Improving the Accuracy of Rapid Tooling for Design Evaluation

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Abstract: The inherent technical limitations of rapid prototyping systems have lead to the development and industrial application of rapid tooling techniques. These techniques allow prototypes to be manufactured in final materials by the final manufacturing process. Enhanced silicone moulding is one such process which offers a rapid, low cost route to the manufacture of prototype plastic components in a metal impregnated rubber mould. During the moulding cycle the mould deforms under the high pressures and temperatures experienced and components produced suffer significant tolerance deviations. The main contributing factors are local deformation due to injection pressure and global mould expansion due to mould heating. In order to understand the individual effects and interaction of these deformation mechanisms on the part a finite element model of the system is developed.

Independent simulations of each of these phenomena are developed and indicate that results can be achieved within this approach using existing technology. Ultimately these simulations provide valuable information, which will help in developing an understanding of the deformation mechanisms involved. Furthermore, they provide the basis for a strategy to combine the two results, compensate for mould deformation and allow rapid low-cost production of more accurate prototypes suitable for thorough design evaluation.

Keywords: Rapid Tooling, Finite Element Analysis, Silicone Moulding

1. INTRODUCTION

The combination of finite element analysis (FEA) tools and advances in materials and processing methods within the injection moulding industry have allowed components of increasing complexity to be designed and manufactured [Stokes, 1995]. Associated with such components are equally complex moulds whose manufacture is expensive and time consuming. It is therefore vital that the component design be evaluated thoroughly with regard to performance and manufacturability before commitment is made to expensive production tooling. This evaluation is often best achieved through use of physical

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prototypes. While the application of rapid prototyping and machining techniques to prototype manufacture is established, the prototypes produced do not have the same materials and process characteristics as final production components [Barlow et al., 1996]. These limitations can be overcome through use of rapid tooling techniques. These techniques involve manufacture of a low cost mould from which prototypes can be obtained as outlined in figure 1.

The most widely used rapid tooling technique is vacuum casting as it is capable of providing low cost replicas in relatively short time periods. The process involves the manufacture of a mould by casting silicone rubber against a master pattern. This mould is then used in the manufacture of prototypes by vacuum casting polyurethane materials.

2. ENHANCED SILICONE MOULDING PROCESS

Although widely employed as a rapid tooling technique, vacuum casting does not provide a complete solution to the materials and process limitations of rapid prototyping [Pham et al., 1998]. Low mould material stiffness restricts the range of materials that can be processed to those which can be gravity cast, polyurethanes for example. Most engineering thermoplastics require injection under pressures which would deform the silicone mould. Consequently the process is only capable of producing prototypes in replica materials by a low pressure casting rather than an injection moulding process.

To overcome these limitations an enhanced silicone moulding process is used [Venus et al., 1996]. The process involves the addition of metal powder to the silicone rubber resulting in improved stiffness, hardness tests carried out showed an increase in hardness from 39 Shore A to 63 Shore A after addition of the metal powder [Dunne et al., 1998].

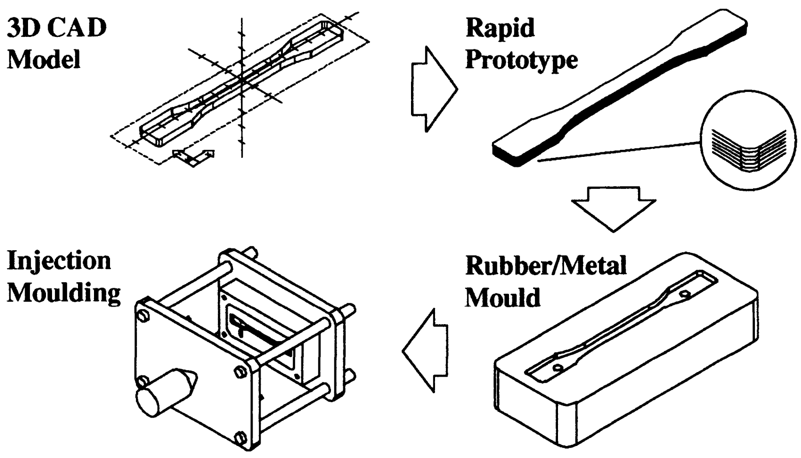

Figure 1; Enhanced Silicone Moulding Stages

While early process trials demonstrated that the injection moulding of thermoplastic prototypes using enhanced silicone moulds was possible further investigation highlighted limitations regarding the dimensional accuracy attainable. Parts produced, in this case tensile test specimens, were oversized with maximum deviations of 30% for part width and 40% for part depth. Although improved over pure silicone, mould material stiffness continued to be insufficient while global thermal expansion of the mould in the bolster was also found to impact on dimensional inaccuracies [Dunne et al., 1998].

These findings, which represent significant thickening of the part, have prompted further research towards process understanding and improvement using finite element techniques. Specifically this involves separation of the deformation mechanisms into the injection pressure effects and the mould heating effects and development of individual finite element models of these mechanisms.

3. INJECTION PRESSURE

During an injection moulding cycle high pressures, often in excess of 70 MPa are required to force the viscous molten plastic into the mould [Bryce, 1997]. When moulding into an enhanced silicone mould such pressures cause local deformation of the cavity. Investigation into these deformation effects comprises 2 main stages (i) simulation of the injection moulding process to obtain the pressure distribution and (ii) simulation of the mould deformation under the predicted pressure distribution as shown in figure 2.

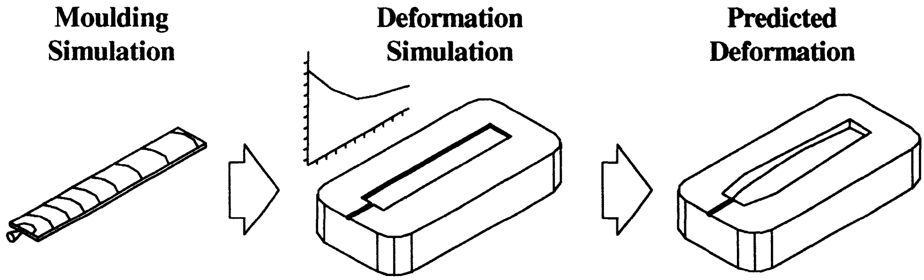

Figure 2; Simulation of the Deformation due to Injection Pressure

3.1 Injection Moulding Simulation

Several approaches to obtain the pressure profile in a cavity have been documented [Rao, 1991]. Typically, however the pressure profile has been used in the calculation of the clamping pressure required for successful part manufacture. From this the capacity of the moulding machine, which is normally based on the clamping pressure, can be decided. Nonetheless the approaches are valid for this situation.

Both Crawford [1987] and Rao [1991] report empirical techniques for a centre gated thin disc while Stevenson [1978] reports on how the pressure drop for other geometries can be obtained. For an end gated thin rectangular strip as chosen for this investigation the relatively simple empirical relation

$$P_z = P_o(1-(z/L)^{1-n}) \quad [1]$$

has proven satisfactory in describing the pressure at any point [Crawford, 1987]. P_o is the pressure at the gate, P_z is the pressure at any point a distance z along the length L of the part, n is the index in power law expression for the polymer melt.

An injection moulding simulation package was used to predict the pressure distribution. A thin rectangular strip geometry was chosen measuring 150mm long, 25.4mm wide and 3.175mm deep. A single gate was specified at one end of the part prior to meshing. Finally material and process conditions were specified. A medium impact ABS thermoplastic was used with a first order (power law) viscosity model [Kohnke, 1996]. Process conditions were set at melt temperature 230°C, mould temperature 60°C, injection pressure 45 MPa, packing pressure 18 MPa and packing time 5 sec [Bryce, 1997]. The simulation provided results for the pressure distribution along the part and across its width during the filling phase in 10% fill intervals and during the packing phase in 1.5 sec intervals.

3.2 Deformation Simulation

The most popular and widely employed finite element approaches to deformation simulation within solid continua are derived from assumptions of small strains [Kardestuncer, 1987]. These include plane stress, plain strain, thick and thin shell approaches which are valid for engineering materials such as metals and composites. For the case of rubbers which undergo large deformations often in the region of 500-1000% [Treloar, 1975] such approaches are no longer valid. As a result alternative techniques based on large displacements are required.

One such technique [Kohnke, 1996] employs the left and right Cauchy-Green deformation tensors which result in an expression for the nominal strain ε^N in terms of the principal stretch ratios λ_1, λ_2, λ_3 and principal directions a_1, a_2, a_3

$$\varepsilon^N = (\lambda_1-1)\,a_1a_1 + (\lambda_2-1)\,a_2a_2 + (\lambda_3-1)\,a_3a_3 \quad [2]$$

A finite element package was used to predict the effects of the pressure profile, determined using the injection moulding simulation, on the mould. A 2D static analysis was performed using a section along the flow direction of the mould with the material constrained in a manner corresponding to the mould closed position. As rubber materials exhibit highly non-linear behavior it is not possible to assign a value to Young's modulus, rather it becomes necessary to define the materials stress-strain behavior using mathematical models such as Neo-Hookean, Mooney-Rivlin and Ogden [Kardestuncer, 1987][Treloar, 1975][Charlton et al., 1994]. While these models are widely used, their application requires information which can only be obtained from a series of experimental tests. As yet, no specific information exists for the metal powder enhanced rubber, consequently generic properties are used.

4. MOULD HEATING

4.1 Deformation Simulation

In addition to the deformation caused by the injection pressure the mould also experiences deformation as a result of heating the mould, this is shown in figure 3. This heating is required so as to prevent the plastic solidifying too quickly which would restrict the filling of the mould.

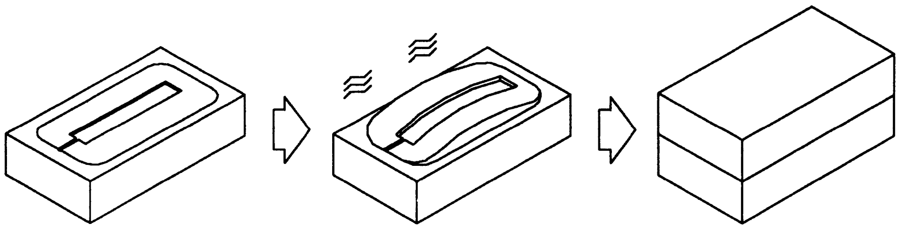

Figure 3; *Deformation due to Mould Temperature*

The deformation resulting from thermal expansion can be given by the thermal strain vector

$$\{\varepsilon^{th}\} = \Delta T\, [\, \alpha_x \;\; \alpha_y \;\; \alpha_z \;\; 0 \;\; 0 \;\; 0\,]^T \qquad [3]$$

where ΔT is the change in temperature and α_x , α_y , α_z are the thermal coefficients of expansion in the x, y and z directions [Kohnke, 1996]. This approach is applied using a finite element model of the silicone mould to predict the deformation due to mould heating. The simulation employed the same geometric model as before. The main material property required for the simulation was the thermal expansion. As an initial estimate the coefficient of thermal expansion (3.5 x 10^{-5} m/°C) for a cured silicone elastomer was used [Mark, 1985]. Finally a simplified thermal loading was applied. This comprised a uniform temperature rise to 60°C which is the recommended mould temperature for the material used [Bryce, 1997]. Consequently the deformation corresponds to the steady state situation only.

5. RESULTS

5.1 Injection Moulding Simulation Results

The injection moulding simulation provided pressure distributions throughout the part for both end of filling and packing stages of the moulding cycle. Figure 4 shows the distributions along the plan of the part, the gate is located to the extreme left. Finally, figure 5 plots the distributions and indicates the approximate maximum pressure distribution used in the deformation simulation.

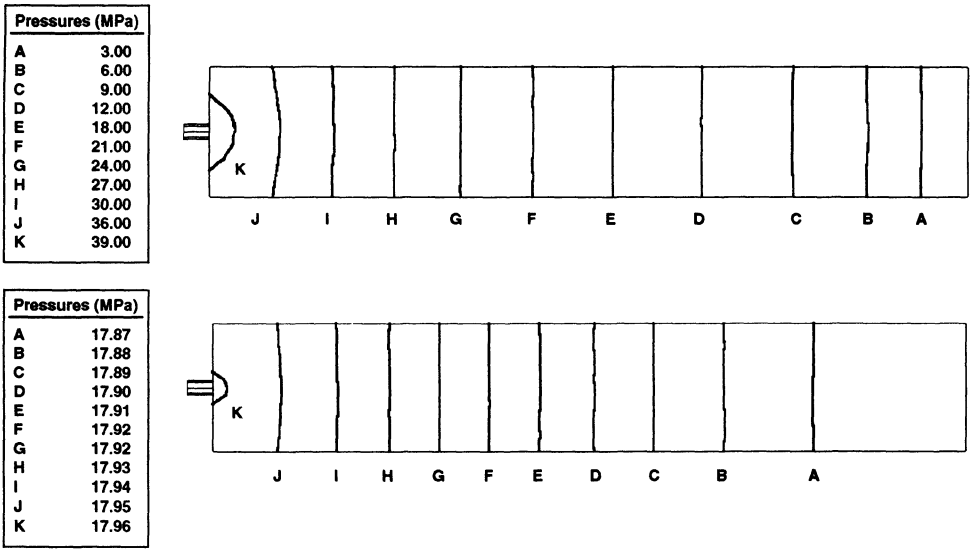

Figure 4; *Pressure Distribution at End of Filling (top) and Packing Stages (bottom)*

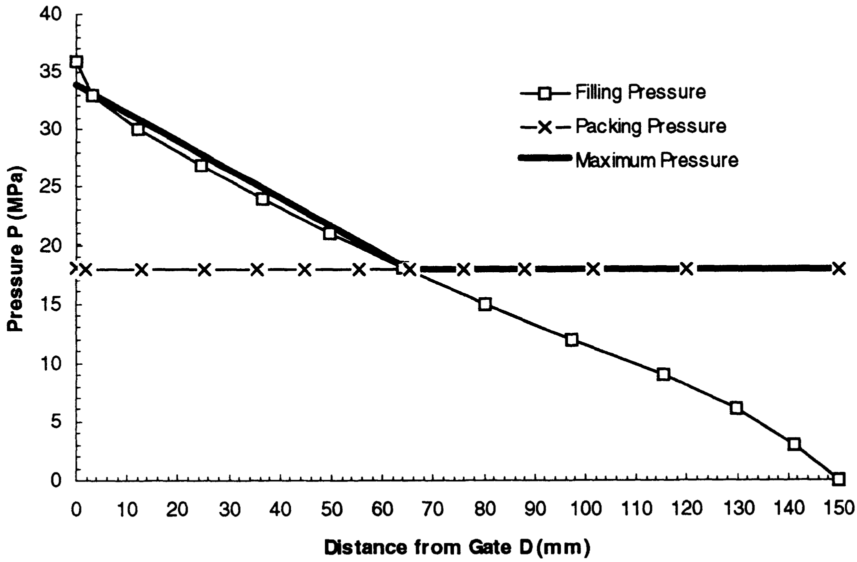

Figure 5; *Filling, Packing and Maximum Pressure Distributions*

5.2 Injection Pressure Deformation Results

The predicted mould deformation due to injection pressure is shown in figure 6. The gate is located on the left hand side. Figure 7 plots the predicted deformation δ_1 of the mould cavity in the vertical direction at 10mm intervals.

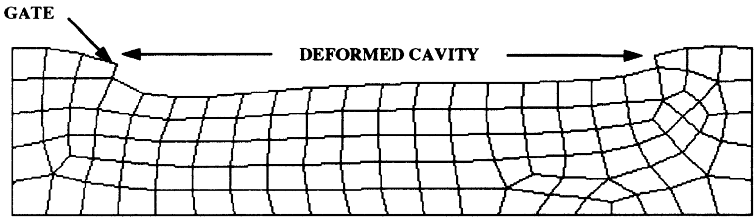

Figure 6; Predicted Mould Deformation due to Injection Pressure

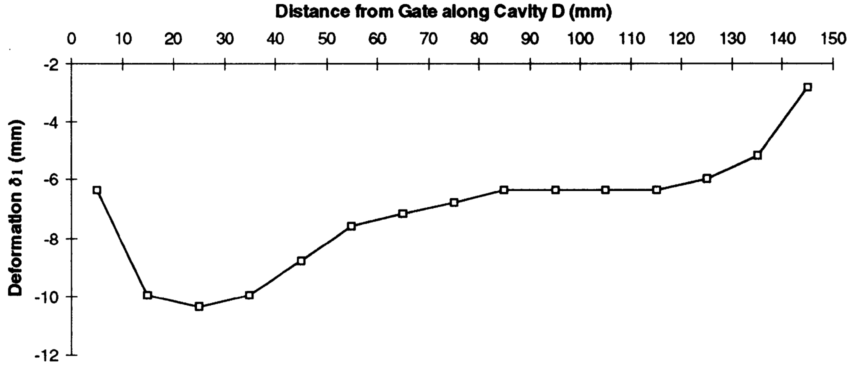

Figure 7; Predicted Deformation δ_1 due to Injection Pressure

5.3 Mould Heating Deformation Results

The predicted deformation due to mould heating is shown in figure 8. Figure 9 plots the predicted deformation δ_2 of the mould cavity in the vertical direction at 10mm intervals.

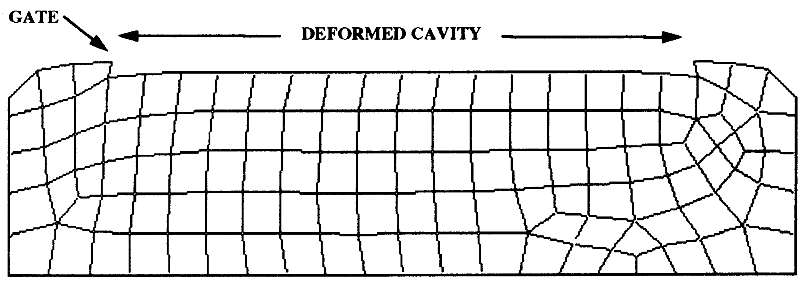

Figure 8; Predicted Mould Deformation due to Mould Heating

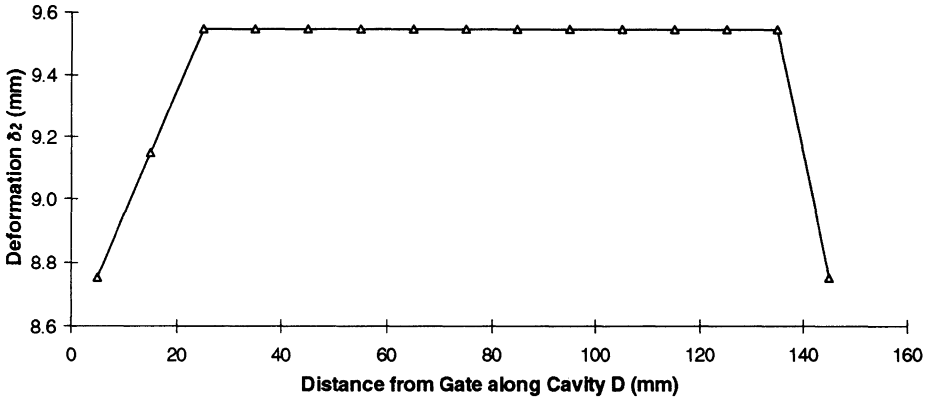

Figure 9; *Predicted Deformation δ_2 due to Mould Heating*

6. DISCUSSION

The results obtained from the injection moulding simulation showed that with the exception of areas close to the gate very little pressure variation was observed across the width of the part. This simplifies the analysis in that pressure distribution in one direction, along the part, need only be considered. Both filling and packing distributions are shown clearly in figure 5. The filling distribution is as expected, with the pressure reducing to zero at the end of the part. This concurs with the empirical relation described in section 3.1. For the case of the packing pressure, very little drop is observed along the part. This is due to the fact that the conditions are close to static.

The main limitation of the simulation is that a rigid mould is assumed, which in this case is not valid. This may be overcome through an iterative approach of obtaining the pressure distribution at say 10% fill, predicting the 10% fill deformed shape in the rubber mould, then using this predicted deformed shape as the starting geometry for 20% fill and so on. While this approach may be feasible and provide more realistic results, it has not been employed in the current work and so the distributions obtained are technically only valid for a rigid mould rather than a rubber/metal mould. Additionally the predictions will suffer from inherent simulation inaccuracies resulting from discretization, formulation, and numerical errors [Niazy, 1997][Kardestuncer, 1987].

In order to predict the deformation of the rubber it is necessary to decide which pressure distribution to use. Clearly the actual filling pressure is dominant in the area close to the gate. However, towards the end of the part the packing pressure dominates. These pressures exist at different times and therefore are related to particular temperature and solidification states for the part material. A thorough analysis would therefore require consideration of the effects of solidification and part temperature on the pressure distributions. For the purposes of this work, the maximum pressure distribution is used, this is indicated in figure 5 and represents a combination of both filling and packing pressures.

The mould deformation geometry is represented as a 2D section model and, in order to obtain an initial estimate, the material properties chosen to represent the rubber/metal mould were based upon generic rubber properties. These simplifications can, however, be easily addressed in future work through use of 3D geometric models and material properties obtained from experimental tests on enhanced silicones.

The predicted deformations show that, in the region where the filling pressure distribution is dominant (0mm $< D <$ 65mm, ref. figure 5), the deformation can be split into 3 main regions (i) the area immediately after the gate, up to $D =$ 15mm, where proximity to the edges of the mould which act as a support limits the deforming effects of the filling pressure (ii) the area between $D \approx$ 15mm and $D \approx$ 35mm where a maximum deformation of approximately 10mm is observed and (iii) the remaining section to $D =$ 65mm where the deformation reduces to approximately 7.2mm, this is due to the reduced filling pressure as we move further from the gate.

In the region where the packing pressure, assumed constant , dominates (65mm $< D <$ 150mm) we can also divide the deformation into 3 main regions (i) the area up to $D =$ 85mm where the neighboring effects of the filling pressure impact on local deformation (ii) the area up to $D =$ 115mm where a constant deformation of 6.4mm exists as a result of the constant load and (iii) the remaining area where we approach the edge of the cavity which acts as a support. Here a reduction in mould deformation is observed.

Finally results were obtained for the deformation due to mould heating. The analysis employed the same 2D geometry and generic materials properties as before. In addition, the loading comprised a uniform temperature rise throughout the mould, effectively treating the thermodynamic effects during the moulding cycle as static. Future models must therefore include the transient effects of not only the mould heating but also the effects of the solidifying hot melt. The predicted results showed a large constant vertical deformation of 9.5mm in the central section of the cavity (from $D \approx$ 25mm to $D \approx$ 135mm) with a varying deformation in the remaining front and end sections. As with the filling pressure deformation, the supporting effects of the edges of the cavity can be seen to impact on the deformation.

It is noted that, the prediction models used are highly simplified. Future work must therefore focus on refining the geometry, materials properties and loadings used within the models.

7. CONCLUSIONS

This paper reports the results of an investigation to examine whether the proposed route for deformation prediction was achievable with existing technology. Through separation of the main deformation mechanisms, it has been possible to predict deformations resulting from both the injection pressure and the mould heating. Coupled, however, with these specific results are many simplifying assumptions. Future work must therefore focus on refining the finite element model through a combination of theoretical and experimental work. These refined models can then be used to achieve a combined finite element model, which will provide the basis for a compensation strategy to be used in the design of a mould geometry which will produce accurate parts from an enhanced silicone mould.

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REFERENCES

[Stokes, 1995] Stokes, V.J.; Thermoplastics as Engineering Materials: The Mechanics, Materials, Design, Processing Link; In: *Transactions of the ASME*, pp. 448 - 455; Vol. 117.

[Pham et al. 1998] Pham, D.T.; Dimov, S.; Lacen, F.; Techniques for firm tooling using rapid prototyping; In: *Journal of Engineering Manufacture*, pp. 269-277; V 212; N B4; UK.

[Barlow et al. 1996] Barlow, J.W.; Beaman, J.F.; Balasubramanian, B.; A rapid mould-making system: material properties and design considerations; In: *Rapid Prototyping Journal*, pp. 4-15; V 2; N 3.

[Venus et al., 1996] Venus, A.D.; van de Crommert, S.J.; Rapid SLS Tools for Injection Moulding; In: *Proc. 13th Conference of the Irish Manufacturing Committee*, pp. 837-845; Limerick.

[Dunne et al., 1998] Dunne, P.; Young, P.; Byrne, G.; Dimensional Stability in Rapid Tooling Processes; In: Proc. *15th Conference of the Irish Manufacturing Committee*, pp. 485-494; University of Ulster.

[Bryce, 1997] Bryce, D.; Plastic Injection Moulding... material selection and product design fundamentals; Society of Manufacturing Engineers; USA; ISBN 0-87263-488-4.

[Rao, 1991] Rao, N.; Design Formulas for Plastics Engineers; Hanser; Munich; ISBN 0-19-520908-7.

[Crawford, 1987] Crawford, R.J.; Plastics Processing; Pergamon Press; UK; ISBN 0-08-032627-7.

[Stevenson, 1978] Stevenson, J.F.; Polymer Engineering and Science 18; p.573.

[Kohnke, 1996] Kohnke, P.; ANSYS Theory Reference; Release 5.3; 7th Edition; DN-000656.

[Kardestuncer, 1987] Kardestuncer, H.; Finite Element Handbook; McGraw Hill; ISBN 007033305X.

[Treloar, 1975] Treloar, L.; The Physics of Rubber Elasticity; Oxford Press; UK; ISBN 0 19 851355 0.

[ABAQUS, 1997] ABAQUS Rubber Elasticity Course Notes; Hibbitt, Karlsson & Sorensen Inc.; USA.

[Charlton et al., 1994] Charlton, D.; Yang, J.; A Review of Methods to Characterize the Behavior of Rubber for use in Finite Element Analysis; In: *Rubber Chemistry and Technology*, pp. 481-503; Vol. 67; Part 3.

[Mark et al., 1985] Mark; Bikales; Overberger; Menges; Encyclopedia of Polymer Science and Engineering; Vol 15; 2nd Edition; Wiley; ISBN 0-471-80947-0.

[Niazy, 1997] Niazy, A.; What you should know about FEA; In: *Machine Design*, pp. 55-58; V69 N21.

[Mohr, 1992] Mohr, G.; Finite Elements for Solids, Fluids and Optimization, UK, ISBN 019856368X.