PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 39, NOS. 3-4, PP. 211-224 (1995)

# SHAPE OPTIMIZATION OF THREADED PLASTIC CAPS BY FEM

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Received: Febr. 3, 1995

## Abstract

To reduce the mass of the widely used plastic caps there were compared two thread profiles and various outer shapes of them analysed by FE models applying axisymmetric, linear elastic finite elements plus contact elements. The result of this investigation by reducing mated threads and modifying the cap's outer geometry produced about 40% reduction in mass.

*Keywords:* plastic cap, finite element analysis, contact problem, shape optimization.

## Introduction

Nowadays several products of the chemical industry including cosmetics and household chemicals as well as different drinks are packed into plastic bottles closed by threaded plastic caps.

These closing elements are manufactured in great variety of geometric shapes with different thread profiles. The applied thread profile at a given construction is mainly influenced by the engineering material and the construction itself [1], [2].

The most frequently used thread profiles have been standardized internationally. To select the thread profile fits the best to task or to design one out of standard which meets perfectly outer geometric shape first the list of requirements should be determined.

The most important technical requirements are as follows:

- appropriate sealing effect by average human hand-force with the possible smallest tangential displacement.
- safe connection against loosening, that is the cap neither by torque nor by jump one lead cannot loose the joint.
- easy and cheap manufacturing in mass with one of usual technologies.
- strive for possible smallest weight.
- use environmental friendly recyclable engineering material.

The aim of present FE analysis is to create the optimal caps for plastic cans including the best utilization of the load carrying capacity of engineering material, and to present the optimization during designing by computer. Our investigations were carried out by the COSMOS/M Explorer software. The optimization partly refers to thread profile partly to outer geometry of the cap. As this paper shows the optimal shape can only be found by parallel optimizations on both fields.

## 1. Theoretical Background

This chapter helps the reader to understand the need of special profiles at plastic caps by comparison of standardized thread profiles with specially shaped ones.

It is well known that high thread-angle thread profiles out of standardized ones are better for joining elements as the seemingly higher friction on connected threads provides higher safety against loosening of the connection.

Another fact is that safe sealing effect with relatively small tangential rotation can only be reached in case of high lead.

But high lead is mated at all the standardized thread profiles high height of thread which fact automatically requires relatively high wall thickness.

Regarding the above mentioned facts it is easy to come to the conclusion that standardized thread profiles are not suitable for this type of constructions made of any plastic as:

- High height of thread requires high wall thickness.
- Fine pitch threads are inclined to loosening by jump over leads.
- Standardized thread profiles are not efficient in load distribution along the length of threads engagement [1], [2].

Caps for plastic cans or bottles are threaded elements manufactured by press-casting. It is quite natural that further the most important technical requirements and a lot of additional ones should meet at the pressure-casting products, among them the good utilization of engineering material, esthetic ones, etc. There are many thread profiles in the present practice manufactured for this purpose but investigating them they all can be classified into two basic geometries. Let us nominate these thread profiles A and B presenting them in *Fig. 1.* Practically all the manufactured profiles show small inclinations from profile A and B which are not standardized of course.

Thread profiles presented in *Fig. 1* are designed by us so that they show the possible smallest stress concentration or local deformation. It is

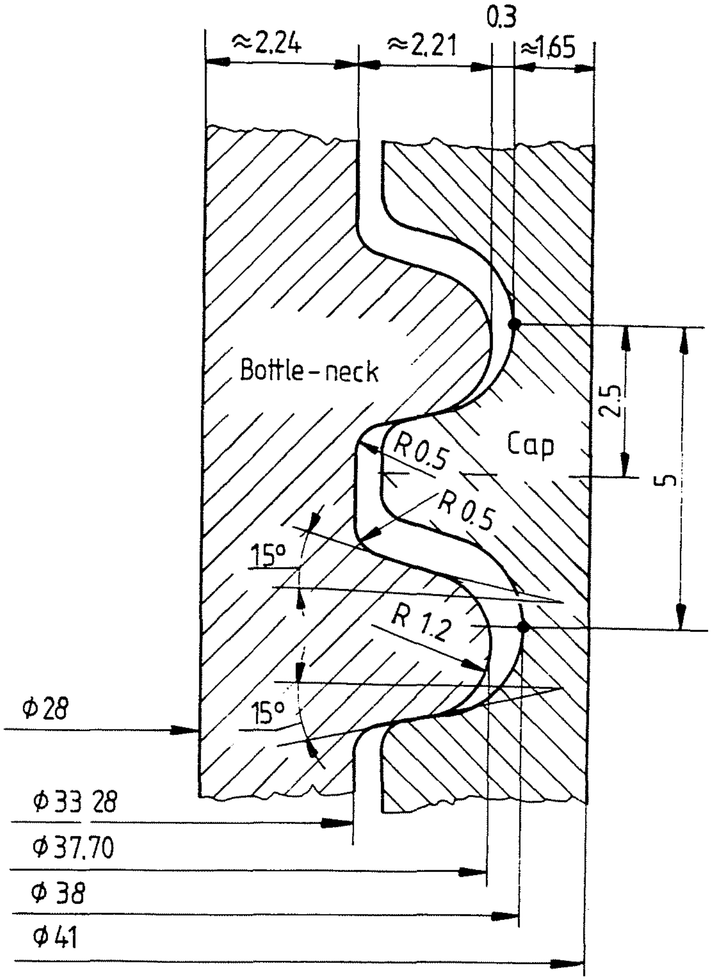


*Fig. 1a.* Geometry of thread profile A

important because the relative small load carrying capacity of the engineering material can optimally be utilized in case of geometry arising the possible smallest stress concentration. The principles to shape up thread profiles A and B are as follows:

- High lead to achieve sealing effect by small tangential displacement.
- Small height of thread to reduce the wall thickness required. It provides the minimum amount of engineering material used.
- Pressure-tight closing by relatively small hand force.
- Displacements caused by contact forces help pressure-tight closing.

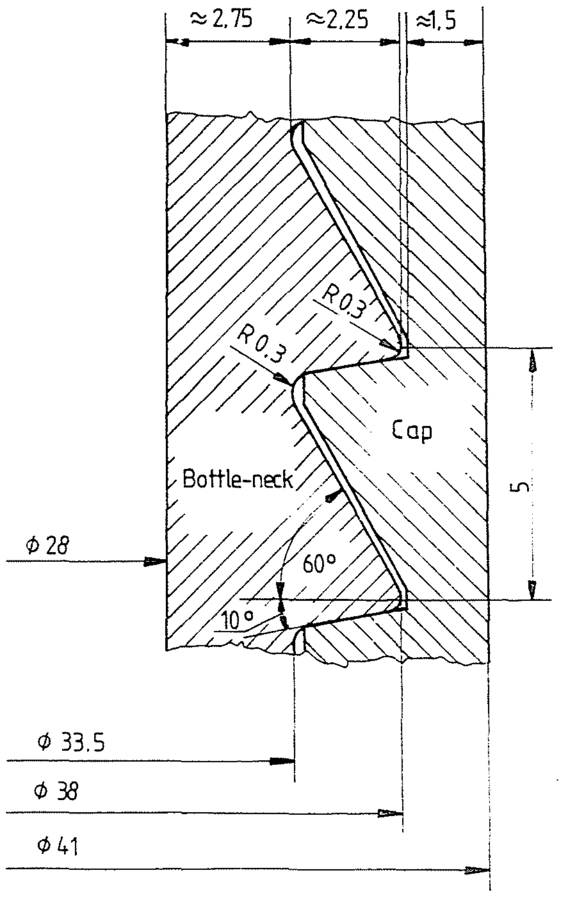


*Fig. 1b.* Geometry of thread profile B

Parallel the investigation of the optimal geometry of the profiles A and B we search for the best outer surface of the caps. The optimal geometry for caps as a whole was obtained by FEA.

## 2. The FE Analysis of the Threaded Connection between a Bottle and a Cap

To testify the suitability in this construction of the thread profiles A and B FE analyses were carried out [3], [4].

### *2.1 Basic Assumptions of the FE Model*

- All threads having small lead can be modelled by a series of rings with thread profile. This simplification allows axisymmetric FE mesh with triangular and quadrilateral elements.
- Along the contact surfaces stiff rod elements as frictionless contact elements transfer pressure normal to the common surfaces while parallel to these surfaces displacements are not restricted.
- Both displacements and deformations are small.
- Both connecting elements have linear elastic material laws.

### *2.2. Material Properties of the Engineering Material Applied*

Both bottles and caps manufactured by press-casting technology can be made of plastics with high variety. True values of local stresses and strains are influenced by the Youngs modules ($E$) and Poisson coefficient ($\nu$) of the engineering materials used though the places and relative values are not influenced. That is why at FEM investigations really applied values $E = 3000$ N/mm$^2$ and $\nu = 0.4$ are not influencing to determine the optimal geometry. The results obtained are valid for all the caps manufactured by similar technology from similar engineering materials.

### *2.3. The Results of the FE Analysis*

To determine the stress state and strain state of the cap and bottle connections (see *Fig. 2*) having thread profile A or B there were prepared finite element meshes given in *Fig. 3a* and *Fig. 4a.* Both types require equal areas in section therefore in case of equal loads it is easy to compare them. The *Fig. 3b* and *Fig. 4b* represent well the fact that the finite element meshes in the vicinity of the expected peaks of stresses were designed having fine mesh while at other areas it was satisfactory a mesh with less elements. The contact elements are located at the contact zone of the threads (*Fig. 3b* and *4b.*)

In our finite element models the boundary conditions were located where the bottle neck and body join to each other. This looks the most reasonable place as the behaviour of the threaded connection has no effect on the stress or strain state of this area. To model the load there were applied uniformly distributed pressure over the surface of the imagined flat gasket. As locking or loosening the cap by average hand-force can generate at about 1 MPa sealing pressure this was used as load during the FE analysis.

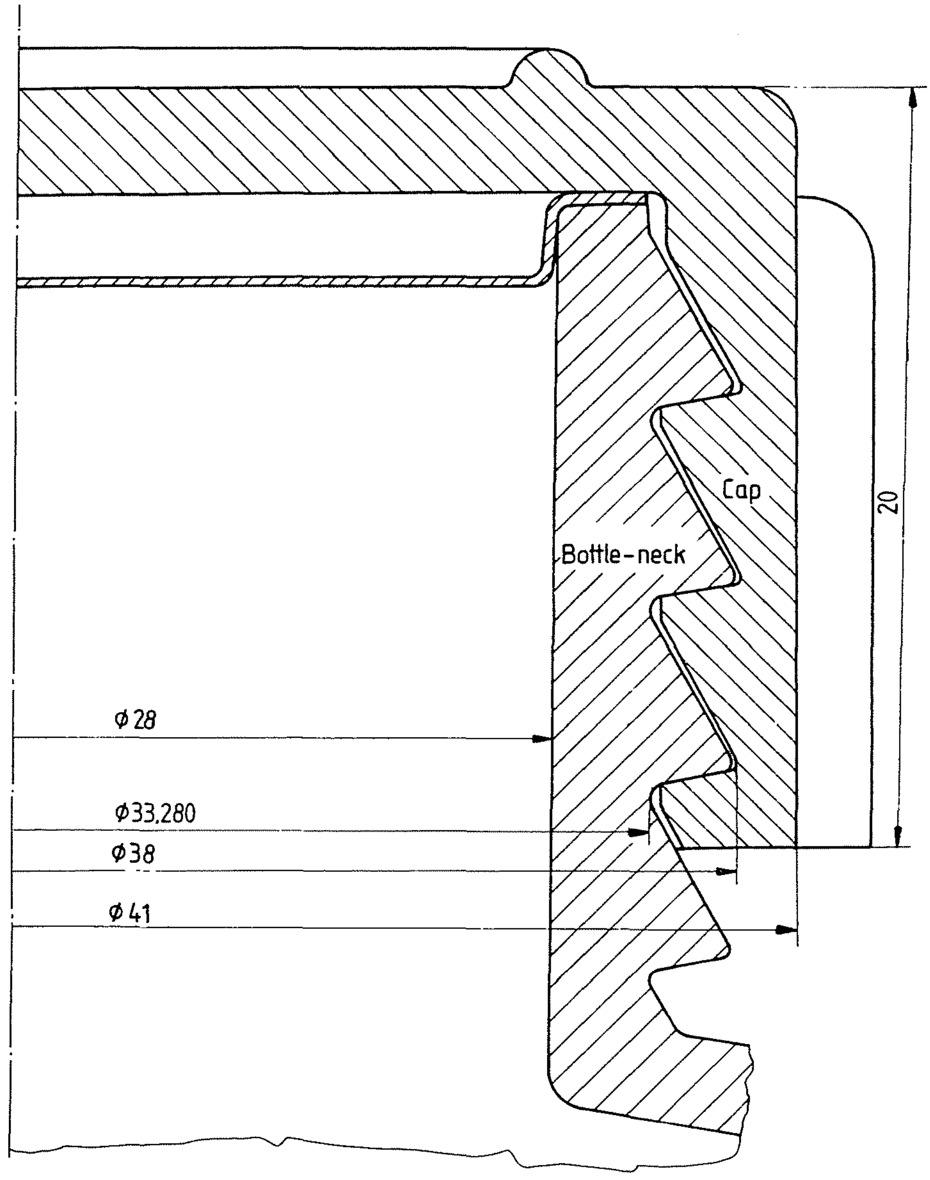


*Fig. 2.* Bottleneck – cap connection with thread profile B

The location of critical stress peaks is not influenced by the value of applied load therefore the local stress and/or local strain peaks were determined under unit contact pressure over the flat gasket area. To characterize the stress state equivalent stresses have been determined according to

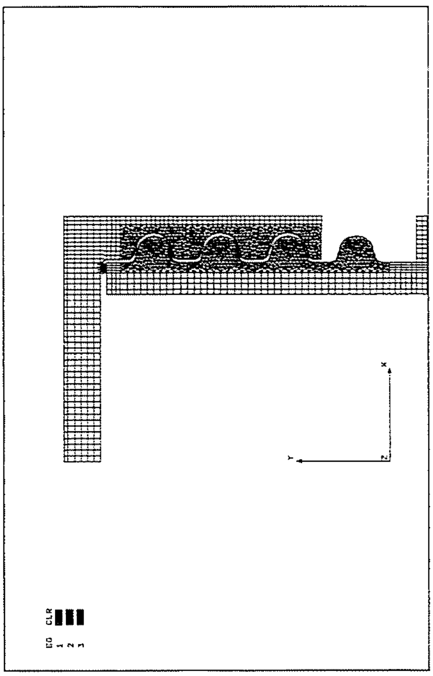

Fig.3a

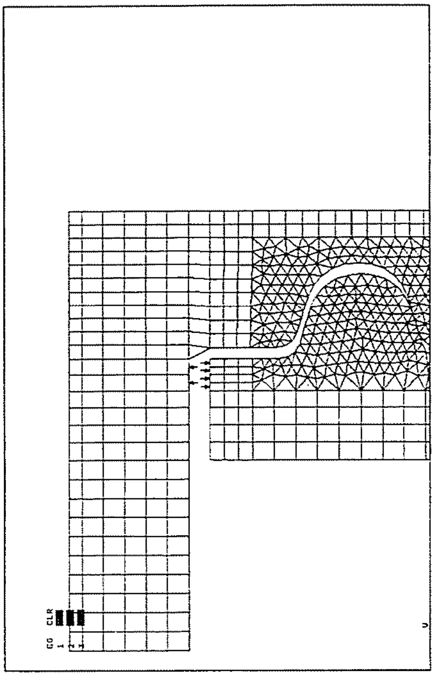

Fig.3b

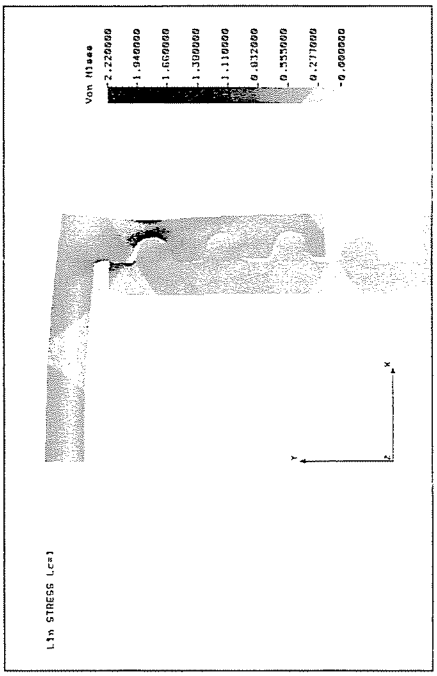


Fig.3c

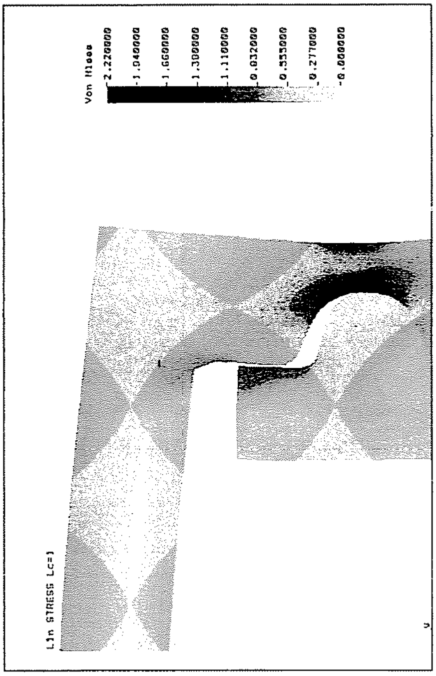


Fig.3d

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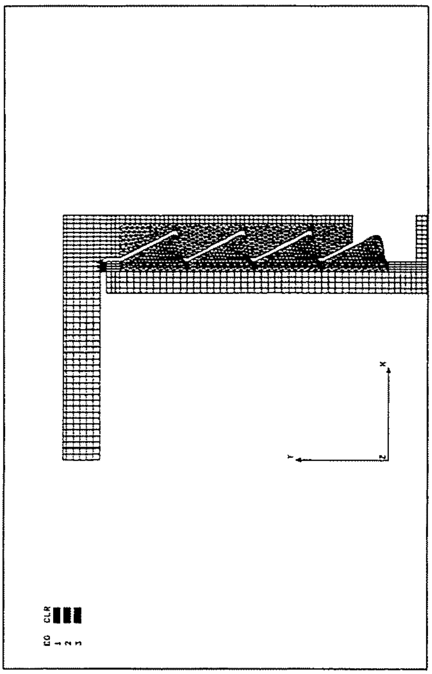

Fig.4a

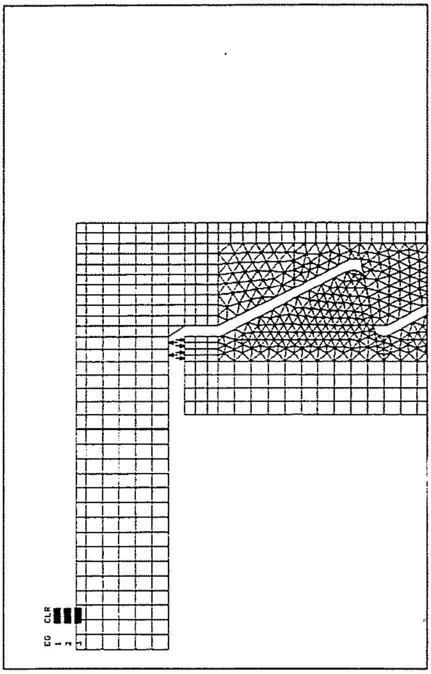

Fig.4b

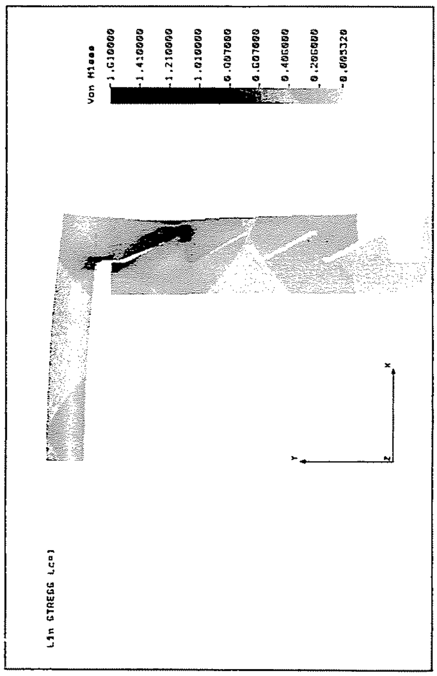

Fig.4c

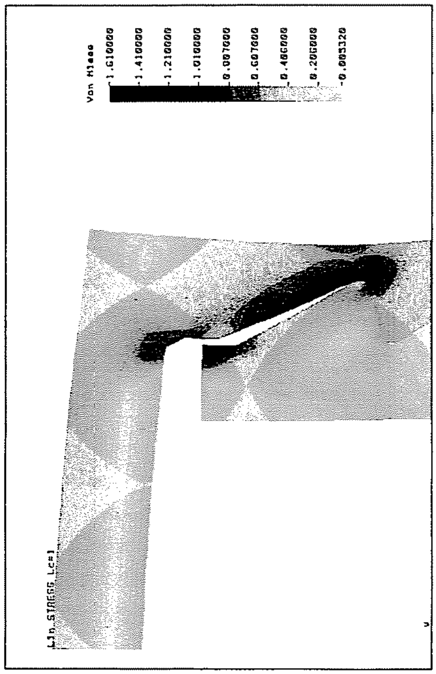

Fig.4d

H–M–H theory for the whole cap and for the bottle neck. Evaluating the equivalent stresses they are presented in *Fig. 3c* and *Fig. 4c* and the regions around the critical areas are given in enlarged scale in *Fig. 3d* and *Fig. 4d*.

The critical areas from the point of damage at both profiles are at the vicinity of the first thread root in the cap as *Fig. 3* and *Fig. 4* present or may directly be read from *Table 1*.

**Table 1**

| Name of model | No. of Figure | Relative mass [%] | Relative max. stress value [%] |
|---|---|---|---|
| A | 3d | 100 | 137.8 |
| M1 | 4d | 100 | 100 |
| M2 | 6a | 93 | 100.5 |
| M3 | 6b | 93.62 | 92.5 |
| M4 | 6c | 94.15 | 86.33 |
| M5 | 6d | 84.7 | 86.9 |
| M6 | 7a | 59.1 | 133.54 |
| M7 | 7b | 59.1 | 119.18 |
| M8 | 7c | 62 | 98.13 |
| M9 | 7d | 66 | 90 |
| M10 | – | 61.4 | 90 |

As *Table 1* makes it clear profile B has a significant less stress concentrating effect. This is the reason why the optimization of cap shape was carried out later with profile B. The critical areas from the point of damage determined by FE model show good correlation experiences of the engineering practice. This shows that the most frequent damage at plastic caps is the crack propagation along the first root of the internal thread at the closed end of the cap. See one example in *Fig. 5* given photo.

## 3. Optimization of the Cap Geometry as a Whole

To shape up the best cap it is worth to start with the results of the FE analysis carried out previously. The aim of the optimization is reducing the mass of the cap while the maximum equivalent stress should not be higher. Round the areas of low stress it is recommended to reduce, while in the vicinity of critical areas it is suggested to increase the wall thickness.

Searching for the optimal geometry of the cap the nominal sizes of threads as well as the sealing surfaces together with the load acting were kept constant. Keeping the above conditions we strive for to minimize the volume of engineering material used and to reduce values of stress peaks.

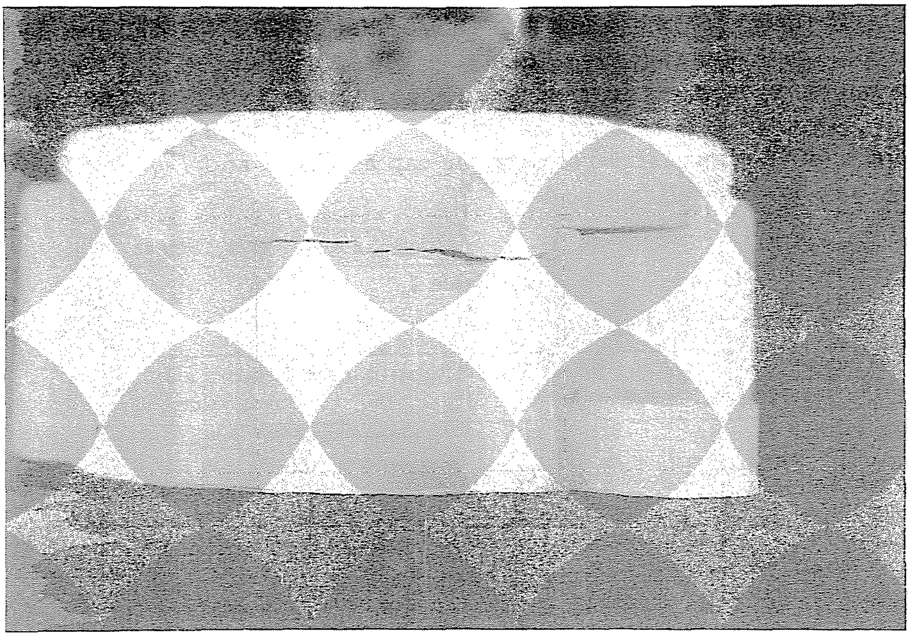

*Fig. 5.* Photo of a damaged plastic cap manufactured with thread profile B

The efforts have been done on this way can be seen in figures collected into two series in *Fig. 6* and in *Fig. 7*. Visible results are made more valuable by collecting numerical results into *Table 1.*

Our investigations were reduced on model M1 having B type thread profile as at the critical points it showed less stress concentration than model with thread profile A type.

To optimize the complex geometry of the cap its main sizes (outer diameter, nut height) were kept constant at first. The possibilities of product development to spare engineering material parallel to achieve stress-peak reduction can be seen in *Fig. 6a – Fig. 6d* collected together. To make easier the evaluation the numerical results have been collected into *Table 1.*

To simplify your guidance let's start at *Fig. 4c* and *Fig. 4d* where the stress-state of the original cap, model M1, can be seen.

During the optimization at first the stress free corner of the cap was removed, see M2 model in *Fig. 6a.* Beside the less amount of engineering material the maximum stress remained practically constant. At the model M3, presented in *Fig. 6b*, at the critical section of the cap an outer ring with hemi-cylindrical section was added to reinforce the cap. This reinforcing

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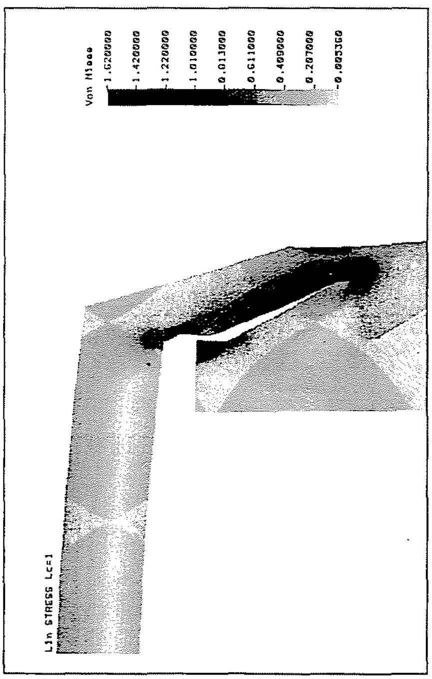

Fig.6a

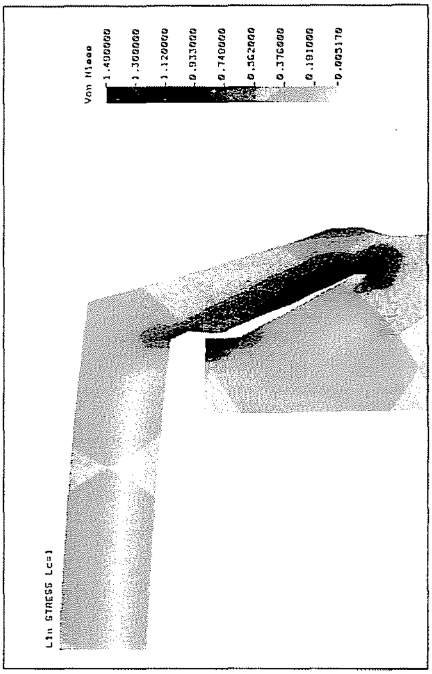

Fig.6b

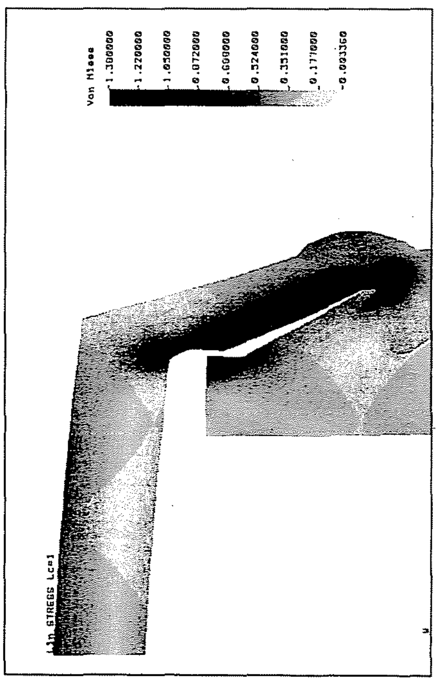

Fig.6c

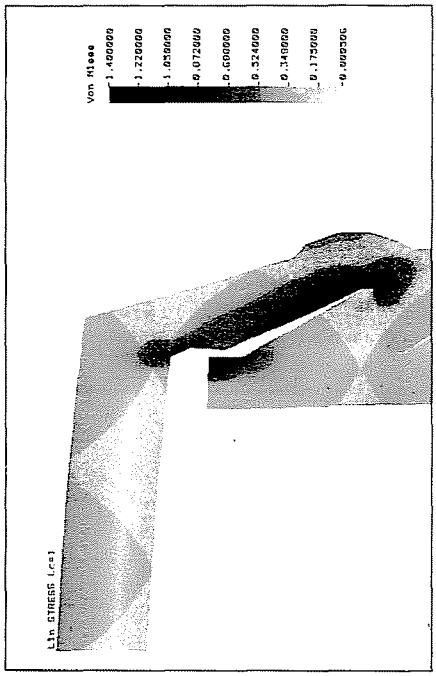

Fig.6d

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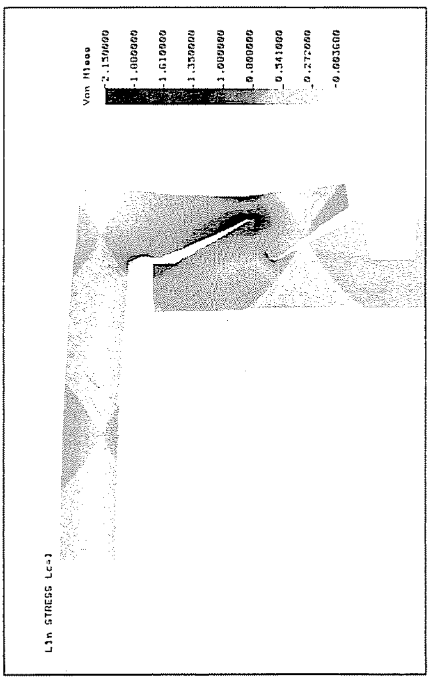

Fig.7a

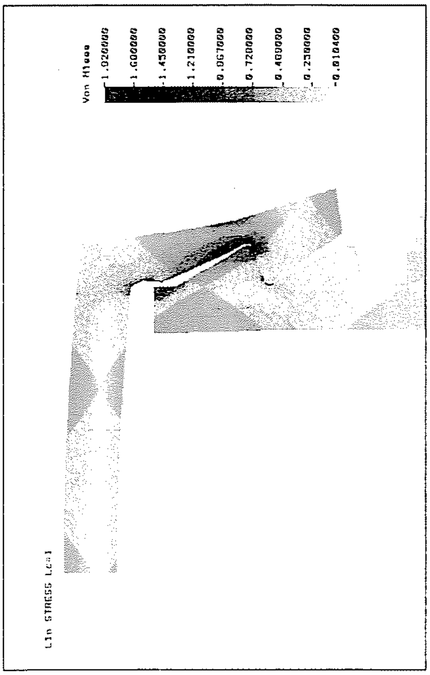

Fig.7b

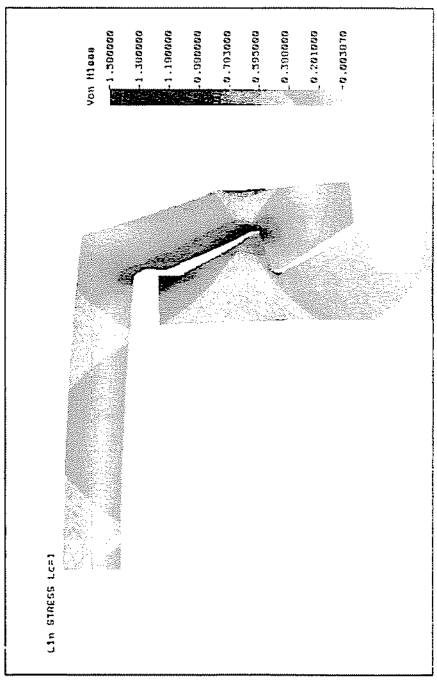

Fig.7c

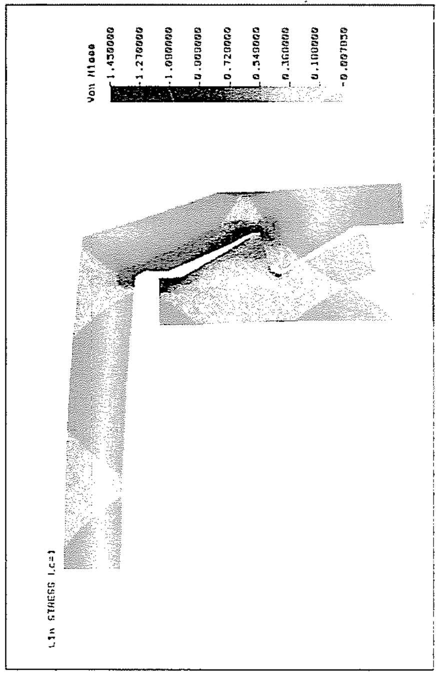

Fig.7d

with a small amount of engineering material surplus resulted 8% reduction in maximum stress level.

Increasing further this reinforcing ring size further decreasing in maximum stress level can be achieved as M4 model shows in *Fig. 6c*. The most significant reduction of the material was possible by reducing wall thickness of the bottle. This change produces 15% less need in material and the maximum stress also was reduced by 13%, as it can be seen in model M5 shown in *Fig. 6d*.

Optimization of the cap shape as a whole was continued by reducing the length of engagement and redesigning the outer surface of it.

The steps done are presented by a serie of figures shown in *Fig. 7a* – *Fig. 7d*.

The M6 model in *Fig. 7a* shows a short cap connection with one thread only while its outer surface remains simple cylindrical.

The same amount of engineering material can be distributed along the axisymmetry cap so that outer surface is a simple cone like the M7 model shown in *Fig. 7b*.

Remember the effect of outer reinforcing rings (Models M3 and M4) on the maximum stress level reduction it was developed M8 model (see *Fig. 7c*) with conical and cylindrical outer surfaces. Comparing to model M7 a very small amount of engineering material should be added and the peak level of stress does not exceed the level of the previously found. The best results of this optimization obtained at models M9 and M10. Model M9 (in *Fig. 7d*) was produced by extending outer surface of model M8 downward so that the No. of internal threads are left constant. The engineering material consumed is small and the reduction of the peak level of stresses comparing to model M1 is large. The required amount of engineering material is 66%, the maximum stress is 90% of the original ones.

Finally, at model M10 the cap is the same as at model M9, it is not presented by separate figure, the possibility still has not been exploited, reduction of wall-thickness at the bottle neck was carried out. Applying on model M10 the changes suggested before all together we can come totally that need of material is 61.4% while peak value of stress is 90% comparing to the original model M1.

All the results are easy to compare reading through *Table 1*.

## 4. Conclusions

The axisymmetric finite element model with contact elements is suitable to investigate stress and strain states and to optimize geometry of different caps. Finite element models made possible to compare different thread profiles and several outer shapes, as well as their different combinations. The mass of cap was reduced at about 60% of the original one as a result of the presented investigations.

During the next phase of this investigation it is planned to use more precise material models to describe behaviour of plastics in time under constant and repeated load conditions.

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