Caed Interactions During A Product Life Cycle Oriented Towards the Decision-Making in the Design of Polymeric Elements

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Abstract: In this work, we present the real case of an industrial product was placed prematurely on the market without having checked the different stages of its life cycle. This type of products must be validated by numerical methods and by mechanical tests to verify their rheological behavior. In particular, the product consists of two small pieces in contact, one made of HDPE and the other one corresponding to a stainless steel. The polymeric piece supports the metal pressure under a constant static load over time. As a result of normal operation, the polymer experienced a “crazing” breakdown, which caused the failure to occur. In the study, design methods and computer assisted analysis software (CAED) have been used. These methods were complemented by scanning electron microscopy that confirmed the initial failure hypothesis. Using the finite element method (FEM), a series of load scenarios were carried out, where the different load hypothesis the product must go through prior to its placing on the market were simulated. It is shown that the failure was initiated by stress concentration on one of the edges of the polymeric piece. The proposed solution of the problem based on the analysis focuses on a simple redesign of the piece, which should have been round, or to the reduction of the thickness of the metal piece. As a result of the alteration of its natural life cycle, the company assumed both monetary costs and the definitive loss of customer confidence.

Keywords: CAED, Crazing, FEM, Life-cycle, Polymers.

1. INTRODUCTION

The life cycle and the lifetime or aging cycle [1], [2] of a particular product are different and complementary concepts that must be considered from the very beginning of the conception of the product. The life cycle affects differently to each of the phases the product will go through, but mainly during the initial design phase in which 80% of the production costs are generated [3], [4]. The time spent by the product in each of the phases of its life cycle will depend on technical and technological factors, with marketing and market research also influencing. In contrast, the aging of the product will be only affected by technical and technological factors, and more particularly, by the rheology of the material itself [5], [6]. It is challenging for any designer to be able to extend the lifetime of a created product, by keeping it in the stages of growth and maturity as long as possible [7]. Any error diagnosed in the product once in the market will lead to increased repairing costs, image costs and also opportunity costs, which are hard to assume. Similarly, any error occurring during these stages will imply an unexpected acceleration of the aging cycle, even causing possible failures in the material. One of such cases is presented in this work.

In the plastics injection technology, countless items made from polymeric materials can be found, which are used
in several fields, such as the food industry [8], [9]. HDPE (high density polyethylene) is one of the oldest thermoplastic materials, highly used for general industry purposes but particularly, consumer goods industry [10], [11]. Its success is due to a number of aspects, such as its good odorless, inert, non-toxic and insoluble characteristics, the fact that it is inalterable to most chemical agents, its low friction factor, its unnecessary maintenance and its long durability. Therefore, HDPE is used to build drinking water pipes and in some good products, as a whole or as part of them [12], [13], [14].

Polymers, as a group of materials, cannot be easily classified from the point of view of their rheology [15]. Deformation mechanisms are preferably of elastic type, plastic or a mixture of both. Specifically, HDPE is a polymer characterized by a high flexibility, which allows it to resist powerful impacts. Nevertheless, the nonlinear behavior of its stress-strain curve suggests that constant and sustained loads over time at room temperature, may generate deformations in the material that lead to failures in its molecular structure, even at levels below its elastic limit [16], [14]. The correct characterization of this kind of materials requires the empirical determination of mechanical parameters such as the elasticity modulus, percentage of elongation, percentage of reduction in the area and yield stress, all of them according to harmonized standards as ASTM D-638-03 or ASTM E 813 [17]. In addition, the nonlinear behavior of these materials can take two forms: non geometric linearity and non material linearity [18], with the former being negligible in relation to the latter. The non linearity of the material affects the stress state during frequency cycles, in which the material goes through ductile and brittle zones that can cause a fatigue failure mode [19]. The S-N curves (Stress amplitude versus Number of cycles) govern the nonlinear behavior of the material, thereby being used in studies on plastic materials, as they are very revealing [17].

On the other hand, it can be considered that a material works at viscoelastic flow [20], [21] when experiencing increasing elongations over time, even under constant, sustained and non cyclical applied loads. The viscoelastic behavior is characteristic of polymeric materials even at room temperature [22]. Tests as the typical creep and stress-relaxation tests [23], [24] are ideal to establish correlations between deformations at constant time and temperature.

In order to study failures in this kind of materials is useful to apply the Finite Element Method (FEM) [25], [26] since, due to its simple formulation, it gives indubitable benefits for simulating the behavior of a state of loads. For this reason, it is essential to assess the type and final geometry of the nodes mesh that is applied to a particular analysis [27]. It is evident that rapid changes in stress can occur in any type of discontinuity, such as the geometry, load, material properties, etc.

This work presents the study conducted on a real case of a set of two elemental pieces whose configuration meets the characteristics of the polymeric materials described above. The set is part of a new product that was placed prematurely on the food market, without having passed a series of tests and numerical simulations to ensure the estimated life time. The particular case used here arises from complaints placed by final customers who used the product during a certain period of time. In particular, complaints began to arrive after 30 days of the start of the product sale. All claims referred to an element breakage in the same place. Hereafter, the failed design is described, and alternatives are proposed to redesign the damaged piece based on CAED interactions. The material behavior against the loads state applied is also illustrated. The main aim is to explain the method that should have been implemented to avoid any uncertainty in the product success.

2. MATERIAL AND METHODS

To start diagnosing the hypothesis of failure is essential to have several samples of the product. In our case, the manufacturer provided a number of samples at different stages of use. Those that had been used for more than 30 days were already broken and whereas others that had not been used for so long exhibited evident signs of the phenomenon causing the breakage. Finally, those samples that had been used for only a few days did not show any apparent damage.
Figure 1. Samples of the internal separate parts forming the study set-up. a) Part of HDPE piece and stainless steel spring; b) set in its operating position with the spring unloaded;

Figure 1a depicts the two components considered in the study, a piece made by plastic injection of HDPE pellets and a stainless steel spring. Figure 1b shows the set in its operating position. Figure 2a shows the set as the external part of the final product and keeping the spring under load whereas in Figure 2b evident signs of failure have been indicated. Finally, in figure 2c, the assemblage is shown in a characteristic failure state.

Figure 2. Samples of the separate external elements forming the study set-up. a) the outer appearance; b) mounted and loaded set where indications of failure are identified; c) set in failure

Additionally, the supplier of the HDPE material used in the manufacture of the parts from granules, provided the characteristic curves of the rheological behavior of the material. The mechanical characteristics of such material have been summarized in Table 1 whereas Figure 3 illustrates the response curve to the tensile tests at 25 °C, according to ISO 527.
Table 1. Mechanical properties of HDPE

| Property                          | Value | Units | Test Method                      |
|----------------------------------|-------|-------|----------------------------------|
| Tensile Strength at Yield (MPa)  | 26    |       | ISO 527-1976: Type 2 Speed D     |
| Elongation at Break (%)          | 1000  |       | ISO 527-1976: Type 2 Speed D     |
| Tensile Modulus (1000 MPa)       | 1000  | MPa   | ISO 376-1997                     |
| Impact Strength (Charpy)         | 6     | KJ/m² | ISO 179-1982                     |
| Hardness (Shore D)               | 65    |       | ISO 908-1976: Type D             |
| Melting Point (°C)               | 131   |       | ASTM D2117                       |
| Vicat Softening Point (1 kg)     | 123   | °C    | ISO 306 (charge 1kg)             |
| Thermal Conductivity (W/mK)      | 0.46  |       | ASTM C177                        |
| Specific Heat (kJ/kgK)           | 2.300 |       |                                 |
| Coefficient of Linear Expansion  | 2x10^-4 | °C | ASTM D566-91                     |

Figure 3. Curves of the behavior of the HDPE used in the tensile test (5 samples), according to ISO 527.

Figure 4. Charts of the behavior of the HDPE used in the creep test

Similarly, the curves of the creep behavior test at the same temperature are indicated in Figure 4. Figure 5
illustrates the dimensions of the pieces to be tested, with this geometric configuration being identified as Example 1 (eV1). The material used in manufacturing the spring was a SS 316L and, given its initial geometry, it reaches a charge level of 8.8N on the HDPE piece.

Prior to start setting up the methodology of analysis, tooling and injection mold tooling were revised in order to rule out possible irregularities in the surface roughness. Likewise, the instability of the material by thermal phenomena was discarded, as such parameter remains constant during regular operation time. Other phenomena caused by fatigue of the material were also discarded due to their low operating frequency cycles. Lastly, the spring must be loaded perpendicularly to the HDPE piece, forming an angle of attack of 90° [28]

Figure 6 observation of the piece with a scanning electron microscope (Quanta 200) allowed to attribute the failure to a crazing rupture (cracking or brittle material breakage) [29 ]. In the micrographs, the intermediate process of this phenomenon can be observed in which, after the critical stress value was reached, the crack due to the elongation and fibril breakage occurred.

Subsequently, the analysis performed is explained and discussed in the next section, where a series of conclusions are also given. Software tools have been used for modeling and simulation of the pieces.
Figure 6. Electron microscope (SEM) images of the study piece at different stages.

3. APPROACH AND PROBLEM DISCUSSION

According to the materials and methods described above, it can be considered that if the piece material yielded enough to cause failure, the value of the creep was then exceeded, reaching the elasto-plastic zone of its stress-strain curve [30], [27]. Therefore, a first dynamic analysis must be assessed in a very short charging time (transient). In order to rule out possible causes of breakage by contact, the reaction of the set “eV1” piece-spring was simulated when the former was subjected to a displacement of the spring, with the two surfaces being in direct contact.

Figure 7. Results of the simulation of the case load based on explicit analysis
In order to carry out the first analysis, data of the polymeric material were implemented into the library of nonlinear materials of the EMF tool. Table 2 summarizes the properties of the HDPE material, according to manufacturer's data.

Table 2. Input data of the nonlinear material HDPE

| Property                                      | Value | Unit  |
|----------------------------------------------|-------|-------|
| Density                                      | 950   | kg m^{-3} |
| Isotropic Secant Coefficient of Thermal Expansion |     |       |
| Isotropic Elasticity                        |       |       |
| Derived from                                 | Young's Mo... |       |
| Young's Modulus                              | 1.1E+05 | Pa    |
| Poisson's Ratio                              | 0.42  |       |
| Bulk Modulus                                 | 2.2917E+09 | Pa |
| Shear Modulus                                | 3.8732E+08 | Pa |
| Uniaxial Plastic Strain-True-True             |       |       |
| Multilinear Isotropic Hardening              | Tabular |       |
| Tensile Yield Strength                       | 2.5E+07 | Pa    |
| Compressive Yield Strength                   | 0     | Pa    |
| Tensile Ultimate Strength                    | 3.5E+07 | Pa    |

Figure 7 shows the result of the simulation based on an explicit analysis using a basic mesh in order to obtain first insights that suggest clues on the cause of the failure. It can be observed that the “eV1” piece gives way to spring without breaking. This behavior indicates that the diagnosis should be oriented towards a phenomenon caused by the following reasons, either acting separately or jointly:

- By stress concentration
- By a bad spring support
- By a bad design of the piece and / or the spring
- By creep of the material

It is evident from Figure 2 that the piece exhibited an uniform breakage, which rules out the cause due to a bad support of the spring. However, in Figure 6 a white mark located in a sharp edge could be clearly seen, a spot where a crazing or an internal network of small cracks that cause the brittle fracture of the piece could have started. Although crazing is the result of a high stress, the presence of such an external stress may not be entirely needed as an internal stress resulting from mold shrinkage can also originate the initiation of cracking in a certain period of time.

3.1 Static load hypothesis

In this type of hypothesis, different CAED scenarios are assessed, in which all the possible casuistries causing the failure situation are addressed. Figure 8 illustrates the described approach where the following load hypothesis can be considered:
Figure 8. Approach to determine the different scenarios to consider in the hypothesis of static load.

A-B scenario

First, a load hypothesis based on the geometries of both the “eV1” piece and the spring described in Figure 4b was considered. The mechanical characteristics of the material of the “eV1” piece (HDPE) are specified. In the particular case defined in B5, a 1 second long simulation of a nonlinear static analysis was run by applying the load on the bearing face of the spring. Figure 9 shows the attachment of the blue face where the piece was clamped, with the load of 8.8N magnitude being evenly distributed on the red face, in a descending and perpendicular direction to the surface of the string.

Figure 9. Fixed supports and external loads.

The mesh of elements used in this type of analysis can be adapted to the study surfaces, i.e. the faces of intersection with the lower base reinforcement. Mapping of the surfaces to be meshed has not been applied for the sake of computational calculation times.
Figure 10. Result of the nonlinear static analysis, indicating the point of maximum effort in the A-B scenario

As indicated in the upper right corner of Figure 10, the analysis simulated a load time of 1 second and the result of the Von Mises effort is 13.7MPa. This value is unreliable according to the process time and the type of mesh applied. An identical simulation was again performed but considering a longer load time. Tetrahedral elements were used in this case, and the aspect ratio in the mesh was mostly close to 1.1. Likewise, the quality of the elements reached a coefficient of 0.88 at a fairly high percentage. A total of 2,674,408 nodes were used in this mesh. The maximum effort value was still located on the same edge, being higher than 42MPa, which is high enough to cause breakage of the material in that particular area.

Clearly, the results suggest a failure due to stress concentration in one of the edges. This could be solved by a redesign of the piece based on the following aspects:

- To model a round edge that replaces the one that caused the origin of the failure.
- To halve the spring section (i.e., by a diameter of 0.3 mm and a static charge on the piece of 3.5N).

E-C scenario

This new geometric configuration gave rise to the so-called eV4 piece. On this new configuration, the E-C simulation was run, whose main feature was a static load of the spring of 3.5N.
A total of 3,067,769 nodes were used in this test, with a quality factor of 0.88, and an aspect ratio of approximately 1.5. Figure 11 shows that the maximum value of the equivalent effort was obtained at the bottom of the perimeter holes, which did not exceed 2.6 MPa, a much lower value than the one obtained with the previous simulation.

E-D scenario

Figure 12 shows how simulation D was run to analyze the eV4 piece subjected to a load of 8.8 N in an attempt to strengthen the hypothesis of failure. In this case, the mesh was structured with a total of 4,197,960 nodes, with a high percentage of elements and an equivalent level of quality and aspect ratio of the elements used. The result reached a value of maximum effort of 6.7 MPa that was located on the upper edge of the prismatic nerves. This simulation was carried out over a period of 4 days under static charge, which may well indicate a further warning on the start of a new crazing in this area. Again, the solution would be to round the edge in order to reduce stress in that particular zone.

According to the analysis performed, it is possible to conclude that the redesign of the piece would diminish the stress in the eV1 version where 40 MPa were reached as in the “eV4” version, it did not exceed 7 MPa.
4. CONCLUSIONS

- All brand new product needs inevitably to go through their entire life cycle without getting altered or skip any of its stages. Any error occurring during the later stages exponentially multiplies the monetary costs and other intangible costs that compromise the brand image.

- The use of CAED techniques combined with electron microscopy and appropriate mechanical tests is sufficient to validate a new product during the design phase.

- Polymeric pieces require a numerical simulation of nonlinear analysis to check their elasto-plastic behavior and compare the results with their stress-strain curves and stress-time curves.

- CAED interactions allow to determine the origin of the failure. In a first transient analysis, the polymeric piece exceeded its elastic limit without causing breakage.

- The phenomenon of crazing in this type of polymeric piece occurred as a result of stress concentration brought about by a poor design.

- A redesign of the pieces ensures a reliable operation under load conditions at the long term.

- It is also convenient to apply other accelerated aging tests in addition to those applied in this work in order to further reduce the risk of failure.

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