IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

EVALUATION OF INTEGRITY AND DURABILITY OF PLASTIC MATERIALS FROM THE AUTOMOTIVE INDUSTRY

PhD Thesis – Summary

for obtaining the scientific title of Doctor at
Polytechnic University of Timișoara
in the doctoral field of *Mechanical Engineering*
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The doctoral thesis has the objective to study the influence of reinforcement by glass fibers of polycarbonates, concerning their static and dynamic mechanical properties.

The investigations defined within the doctoral research start from the current status in the characterization of polymeric materials and propose to complete the already existing, but few studies, respectively to lay down the basis for areas linked to the mechanics and strength of materials where the availability of data is very limited.

For reaching the above-mentioned scope, on one hand an extended experimental program has been proposed, and on the other hand the development of specific material models for the numerical evaluation of the behavior of polycarbonates in different mechanical loading conditions.

With the help of the obtained results in the experimental investigations, performed on dedicated test machines, by respecting a series of international standards, and by the development of validated material models with the scope of evaluating the integrity of components made from polymeric materials, the PhD thesis presents a high potential in the domain of mechanical design from the automotive industry.

The thesis is structured in six chapters, out of which five presents specific contents, by describing the experimental measurements and numerical studies, and one chapter focusing on the conclusions and personal contributions of the author.

Chapter 1, entitled „**Polymeric materials used in the automotive industry**”, presents, in general, polymeric materials, their development and characteristics, the injection molding process, respectively general aspects about polycarbonate and about the selected Makrolon grades for the proposed investigations.

In the automotive industry polymeric materials have undergone a very high rate of assimilation. The evolution of the usage of plastic materials, in terms of volume, in this industry went through an increase from 2%, in the year 1962, to approximately 50% nowadays. The percentage of plastic materials from the medium total weight of a vehicle reaching therefore approximately 10-13%.

The major benefits brought by the usage of plastic materials in the automotive industry include the reduction of weight of specific sub-assemblies, the improvement of safety conditions, the reduction of manufacturing costs, respectively, as another important benefit, the improvement of the visual aspect of the components, which by conventional manufacturing methods and using metallic materials, would have been almost impossible to obtain, thus offering more freedom for the creativity of design engineers.

Figure 1 presents some examples of components from an automobile manufactured from plastic materials.

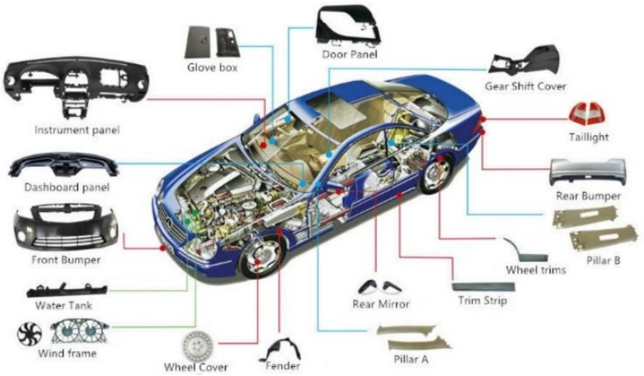

Fig. 1. Examples of plastic components from an automobile.

The mechanical behavior of the chosen material for the specific application is, however, influenced also by the manufacturing process of the final part, besides the type or combination of materials selected.

The most common fabrication method in the case of plastic materials is the injection molding process, which, however, comes with a series of parameters that should be known and controlled to ensure the required quality of the components manufactured. The way the melted materials flow, or the thermal transfer effects can have a major influence on the homogeneity of the material or over the fibre orientation, if the process is not controlled in a suitable way.

The optimal injection parameters can be determined by specific numerical fluid flow analyses of the melted material inside the mold, however, the mitigation of risks in case of an injected part can be achieved also by following a set of design rules, specific for the needed materials and geometrical shapes. All these actions, cumulatively, can minimize the appearance of some defects, which on their side, can be only visual ones, concerning the aspect of the parts (e.g., sink marks), but can also be defects which will influence the strength of the material (e.g., weld lines, residual stresses).

Polycarbonates are known as naturally transparent thermoplastic materials, characterized by high stiffness, relatively good thermal resistance, or low viscosity during material processing.

This represents one of the most frequently used thermoplastic materials from the different engineering domains, due to the advantages which this can offer, such as: excellent impact strength, dimensional stability, thermal stability, light weight, electrical isolation etc. [1].

Like other thermoplastics from its category, polycarbonate also comes with a series of disadvantages. Some of the most important minuses of this material include poor resistance to chemicals, scratch sensitivity [2], [3] or UV sensibility.

Although the disadvantages, polycarbonate has become the material of choice in a wide range of commercial and engineering applications, for security and protection products, such as riot shields, windshields [4], [5] or covers and housings in household and consumer electronic devices.

The state-of-the-art injection molding technologies have led to superior surface qualities for the polycarbonate applications, permitting them to emerge at a high scale in the automotive industry, in a wide variety of products, mainly in the interior applications, out of which one can mention instrument clusters, Head-Up Displays, navigation devices etc.

The material grades considered in the doctoral thesis are three types of polycarbonates from the Makrolon product family, belonging to Covestro AG. Makrolon grades obtained by glass fibre reinforcement possess special characteristics like flame resistance, increased impact strength, high stiffness, or dimensional stability.

The materials for the investigations have been selected based on their utilization in the different interior applications and are the following: Makrolon 2405 – unreinforced polycarbonate, Makrolon 9415 – polycarbonate reinforced with 10% of glass fibers, respectively Makrolon 8035 – polycarbonate with 30% of fiber volume ratio.

Chapter 2, entitled „**Current status of research concerning polycarbonate and its derived composites**”, as the name suggests, treats the actual status of the research with respect to polycarbonate and its derived composites, focusing both on experimental studies and on numerical investigations from the specialized literature.

Reinforced polycarbonate found its applicability in a wide variety of industries, with the scope of replacing metallic materials for various reasons.

Many authors have studied the behavior of polycarbonate, in the context of multiple fields of use, such as mechanical applications (e.g., housings for different products), optical applications (e.g., automobile headlights), applications which require a higher strength and durability of the chosen polycarbonate as base material.

Color stability, low scratch resistance, respectively the negative effects of long-term exposure to UV rays or of the weather conditions, have represented the subject of research for many scientists [6].

Regarding the subject of the doctoral thesis, the most important studies conducted, and which represented the starting point of the experimental and numerical investigations, are related to the static and dynamic behavior and to the fracture mechanisms of polycarbonate or of its reinforced derivatives.

The rate and temperature dependency on the stress – strain response of the unreinforced polycarbonate has been investigated experimentally over a wide range of strain rates and temperatures, by a high number of authors [7], [8], [9], [10]. Numerous authors from the domain have also carefully studied, the impact behavior of polycarbonates and of polycarbonate composites [11], [4], [12], [13], [14], [15], [5].

From the perspective of numerical analysis using the finite element method, the most common mathematical models based on uniaxial experimental investigations are elastoplastic constitutive and three-dimensional models, proposed by many authors, such as Cao et al. [16], Mulliken et al. [17], Richeton et al. [18] or Yu et al. [19], in order to replicate the behavior of the material before and after yield, as function of strain rate and temperature, when this is subjected to tensile loadings.

On the other hand, for the numerical study of the dynamic impact loadings, numerous scientific articles describe material models, like the MAT_024 or MAT_081, plasticity models, belonging to the finite element solver ANSYS LS-DYNA, coupled with different damage parameters, such as the admissible strain or parameters derived from the triaxiality curves [14], [13].

A very small number of studies consulted from the specialized literature have been focusing, however, on a more thorough comparison between the static and dynamic behavior of the unreinforced polycarbonate compared to one or more derived reinforced grades, with different fiber volume ratios. Even less studies have proposed the impact investigations of notched probes from the reinforced or unreinforced polycarbonate grades. Similarly, the same can be said about the fatigue of polycarbonates, for which only very limited information is available in the literature.

Chapter 3, entitled „**Quasistatic characterization of polycarbonate materials**”, has the objective of describing the quasistatic measurements performed for the determination of the influence of a set of parameters on the quasistatic response of the three Makrolon grades subjected to the investigations.

The scope of the investigations has been the evaluation of the influence of strain rate and temperature – both the effects of the constant heating and of the aging of the material – on the mechanical properties of the three Makrolon grades subjected to tensile testing, respectively the evaluation of the static fracture toughness of the selected materials.

During the tensile tests one could observe that the strain rate has a small influence on the elastic modulus, the linear portion of the characteristic curves being almost identical for all the tested strain rates. Similar results have been presented in the specialized literature for other types of polymers [20]. The biggest influence on the increase of the elastic modulus comes from the increase of the fiber content.
Another observation concerns the increasing tensile strength for all the materials, due to the increase of the strain rate (Fig. 2).

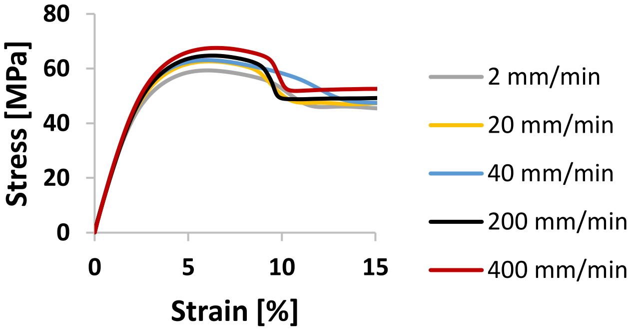

Fig. 2. Characteristic engineering curves at different strain rates for Makrolon 2405.

For the tensile measurements, based on the initial constant heating of the probes, a common observation for all the studied material grades is the dependence of the tensile strength on the variation of the temperature.
For all the investigated materials a decrease of the tensile strength could be observed with the increasing temperature from 22°C to 80°C, by 43.61% for Makrolon 2405 (Fig. 3.a), 51.45% in the case of Makrolon 9415 and 36.20% for Makrolon 8035.

Like the tensile strength, the elastic modulus is influenced by the temperature as well. This undergoes a decrease of up to 13% for Makrolon 2405 and for Makrolon 9415, respectively a smaller decrease of 7.5% for Makrolon 8035.

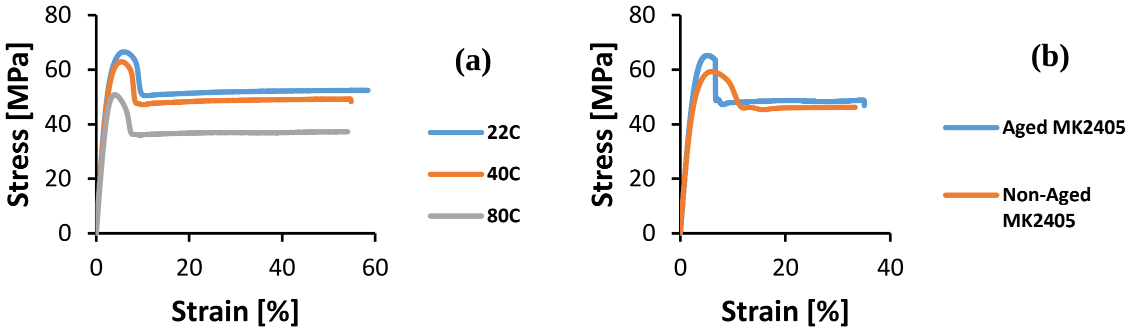

Fig. 3. Stress – strain curves for Makrolon 2405: (a) as function of temperature and (b) aged and non-aged probes

With respect to the Poisson's ratio, one could observe that all three materials have shown stability despite the increase of the temperature. There is a variation of approximately 3% for all the grades, however, there is no clear indication of the negative influence of the temperature.

The curves belonging to the aged samples respect the same tendency as of the ones belonging to the non-aged probes, however, a high degree of similarity could be observed only up to the yield limit. Beyond this point the aged samples show a sudden drop (Fig. 3.b), concerning the stresses, opposed to the non-aged materials where the softening of the materials happens much slower.

Although the behavior shown by the aged specimens is different from the one observed by Sonja et al. [21], the sudden drop of the stresses, in comparison to the non-aged probes, is expected to be due to the physical and chemical aging of the materials at microscale level, resulting in bond breakages which make room for degradations.

From the presented values a small increase (1.2%) could be observed for the elastic modulus and for the tensile strength (10%) in favor of the aged specimens, but only in case of the unreinforced grade.

For the glass fiber reinforced materials, the tendency gets modified, making the non-aged materials much more stable in case of loadings with magnitudes appropriate to the tensile strength.

It can be stated that the effect of aging on the Poisson's ratio is minimal, the values remaining almost constant.

As a conclusion, in case of the tensile tests, the current investigations highlight the fact that the stiffness of the material is barely affected by the strain rate. Nevertheless, when the tensile strength is the decisive factor, its variation with the strain rate and with the temperature conditions must be considered during the design phase of the mechanical components.

In case of the fracture toughness, for all the materials, a very good repeatability of the measured values could be observed, without a significant dispersion of the results determined in terms of force – displacement.

From the microscope analysis of the rupture zones important conclusions could be drawn: the unreinforced or base material has shown a fragile behavior at breakage, however, opposed to this observation, the two, glass fiber reinforced grades did not suffer o complete breakage by the end of the tests. The specimens subjected to the bending loads have plastically deformed, but the crack generated by the mechanical processing has not propagated throughout the entire cross section of the specimen.

The values of the fracture toughness are increasing with the increase of the glass fiber volume ratio, however, a flattening of the values could be identified, after which these would start to decrease if the percentage of the glass fibers exceeds a specific threshold.

Chapter 4, entitled "**Dynamic characterization of polycarbonate materials**", focuses, in the first part, on the dynamic, Charpy impact measurements, both for the notched and unnotched specimens. The second part of the chapter presents the fatigue tests performed for the three polycarbonate grades, the test setup used and the construction of the Wöhler curves, with the scope of using the curves in the durability evaluation of the mechanical parts used in the automotive industry.

Over the lifecycle of many products these can be exposed to specific external loads, such as shocks, collisions or drops, which might require rapid energy absorption. One of the most difficult tasks is to ensure the mechanical properties, mainly the maximum impact strength, considering that these parameters are very dependent on the geometrical effects.

Figure 4 presents the microscopic images of the cross sections for the broken, notched specimens, for all three tested materials. In the case of Makrolon 2405 and Makrolon 9415 one can clearly differentiate the ductile zones, with local deformations before the breakage of the material, proportional to the glass fibre volume fraction. For Makrolon 8035 the cross section is characterized to the greatest extent by fragile rupture.

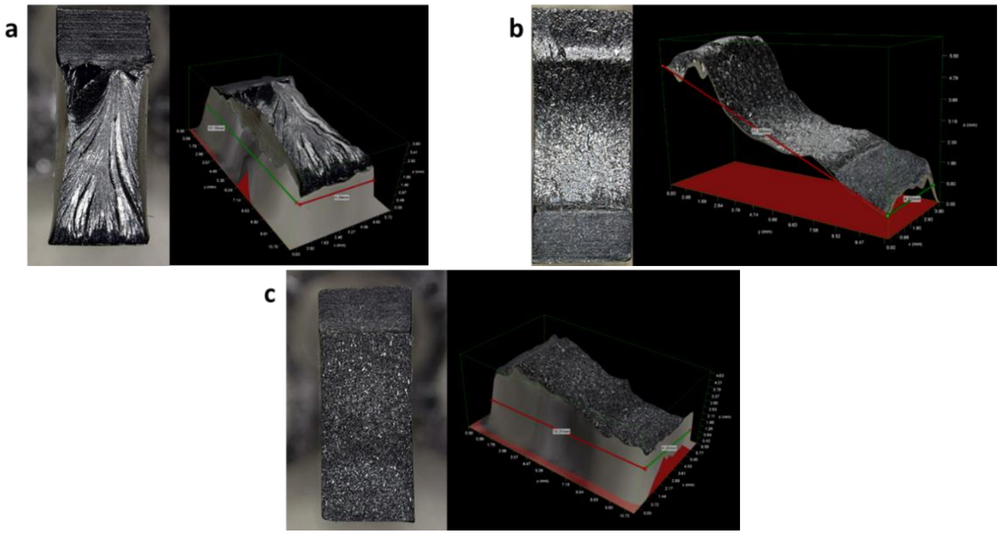

Fig. 4. Broken probes after the dynamic Charpy impact tests, using a 5 [J] hammer: (a) Makrolon 2405; (b) Makrolon 9415; (c) Makrolon 8035.

The unnotched specimens, due to the material's plasticity which precedes rupture, have absorbed much higher energy levels during the impact tests.

Beyond the differences between the notched and unnotched specimens, a significantly higher delta has been observed between the impact energy absorbing capacity of the unreinforced polycarbonate and of the reinforced grades. The energy absorbed by the unreinforced material is by an order of magnitude higher than the energies absorbed by the glass fiber reinforced grades.

Based on the recorded data the values of the Charpy impact strength have also been calculated (Fig. 5).

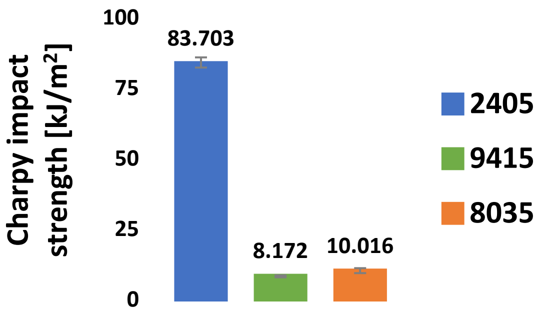

Fig. 5. Charpy impact strength values of the three polycarbonate grades.

Although in the specialized literature there are not too many studies focusing on the impact behavior of notched polycarbonates, Allen et al. [11] mentions almost identical Charpy impact strength values for the unreinforced material as the ones obtained during the dynamic investigations.

The increase of the Charpy impact strength values in an inverse proportional manner with the increase of the fiber volume fraction has been remarked for both types of probes subjected to the impact loadings.

Based on this remark and on the previous observation, one could draw the conclusion that in case of applications that during their lifetime must withstand severe impact or shock loadings, the usage of a material with a reduced fiber volume fraction or even the usage of an unreinforced material is recommended to ensure the optimal strength and toughness conditions.

In the case of the fatigue tests for the proposed material grades, the study has been focusing on the high cycle fatigue domain, representative for the automobile parts which, during their lifecycle, will be subjected to a series of repetitive and variable cycles.

This study has been proposed in the context in which numerous investigations were made for determining the behavior and fatigue strength of metallic components, however, only a small number of studies have focused on the fatigue characteristics of thermoplastic materials, although these are found in a high number of applications, from different industries.

By conducting the measurements consistent results, with a very low scatter, have been obtained, which were processed afterwards and represented in the form of a Wöhler curve.

Figure 6 presents the fatigue curve for the 30% reinforced material, together with the equation of the line obtained by the linear regression of the points measured, respectively together with the values of the coefficient of determination R^2.

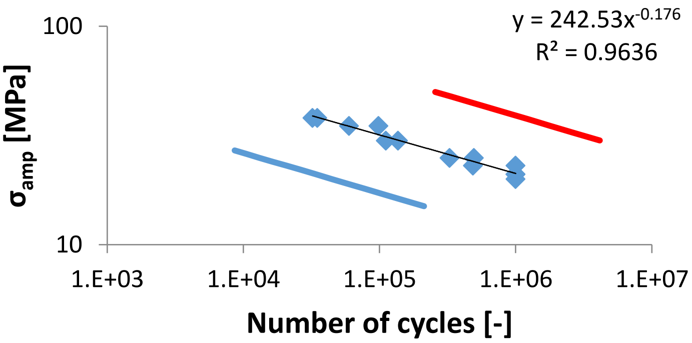

Fig. 6. Fatigue curve and equation of the line obtained by linear regression for Makrolon 8035.

The performed fatigue tests represented the starting point for the durability study of the three Makrolon grades, taking into account that by an extensive study of the state-of-the-art information and know-how, a method or CFL diagram, which would predict with a higher accuracy the durability of the thermoplastic materials, accounting for multiple external factors, such as temperature, humidity, or various fatigue stress ratios (R), is only treated in particular cases, therefore represents one direction which could offer multiple possibilities both for the academic and industrial worlds.

Chapter 5, entitled “**Material models for finite element analyses**”, relates the development of specific material models to be used in finite element analyses, based on the data obtained in the static and dynamic tests.

The principle which represents the base for the modelling of materials, with the scope of using these models in different numerical analyses, is that the material model must be selected as function of the objective of the investigation. This must be chosen as a function of the type of component to be analyzed, where one can differentiate components as polymeric, elastomeric, or metallic, respectively as function of the type of loading and of the deformations produced by that specific loading type. Based on this, three major mechanical loading categories can be defined: quasistatic loadings, dynamic vibration loadings and dynamic impact loadings.

Either mechanical loading category is characterized by different particularities. For the dynamic loading category, the utilization of linear, elastic material models is specific, imposed mainly by the nature of vibration analyses, but also by the permitted deformations, which represent a very small percentage. The loading categories characterized by non-linearities, and thus by more complex material models, are the quasistatic loading category and the dynamic impact loading category.

For the investigations the quasistatic loading category has been divided into two parts: the first part having the objective of finding a model which is capable to replicate the elastic-plastic behavior of materials, until the onset of the necking phenomenon, respectively the second part, having the scope of finding a viscoplastic model, which describes the response of materials after the onset of necking, but, in the same time, which is also capable to account for the variation of strain rate or for the cyclic loadings.

A multilinear isotropic hardening model has been selected for the first part of the quasistatic loadings. After the numerical analyses one could observe a perfect description of the elastic-plastic behavior of all three polycarbonate grades for the tensile loading condition. Therefore, it can be concluded that when the response of the material until reaching the tensile strength or until the onset of necking is of interest, the multilinear isotropic hardening model represents the ideal choice.

For the second part of the quasistatic loadings, valid, however, simultaneously, also for the dynamic impact loadings, the ANSYS Three Network Model (ANSYS TNM), developed by [22] has been selected. This is characteristic for the non-linear, viscoplastic models, specially calibrated for thermoplastic materials, and is characterized by its capacity to consider the rate dependency and temperature dependency of the material. The usage of such a model is necessary for describing the behavior of the material beyond the tensile strength when the material undergoes a significant necking.

For validating the obtained material model by the MCalibration software, a numerical analysis has been set up in ANSYS Mechanical. By using the TNM model the necking phenomenon could be replicated in the calibrated region of the specimen. In addition, the material model has captured, with a high accuracy, also the area in which the breakage of the material might occur, after a significant extension of the necking.

For the numerical modelling of the dynamic Charpy impact loadings, the analyses have been performed with an explicit setup in ANSYS LS-DYNA.

Within the numerical study, for the unnotched specimens, like for the quasistatic loadings, a multilinear isotropic hardening model has been used, together with a damage criterion, based on the plastic strain, with the purpose of modelling the response of the materials after the occurrence of rupture by using the element erosion method. A very good correlation could be observed in the case of Makrolon 2405 and 9415, concerning the maximum force and the slope of the curve in the elastic region.

The numerical analyses corresponding to the notched samples have been set up in a similar manner to the previous analyses, however, in terms of material model the *MAT_089 (*MAT_PLASTICITY_POLYMER) has been chosen, a material model which permits the definition of the entire stress – strain curve, without the need to separate the true stress – plastic strain value pairs, specific for the isotropic hardening models used in the previous cases. Having the scope of reproducing the observed rupture of the material during the experimental measurements, *MAT_ADD_DAMAGE_DIEM parameters have been defined, based on the strain rate dependency of the admissible strain limit.

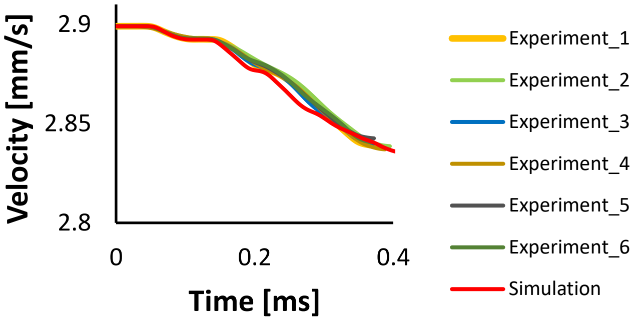

Fig. 7. Graphical representation of the velocity – time curves from the impact measurements, respectively from the numerical analyses for Makrolon 8035.

In case of Makrolon 8035 the obtained curve is characterized by repetitive variations, both for the experimental data and for the numerical results, showing, however, a slightly more significant velocity drop in the explicit model than in the physical measurements.

With the objective to determine the most suitable material model which can predict, with a higher accuracy, the modes shapes, and corresponding natural frequencies, for the 30% glass fiber reinforced polycarbonate, two numerical analyses have been performed based on two different approaches.

The first approach, the classic one, considered the material as homogeneous, defining its properties only by linear elastic parameters. The second approach involved the modelling of the material as anisotropic, inhomogeneous, considering the differences in terms of stiffness caused by the orientation of the glass fibers, because of the injection molding process.

By considering the orientation of the glass fibers, and comparing the structural analyses results, one could observe the differences both for the values of the resonance frequencies and for the mode shapes, because of the local effects of the glass fiber reinforcement on the dynamic behavior of the material compared to the homogeneous one.

To validate the previous conclusion a lab measurement has been performed. According to the validation it became clear that when an assessment with a high degree of accuracy is targeted (approx. 6%) considering the fibre orientation inside the material is mandatory. In case these are not considered for the scope of the simulation, the differences compared to the real values can get even up to 27%.

Based on the fatigue curve obtained in chapter 4 of the thesis, for the 30% glass fiber reinforced polycarbonate, respectively on the experimental validation of the numerical model, a fatigue analysis has been performed for the housing of the Head-Up Display.

By performing a fatigue analysis based on the equivalent stress obtained by applying a force in the quasistatic regime, a durability higher than 10^6 has resulted for the material of the housing, which one can interpret as an infinite lifetime of the component's material if it is loaded in ideal conditions, with cyclic sinusoidal excitations.

Chapter 6, entitled "**Final conclusions**", presents the general conclusions of the performed investigations.

Besides, the personal contributions of the author are also highlighted, out of which to be mentioned:

- The study of the influence of glass fiber reinforcement on the static and dynamic mechanical properties of polycarbonate.
- The analysis of the temperature effect on the Poisson's ratio for all three polycarbonate grades.
- The analysis of the aging effect on the tensile behavior of the three Makrolon grades.
- Mechanical processing of tensile specimens to obtain the impact testing specific probes.
- Sensibility study of the notch, considered as one of the major issues associated with polycarbonate materials, by dynamic impact testing of notched probes, as in the specialized literature and in the information provided by the material suppliers only data for the unnotched probes can be found.
- Development of specific material models, validated experimentally, for the integrity evaluation of polymeric components.
- Determination of fatigue strength and obtaining of the Wöhler curves, for the three Makrolon grades, in the context in which numerous investigations are available for metallic materials, however, only a small number of studies are focusing on the behavior of thermoplastic materials.
- Calibration of the viscoplastic ANSYS TNM material model for the three material grades, considering the influence of the rate dependency.
- Mapping of the fiber orientation resulting from the rheological analyses for Makrolon 8035 and performing a modal analysis with the obtained numerical model.
- Performing the experimental validation of the resonance analysis for the housing of the Head-Up Display.
- Performing a fatigue analysis for the validated housing of the Head-Up Display.
- From the experimental and numerical studies conducted to determine the static and dynamic behavior of the three polycarbonate grades, representing the basis for the elaboration of the thesis, 4 scientific papers have resulted, published in international journals and conferences (2 ISI and 2 SCOPUS).

The last part of the chapter presents the main, future research directions identified by the author.

The doctoral thesis is of high interest and scientific relevance as it proposes a complete methodology for evaluating the material properties of a class of polymeric materials frequently used in the automotive industry.

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