INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 2005 MELBOURNE, 15-18 AUGUST 2005

DESIGN OF NEW STRUCTURED WALL PIPES: PROBLEM FORMULATION

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Abstract

PVC Poly (Vinyl Chloride) pipes are widely used in the field of water evacuation. PVC constitutes a good quality material alternative for buried sewer systems instead of cast-iron. The manufacturers developed foam core pipe to save raw materials and reduce the cost. Since 1990's the performance of PVC pipes must be in accordance with the European Standards. These imply for PVC pipes to be conform to rigidity, tensile impact tests. Impact tests are the most severe and cause a lot of waste parts. Currently, PVC pipes are not optimised from the point of view of mechanical properties.

Thus, the objective here is to develop a new extruded pipe in respect to European standards by optimising the product economically.

Keywords: Inventive design, process, PVC pipes, impact strength.

1. Introduction

In the boarder of engineering design, several types of design are considered: routine design, variant design and inventive design. According to [1], the related level of inventiveness goes from apparent solutions to discoveries. Because the actual pipe solution is not anymore adapted to the new constraints, new concepts of solutions have to be developed. However, the already defined variants of the actual solution do not give satisfaction. Therefore an inventive approach is required. Classical engineering design methods such as Systematic design [2] or Axiomatic design [3] are not really dedicated to inventive design.

For inventive design, several methods are generally applied:

- Brainstorming to generate many ideas,
- Combination of separated elements to generate new solutions,
- TRIZ, a human-oriented knowledge-based systematic methodology of inventive problem solving [4].

Due to the results obtained, in our laboratory, in using TRIZ on many industrial cases this last decade, this theory has been chosen to support the design of the new pipes.

Due to the extrusion process, the design of the pipes and its manufacturing process are closely linked. So, it has to be considered as a concurrent engineering approach as defined in Chapter 4 of [5] by B. Prasad.

The TRIZ theory includes four essential steps to solve inventive problems (Figure 1).

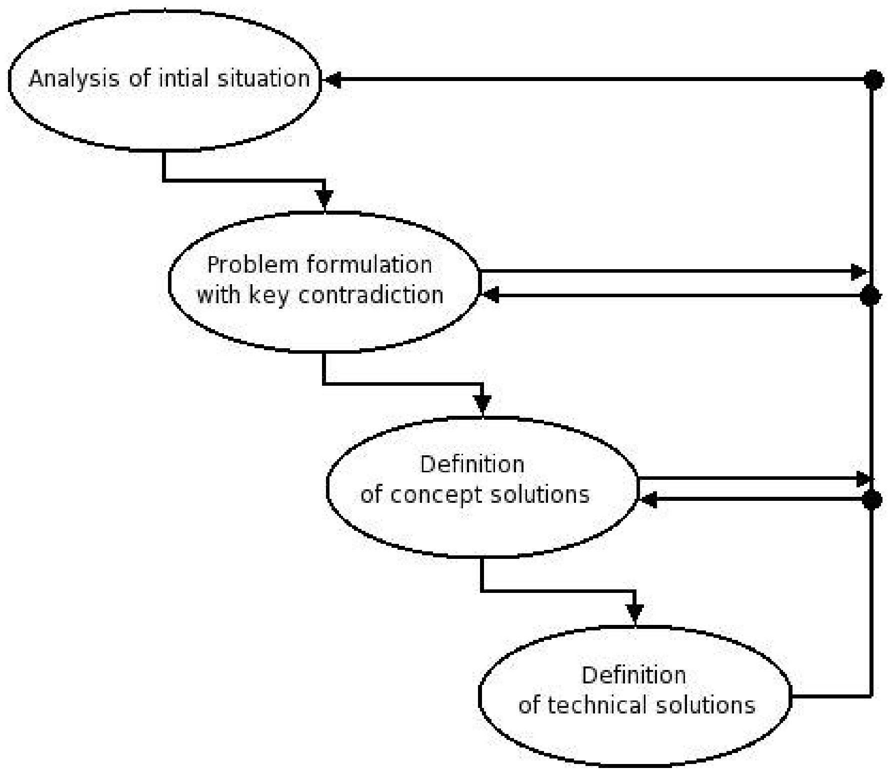

Figure 1. Design process in TRIZ theory

The first step is the analysis of the initial situation. To solve inventive problems, the specific conditions of the problem as well as the final goal must be defined carefully. The analysis performed during this first step enables, during the second step, to formulate the problem precisely in the form of key contradictions. Key contradictions describe two opposite characteristics that are difficult to guarantee together. From these contradictions, the ideal final result to obtain is defined. To solve these contradictions, existing solutions are analysed and concepts of solutions defined. This third step allows to identify if the existing solutions can be applied to the study case. The last step consists to adapt the concept solutions and to develop technical solutions to solve the problem. In our case, the design of plastics parts requires to take into account the manufacturing process. Indeed, the extrusion process modifies the parameters and the properties of the structure. The knowledge of the relationships between the product properties, the product parameters and the process parameters, from the standpoint of impact strength, would be useful to redesign the structure.

First at all, the initial situation analysis consists here to analyse the actual pipe structure and the expected properties. Secondly, to formulate the problem, we focus more precisely on the most crucial property: the impact strength. How to design a new pipe structure to improve the impact strength? The analysis of the impact strength highlights a key contradiction that we report in the third paragraph. How to insure two different properties: the rigidity and the toughness? Thirdly, to obtain this ideal final result, existing concept solutions are described and analysed according to the industrial design constraints. Finally, we describe relationships between the process parameters, the product parameters and the product properties to make easier the definition of the future technical solutions.

2. Analysis of the initial situation

2.1. Pipe structure

The studied PVC pipes have a multi-layer structure composed of micro cellular polymeric foam of PVC between two layers of compact PVC (Figure 2 and Figure 3). The diameter of the pipes varies from 110 mm to 400 mm. A 200 mm diameter pipe has a 10 mm thickness: 1 mm for each compact PVC layer and 8 mm for micro cellular PVC layer. The European standard specifies the dimensional and mechanical characteristics of the pipes. Currently, it is difficult to insure the compliance with the impact tests. Therefore, a new structure must be designed.

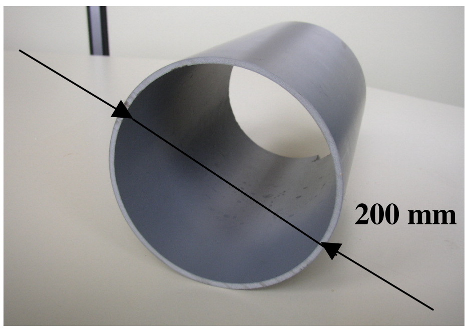

Figure 2. Unplasticized PVC Pipes

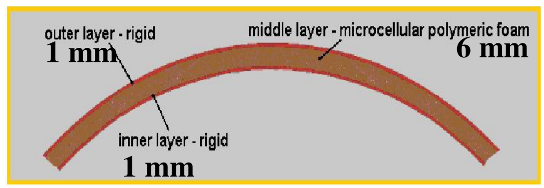

Figure 3. Internal structure of pipes

2.2. A complex design

The objective of this study is thus to design a new structure by optimising the product economically. A lot of constraints limit the design. Indeed, pipes must absolutely:

- Respect the mechanical properties;
- Be in conformity with the dimensional constraints fixed by the norms. The internal, external diameters and the thickness of the internal layer of compact PVC are fixed;
- Insure the flow capacity. The flow rate of fluids must be constant inside the pipe;
- Assure the watertightness of the sewer system;
- Be produced through the extrusion process.

Extrusion is a continuous process (Figure 4). The machine is divided in three zones. Firstly, the polymer enters from the barrel. The polymer is compressed in the annular space between the extruder screw and the barrel. The screw rotates in the stationary barrel. The frictional forces act on the materials, the polymer is melted. At the end of the barrel, the melt polymer is pushed through a die. The die gives the annular shape to the final product. During the second step, the product is cooled, and the final dimensions are fixed. Finally the product is pulled and cutted out to the required length.

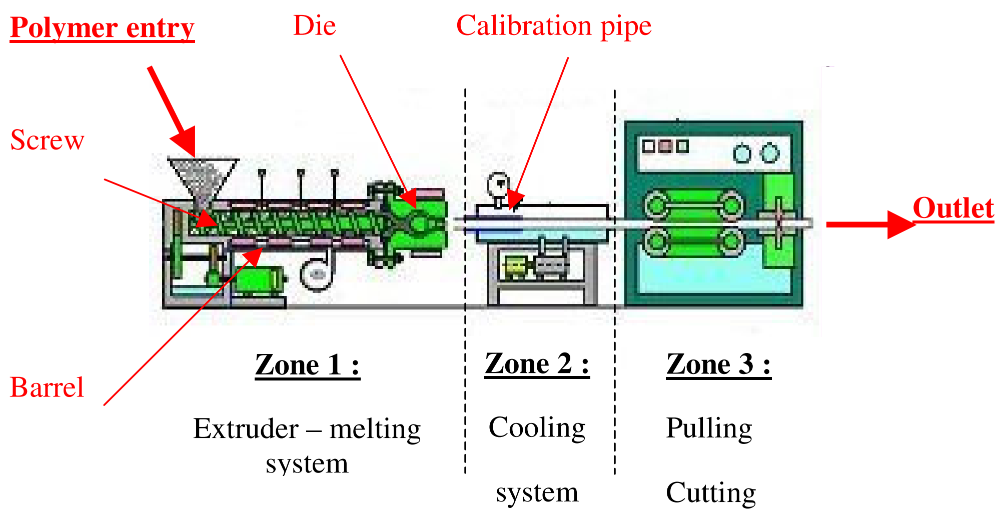

Figure 4. Extrusion process

The difficulties of this study are to deal simultaneously with all constraints. Mechanical properties are especially difficult to respect. They are tested through the following tests specified by the standard XP P 16-362:

- Tests of thermal shrinkage;
- Traction tests;
- Ring rigidity tests;
- Falling weight impact tests at 0°C (-273,16°K);

A pipe is considered as conform if all tests are successful. For example, the target of ring rigidity tests is to check if PVC pipes sustain static loads. The deformations must be weak to insure the flow capacity of the pipes. The most difficult test is the falling weight impact test. This test, that guarantees the ability of pipes to resist to sudden loads, is the main cause of scraps. The major difficulty of the impact test is linked to the repetition of the impact on several generatrixes of the pipes. The impact test consists in releasing a striker of mass M at a height H (Figure 6), whose characteristics are defined in standard XP P 16-362, on several generatrixes of the pipe samples. To conform to this test, no damage must be visible. Generally, cracks are initiated the under impact point and propagated through the thickness and the length of the pipe. In order to improve the design of the pipe from the point of view of impact strength resistance, knowing in details impact mechanisms would be useful. The analysis, proposed by Christoforou [6] allows to clarify this task. This study is developed in the next section and leaded to the formulation of the problem with contradiction.

3. Problem formulation with a contradiction

To improve the impact strength, contact forces between the impactor and the structure must be reduced [6]. To quantify these forces, Christoforou proposes the following model. Two parameters are defined (ζ and λ) to identify the impact response. The loss factor ζ represents the energy transferred to the structure during the impact. λ is defined as the ratio between the global rigidity and the contact rigidity under the impact point. These parameters enable to quantify the magnitude of the impact forces and to predict the structural response.

3.1. Definition

Firstly, the Hertz rigidity K_h and the contact rigidity K_c must be defined. These parameters are given by:

$$\begin{cases} K_h = \frac{4}{3}\sqrt{R}E & (1) \\ K_c = \frac{3}{2}K_h\sqrt{\alpha_c} & (2) \end{cases}$$

The parameters R, E and α_c are defined as:

$$\begin{cases} \frac{1}{E} = \frac{(1-\nu_1)^2}{E_1^2} + \frac{(1-\nu_2)^2}{E_2^2} & (3) \\ \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} & (4) \\ \alpha_c = \alpha_1 - \alpha_2 & (5) \end{cases}$$

E_i, ν_i, R_i are respectively the Young's modulus, poisson's ratios and curvature radius. Numbers 1 and 2 are associated to the impactor and the structure. E_2 is the Young's modulus of the polymer directly in contact with the striker during the test, the compact PVC. α_c represents the critical indentation, *i.e.*, the difference between the striker and the structure displacement (Figure 6).

Finally, the loss factor ζ and the relative rigidity λ are calculated by the following relations:

$$\begin{cases} \zeta = \frac{1}{16}\sqrt{\frac{mK_c}{\rho h D^*}} & (6) \\ \lambda = \frac{K_{st}}{K_c} & (7) \end{cases}$$

where m is the mass, ρ the density, h the thickness of the structure. D^* is the flexion modulus and K_{st} the global rigidity of the structure. The global rigidity is equivalent to the rigidity measured during rigidity tests of the pipes.

3.2. Analysis

According to the previous definition, there are two possibilities to decrease the contact force and obtain a global deformation of the structure: increasing the loss factor ζ or minimizing the relative rigidity λ (Figure 5).

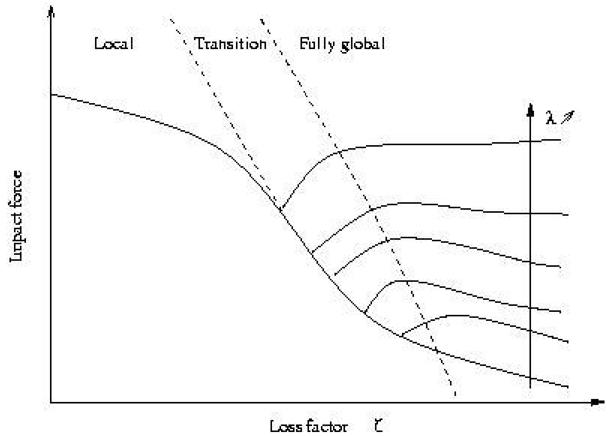

Figure 5. Relationships between the maximum impact force and the loss factor (Christoforou 2001)

In our specific case, the curvature radius of the striker R_1, the external radius of the pipes R_2 and the impactor material are fixed. The external layer of the pipes must be in compact PVC, so E_2 is fixed. As a consequence, the contact rigidity K_c depends only on the critical indentation α_c. The mass of the striker m and the thickness h of the pipe are also imposed. The flexion modulus depends on the rigidity of the pipes, which must be constant. So, the only factors that can be modified are the density ρ and the critical indentation α_c. For example, a decreasing of the alveolar PVC density induces an increasing of the indentation and the loss factor ζ. Consequently, to maximize the loss factor, the density of the structure must decrease.

A second possibility to improve the impact strength, is to minimize the relative rigidity λ. The global rigidity K_{st} must be equal to or higher than the one required in the rigidity norm. The contact rigidity K_c depends on the critical indentation α_c. According to equation 2 and 7, to minimize λ, the critical indentation must be increased, and the density decreased.

Finally, whatever the selected solution, to improve the impact strength, the density of the structure must be decreased. But, to insure the required global rigidity of the pipe with the actual structure, the density of the pipe cannot decreases. So, this analysis highlights a fundamental key contradiction: how to insure two opposite mechanical properties, the rigidity and the impact strength *i.e.* the toughness.

3.3. A key contradiction – rigidity and toughness

The rigidity is the material ability to resist to deformation. Rigidity norms impose a minimal rigidity of 8 kN/m². The impact strength or the toughness is the ability of a material to absorb the energy of a sudden impact. So, the key contradiction can be expressed as:

- The pipe has to be stiff, thus static loads do not deform the pipe.
- The pipe has to be tough, thus the impact does not create any damage.

Rigidity and impact strength balance is often difficult to maintain [7]. This behaviour is observed for the studied PVC pipes. The toughness is measured by the percentage of conform pipes for the impact tests. We observed that a decreasing of the rigidity induces an increasing of the percentage of conform pipes. For a 200 mm diameter pipe, if the rigidity is equal to 9,5 kN/m², 50% of the pipes are conform to impact tests. If the rigidity is decreased to the minimal value, 8 kN/m², 80 % of pipes are conform. So, even if the rigidity can be decreased to the minimal value to improve the impact strength, the results are unacceptable for the manufacturer. Other solutions must be found to solve the problem. This key contradiction highlights an ideal final result: to obtain a rigid and impact strength pipe.

4. Concept solutions

Impacts of the striker on PVC pipes can create damages. Damages depend on many parameters like the initial energy of the striker and the capacity of the impacted structure to absorb the impact energy. During the impact test, the initial energy E_i of the striker is converted into:

- Restoring energy to the striker E_r;
- Elastic strain E_e;
- Plastic strain E_p;
- Initiation and propagation of cracks E_c.

The initial energy is expressed as following:

$$E_i = \frac{1}{2} MV^2 = \mathrm{E_r} + E_e + E_p + E_c \tag{8}$$

M and V are respectively the mass and the velocity of the striker.

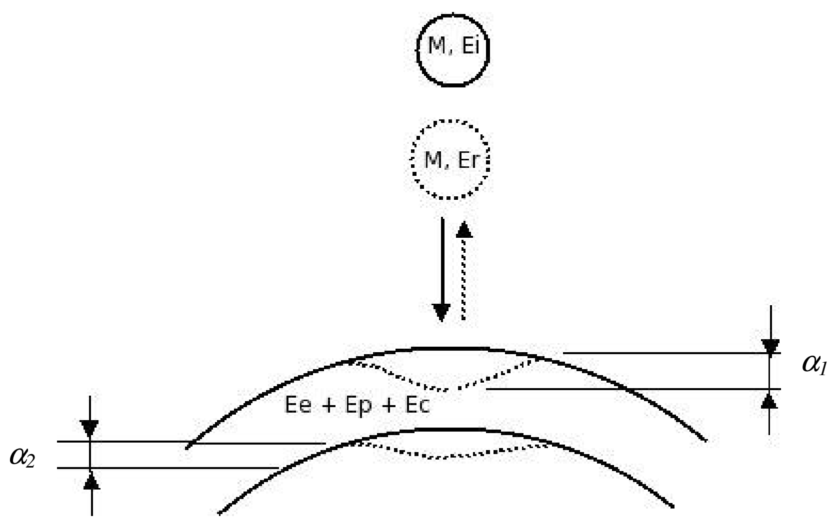

Figure 6. Impact of the striker on pipe

Impact norms impose to carry out the test at a 0°C temperature. A 200 mm diameter pipe is impacted by a 1,6 kg drop mass providing an impact energy of 33,8 J. In this case, the impact velocity is equal to 6,5 m/s. As polymers, the PVC behaviour depends on the temperature (Figure 7) and the strain rate (Figure 8). Figure 7 shows the variation of the Young modulus according to temperature. With the conditions imposed by the impact norms, i.e. a temperature of 0°C and high deformation rate, PVC pipes and especially the foam are brittle [8]. PVC behaves like an elastic solid. Pipes are essentially able to absorb the impact energy in elastic deformation and through damage mechanisms. Plastic deformations are weak. So, cracks are immediately initiated and concentrated in a small volume under the impact point. Visual analysis of the pipe after impact tests show that the damages are localized in this area.

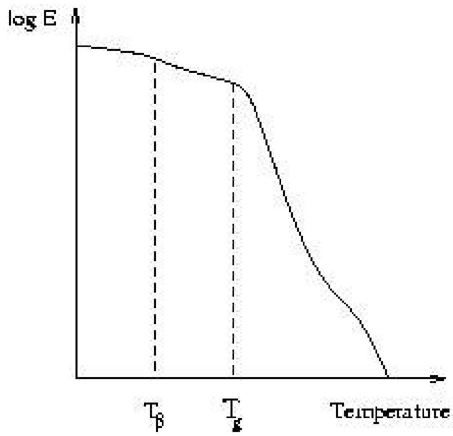

Figure 7. Behaviour depending on temperature

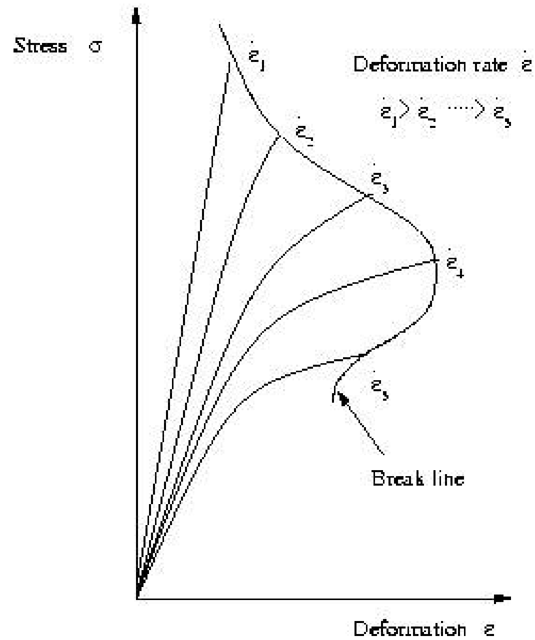

Figure 8. Behaviour depending on deformation rate

Four principles exist to improve the impact strength of the structure:

- Firstly, soft particles can be introduced in the brittle matrix in order to improve the impact strength. The impact energy is absorbed by the deformations of these particles and the debonding between the particles and the matrix.
- A second solution consists in adding stiff particles into the matrix. In this case, only debonding mechanisms absorb the impact energy. Whatever the chosen solution, the toughening effect is obtained by a reduction of the overall deformation resistance [9]. The reduction of the deformation resistance results from uniform cavitations, i.e., creation of micro voids located in debonding zones.
- The third solution consists in modifying the molecular structure of the polymer. In this case, the molecular chains must be modified in order to become more difficult to break, such polymers are able to absorb more energy.
- The last possibility is to create an anisotropy in the polymer that modifies its mechanical properties.

There are a lot of examples in the literature illustrating the principles described above. The first principle can be achieved by adding compatible rubber material for toughening the brittle PVC matrixes. Rubber particle well dispersed in the matrix can be deformed and absorb a lot of energy. Unfortunately, even if the impact strength increases, the rigidity decreases.

The second principle consists in adding stiff particles like glassy particles of micro voids to improve the impact strength. Rigid particles like the calcium carbonate $CaCO_3$ enable to obtain the same results. These particles have totally different mechanical properties than the rubber particles. In fact, the toughening of a polymer is linked with the debonding mechanism between the stiff particles and the matrix and not with the mechanical properties of the particles. These two solutions allow to insure stiffness and toughness.

The third principle consists to rigidify the structure in increasing the molecular weight of the polymer. Polymers with a high molecular weight have a lot of entanglement. As a consequence, the molecular chains are more difficult to break and the capacity of the polymer to dissipate the impact energy increases.

The last possibility is to orient the polymer. The main interest of the molecular orientation is the increasing of the polymer flexural modulus, which enables to increase its rigidity. The mechanical properties in the hoop direction of the pipe therefore increase. Moreover, compared with non-oriented pipes, the major failure mode is the delamination. Instead of propagating through the pipe thickness, cracks propagate in the hoop direction. Cavitations concentrate in this favour direction.

Actually, the design constraints fixed by the manufacturer limit the possible solutions. Even if rubber particles are efficient to improve the impact strength, the cost of such additional material is too expensive. Moreover these particles can reduce the rigidity of the pipes below the critical values fixed in the rigidity norm. The use of microvoids calls the same economical questions. Actually, calcium carbonate is introduced inside the PVC matrix, but it is difficult to evaluate the adequate quantity to be used. Too few particles do not produce an efficient effect and an excess of calcium carbonate weaks the structure.

The third solution of increasing the molecular weight, induces extrusion difficulties of the polymer. The actual process creates a natural molecular orientation in the extrusion direction that cannot be modified. As a consequence, different ways to design a new pipe structure are not easy to find.

So, links between these concept solutions and the actual multi-layer structure (a foam PVC layer between two layers of compact PVC) can be made. Few questions can be asked:

- Is the current structure with three layers ideal to resist to impact test?
- Foam PVC is especially brittle. Is it possible to avoid the initiation of damage mechanisms or to orient it inside the foam?
- How can the two interfaces compact/foam be exploited to promote cavitations mechanisms in these zones?

The answer to these questions cannot be given without analysing more in detail the extrusion process. Indeed, as described above, the process limits for example the molecular weight of the polymers. So, the relationships between process parameters, product parameters and product properties must be defined and studied carefully.

5. Product properties, product parameters and process parameters

Improving the impact strength is important to design new PVC pipes. However, to succeed in this redesign, the knowledge of relationships between the product properties, the product parameters and the process parameters, from standpoint of impact strength, would be useful. Knowing and managing these relationships allow to highlight how to enhance the shock resistance(Figure 9). Unfortunately, there is a lack of theoretical knowledge about the study of these links.

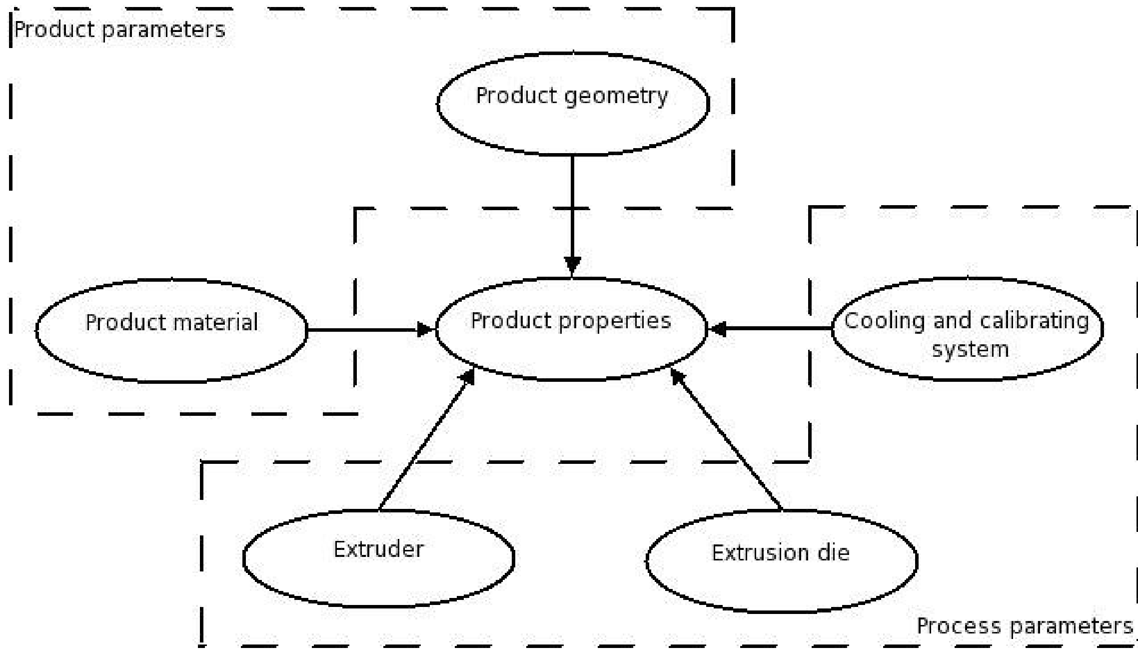

Figure 9. Relationships between the product properties, the process parameters and the product parameters

As described in section 2.2, the extrusion process is divided in three steps. Firstly, the polymer is melted, then the extrusion die gives the shape of the product. During the second step, the pipe is cooled with water on the external surface, dimensions are fixed. Consequently, the cooling is not homogeneous between the internal and the external surface of the pipe. The residual stress generated can modify the mechanical behaviour of the structure. Ritchie et al. [10] studies the possibility to improve the toughness in polyethylene at different cooling rates. They highlight that slowly cooling structure requires more energy to break. So, a decreasing of the cooling rate induces an improvement of the impact strength [10].

However, decreasing the cooling rate imply a slowing of the pipes manufacturing that is in contradiction with the industrial constraints. Reducing the productivity is difficult to consider. This solution cannot be used for our application.

Two others relationships are known. Firstly, the use of recycled PVC induces lot behaviour variations of the melt polymer. Inhomogeneities created in the microcellular PVC, deteriorate the impact strength. The second relation relates to the geometry of the extrusion die, the thickness of the internal layer and the impact strength. Conventional spider-supported dies are used to produce the PVC pipes (Figure 10). This technology enables to extrude hollow circular sections. To carry out the multi-layer pipes, a double system of spiders is implemented. Spiders by supporting the internal core are an obstacle to the melt stream. The polymer separates and flows around the spiders. When melt streams recombine themselves, weld-lines are created. Depending on the number of spiders, their geometry, the pressure in the die, weld-lines are more or less important. The drawback of this technology is the creation of weld lines. Weld lines causes a decreasing of the internal layer thickness. The pipe is locally weaken and the impact strength reduced. Thus, the design of extrusion dies is of major importance to limit the influence of spiders on weld-lines.

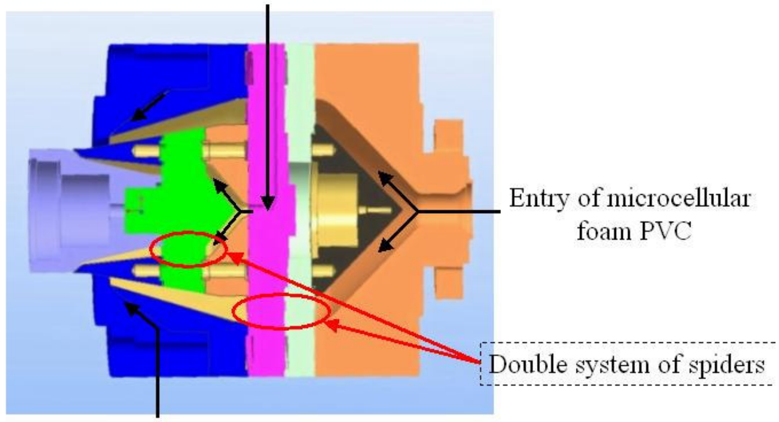

Figure 10. Extrusion die

The analysis of this example shows that the extrusion process must be taken into account in the design a new structure. Internal stresses, inhomogeneities in the foam layer or thickness variation of the internal layer modify the mechanical properties of the pipes and in particular the impact strength. Moreover, whatever the chosen solution, i.e., keep the actual pipe structure and modify the die design to avoid weld lines or design a new pipe structure, the consequences on the design process are the same. A new extrusion die must be designed.

6. Conclusions

The design of a new pipe structure resisting to the impact tests, is a crucial endeavour in the PVC pipe industry. Managing efficiently such a design requires a methodological support. To solve this inventive problem, the TRIZ theory is used. Three steps of this theory have been developed: the analysis of the initial situation, the formulation of the problem and the description of concept solutions.

After a first analysis of the existing pipe structure and the design constraints, we focus on the most important property, the impact strength. The study proposed by Christoforou leads to formulate a key contradiction: the pipe has to be stiff, because the static loads must not deform the pipe; the pipe has to be tough, because the impact must not create damage. To help us in the resolution of key contradiction, concept solutions are described. To design a stiff and impact strength pipes, several solutions exist. Additional particles can be added. The deformations of these particles and/or the debonding mechanisms between the matrix and particles absorb the impact energy and increase the shock resistance. Increasing the polymer molecular weight and orienting the molecules produce the same effects. Different ways solution are proposed. However, industrial constraints and the extrusion process limit the design of a new structure. The relationships between the process parameters, the product parameters and the product properties must therefore be taken into account. We have showed that these relationships imply the design of a new extrusion die.

In the future, we will use the relationships between the process parameters, the product parameters and properties to solve this design problem. Moreover, based on the identified solution concepts to improve the impact strength, we shall develop more precisely technical solutions for designing impact strength pipes with respect to economical constraints.

References

[1] Altshuller G.S., "The Innovation Algorithm", Technical Innovation Center, 2000.

[2] Pahl G.A. and Beitz W., "Engineering Design: A systematic Approach", Springer Verlag, London, 1996.

[3] Suh N.P., "The principles of design", Oxford University Press, 1999.

[4] Salamatov Y., "TRIZ: the right solution at the right time", Insytec B.V., 1999.

[5] Prasad B., "Concurrent engineering fundamentals", Prentice Hall, 2002.

[6] Christoforou C., "Impact dynamics and damage in composite structures", Composite Structures, 52, 2001, 181-188.

[7] Latado A.a.E., Neto M., Mattos A.G. and Pinto J.C., "Modeling of end-use properties of poly(propylene/ethylene) resins", Polymer Testing, 20, 2001, p. 419-439.

[8] Mandell J.F., Darwish A.Y. and McGarry F.J., "Time and temperature effects on the fracture toughness of rigid poly(vinyl chloride) pipe materials", Polymer engineering and science, 22, 1982, p. 826-831.

[9] Argon A.S. and Cohen C.E., "Toughenability of polymer", Polymer, 44, p. 6013-6032.

[10] Ritchie S.J.K., Davis P. and Leevers P.S., "Brittle-tough transition of rapid crack propagation in polyethylene", Polymer, 19, 1998, p. 6657-6663.

Acknowlegment

We thank Dmitry Kucharavy for his help in this research as a TRIZ expert.

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