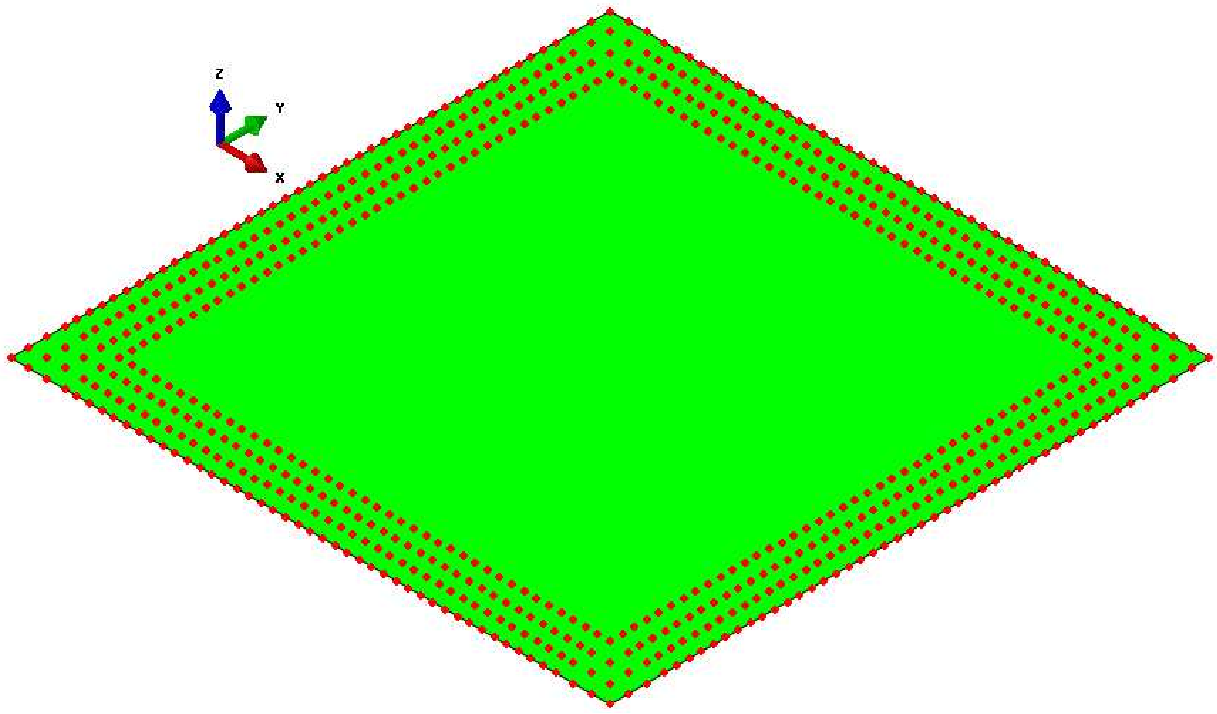

Fig. 5. Nodes with displacements and rotation constrained by the boundary conditions

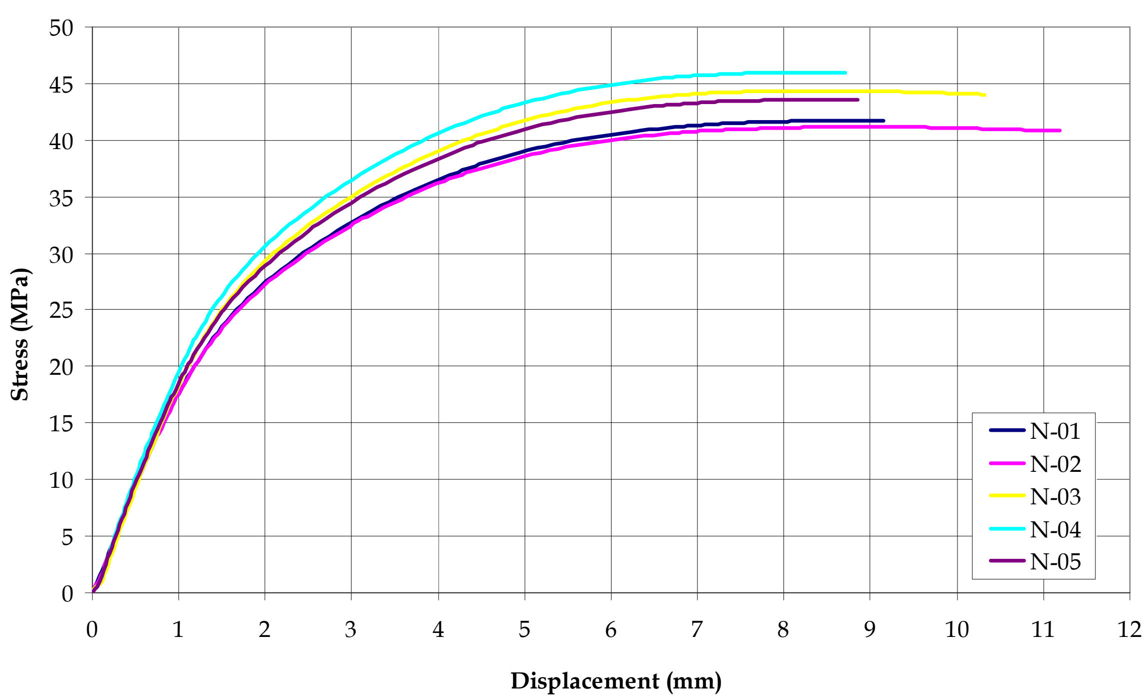

Fig. 6. Stress-displacements curves of the original polypropylene samples

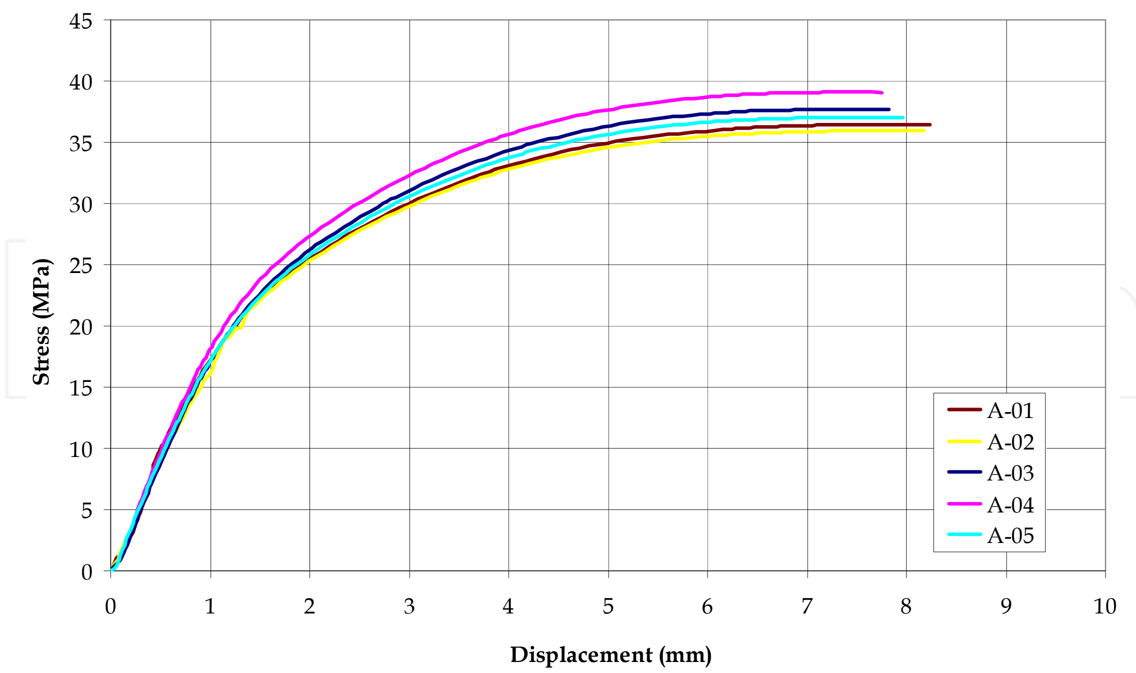

Fig. 7. Stress-displacements curves of the polypropylene subjected to artificial aging samples

The results of tensile tests recorded allow for obtaining the mechanical properties of the materials studied. The Young's modulus of both materials was calculated from σ_1 (stress at a strain of 0.0005) and σ_2 (stress at a strain of 0.0025) according to the standard UNE-EN ISO 527-1. Tables 2 and 3 shown the Young's modulus and the tensile strength obtained of the tensile tests. The other mechanical properties used were density γ = 7850 kg/m^3 and Poison ratio υ = 0.3.

Non-aged samples	E_t [MPa]	R_m [MPa]
N1	671,160	41,732
N2	718,130	41,177
N3	841,690	44,369
N4	744,030	46,011
N5	746,610	43,563
Mean	744,324	43,370
Standard deviation	55,72	1,77

Table 2. Mechanical properties of non-aged polypropylene

Aged samples	E_t [MPa]	R_m [MPa]
A1	717,650	38,338
A2	724,760	36,001
A3	652,320	36,472
A4	688,720	37,025
A5	805,950	37,714
Mean	717,880	37,110
Standard deviation	50,89	0,839

Table 3. Mechanical properties of aged polypropylene

Once the virtual tests through the MEF had been run, the analysis of the mechanical behaviour variation of the polypropylene subjected to artificial aging with respect to the original material began. First, the maximum vertical displacements in the sheet were compared for each of the three load cases analyzed. In all cases the maximum vertical displacement and permanent deformation were higher in samples subjected to artificial aging. The difference of vertical displacement and permanent deformation between sheets of material subjected to artificial aging and sheets of original material was greater on increasing initial height of the test. These results are shown in figure 8.

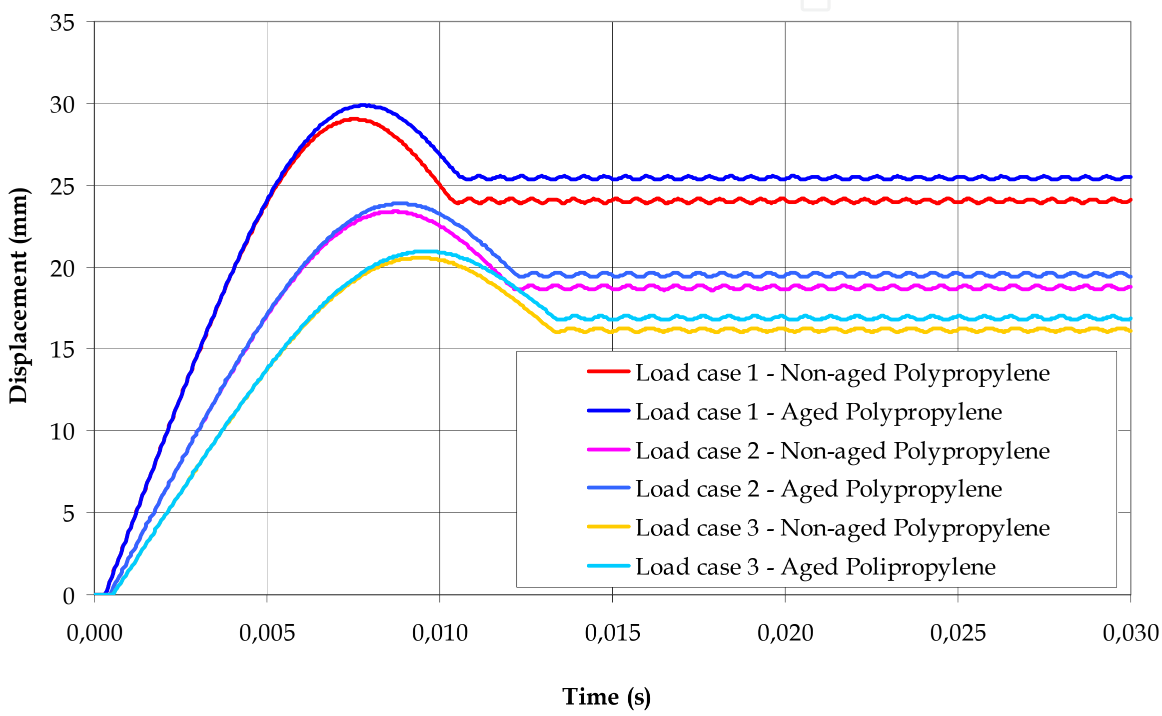

Fig. 8. Maximum vertical displacement on the sheet

The second parameter analyzed is the kinetic energy of the semi sphere, figure 9. The results obtained show that the kinetic energy of the semi sphere after the impact against the sheets of polypropylene subjected to artificial aging is lower than in the impact against the original material sheets for the three load cases analyzed. This greater reduction of the kinetic energy implies a lower speed of the semi sphere in the simulations with polypropylene subjected to artificial aging with respect to the simulation with original material.

The third parameter analyzed is the strain energy, figure 10. This parameter represents the energy used in the deformation of the Polypropylene sheet on the impact. The results obtained show that the energy used in the deformation of the polypropylene sheet subjected to artificial aging is higher than in the original material for the three load cases analyzed.

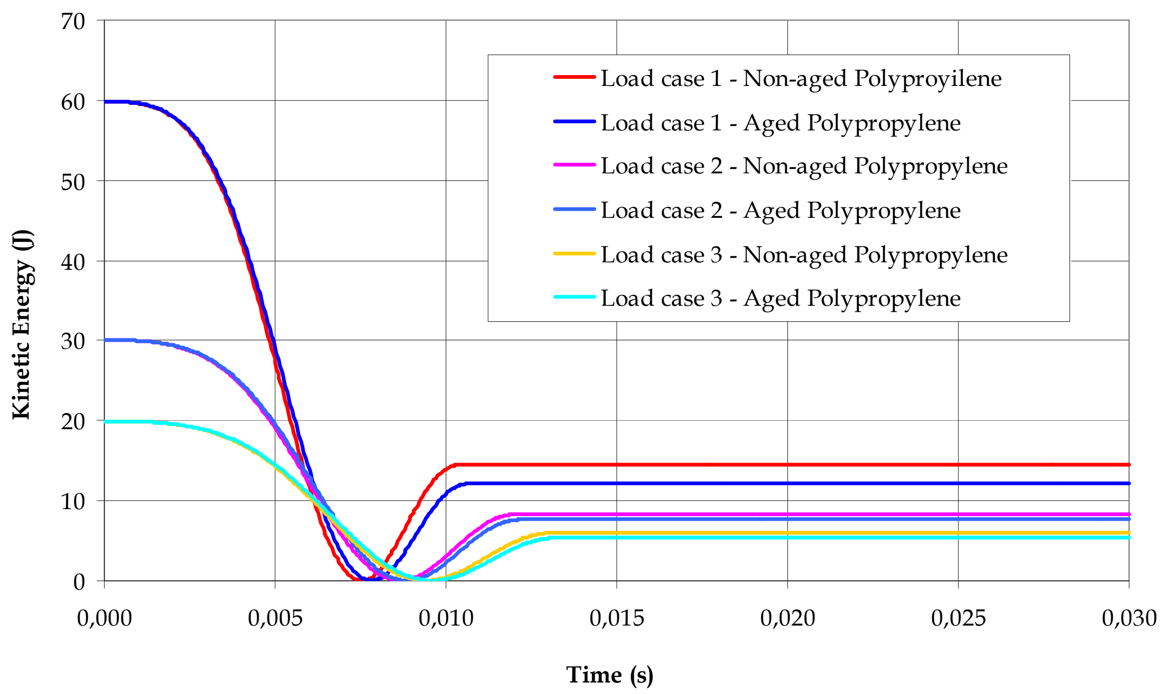

Fig. 9. Kinetic energy of the semi-sphere

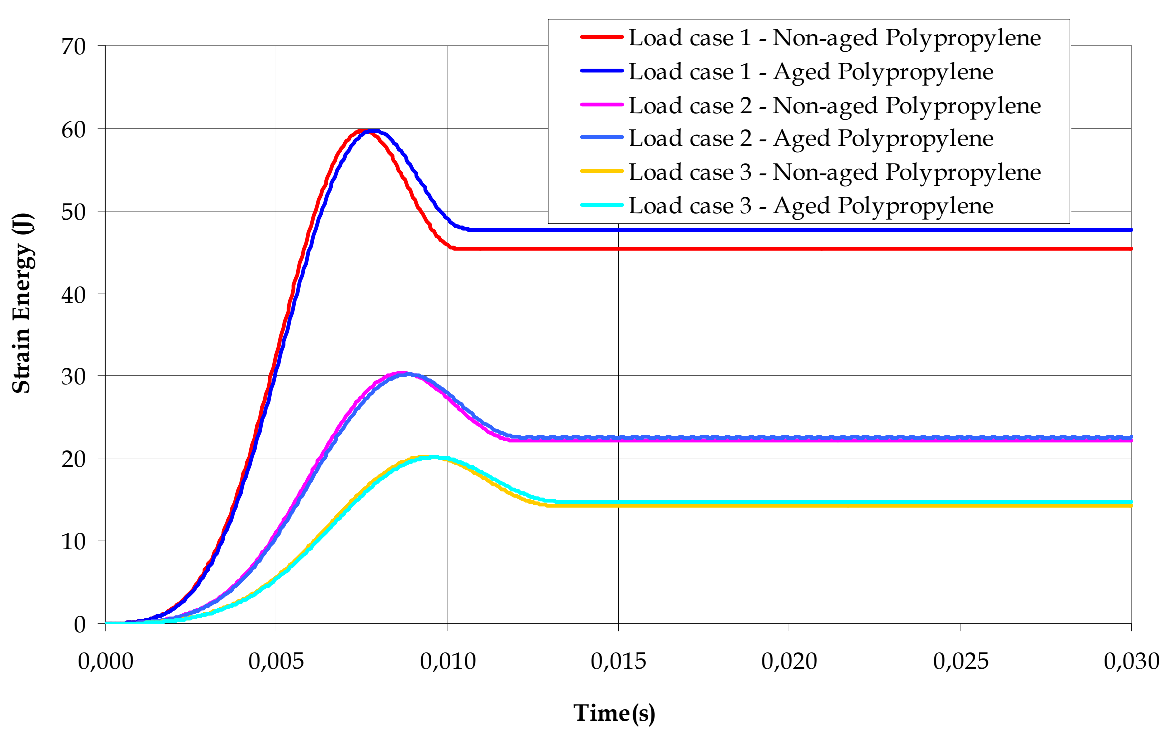

Fig. 10. Strain energy in the sheet

Table 4 summarizes the results of maximum displacements and strain energy in the sheet and the kinetic energy of the semi sphere obtained of the virtual simulations by means of the MEF.

Load case		Non-aged Polypropylene	Aged Polypropylene
1	Initial Kinetic Energy (J)	59,85	59,85
	Final Kinetic Energy(J)	14,44	12,12
	Reduction of Kinetic energy (%)	75,87	79,75
	Reduction of Kinetic energy (J)	45,41	47,73
	Final Strain Energy (J)	45,34	47,72
2	Initial Kinetic Energy (J)	30,05	30,05
	Final Kinetic Energy(J)	8,32	7,63
	Reduction of Kinetic energy (%)	72,31	74,61
	Reduction of Kinetic energy (J)	21,73	22,42
	Final Strain Energy (J)	21,21	22,35
3	Initial Kinetic Energy (J)	19,95	19,95
	Final Kinetic Energy(J)	6,02	5,39
	Reduction of Kinetic energy (%)	69,82	72,98
	Reduction of Kinetic energy (J)	13,93	14,56
	Final Strain Energy (J)	13,86	14,25

Table 4. Results obtained of the virtual simulations by means of the FEM

4. Conclusions

The research process developed allows for obtaining the mechanical properties variation of isotactic polypropylene copolymer subjected to artificial aging.

For this, 10 samples were machined from a sheet of polypropylene copolymer. Five samples were subjected to artificial aging in a climatic chamber.

Subsequently, 10 samples (5 of material subjected to artificial aging and 5 samples of original polypropylene) were subjected to tensile tests in order to obtain the mechanical properties of the original polypropylene and the material subjected to artificial aging.

After obtaining the mechanical properties, numerical analysis by Means of the Finite Element Method (FEM) with explicit integration of dynamic equilibrium equation was carried out. These numerical techniques allow for obtaining reliable results of impacts against polypropylene sheets. Virtual simulations allow for obtaining the maximum displacements in the sheets, the kinetic energy reduction of the semisphere and the energy absorbed by the sheet in the load cases analyzed.

The results show a mechanical behaviour similar to the material subjected to artificial aging with respect to original polypropylene in all the load cases analyzed. Moreover, in all the load cases analyzed the sheets of the material subjected to artificial aging reduce the kinetic energy by a greater amount with respect to the sheets of the original polypropylene. Thus, artificial aging improves the behaviour of the material for use in energy absorption systems.

The minimal variations obtained of the mechanical properties of polypropylene subjected to artificial aging with respect to the original material show that the polypropylene is a suitable material for the design of systems to protect motorists and cyclists. These protection systems are continually exposed to environmental effects, and therefore a continuous aging process.

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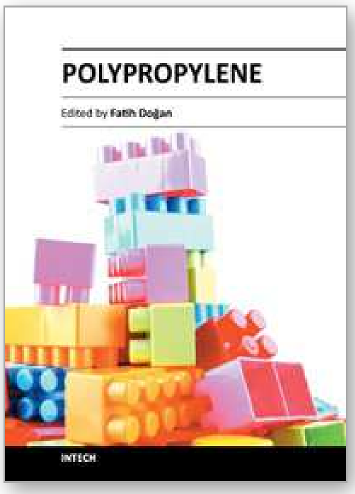

Polypropylene
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This book aims to bring together researchers and their papers on polypropylene, and to describe and illustrate the developmental stages polypropylene has gone through over the last 70 years. Besides, one can find papers not only on every application and practice of polypropylene but also on the latest polypropylene technologies. It is also intended in this compilation to present information on polypropylene in a medium readily accessible for any reader.

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