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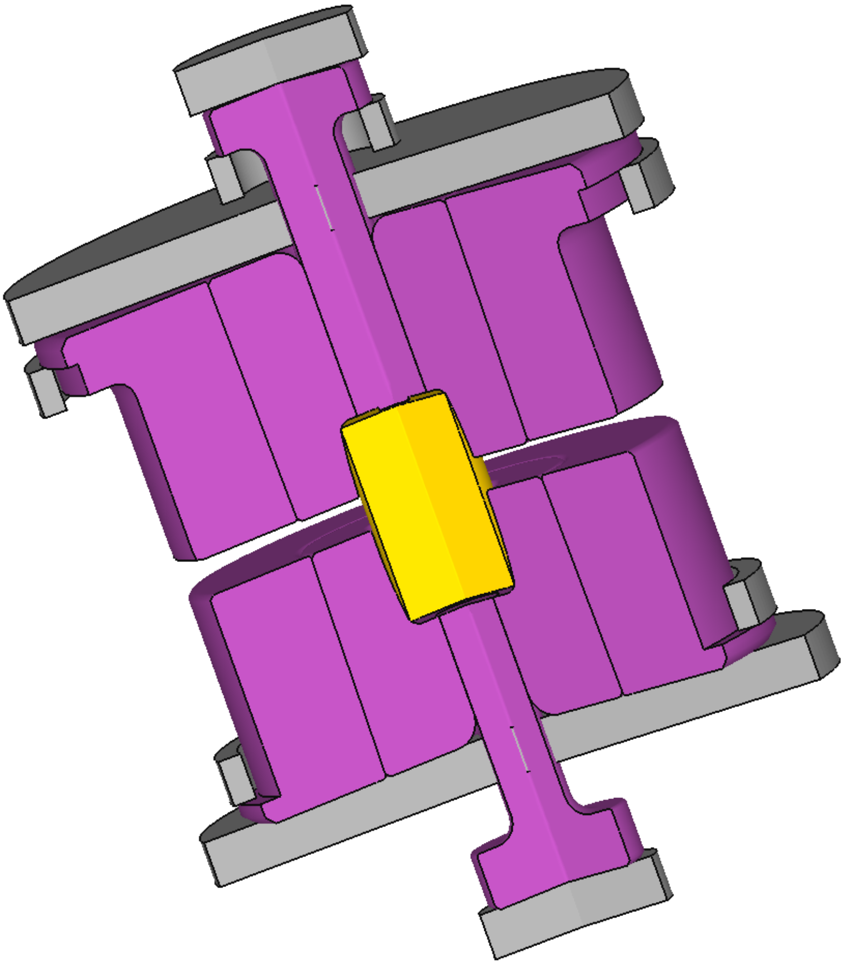

Optimization of shrink fit in press tools

Master’s thesis in Production engineering

John Lövgren

Department of Product and Production Development
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Cover:
An assembly of press tools

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ABSTRACT

Cold forming is a cost effective way of producing parts with a near-net-shape. High forces during the forming process make the press tool to have a limited service life. The service life is determined when the tool starts to crack or when wear causes inaccurate geometries of the part. In order to increase the service life often a shrink fit container is used to pre-stresses the tool to avoid cracks.

This work was conducted to investigate if an optimized shrink fit ratio has a beneficial impact for the service life of press tools. Meanwhile a new design of experiment (DOE) module in the simulation software DEFORM was evaluated in the aspect of its usefulness to assist in designing the press operation.

Information from production and literature were gathered to obtain knowledge how todays press tools are performing and how an optimized shrink fit ratio would effect the service life. This knowledge was then used to optimize the current press tools. The optimization process was performed in DEFORM. The optimization process was aimed to increase the service life of the press tools. The Service life was estimated with Morrow’s local stress approach. An endurance test was performed to validate the service life estimations. In order to evaluate the DOE module two problems were defined; optimizing of blank geometry and evaluate the movement speed and friction’s influence on the maximum effective stress in press tool.

Simulations showed that a changed shrink fit ratio often resulted in an unchanged or lowered service life. However if the design of the press tool allowed a changed shrink fit ratio the service life estimated to increase with a factor of two. This was also validated with an earlier production test. The endurance test indicated that the service life calculations can be trusted. Evaluation of the DOE module displayed that it could be useful to use when designing a press operation.

Keywords: Cold forming, Shrink fit ratio, Service life calculation, DOE

PREFACE

Optimization of shrink fit in press tools is a master thesis that is a completion to the Production Engineering master program at the Department of Product and Production Development, Chalmers University. The thesis has been performed at Manufacturing Development Center (MDC) at SKF Göteborg.

ACKNOWLEDGEMENTS

I would like to thank Johan Facht and the team of Material Technology at MDC for providing the opportunity to perform this master thesis. I would also express my gratitude to Johan and the team for the support and motivation during the thesis.

I would also thank Ulrika Vestin for her invaluable support. Without her the project had been almost impossible to complete.

I'm also deeply grateful to Per Nyqvist for his insightful comments and suggestions.

Göteborg, May 2015

John Lövgren

List of acronyms

CAD – Computer Aided Design
CMM – Coordinate measurement machine
Dead end – Turning point for press cycle
DEFORM – Simulation software
DOE – Design of experiments
FEA – Finite Element Analysis
FEM – Finite element method
HCF – High Cycle Fatigue

Contents

1 Introduction

SKF has been one of the leading bearing manufacturers since 1907. They produce many types of bearings for examples ball bearings and roller bearings. The difference between these two is the rolling elements. The difference can be seen in Figure 1 and Figure 2. In Gothenburg today the company only produces roller bearings. (SKF, 2014)

Figure 1 - Roller bearing

Figure 2 - Ball bearing

Rollers for the roller bearing can be manufactured by cold forming. Cold forming is a cost effective manufacturing process due to its speed and its near-net-shape capabilities. The limitation lays in the size of the rollers. When the roller grows large the forces needed to form it growths out of scale and then other ways of forming the rollers are needed.

This project will be working with a production line that has mechanical eccentric presses with the capability to achieve a pressing force up to 320 tons. The production line is producing around 40 product variants. The size of the product variants varies from 0.1 kg to 0.7 kg with a diameter variation from 25 – 45 mm and with a length variation 28 – 60 mm.

Primary tools of the press operation are insert dies, support pins and shrink fit containers. Each product variant has a specific insert die. The insert die is what shapes the ingoing material to a roller. The ingoing material is called blanks. To be able to remove the formed roller from the insert die support pins are used. Figures of an insert die and a support pin can be seen in Figure 3 and Figure 4. The shrink fit container has the function to pre-stress the insert die to be able to withstand more forces and keep dimensional accuracy. A shrink fit container can be seen in Figure 5.

Obtaining a cost effective process the insert dies need to have a predictable and long service life. Therefore SKF had a request to investigate the possibility to achieve a longer and more predictable service life of the insert dies with an optimized shrink fit. With this request came also a secondary request to evaluate a new module in the simulation software (DEFORM). The module is a *Design of* experiment (DOE) module and the company wants to try out its capabilities and believed that it would be appropriate to do so when searching for an optimized shrink fit. This lead to the master thesis “*Optimization of shrink fit in press tools”.*

The project was carried out at *Manufacturing Development Center (MDC) at SKF*. The project was accomplished by one student with the background from mechanical engineering and the master program Production Engineering. Simulations were performed in DEFORM. This software is a finite element software that is specialized in deforming material (Scientific Forming Technologies Corporation, 2014). The project was carried out during the spring of 2015 and will be finished in middle of May. Stakeholders of this project were Factory Gothenburg at SKF as the receiver, MDC as the client of the project with Johan Facht as the supervisor. Supervisor from Chalmers was Per Nyqvist from the Department of Product and Production Development.

Figure 3 - Insert die

Figure 4 - Support pin

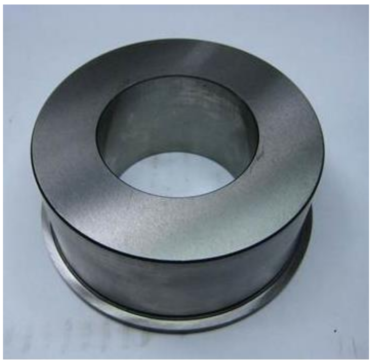


Figure 5 - Shrink fit container

1.1 Aim

The project "*Optimization of shrink fit in press tools"* aim was to find an optimized shrink fit to obtain longer and more predictable service life of insert dies. Meanwhile the project was also aiming to evaluate the DOE module in DEFORM to see its capabilities to create and maintain press tools. The aim could be summarized as

Evaluation of the impact an optimized shrink fit has on the service life for press tools with the help of simulation

1.2 Objective

Main objective with the project was to gain knowledge how the impact of the shrink fitting has on the service life for the insert dies. With this knowledge recommend how new tools could be designed to meet the wish of a long service life. Also the possibility to create a template for designing shrink fit container that only needs a few well defined parameters.

The secondary objective was to investigate how useful the new DOE module in the DEFORM software is when designing the press operation.

When the project was completed it were able to answer these following questions:

- Would an optimized shrink fit increase the service life of the insert dies with the current design?
- Could an optimized shrink fit for a product variant be calculated from its attributes?
- Is the current design of the shrink fit container sufficient to achieve a service life level that is satisfactorily?
- Is the DOE module suitable to assist the designing of the press operation?

1.3 Limitations

The project was limited to search for an optimized shrink fit for the press tools that are used in the production line specified in the introduction. Thus a shrink fit ratio that is suitable for todays insert dies without a need of changing its profile design. Therefore the project was not going to analyze what impact a new shrink fit will do to the geometry of a produced roller. Due to the limited time frame the project was also limited to only search for an optimized shrink fit for a few selected product variants.

Changes to the outer diameter of the shrink fit container were not allowed due to existing machine components uses this surface.

Manufacturing of the insert dies is made by hard turning. This process will leave residual stresses on the surface of the insert dies. The stresses depend on the process parameters that are used during the manufacturing and today there are several suppliers of the tools. Thus the stresses could be assumed to differ between the suppliers. (Matsumoto, et al., 1999) Therefore these stresses were not included in the simulation due to difficulties to measure them and their probability to vary from tool to tool.

Evaluation of the shrink fit was only performed on product variants that had a design with a shrink fit container with an internal diameter of $60mm$. This was because the majority of the product variants were using this size of a shrink fit container.

Physical test was limited to one endurance test due to the project's limited time frame and because of the cost aspect. The product variant that was tested was chosen in consultation with the supply chain department to suit the current production.

Due to the dividing of the press operation in an assembly and forming operation it became an advanced task to make a DOE to optimize the shrink fit. Therefore the project was looking at two other common tasks in designing the press operation.

2 Theory

Below presents the theory that was used during the project.

2.1 Shrink fit ratio

In order to calculate the shrink fit ratio between two objects equation [1] was used. How to define the interference can be seen in figure 6. With this approach it's possible to compare the level of shrink fit between objects that have different geometries. For examples comparing press tools that produces small and large products. If the interference level between objects is the parameter that defines the shrink fit then the possibility of comparing two objects with different sizes disappears.

$$Shrink\ fit\ ratio = \frac{\delta}{u_0} \qquad [1]$$

$$\delta = u_o - u_i \qquad [2]$$

$$\delta = interference\ of\ shrink\ fit, \qquad u_o = inner\ radius\ of\ stress\ ring,$$
$$u_i = outer\ radius\ of\ insert\ die$$

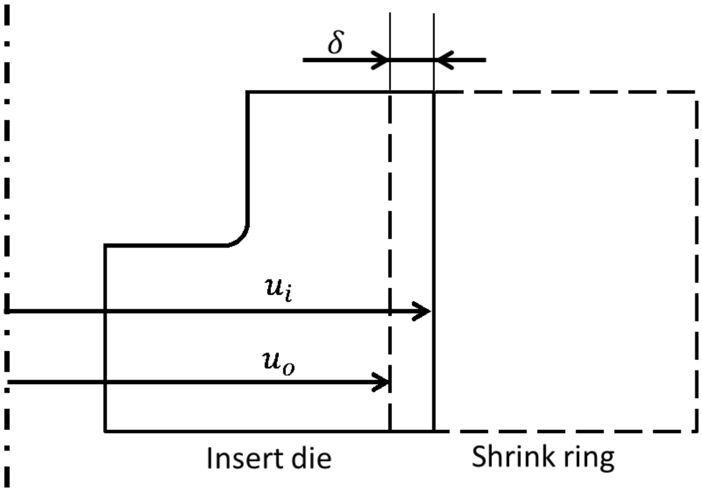


Figure 6 – Defining interference

2.2 Estimation of service life

To estimate the service life of an object due to fatigue failure Morrow's local stress approach can be used, equation [3]. This approach assuming the failure type is high cycle fatigue (HCF).This formula is derived from Morrow's local strain approach under the assumption that the plastic strain is close to zero and thus could be neglected. To estimate the service life the amplitude and mean stress are used together with material specific coefficients. How to defining the amplitude and mean stress can be seen in figure 7. The derivation of equation [3] can be found in appendix A. (Bannantine, et al., 1989)

$$2 \cdot N_f = \left(\frac{\sigma_a}{\sigma_f{}' - \sigma_m}\right)^{\frac{1}{b}} \qquad [3]$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \qquad [4]$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad [5]$$

$$2 \cdot N_f = Number\ of\ reversals$$
$$\sigma_f' = fatigue\ strength\ coefficient, \qquad b = fatigue\ strength\ exponent,$$
$$\sigma_a = stress\ amplitud, \qquad \sigma_m = mean\ stress$$

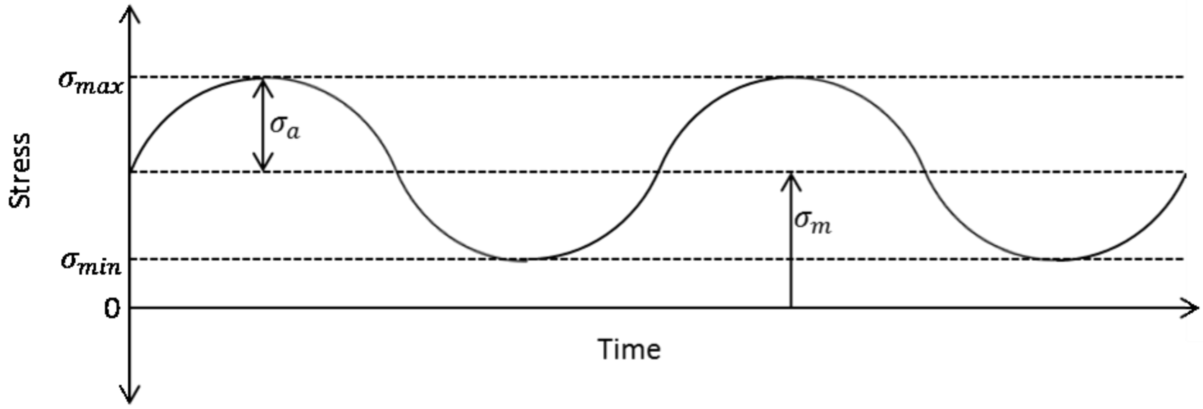


Figure 7 – Stress over time curve

2.3 Parameterization of drawings

Modeling objects in DEFORM can either be made by importing CAD files that represents the geometry or describe it manually with coordinates. Because of the projects access restrictions to the CAD files of the press tools they were manually transferred from printed drawings to the software.

A drawing defines a curve with a starting point, an end point and a radius between them. This can be seen in figure 8. Meanwhile the software defines a curve with a starting point, an end point and the intersecting point of the tangents of the two first points. This can be seen in figure 9. In order to calculate the intersecting point equation [6] and [7] were used. The derivation of the equations can be found in appendix B.

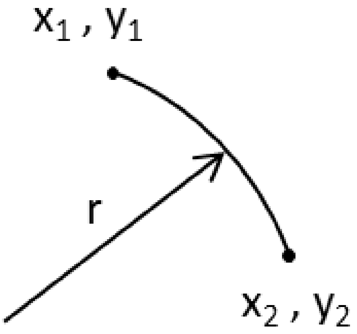


Figure 8 – Radius between two points

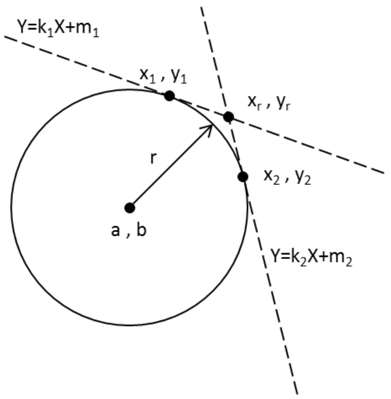


Figure 9 – Define intersecting point behind curve

$$X_r = \frac{k_1 \cdot X_1 - k_2 \cdot X_2 - Y_1 + Y_2}{k_1 - k_2} \qquad [6]$$

$$Y_r = k_1 \cdot (X_r - X_1) + Y_1 \qquad [7]$$

2.4 FEM – Finite element analysis

DEFORM is using finite element analysis (FEM) to calculate stresses, heat generation etc. for a defined problem (Scientific Forming Technologies Corporation, 2014). FEM is a numerical approach to solve general differential equations in an approximate fashion. These equations describe a physical problem over a defined region. It could either be one-, two- or three-dimensional. Instead for seeking an approximate solution over the whole region FEM seeks a solution that holds for part of the region, finite elements. Even if the variable varies in a nonlinear fashion over the whole region it may be a good approximation that it varies linear within an element. Elements that represents the region is called a finite element mesh. The elements is defined with nodal points. (Ottosen & Petersson, 1992)

3 Method

The project was started to define the different tasks that should be performed during the project. In figure 11 the tasks is visualized. A description of the different tasks is presented below.

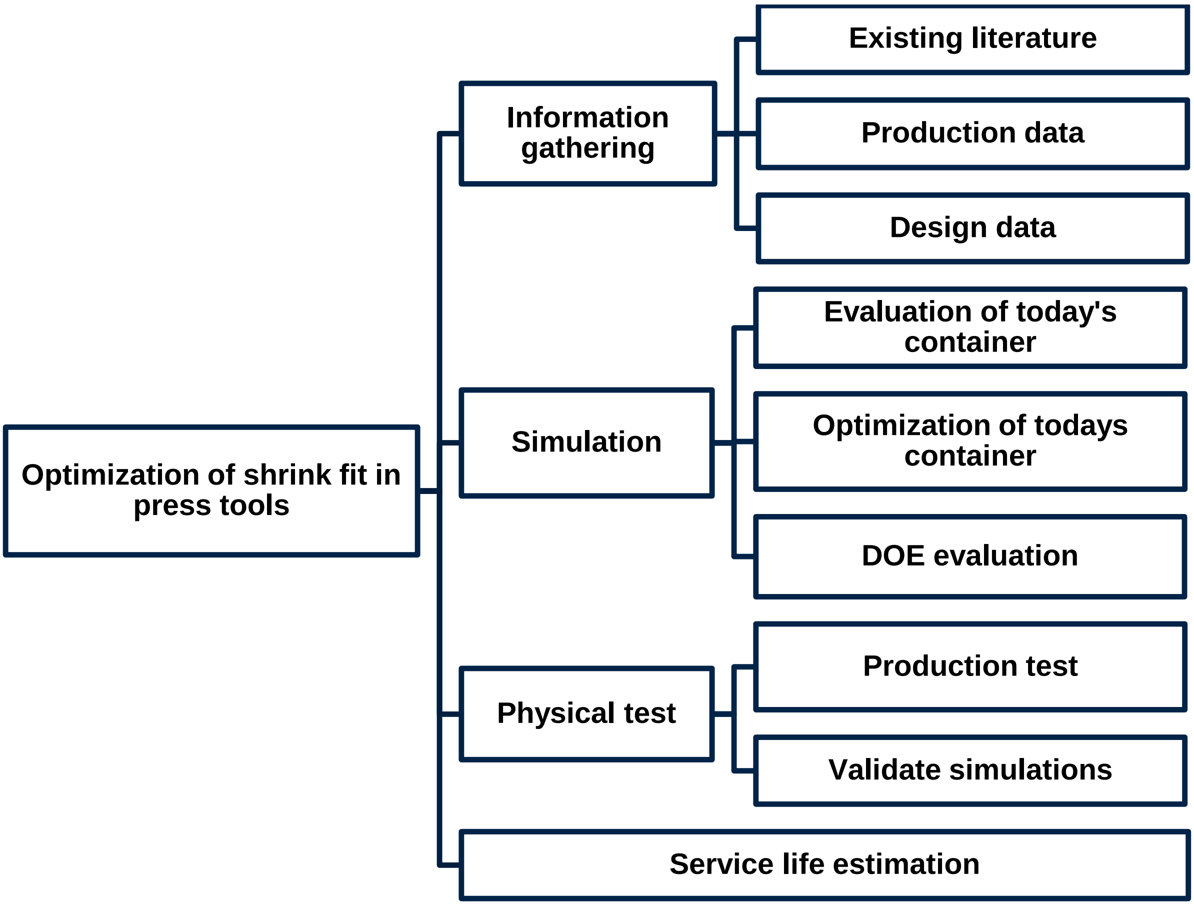


Figure 11 – Project tasks

3.1 Information gathering

First part of the project was to gather information that were currently available both in-house and could be obtain from external sources. This step could be divided into three sub branches, which were: *literature survey, collection of production data* and *collection of design data*. The literature survey was made to scout after earlier work made in this area. Chalmers library internet resource Summon was mostly used to find relevant articles and papers.

Available production data of the current service life of the insert dies for the different product variants was collected. This data was gathered manually by transferring paper records to Microsoft Excel for evaluation. From the service life data a mean service life was calculated for respective product variant. In order to address the lack of detailed causes for replacing an insert die an analysis was performed to see how often a specific product variant consumed more tools than the set target. It was also collected information of the press machines different properties.

Furthermore a survey was conducted to see if there is any data available from earlier attempts in changing the shrink fit and obtaining a changed service life that could be used for the project. An interview was held with the design department to learn how shrink fit containers are designed today. Thus to find out if there were any design rules or templates.

3.2 Simulation

In order to imitate the reality as much as possible the press operation was divided into two parts. One when the insert die and shrink fit container gets assembled and one with the actual forming operation. How the simulation was setup is explained in the chapter 3.2.1.

The simulations of the different product variants were divided into two parts. In part one different product variants where simulated with the original shrink fit ratio. This was to search for any commonalities between the product variants different attributes and their maximum effective stress. In part two a few selected product variants were simulated with different shrink fit ratios. The selected product variants were chosen to cover most of the variation of the product variants attributes. The range of shrink fit ratio was chosen to have approximately half of the range from the earlier production test and the original one. The original shrink fit ratio is 0.33% and 0.58% was used in the production test. Thus the ratios that were chosen were:

$$0\%, \quad 0.165\%, \quad 0.33\%, \quad 0.455\%, \quad 0.58\%, \quad 0.705\%, \quad 0.83\%, \quad 0.955\%$$

An attempt was also made to induce an axial pre-stressing force. This was done by applying the pressure as a boundary condition on the top and bottom of the insert die. This can be seen in figure 12. The pressure levels that were examined were $200MPa, 300MPa$ and $400MPa$. These values were chosen because of it is roughly the pressure between the shrink fit container and insert die when they were pre-stressed with the shrink fit ratios of 0.33%, 0.455% and 0.58%. The pressure was divided in half so that one half of the pressure was defined on the top part of the tool and the other half on the bottom part of the tool.

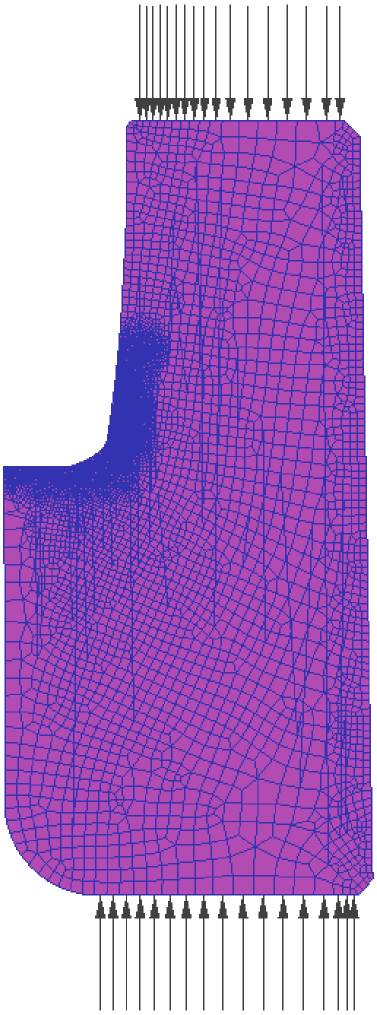


Figure 12 – Axial pre-stress of lower insert die

3.2.1 Model and running simulation

In order to simulate the first step was to define the geometries for the different objects that the press operation contains. DEFORM was capable to import CAD files that describes the different parts geometries. Due to access restrictions for the project, the objects geometries were manually transferred from printed drawings to the software. This was done with the help of Microsoft Excel. A template was created to quick transfer the measurement from the printed drawings to a format that software could read. With this approach the project has also a greater control over the geometry of the different parts. For example fillets and radius that are not of interest could be taken away from the models. In this project all radii equal or smaller than $0.5mm$ were neglected. In order to represent those geometries in a good way the density of the mesh must had been considerably denser than the density that were used for the objects in the critical regions. If the density would have further increased it would have lead to an increased number of elements for the different parts and resulted in an increased simulation time.

The geometries of the different parts were defined by its nominal measurements. If the tolerance for a specific measurement was skewed the modeled measurement was set in the middle of the tolerance. For example a measurement that looks like this: $\emptyset 12.00\,^{+0.00}_{-0.20}$ it was modeled as $\emptyset 11{,}90$.

In order to describe a radius between two points in DEFORM the software needs the start point, the end point of the radius and the point where the tangents meet behind the radius, see figure 13. To calculate this point equation 6 and 7 were used.

When the geometry was defined, a mesh grid was laid on top of it. In order to get a good representation of the geometry in the critical areas the element length was aimed to be shorter than $0.1mm$ for the insert dies and support pins. For the shrink fit container the shortest elements aimed to be around $1.5mm$. This was because the containers don't have any critical areas.

In order to specify where the density of the mesh should be heavier (have more and smaller elements) mesh windows were used. Mesh windows creates a mesh grid that has elements with different sizes. With a mesh window it is possible to specify which size ratio the elements inside the window should have compared to the ones outside the window. Mesh windows can be seen in figure 14. This feature was also linked to the movement of the tools. Thus when remeshing during the forming operation was needed the mesh was generated with the same parameters as it was when the original mesh was created.

In order to handle node penetration between the objects a maximal interference depth was set to half of the element length of the shortest element of an object (Scientific Forming Technologies Corporation, 2014). Thus for the insert dies and blanks the maximum interference depth was set to ~0,05mm.

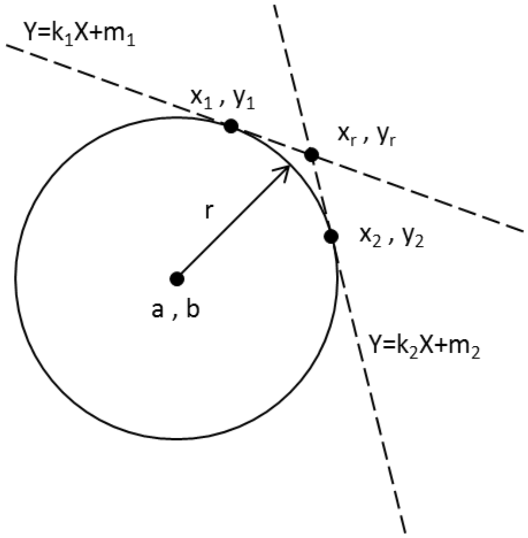


Figure 13 – Define intersecting point behind curve

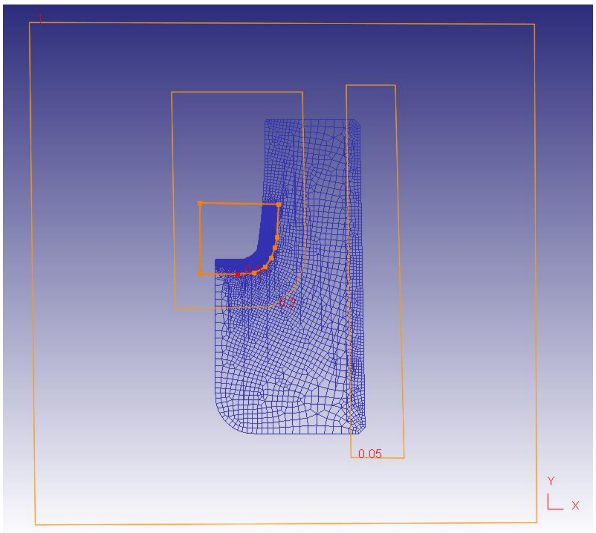


Figure 14 – Mesh windows

When the software remeshs during the simulation it becomes interpolations errors when it transfer the data from the old mesh to the new one. Different meshes on the same object can also give slightly different results. To minimize the potential difference in the results caused by different meshs the same shrink fit container model was used for every product variant. Furthermore when a new shrink fit ratio was used for the same product variant the same insert die was used. The same approach was made for the blanks. For the support pins two versions were used. One with the nominal size and one with its diameter decreased with $0.05mm$. This due to when a higher shrink fit ratio is used the clearance between the insert die and the support pin goes towards zero. When the clearance becomes near zero the support pins was changed to the smaller one. This change was made where the shrink fit ratio exceeded 0.58%.

Next the objects were assigned with their respective material. Material data for the shrink fit container and the blank was gathered from DEFORMs material database. Material for the shrink fit container was defined as tool steel and for the blank common bearing steel was used. For the insert dies and support pins an own material model was created based on the available data found on the suppliers homepage. The tool material is kept unrevealed because of the company discretion but it can be assumed to be a steel material.

When simulating the forming operation the project assumes that the blank was a plastic object and the other parts were elastic ones. Depending on if an object was defined as an elastic or elasto-plastic object the software calculating stresses differently. In the first case the software uses a stiffness matrix that was not going to be updated during the simulation and if the displacement was large under the simulations the calculations will be misleading. The simulations that were performed during this project have a displacement around 10mm and thus this type of calculation can’t be used. The option was then to assign the objects as elasto-plastic objects. This lead to that flow stress data was needed to simulate the process. Data for the shrink ring and the blank could be collected from the DEFORM material database. For the tool material the supplier didn’t provide this data. However the first assumption that the tool material should be considered as elastic solved this problem. By defining the yield strength for the material as an arbitrary large value the object will behave as an elastic one. A drawback with this approach was when defining objects as elasto-plastic is convergence problems which lead to longer simulation times (Scientific Forming Technologies Corporation, 2014).

In order to make the simulations of the forming operation more similar to reality they were thermocoupled. The objects were set to an initial temperature of $20°C$ and with an environment temperature of $20°C$. This mean the simulations that were performed could be identified as the first product that is produced in an order.

Friction type and its value were set to shear with a constant value of 0.12. This was the recommendation from DEFORMS vendor that suggest this value for dry steel insert dies (Scientific Forming Technologies Corporation, 2014). Same goes for the heat transfer coefficient that was set to a constant value 11 N/sec/mm/C for the forming. The friction and heat transfer boundary condition were set between all the objects in the simulation.

The simulation of the press operation was made to replicate to the real situations as close as possible. Therefore the process were divided into two stages, first a separate simulation that assembles the insert die with the shrink fit container. Then the assembly simulation’s last step was imported to the forming simulations. In this way the project was able to have good control over the shrink fit and that the software was working as intended.

Simulation of the assembly was modeled so the insert die and shrink fit container was in contact with each other and two rigid object is supporting them in position. This can be seen in figure 15 and 16. One of the rigid objects which was in contact with the insert die is also acting as the primary die. The assembly speed was set to 20 mm/sec. The assembly was completed when the Z-distance between the rigid objects reaches the nominal height of the shrink fit container. These simulations were not thermo-coupled as the heat generation during the process was considered negligible because of the low process speed. The temperature of the tools will also have time to be stabilized to the room temperature before they were placed in the press machine in the reality. Due to this the temperature generation created by the assembly operation was not of interest for the next simulation. The step size of the simulation was set to $0.05mm$.

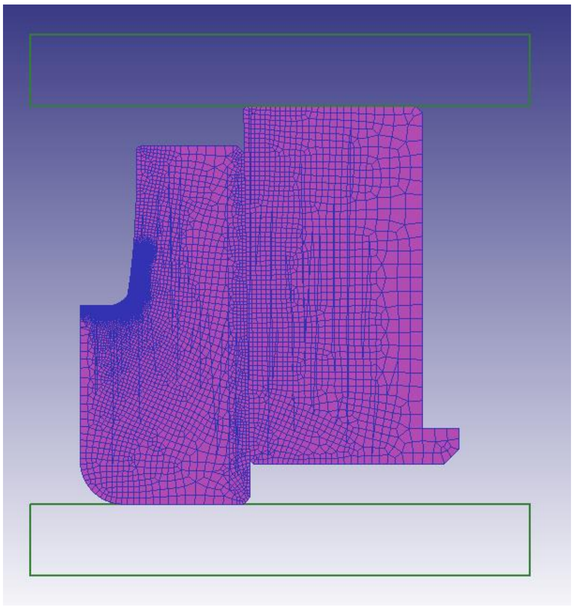


Figure 15 – Assembly of lower tool

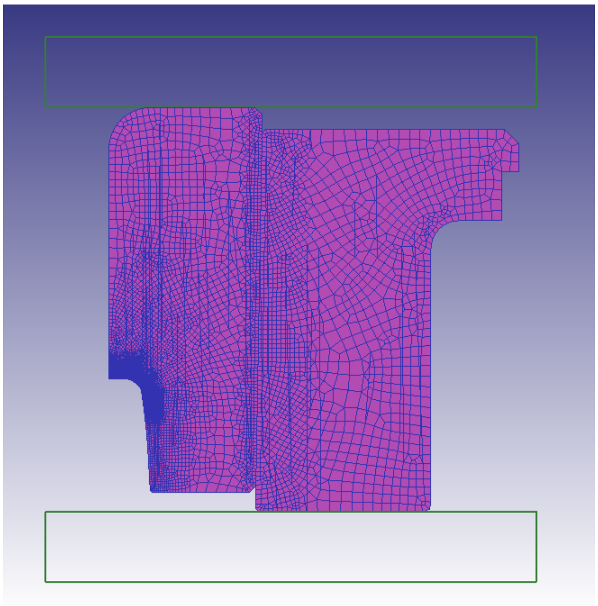


Figure 16 – Assembly of upper tool

The forming simulation was modeled with the lower insert die as the starting point. The blank and the upper insert die were then positioned in contact with each other. Support pins were aligned horizontally with their respective insert die. Due to this approach the support pins will be a few hundredths of a millimeter below the edge of the insert die when the forming operation reaches its dead end. Depending on the product variant size and the designs of the insert die and support pin the distance will differ. Due to the time limitation it was not possible to adjust the support pins to be at horizontal level with the insert dies and therefore the pins were allowed to be compressed during the forming process. Also the height reduction was in the same levels as the allowed node penetration and because of this they were not causing any high stress components in the corner of the insert die. Six rigid objects were used to support the tools during the forming process. All rigid objects except the *Bottom Support* and the *Stop* were moving during the simulation. *Top Support* and *Top Pin Support* were the ones that act as the moving ram during the forming with the *Top Support* set as the primary die. The objects *Top Lift* and *Top Pin Lift* were following the primary dies movement during the forming operation. The movement of the ram was set to follow mechanical press cycle with a stroke of $120mm$ and with a movement speed of $0.5\ cycles/sec$. How the forming operation was modeled can be seen in figure 17. In figure 18 the forming operation has reached its dead end position.

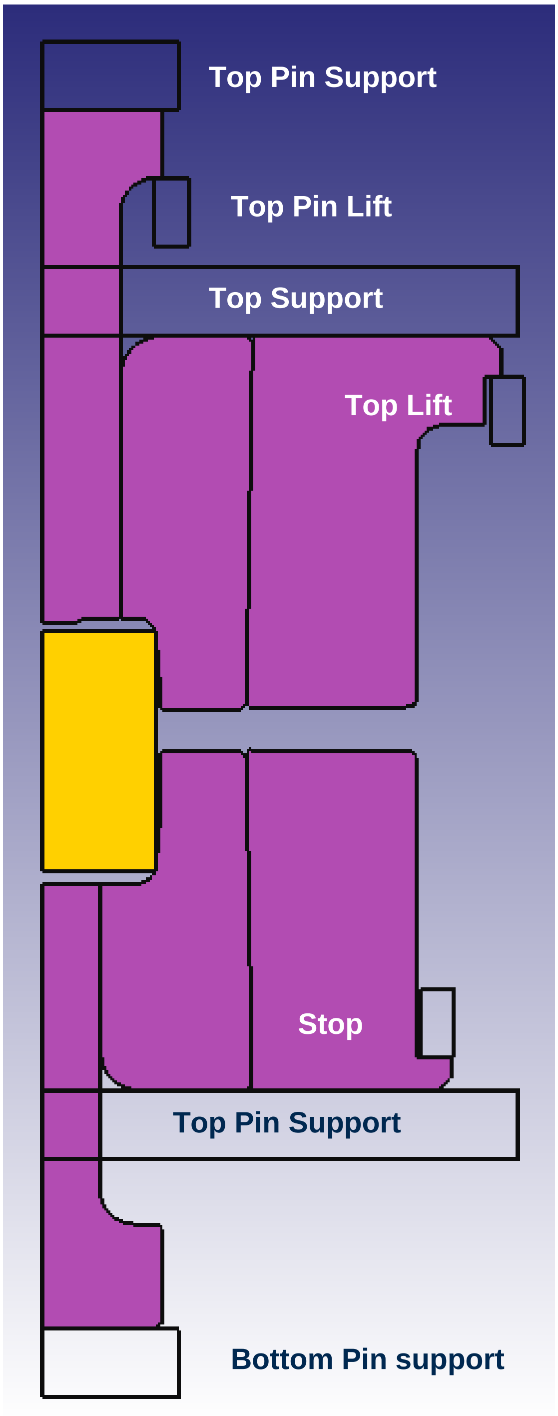


Figure 17 – Modeled press operation

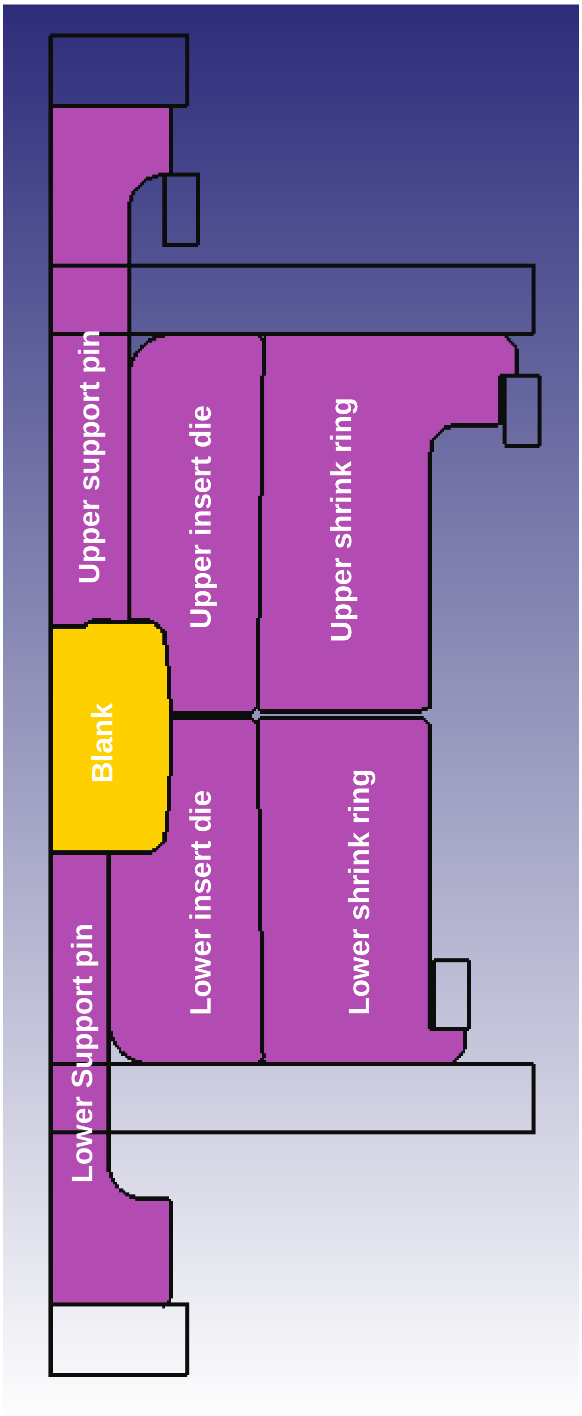


Figure 18 – Press operation in dead end

When the simulation reached the dead end the movement speed was changed for all of the rigid objects. *Bottom Pin Support* was set to start moving upwards with the same movement speed as the primary die had before it reached the dead end. This was made in order to lift the roller out of the lower insert die. The movement speed for *Top Support* and *Top Lift* was increased to $0.8\ cycles/sec$ and the movement speed for *Top Pin Support* and *Top Pin Lift* was increased to $0.6\ cycles/sec$. This was done to get an early release of the roller from the insert die to save simulation time.

To ensure that all simulations were forming the roller as equally the rollers height was set as the stopping parameter. Why not the rollers diameter was chosen as the stopping parameter was because the software needs a non-zero distance between two objects to be able to stop. Therefor it was not possible to use the blanks itself or the distance between the wall of the insert die and the blank because the distance becomes zero. The reason why the stroke of the ram wasn't used as the stopping parameter was then it had to be assumed that the design of the insert die and blank is optimized. Thus the distance between the tools when they reaching the dead end were the same as well the displacement of the tool was the same for every product variant and shrink fit.

DEFORM was using distance between nodes to determine when to stop a simulation. Due to remeshing during the simulation the nodes changes places. Thus it was not possible to select a stopping distance between two nodes from the start of the simulation. Therefore the simulation was first set to stop at a specified stroke close to the dead end. When the specified stroke was reached nodes were selected from the lower and upper tool close to the inner radius. Then the roller's height was set as the stopping parameter between those nodes and the simulation was continued. When the simulation had reached to the specified height of the roller it was stopped and the simulation was defined to have reached the dead end. When ejecting the roller from the tools the simulation was set to run until a specified time was reached.

Step size of the simulations was set to 0.01mm for the first part of the simulation. When coming close the dead end of the simulation the step size was reduced to 0.001mm. When ejecting the roller from the press tools the step size was first set to 0.001mm and when the roller had no longer any contact with the inner radius of the lower insert the step size was increased to 0.01mm.

In some of the simulations the software was not able to converge to a solution when ejecting the roller from the press tools. In order to make a simulation to converge to a solution the elasto-plastic objects needed to be changed to elastic ones. Thus the stiffness matrix was not updated during the last part of the simulation. But the simulation had already reached their maximum stress levels and from now on the simulation will only show the spring back of the material. The lower insert die don't experience any large displacement due to it was stationary and therefore the calculation with a non-updating stiffness matrix could be considered as valid. Also for the upper tool was only in contact with the roller for a short time before it releases from each other. In terms of contact during displacement it was around $1mm$ of displacement. It means an approach with elastic objects will also be valid due to the small displacements.

When a simulation was completed it was post-processed to extract data of the calculated stress levels. Only data from the area of interest, inner radius of insert dies, were extracted. 50 nodes starting from the bottom of the insert die's inner radius and upwards along the boundary were selected and data were extracted, figure 19 and 20. This data were then exported as a .txt file for further analyze.

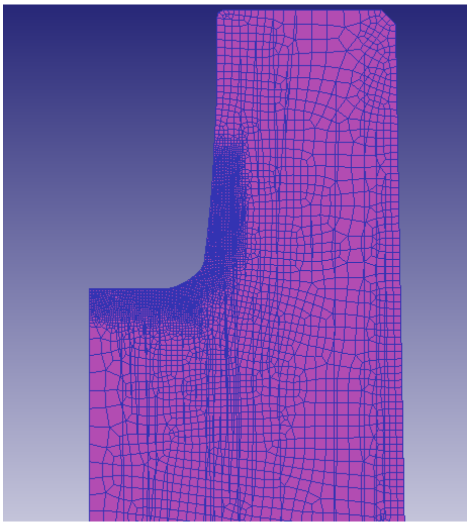


Figure 19 – Insert die

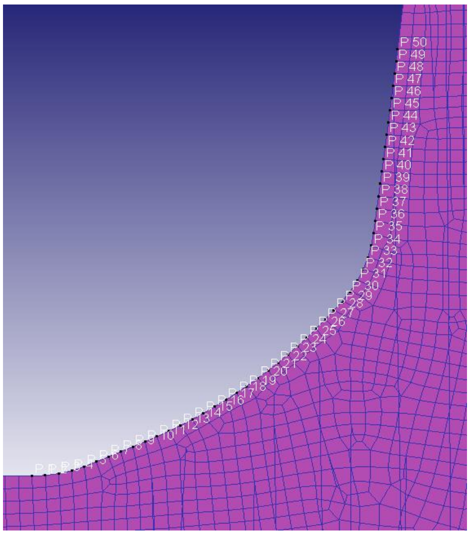


Figure 20 – Node selection

3.3 Practical test

In order to validate the service life estimation based on the results from the simulations one production endurance test was performed. Two other tests have been conducted to validate the software. This was to evaluate the software's capabilities to accurate replicate the reality. These tests were a displacement test and a heat generation test. Below these tests are described in detail.

3.3.1 Production test

From the production survey and with discussion with the supply chain department a suitable product variant was chosen. The product variant was first simulated with different shrink fit ratios to estimate what change in service life that could be expected. When a suitable shrink fit ratio had been found a shrink fit container with that ratio was ordered. The endurance test was performed as normal production would have been. During the test the insert dies were controlled every hundred produced rollers and if they had fractured the number of cycles was noted.

3.3.2 Validation of software

Below the two tests to validate the software are presented.

3.3.2.1 Displacement test

Test one was to investigate if the measurements of the insert die and shrink fit container was changed similar in the simulations as it does in reality when they were assembled. A new insert die and shrink fit container were sent away to be measured with a coordinate measurement machine (CMM) before and after the assembly. With the data acquired from the CMM a model of the shrink fit container and insert die was created and simulated. The result from the simulation was then compared to the measured values.

3.3.2.2 Heat generation

Test number two was to examine if the estimated temperature increase due to the deformation of the blank corresponds to the real temperature increase. Five rollers were taken from the production line shortly after they were produced. These rollers temperature were measured approximately 15 seconds after they had been produced. Thereafter the production was stopped to get access to the tools and to be able to measure them. The measuring were made approximately 15 seconds after the production was stopped. Two blanks were also measured. The blanks had been stored inside beside the machine for at least 24 hours and the production had been running for more than one hour. Thus it can be assumed that all the blanks have approximately the same temperature and the tools have reached a steady state temperature. To measure the temperature a tactile thermometer was used. With these results a model was created that had these temperatures and simulated. The simulation was extended to let the roller be cooled down by the surrounding room temperature for 15 seconds. The simulations results were then compared to the measured values.

3.4 Evaluation of DOE module

Two problems were defined to evaluate the DOE module usefulness for designing the press operations. These were; optimization of blank height and evaluating the influence the movement speed and friction has on the maximum effective stress. The optimization of shrink fit was not chosen because of its complexity. The two chosen problems were performed by exploring the functionality of the software and presenting it.

3.5 Service life estimation

To estimate the service life for the different product variants Morrow’s local stress approach was used. Data from every node in the critical area was extracted and the service life was calculated for each of them. The node with the lowest service life was selected to represent the service life of the tool. The parameter material strength coefficient was chosen the same as the tool material’s ultimate yield strength (Bannantine, et al., 1989). Material strength exponent was determined from product variant to product variant. This due to the parameter was not supported by the vendor of the material

4 Results and discussion

Below presents the results from the *information study, simulation, practical test* and the *DOE evaluation*.

4.1 Information study

Below the results from the *literature study, production study* and *design study are* presented.

4.1.1 Literature survey

An extensive literature survey has been performed to scout after existing works that have been conducted in the area of shrink fitting of press tools. The first thing to be defined was why shrink fitting exist. All literature that has been researched describes a shrink fit system as a way to achieve acceptable service life, (Lee, et al., 2009) (Groenbaek & Lund, 2008). Service life of an insert die can be defined as how many cycle loads the tool withstand until cracks initiation begins (Falk, et al., 1998). Tool failure in cold forming processes is generally caused by fracturing (Fu, et al., 2008). Failure due to wear is not as common as for fracturing because the service life is often too short to cause wear failure (Knoerr, et al., 1994).

Fracturing as cause of failure can be divided in to two different groups, overload fracture and fatigue fracture. Overload fracturing can be caused by large deformation loads which exceed the strength limited of the tool material. This type of failure can be addressed with good control over the forming parameters. Second type of die failure, fatigue fracturing, is a result of the tools working under severe loading condition. This condition is beneficial to initiate micro cracks to start grow. Micro cracks growth can be divided into four stages: crack initiation, crack growth, accelerated crack growth and last rapid fracture. (Fu, et al., 2008)

With an optimized shrink fit ratio it is possible to decrease the effective stress levels in the tools. This will lead to an increased service life of the tools. (Lee, et al., 2009) (Groenbaek & Lund, 2008) If it is possible to lower the stresses to moderate levels and also decrease the deformation load the service life of the tools can in some case be increased up to ten times (Fu, et al., 2008). Pre-stressing an insert die with a shrink fit container in controlled way has great impact on the stress levels in the tool. But this desired effect dispersers when high plastic strains are reached. (Garat, et al., 2004)

An optimized shrink fit ratio is not as large as possible. (Lee, et al., 2009) shows that when a certain shrink fit ratio is reached the service life of a tool will start to decrease if the ratio is further increased. But there are applications were a very high ratio level is needed and were not conventional shrink fit containers are capable to achieve that. The solution is then a strip wound container that is offering up to 100% higher ratio level than a conventional shrink fit container (Groenbaek & Lund, 2008).

In order to withstand high forces and wear the tool material in cold forming processes has high hardness and thus also high brittleness. Therefore when designing a new tool the aim is to avoid tensile stresses and strains in the critical die regions. (Koch, et al., 2008)

When designing insert dies and shrink fit containers there are few rules that allows the designer to choose an optimum ratio between these two. What ratio the tools should have comes from experience and simple numerical calculations (Lee, et al., 2009). Some guidelines that have been found in the literature are for example high stress concentrations in corners near the bottom hole of an insert die can be addressed by enlarging the bottom hole to as much as possible. This change can result in an increased service life for the insert die up to five times. Another design suggestion is instead of pre-stressing the whole height of a tool only pre-stress the cavity region of the tool. This change can lead to an increase of the service life with a factor of two. (Jin, et al., 2009)

Predicting the service life of a tool can be made with different approaches. For example Woehler-, Local strain- and Local energy approach. Last two approaches predict the service life better than the first one. But they still predict a longer service life than the real service life of a tool. Due to the calculations is heavily depended on material properties and are difficult to obtain the prediction doesn’t get more accurate than the input data. (Falk, et al., 1998)

Calculations of stresses in the tools can be made either with a traditional thick-wall approach or with Finite Element Analysis (FEA). If a traditional thick-wall cylindrical approach is used to calculate the stresses in an insert die and shrink ring assemblies compared to a finite element analysis the FEA will predict much higher stresses in the tools. If the geometry of the insert die is complex the cylindrical approach will not be sufficient and FEA should to be used. (Eyercioglu, et al., 2009)

In the literature the chosen software to perform the FEA is often DEFORM. For examples in the papers of (Falk, et al., 1998), (Knoerr, et al., 1994) and (Krušič, 2010) uses this software. This may indicate that the software is commonly accepted as trustful.

4.1.2 Production survey

A production survey was conducted to collect any available data about the current service life of the tools and if any experiments has been performed. Also an interview was held with the design department. Below presents the results.

4.1.2.1 Service life data

Available data of the service life for the insert dies was collected and processed. One and a half year of recordings of the service life was gathered. From this data the mean service life for the upper insert die was calculated to be approximately 14000 produced products. For the lower insert dies the mean was calculated to approximately 13500 products. The standard deviation of the service life for both upper and lower insert dies was roughly 7000 produced products. Figure 21 shows the mean service life for respective product variant.

The service life data was only describing how many products that were produced and how many tools were needed to do so. It didn’t tell why a tool has been changed. Therefore in some cases a tool may has been changed before it was worn out because the order quantity was smaller than the service time. This will decrease the mean service life of the tools. In other cases the tools may was continued used after the crack initiation has begun. Thus this will increase the mean service life.

In order to handle the problem with order sizes smaller than the service life was to look how often an order of a specific product variant consumes more tools than the service life target. In this way it is possible to identify product variants that were performing great or poor in terms of consuming tools. Figure 22 shows how often a product variant consumes more tools per order than the set target. It shows product variants on average consume more tools per order than the set target 20% of the orders. It also reveals that four of the product variants consume more tools than the target 70% of the orders.

There were no recordings for the service life of the shrink fit containers. According to the production technician the service life of a shrink ring is decided more on an appearance than on its function. Also that judgment was made individually with only experience as guidance.

4.1.2.2 Earlier tests

A survey was conducted to see if there were any earlier attempts of changing the shrink fit ratio to obtain a longer service life. The result was that one earlier attempt was recorded.
The attempt was performed on the product variant D1 by increasing the shrink fit ratio from 0.33% to 0.58%. This change resulted in a service life increase with 100% for the lower insert die from a mean service life of 20,000 to 40,000 load cycles. This also changed the reason why the tool was replaced. This time it was due to wear and not because of fracture. The service life for the upper insert die was still undetermined due to it was still in service. It has reached above 60,000 load cycles and still has the wear in acceptable levels. Thus the upper insert die has also increased its service life with at least by 100% from 30,000 to 60,000 load cycles.

4.1.3 Design survey

The interview with the design department revealed that for this production line a shrink fit container was never redesigned if a new product variant was introduced. Today two different variants of shrink fit containers exist, one with 60 mm inner diameter and one with 70 mm inner diameter. Both of the variants have the same outer diameter. Which one that was used for a specific product variant was decided on that an insert die must have a minimum wall thickness. Thus the 60 mm shrink fit container will be used as long the wall thickness was thicker than a minimum value. The shrink fit ratio of the 60 mm shrink fit container was 0.33% and for the 70 mm shrink ring container was 0.43%

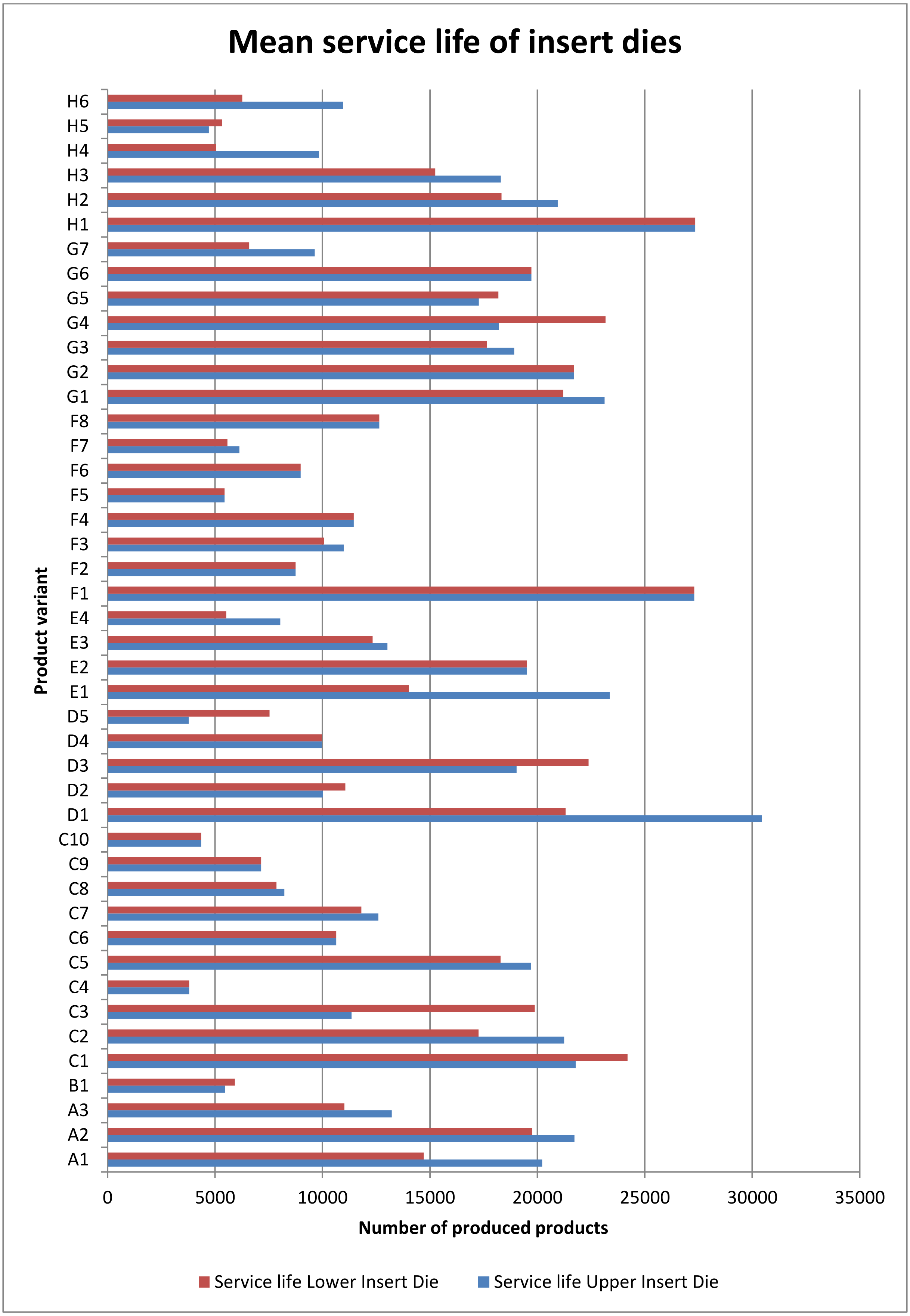


Figure 21 – Mean service life

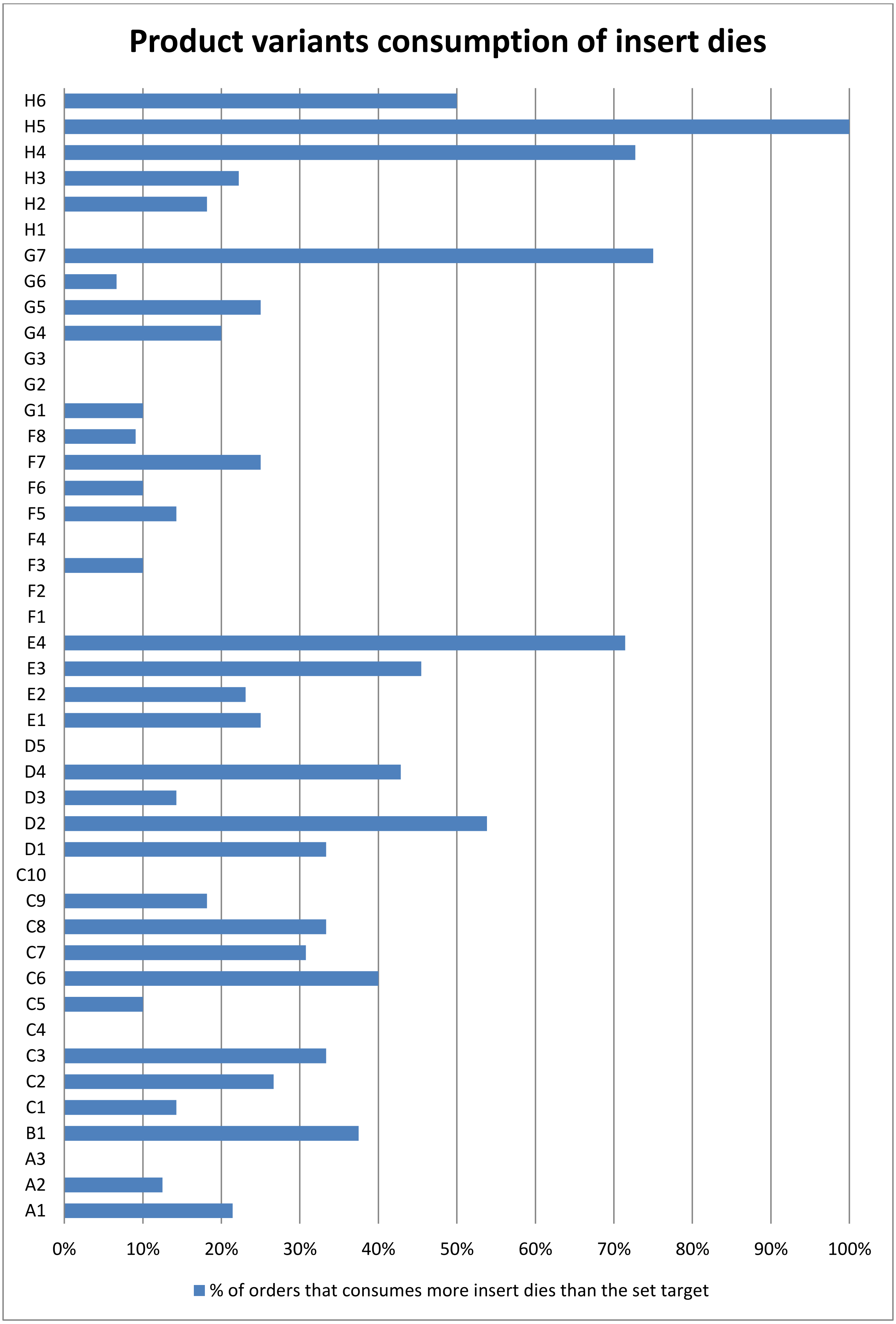


Figure 22 – Orders that consumes more tools than the set target

4.2 Simulation results

This chapter presents first the results of 11 product variants with the standard shrink fit ratio of 0.33%. The aim was to find any trends or similarities between the product variants attributes such as blank height or weight and their maximum effective stress. Next the result of the optimization process of the shrink fit ratio to obtain longer service life is presented. This optimization process was made on five product variants. Moreover the results of an axial pre-stressed insert die is presented

4.2.1 Simulation of product variant with original shrink fit ratio

When comparing the different product variants in terms of their effective stress curve it can be seen that all product variants reaches above $2000\ MPa$ for the lower insert die. The maximum effective stress for almost all variants is around $2500\ MPa$. This can be seen in figure 23. In figure 24 it can be observed that the upper tool for most of the product variants estimates to have a higher maximum effective stress than the lower tool. Simulation of the different product variants shows also that two, product variant C6 and H5, doesn't completely fill the tools. This can be seen in figure 27 and 28. This can also be observed in figure 23 and figure 24. Due to curves for those product variants doesn't have the same trends as the other ones. In figure 25 and 26 it can be seen that for all product variants except one the theta stress goes from compressive to tensile. The one that stays as compressive is product variant is C6 and it is one of the variants that don't fill the tool completely.

Attempts were made to find any relations between the attributes of the product variants and the maximum effective stress. This can be seen in figure 29, 30 and 31. No clear trends could be detected and thus no conclusion could be drawn from these results. An attempt to find common material parameters for the service life calculation formula can be seen in figure 32 and 33. Due to the formulas sensitivity and the reliability of the production data there could not be established common materials parameters from the equation. There should also be noted that for product variant C6 and H5 the service life estimation is incorrect due to the press operation has not achieved their specified geometry.

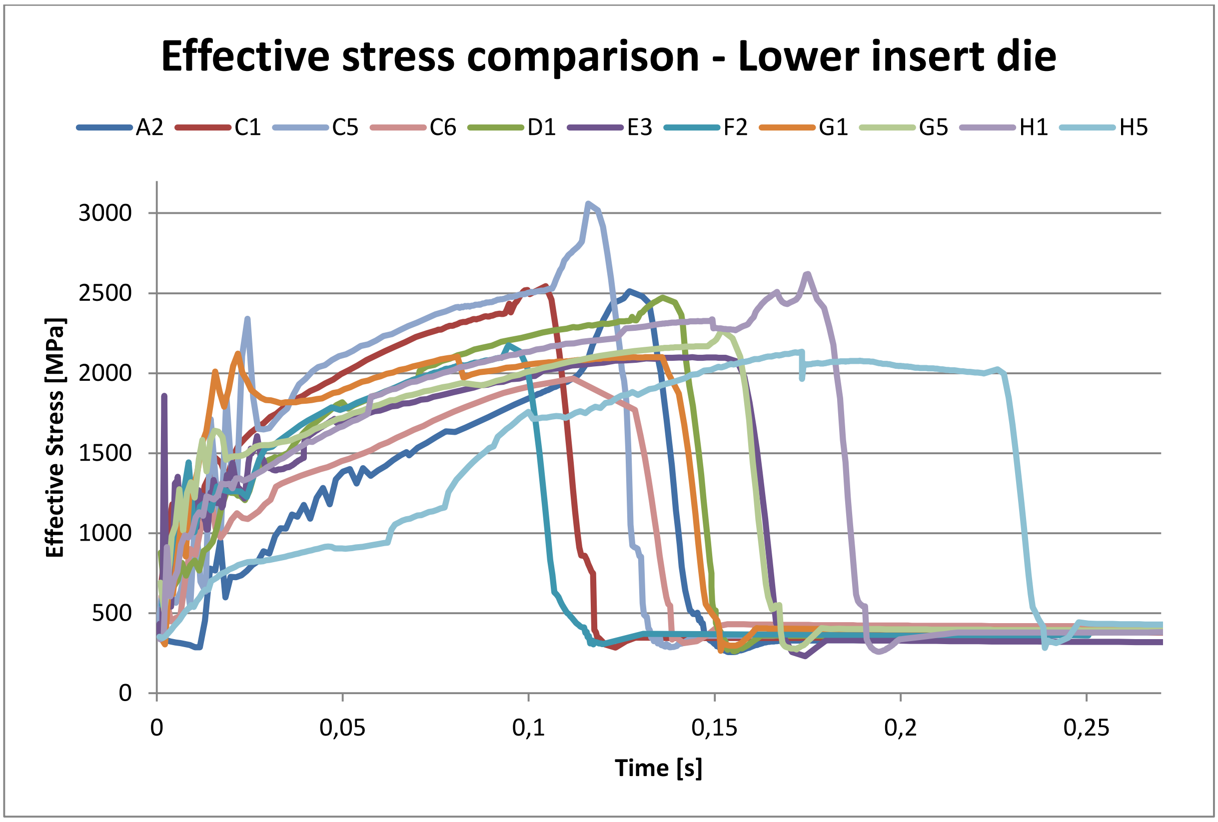


Figure 23 - Effective stress comparison - Lower insert die

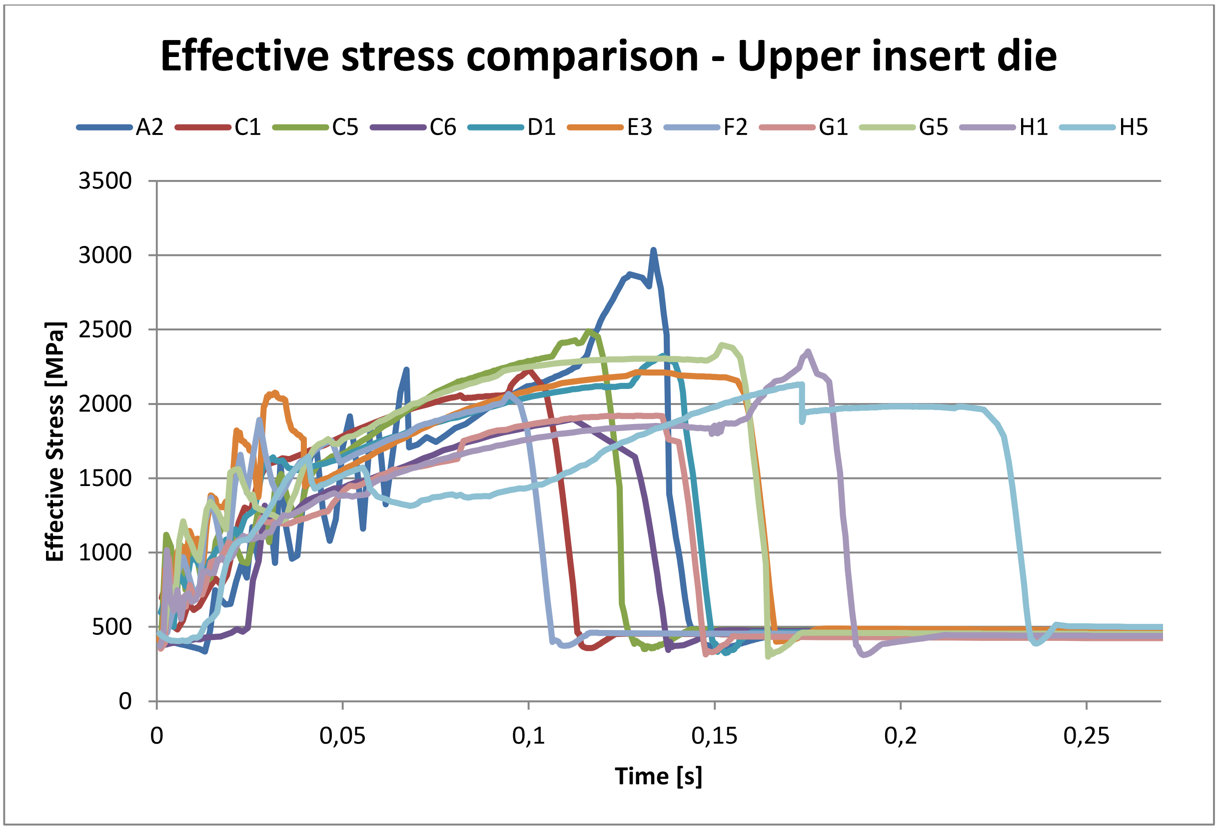


Figure 24 - Effective stress comparison - Upper insert die

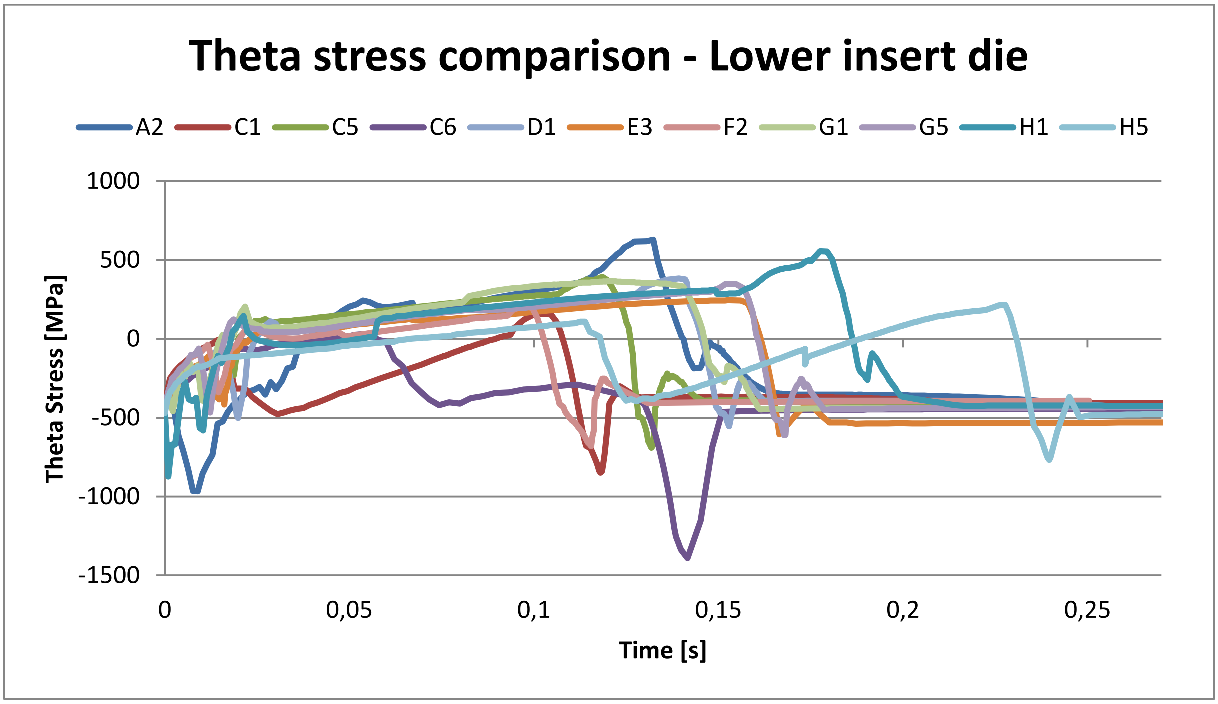


Figure 25 - Theta stress comparison - Lower insert die

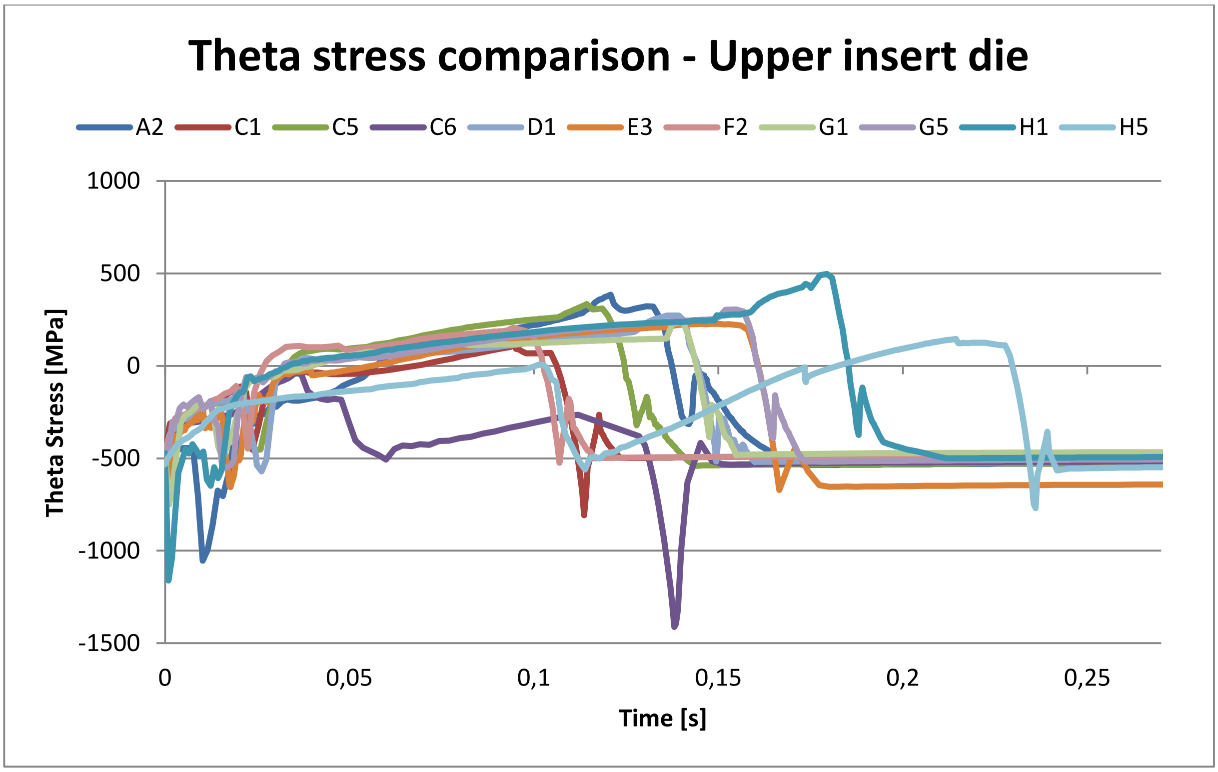


Figure 26 - Theta stress comparison - Lower insert die

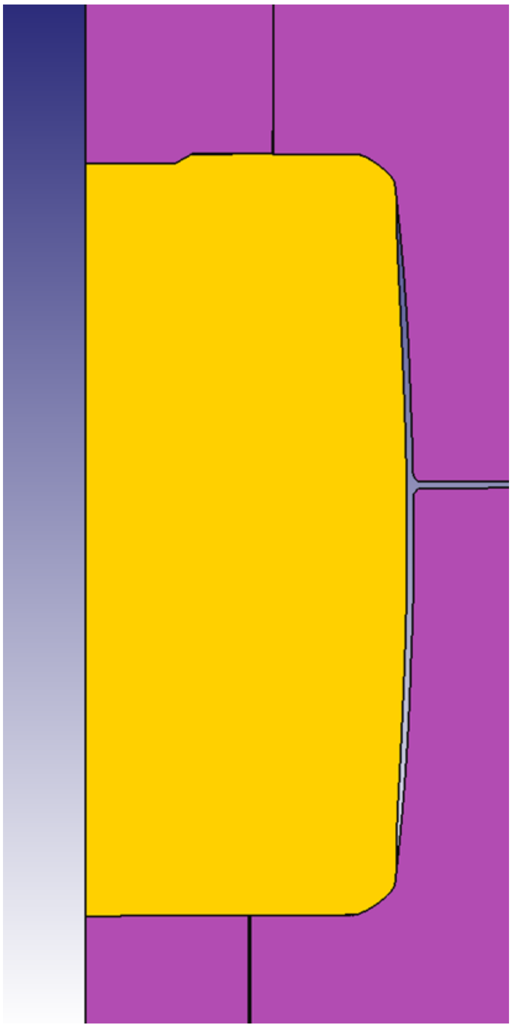


Figure 27 - Product variant C5

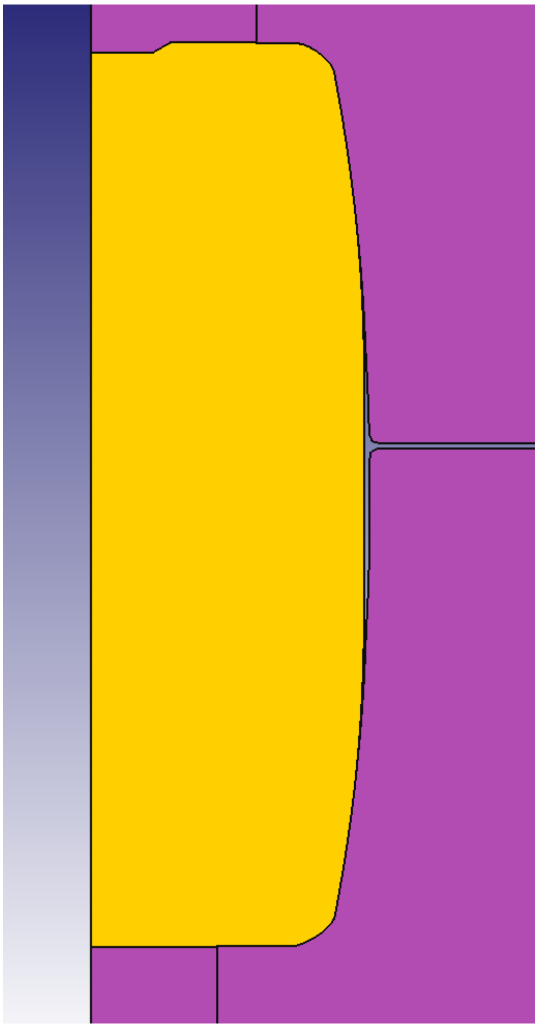


Figure 28 - Product variant H5

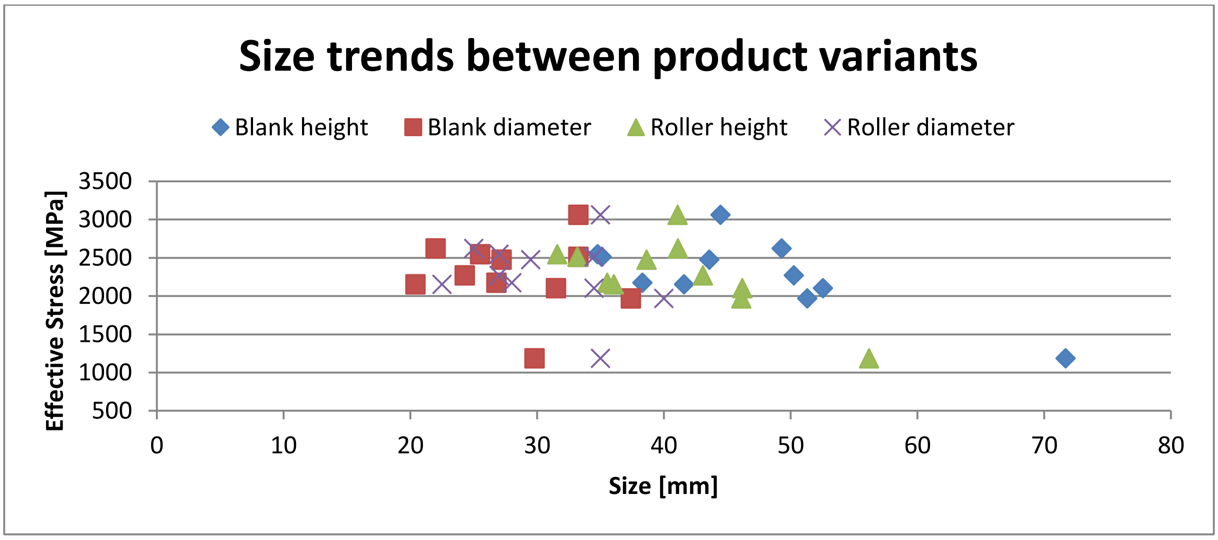


Figure 29 – Size trends between product variants

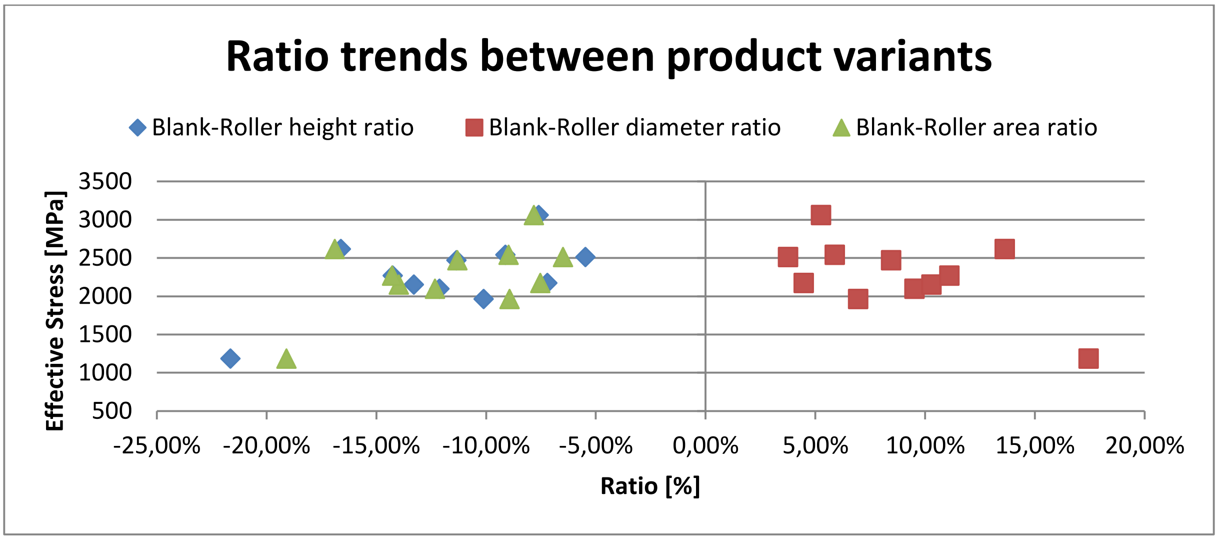


Figure 30 - Trends of ratios between product variants

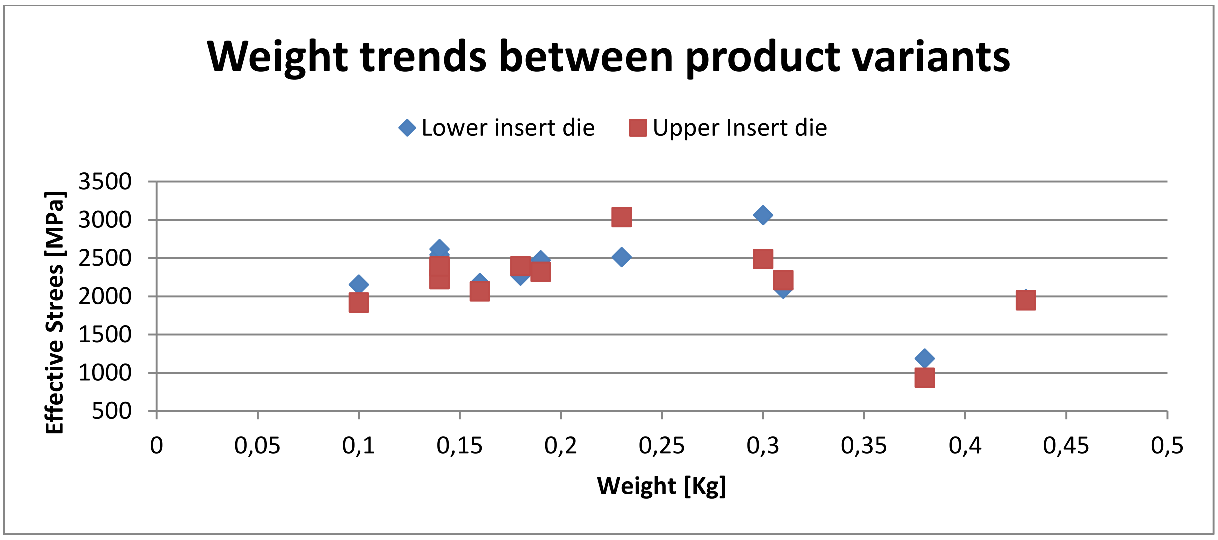


Figure 31 – Weight trends between product variants

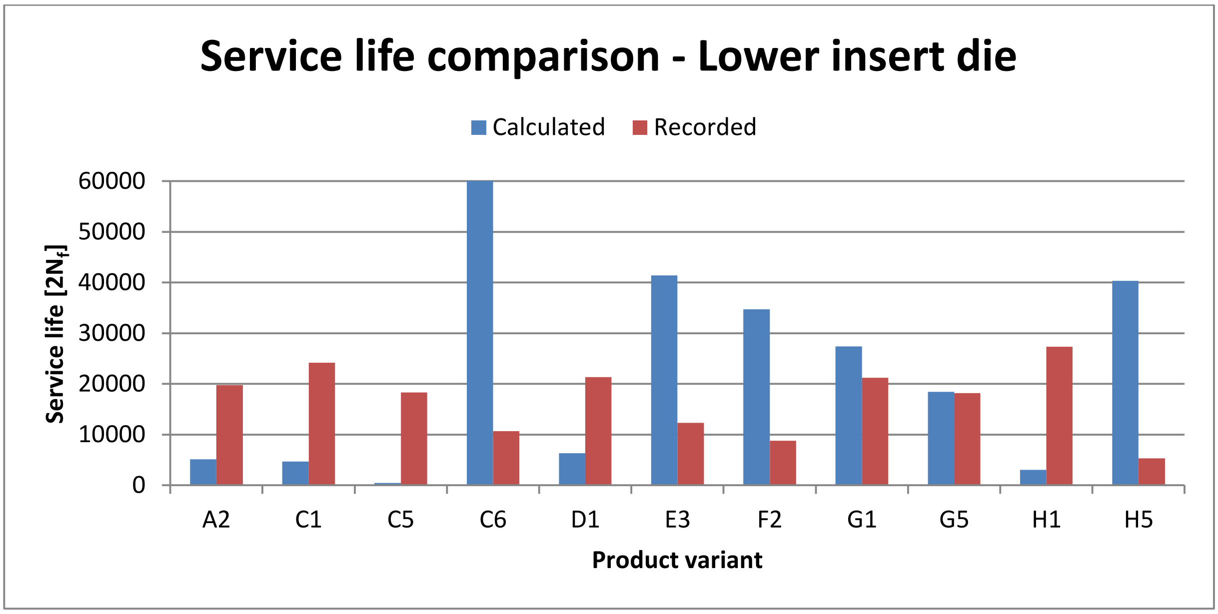


Figure 32 - Service life comparison - Lower insert die

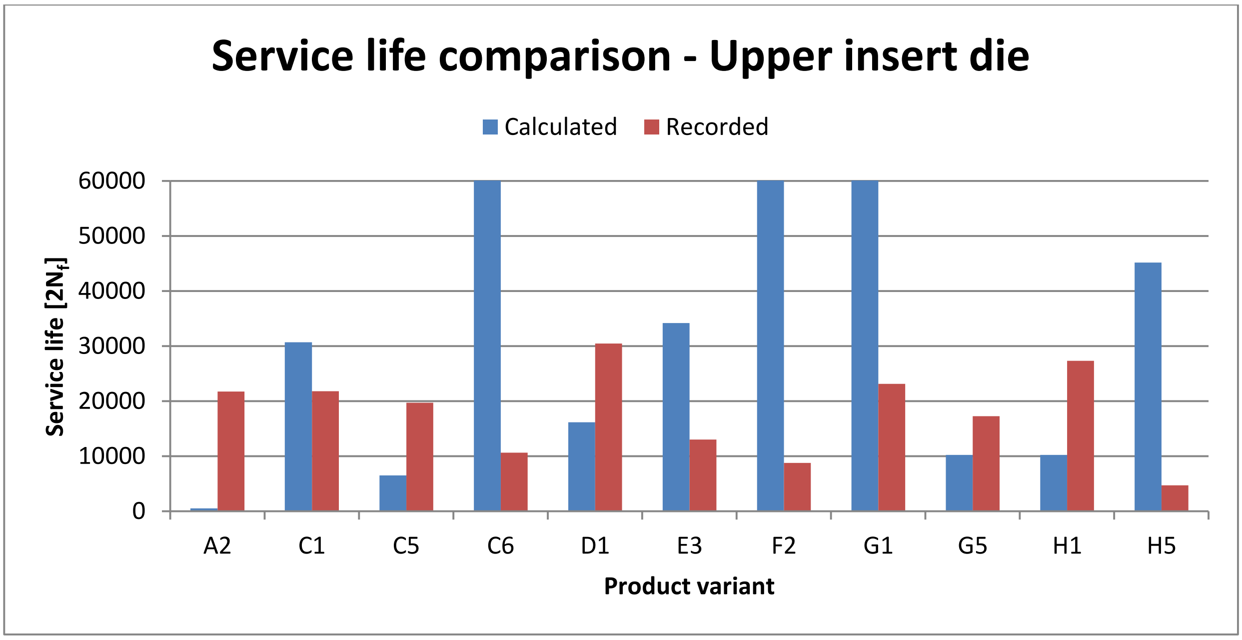


Figure 33 - Service life comparison - Lower insert die

4.2.2 Optimization process

Five product variants have been simulated with nine different shrink fit ratios to search for a shrink fit ratio that will increase the service life. These results are presented below.

4.2.2.1 Product variant A1

In figure 34 the result from the different shrink fit ratio is presented. It shows clearly that the service life of the insert dies decreases with an increased shrink fit ratio. This depends on the current design of the tools and blanks. The design is already filling the tools completely with a low shrink fit ratio.

A comparison of the nodes with the highest effective stress can be seen in figure 35 and figure 36. They clearly show when the tool is filled and when overfilling has begun. This is when the stress curve becomes linear. In figure 35 and 36 the curve for 0.955% shrink fit ratio makes a jump close to the dead end of the forming operation. This is probably caused by a remesh and an unbeneficial replacement of nodes.

Figure 37 and 38 shows the node for respective shrink fit ratio with the highest theta stress. Even if the tools become overfilled with high shrink fit ratio the theta stress levels can be kept as compressive stress if the ratio is higher then 0.58%. Furthermore the figures displays that with a 0% shrink fit ratio the software has difficulties to calculate the springback and leave residual stresses after the forming operation.

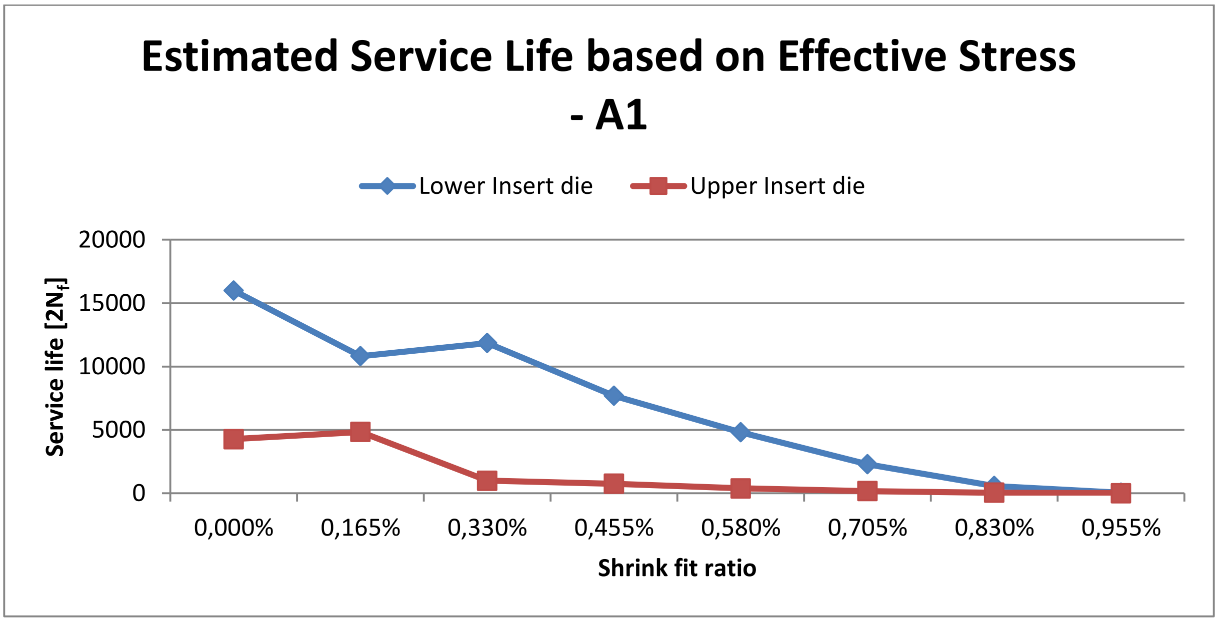


Figure 34 – Estimated service life for product variant A1

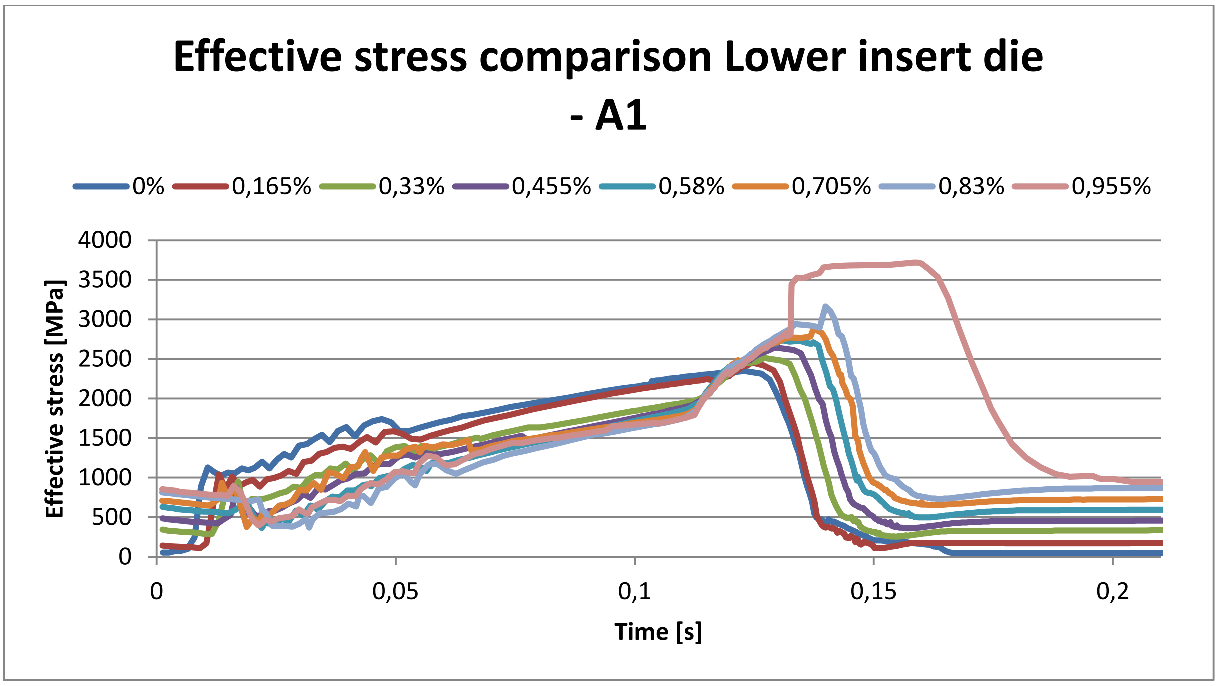


Figure 35 – Node with highest effective stress – Lower insert die - Product variant A1

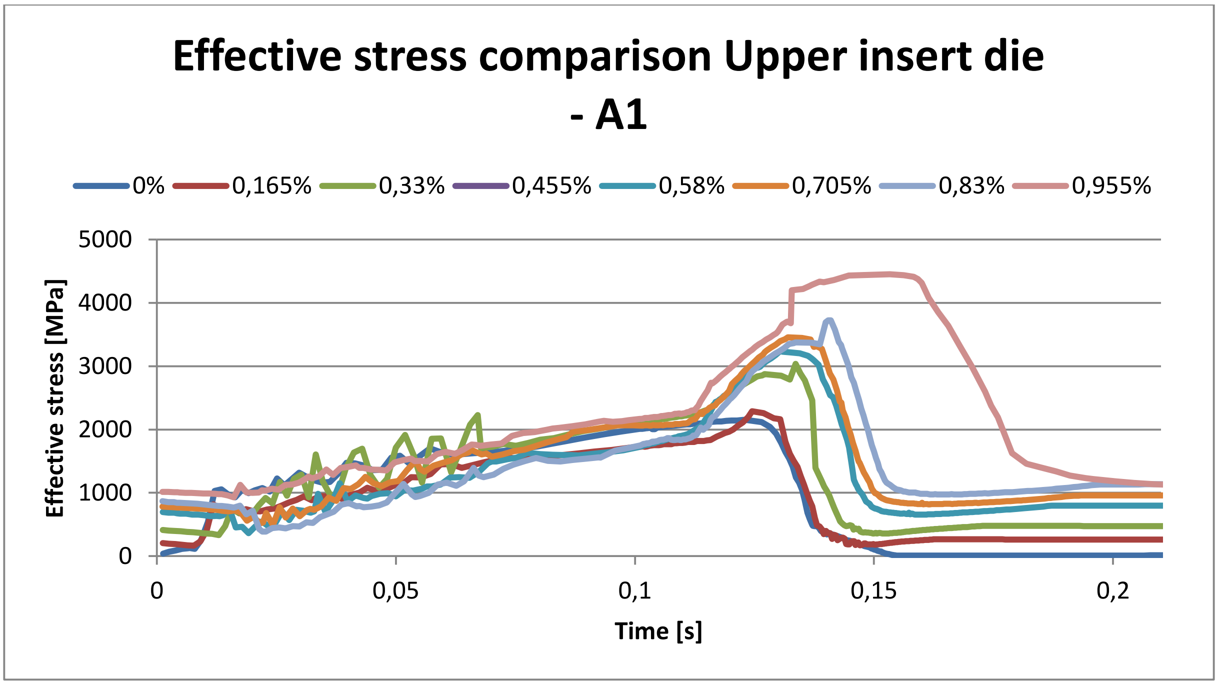


Figure 36 – Node with highest effective stress – Upper insert die - Product variant A1

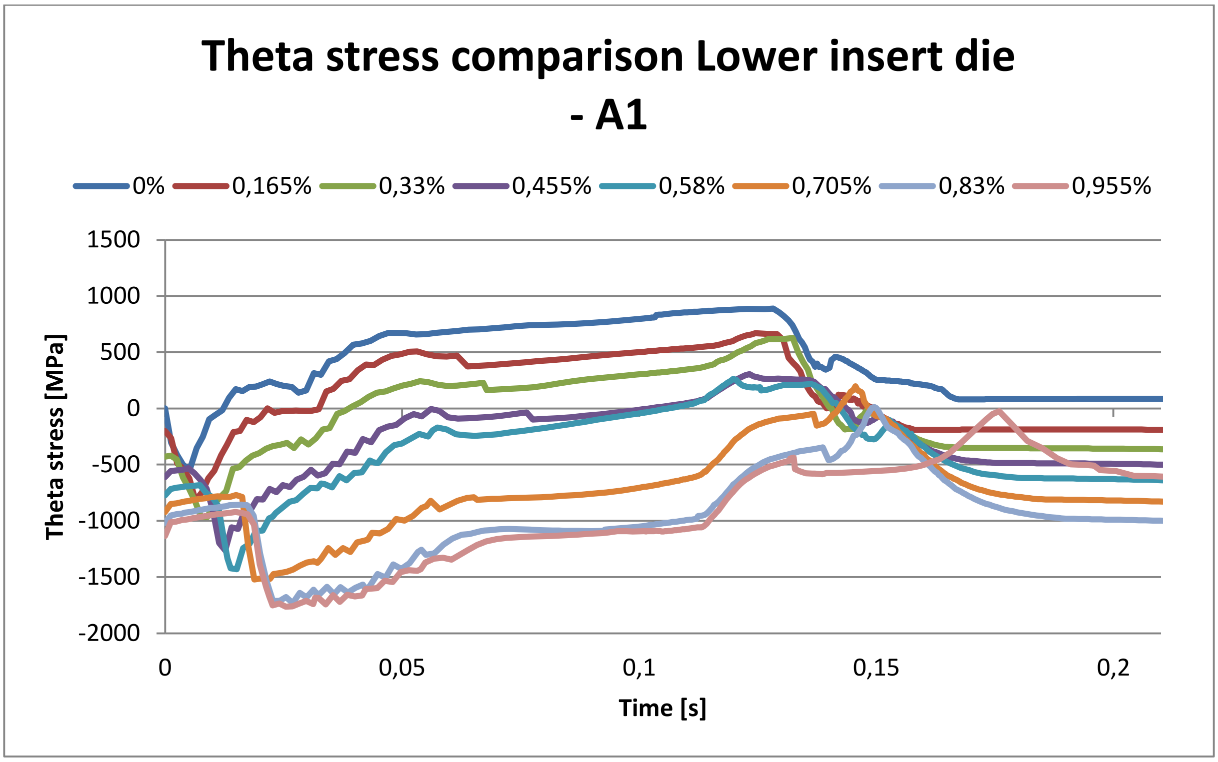


Figure 37 – Node with highest theta stress – Lower insert die - Product variant A1

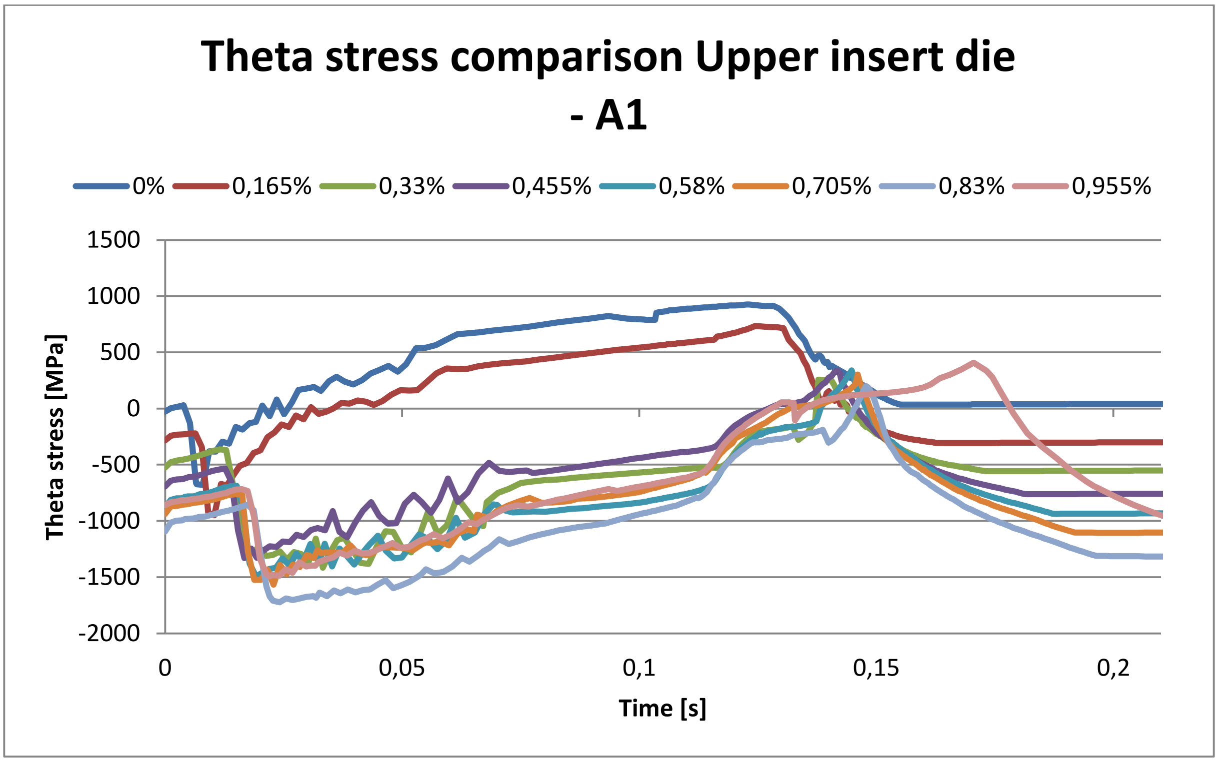


Figure 38 – Node with highest theta stress – Upper insert die - Product variant A1

4.2.2.2 Product variant D1

In figure 39 the estimated service life depending on the different shrink fit is presented. This product variant clearly benefits of a higher shrink fit ratio. This result corresponds well to the earlier production test. In figure 42 and 43 it can be observed that lowest theta stress is obtained with a shrink fit ratio of $0{,}58\%$ for the lower insert die. Meanwhile for the upper insert die shrink fit ratios higher the $0{,}455\%$ results in that compressive theta stress is achieved during the whole forming operation.

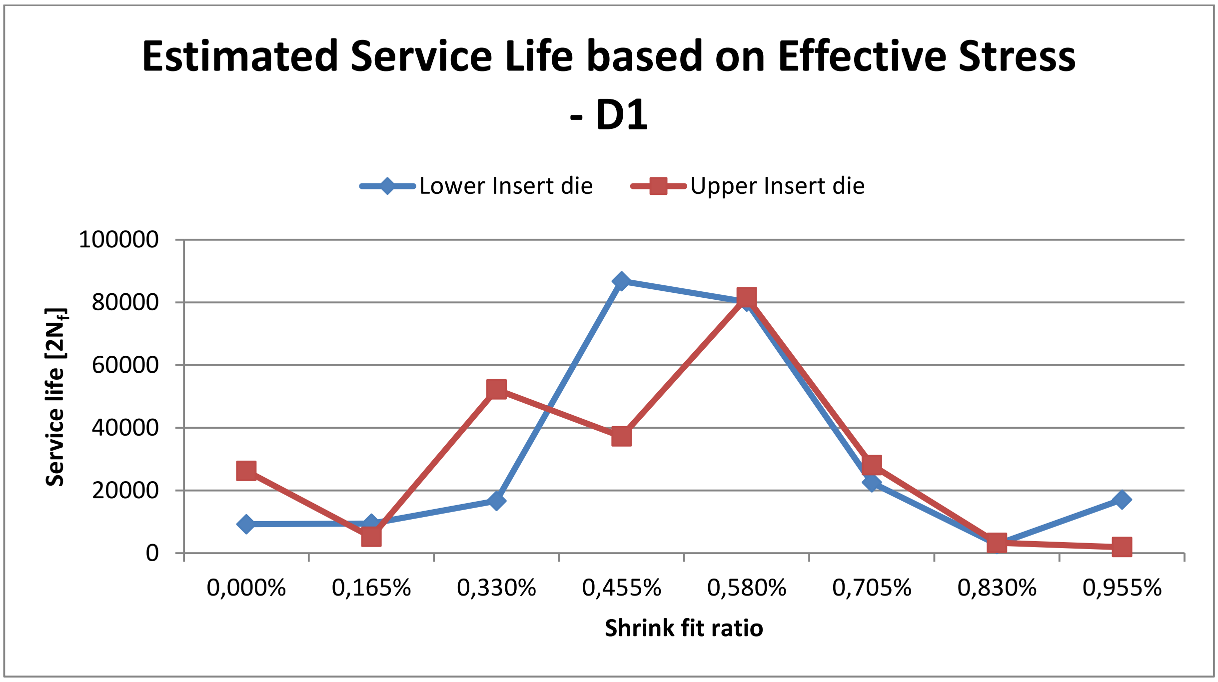


Figure 39 – Estimated service life for product variant D1

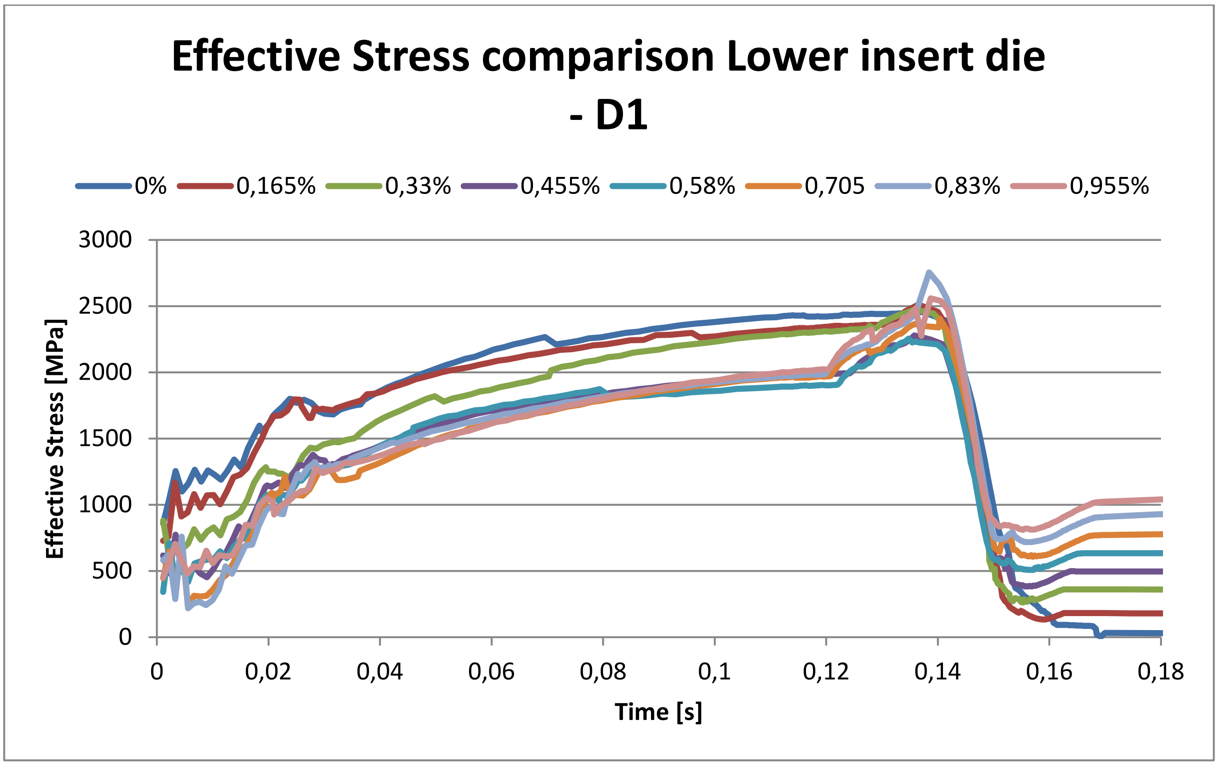


Figure 40 – Node with highest effective stress – Lower insert die - Product variant D1

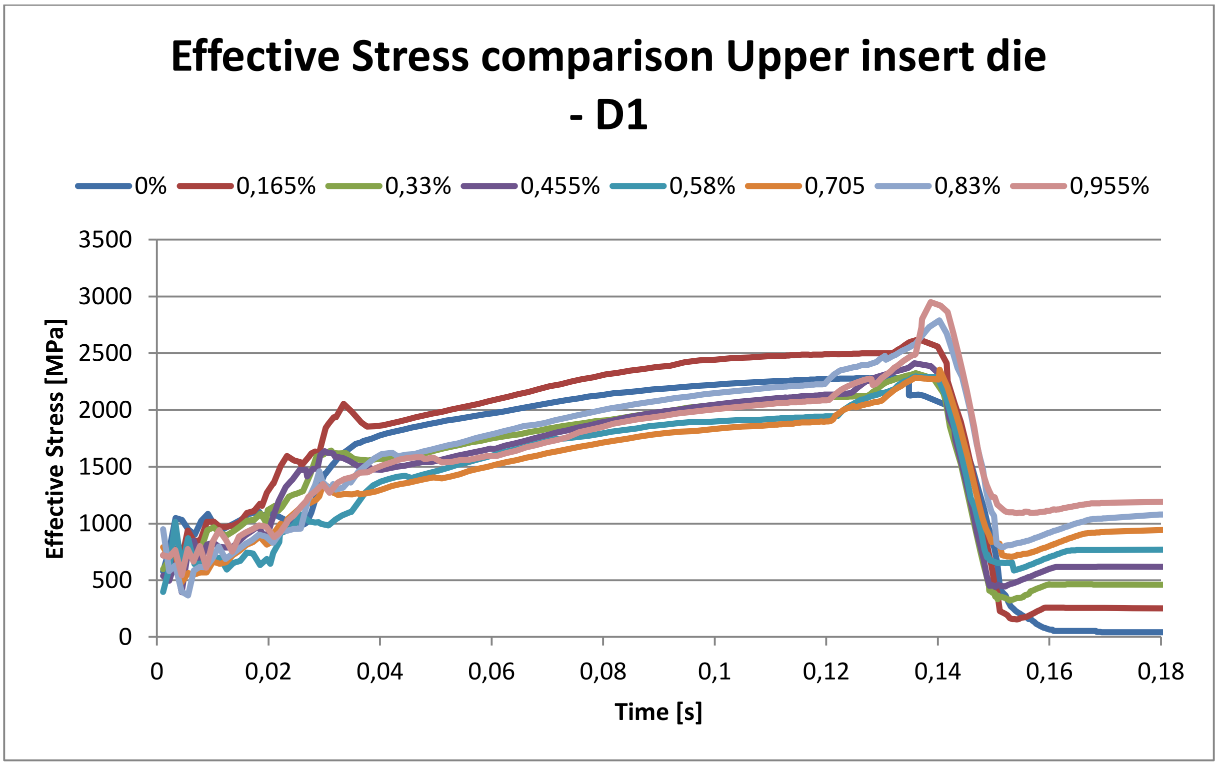


Figure 41 – Node with highest effective stress – Upper insert die - Product variant D1

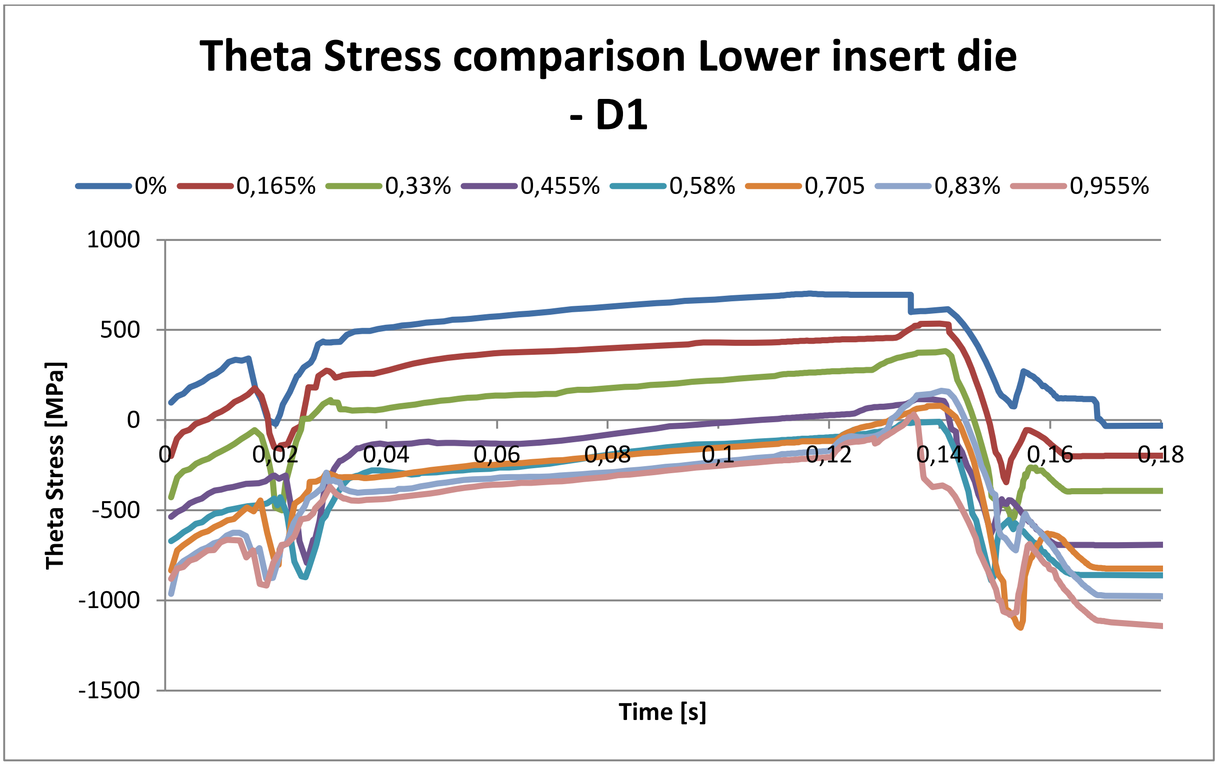


Figure 42 – Node with highest theta stress – Lower insert die - Product variant D1

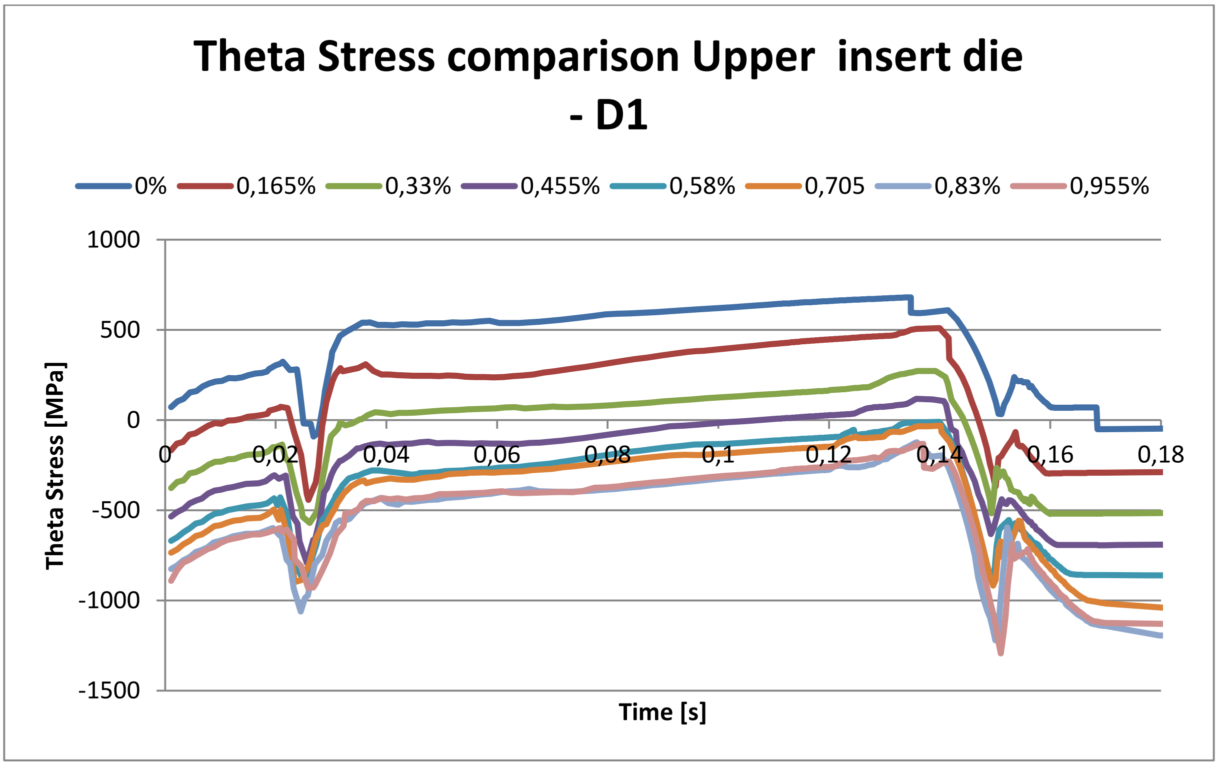


Figure 43 – Node with highest theta stress – Upper insert die - Product variant D1

4.2.2.3 Product variant E3

The estimated service life is presented in figure 44. This product variant estimates to have an optimal shrink fit ratio between 0,33% and 0,58%. It also can be noted that the estimated service life for the shrink fit ratio of 0,955% is almost the same as for the ratio of 0,33% and 0,58%. This could be explained due to favorable remeshing. Evidence for this can be seen in figure 46. Even if the evidence is from the upper insert die the remeshing is made on all the objects and therefore the lower insert die may have got a favorable mesh.

When the reaching a shrink fit above 0,33% the theta stresses will stay as compressive stresses during the whole forming operation. This can be observed in figure 47 and 48.

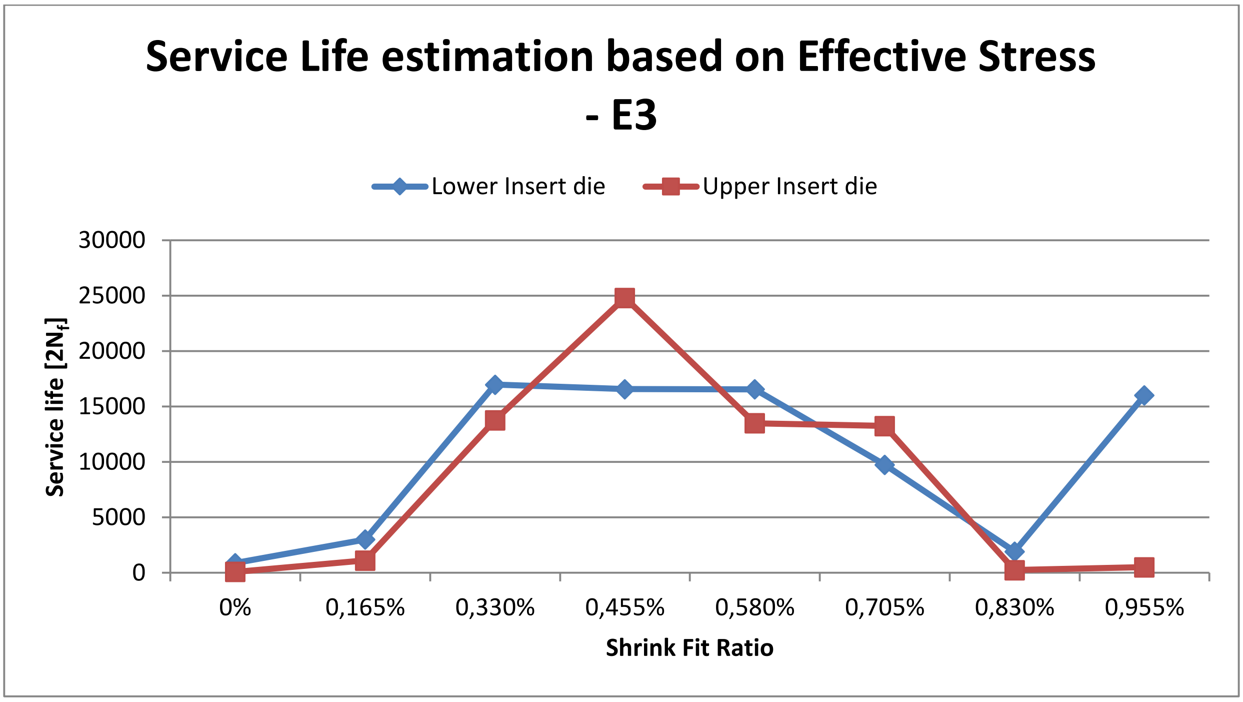


Figure 44 - Estimated service life for product variant E3

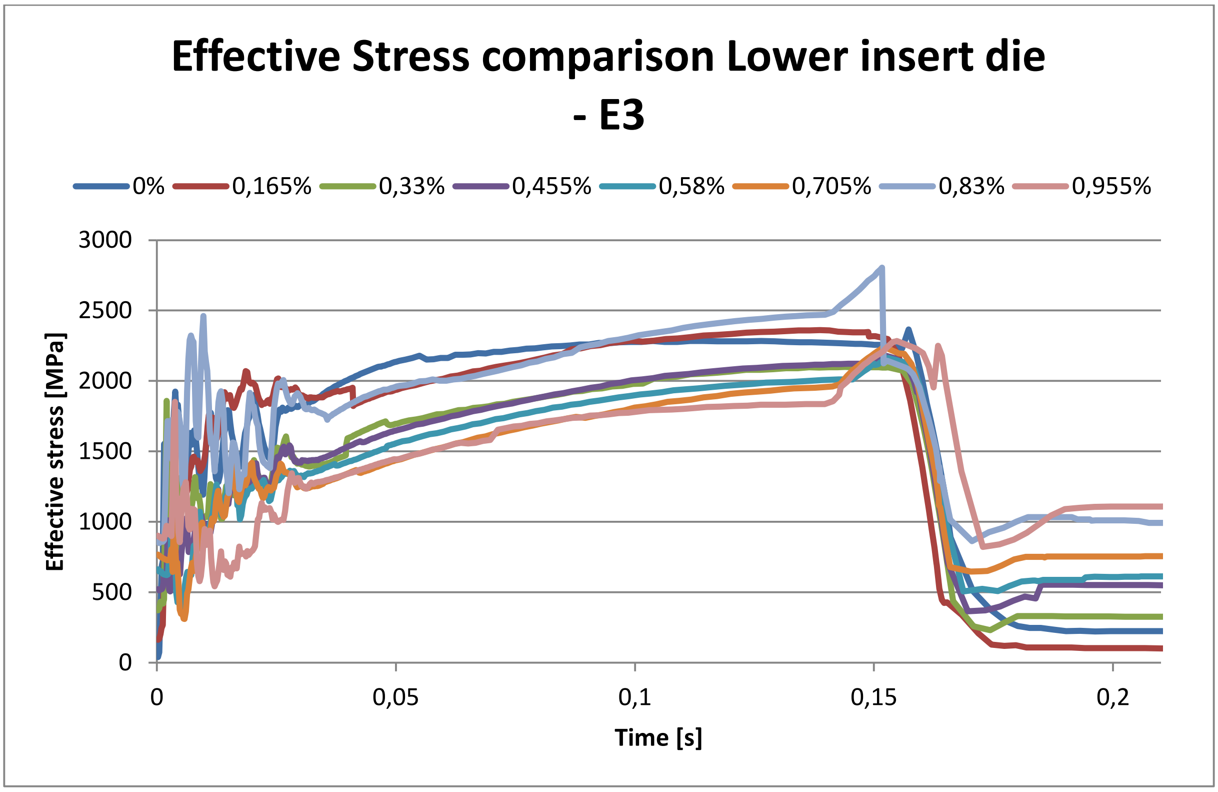


Figure 45 – Node with highest effective stress – Lower insert die - Product variant E3

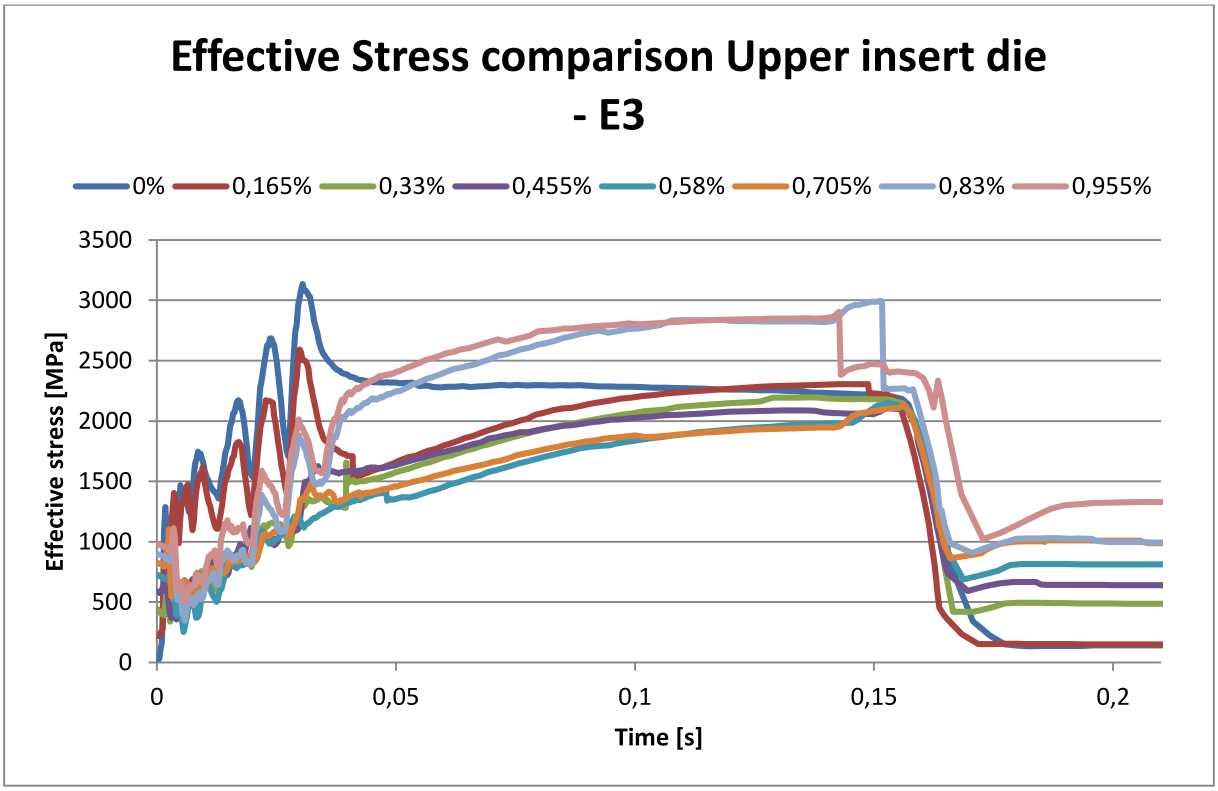


Figure 46 – Node with highest effective stress – Upper insert die - Product variant E3

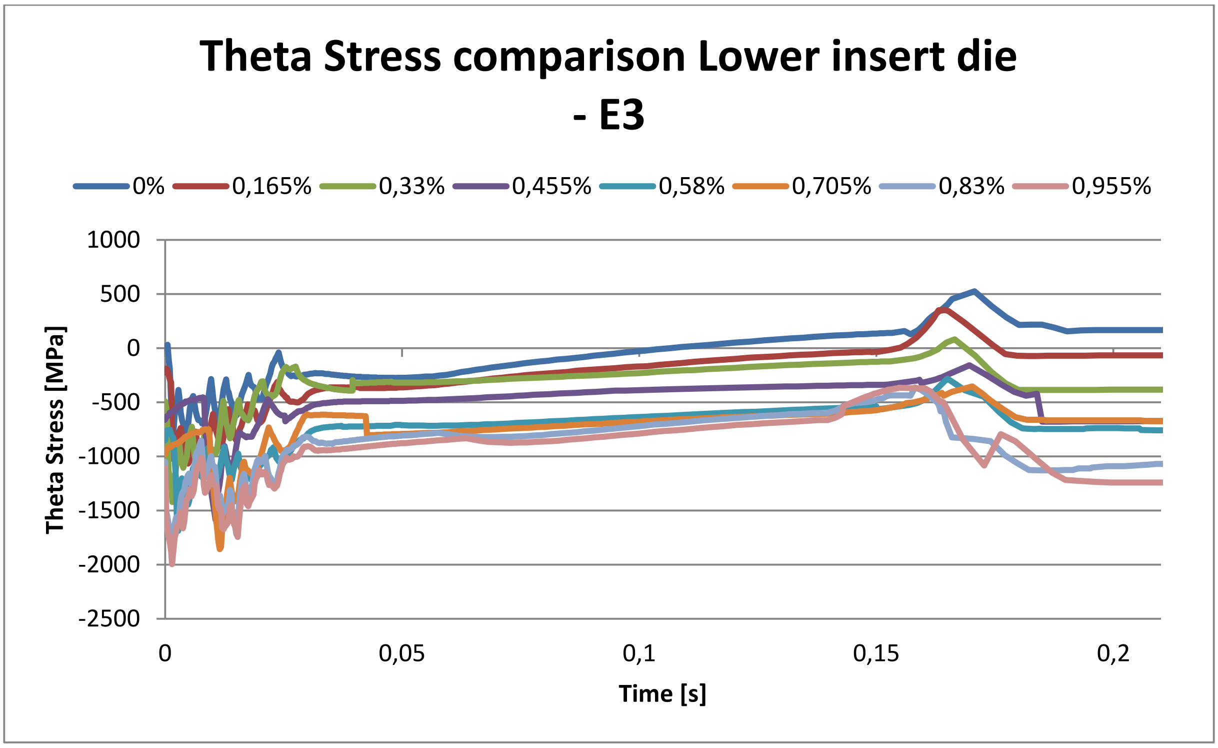


Figure 47 – Node with highest theta stress – Lower insert die - Product variant E3

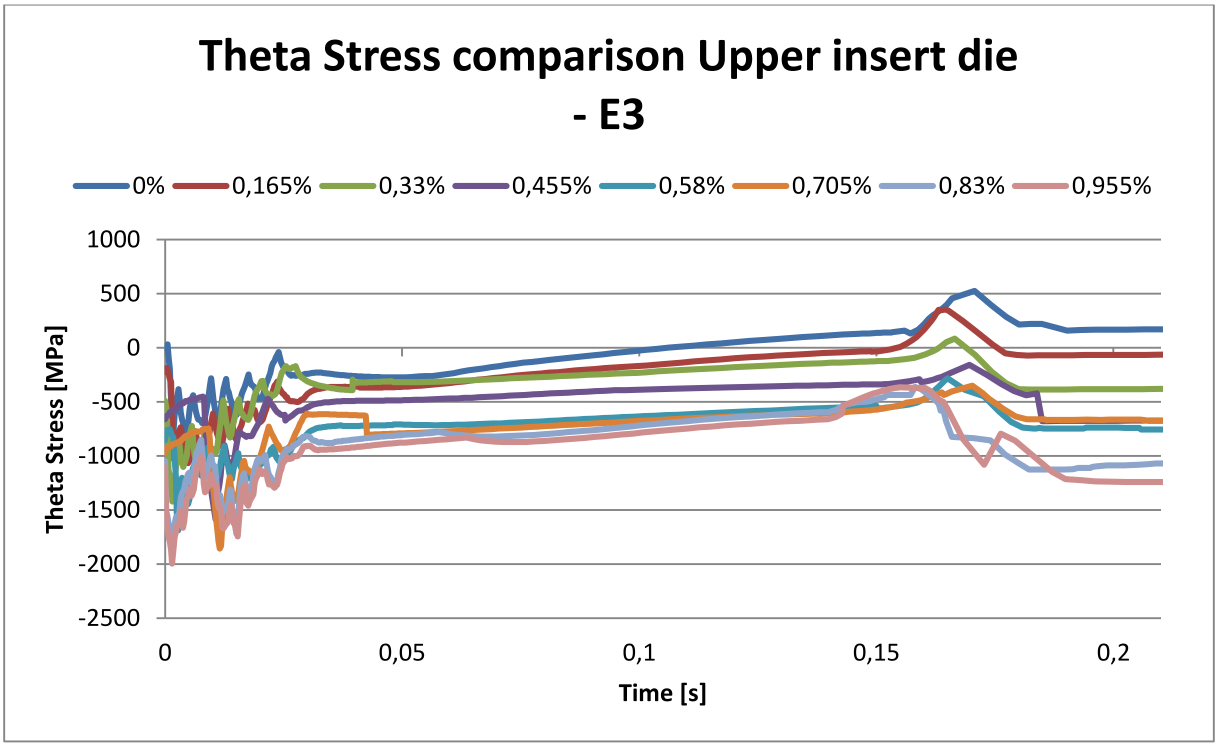


Figure 48 – Node with highest theta stress – Upper insert die - Product variant E3

4.2.2.4 Product variant F2

Figure 49 shows the estimated service life for product variant F2. This variant estimates to be beneficial from a raised shrink fit ratio. Also it can be noted that this is the first product variant that has a clear distinction between the upper and lower insert die. In figure 50 and 51 it can be observed that the simulations for the ratios $0.705\%, 0.83\%$ and 0.955% suffer from remeshing. In figure 52 and 53 it can be observed that a shrink fit ratio over $0{,}455\%$ will keep the theta stress as tensile under the whole forming operation.

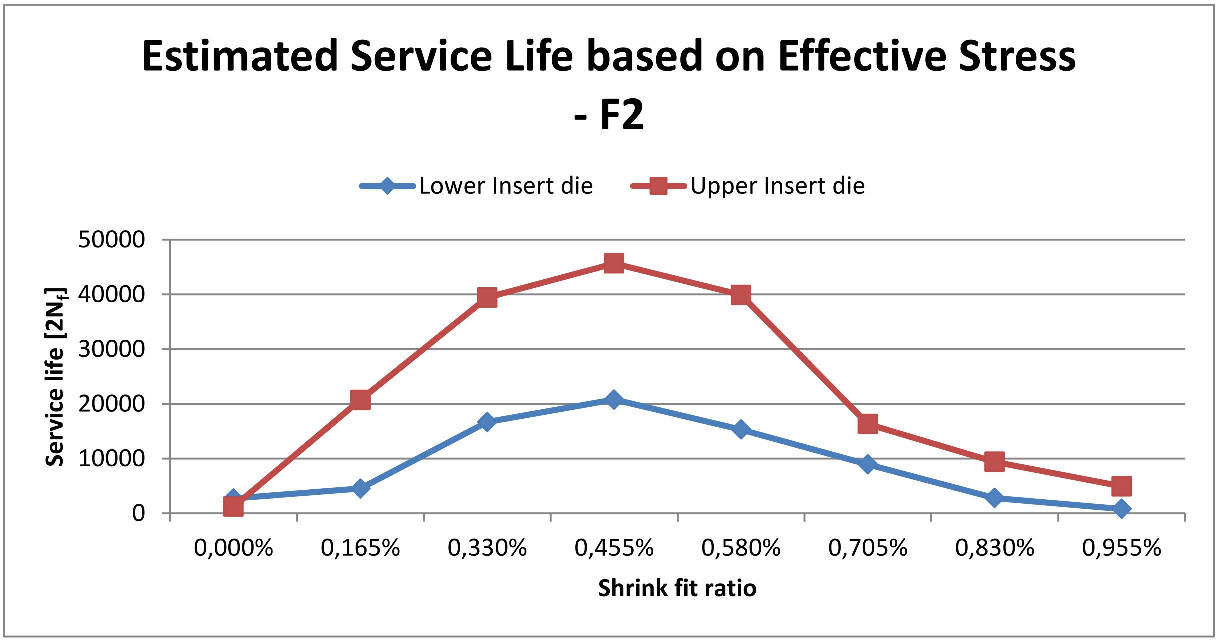


Figure 49 - Estimated service life for product variant F2

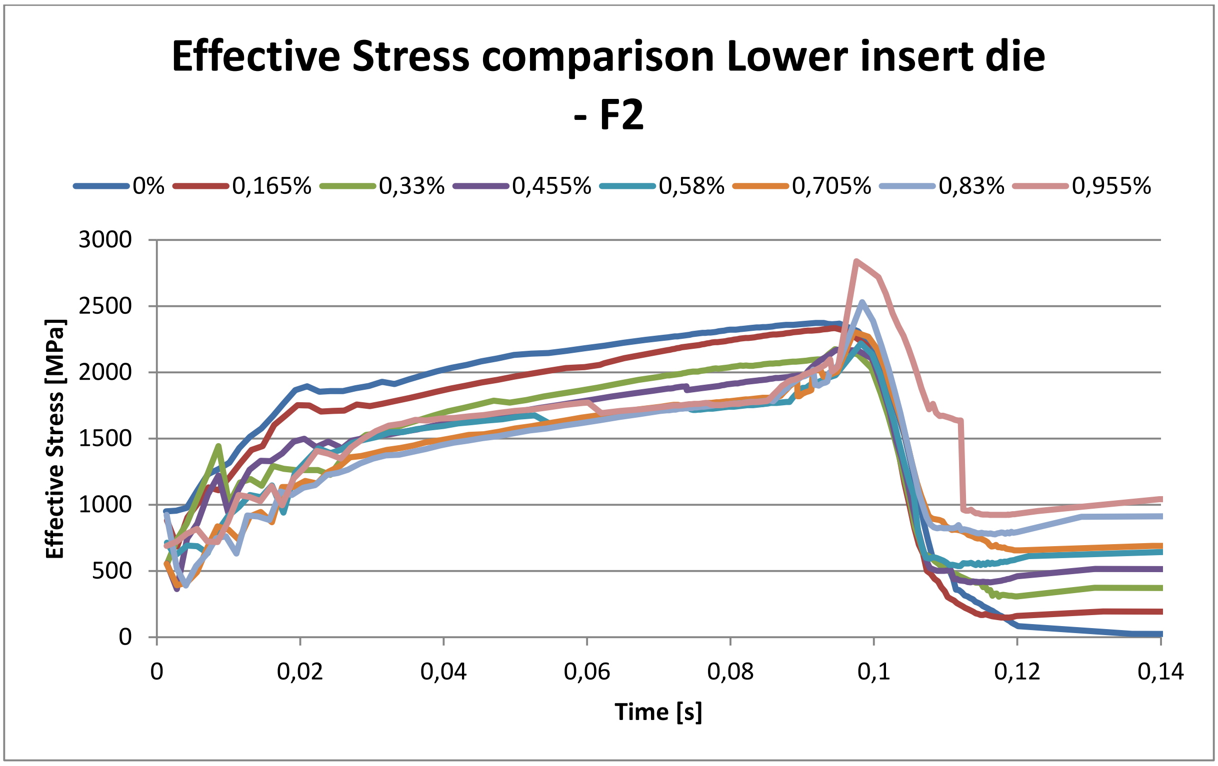


Figure 50 – Node with highest effective stress – Lower insert die - Product variant F2

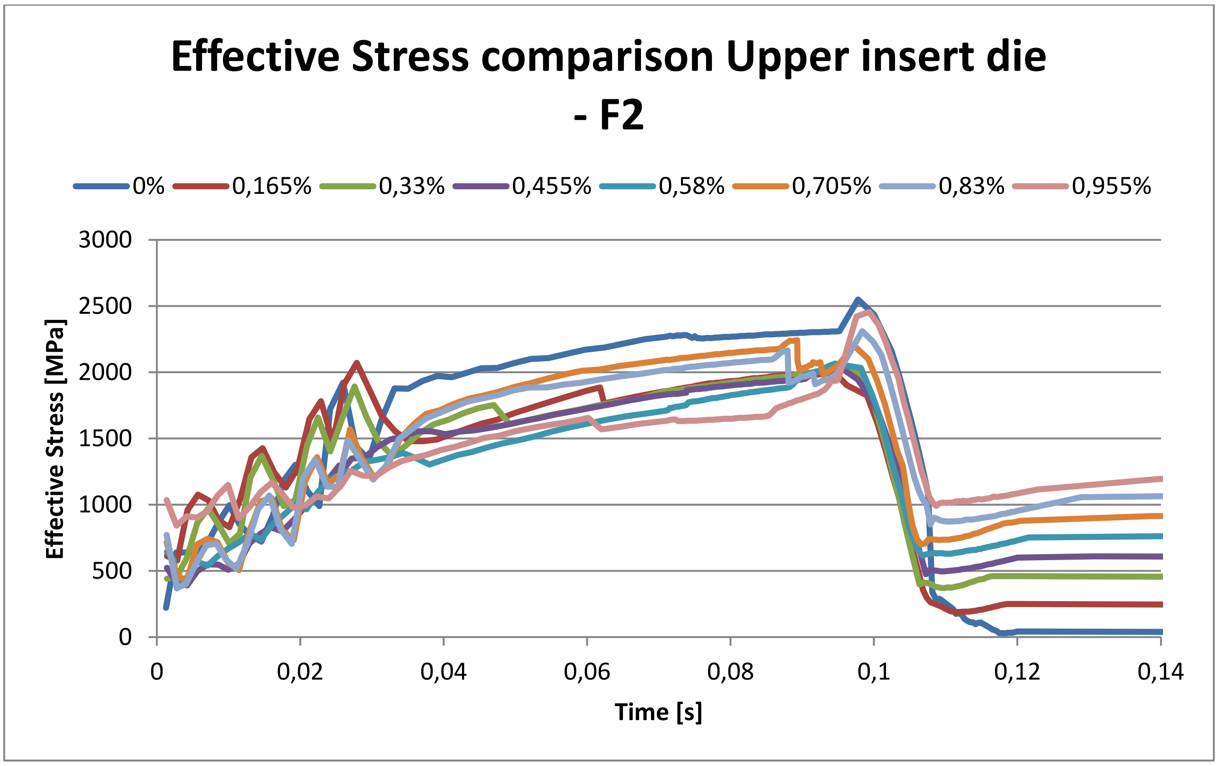


Figure 51 – Node with highest effective stress – Upper insert die - Product variant F2

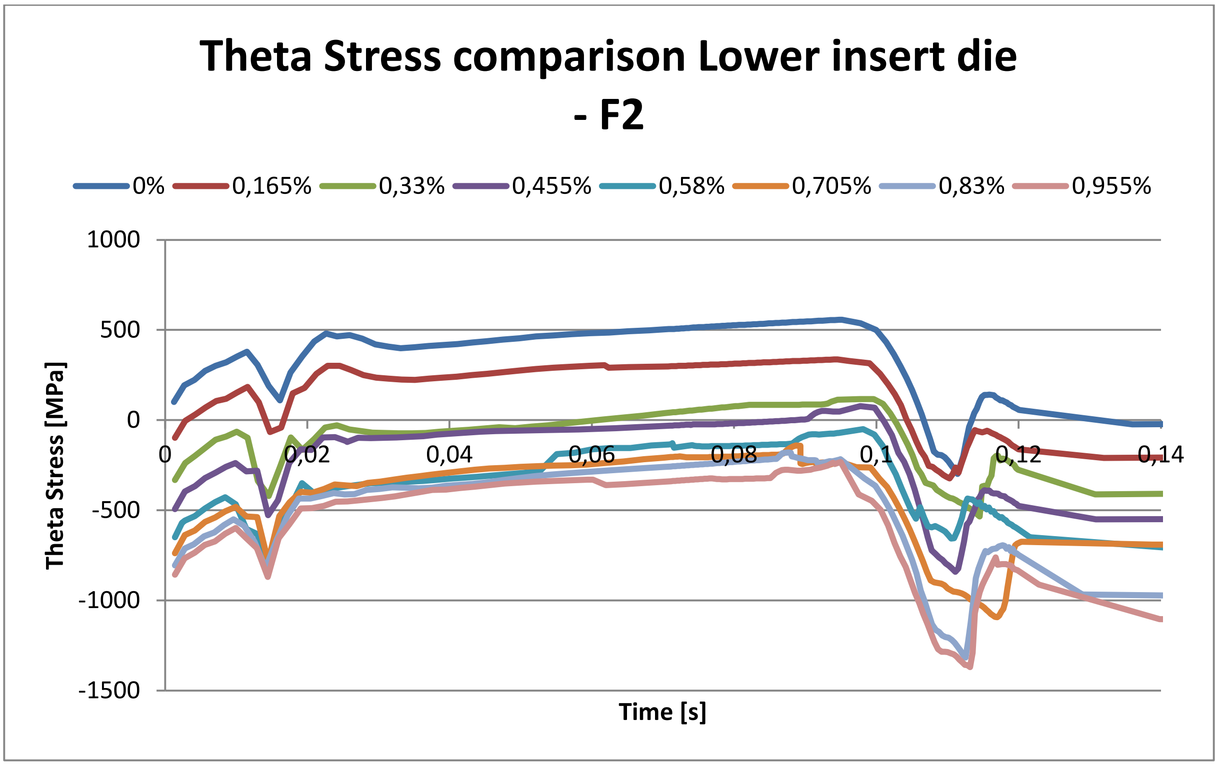


Figure 52 – Node with highest theta stress – Lower insert die - Product variant F2

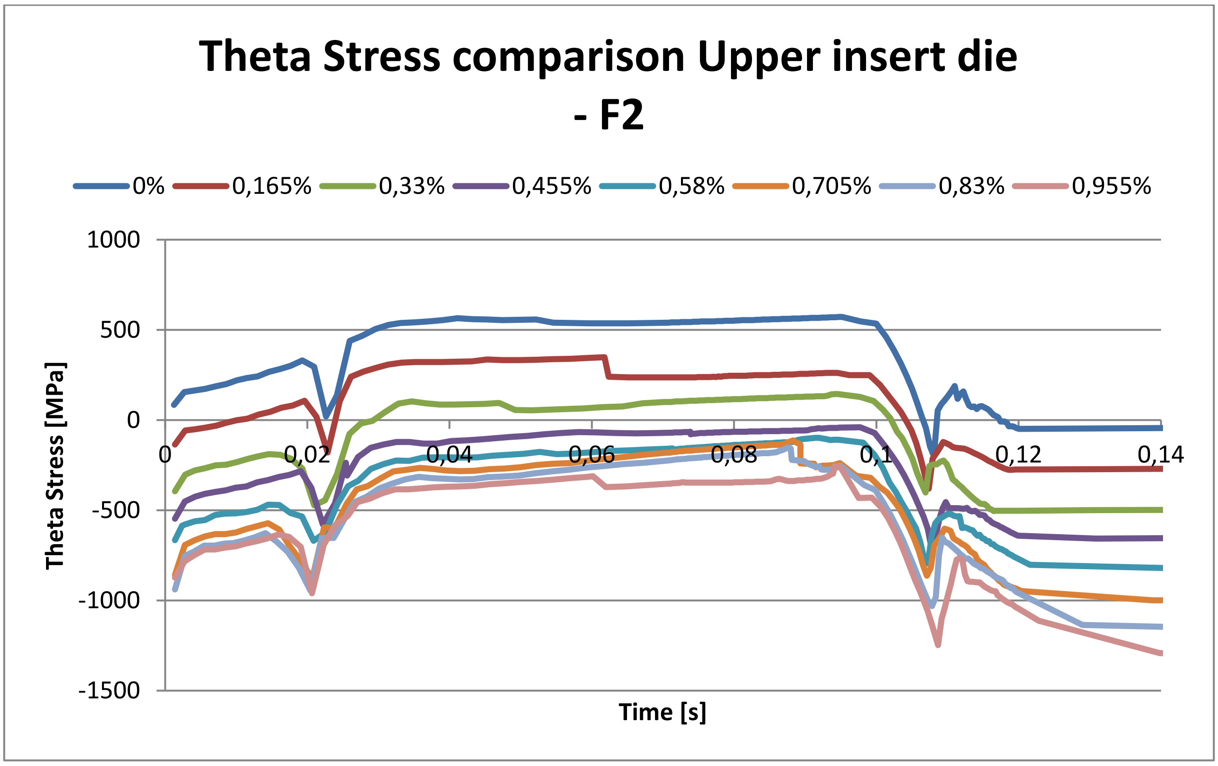


Figure 53 – Node with highest theta stress – Upper insert die - Product variant F2

4.2.2.5 Product variant G1

For product variant G1 the estimated service life is presented in figure 54. The upper insert die service life is clearly different from the earlier estimations for the other product variants. This can be explained with the help of figure 55. Due to how the simulations are modeled the support pins displacement during the forming operation is neglected. In most cases this is a valid approach but in this case when the displacement of the support pin is much larger than the displacement of the insert die it changes the stress levels in the tools. Considering the lower insert die estimated service life the optimum lays with a shrink fit ratio of 0.33%.

In figure 58 and 59 it can be observed that for every shrink fit ratio except for 0,955% will the theta stresses shifts from compressive to tensile stress. In figure 56 it can be seen that some of the simulations remeshings that have resulting in a large change in the stress curve.

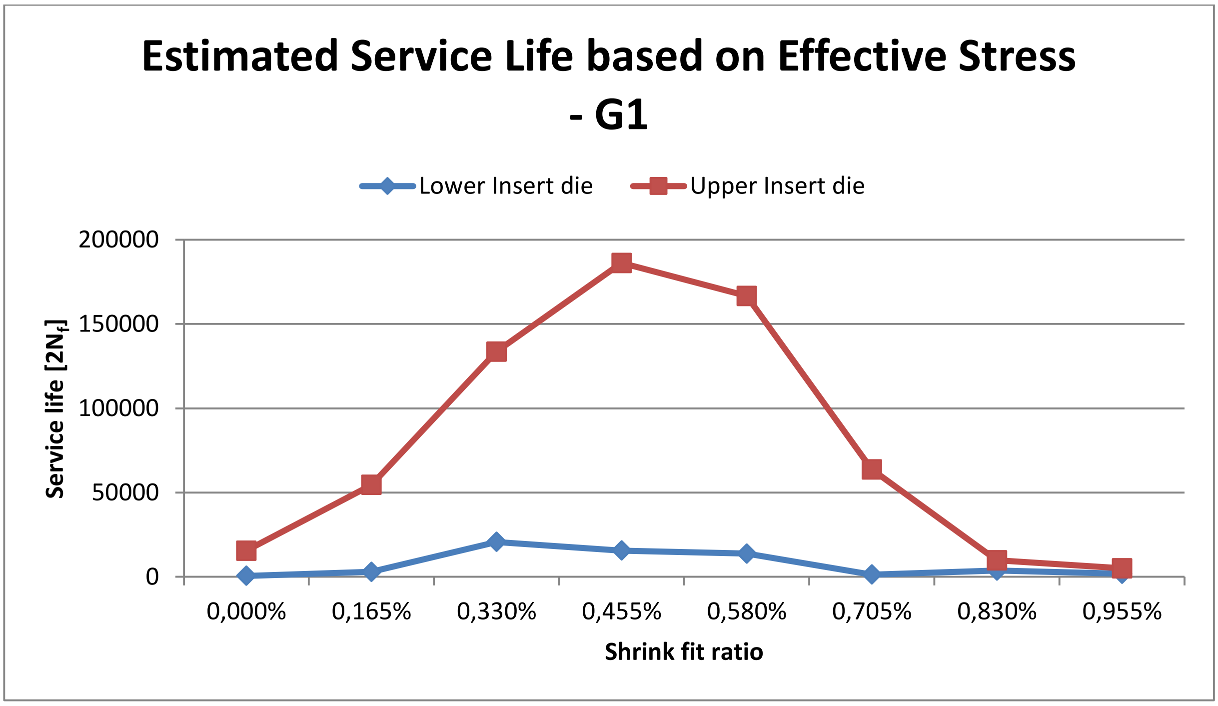


Figure 54 - Estimated service life for product variant G1

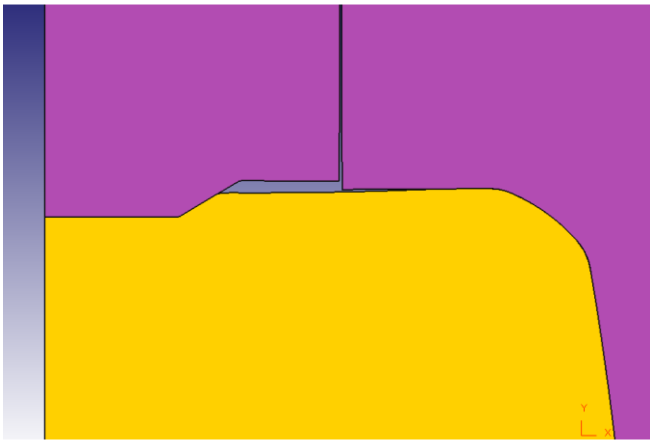


Figure 55 - Product variant G1

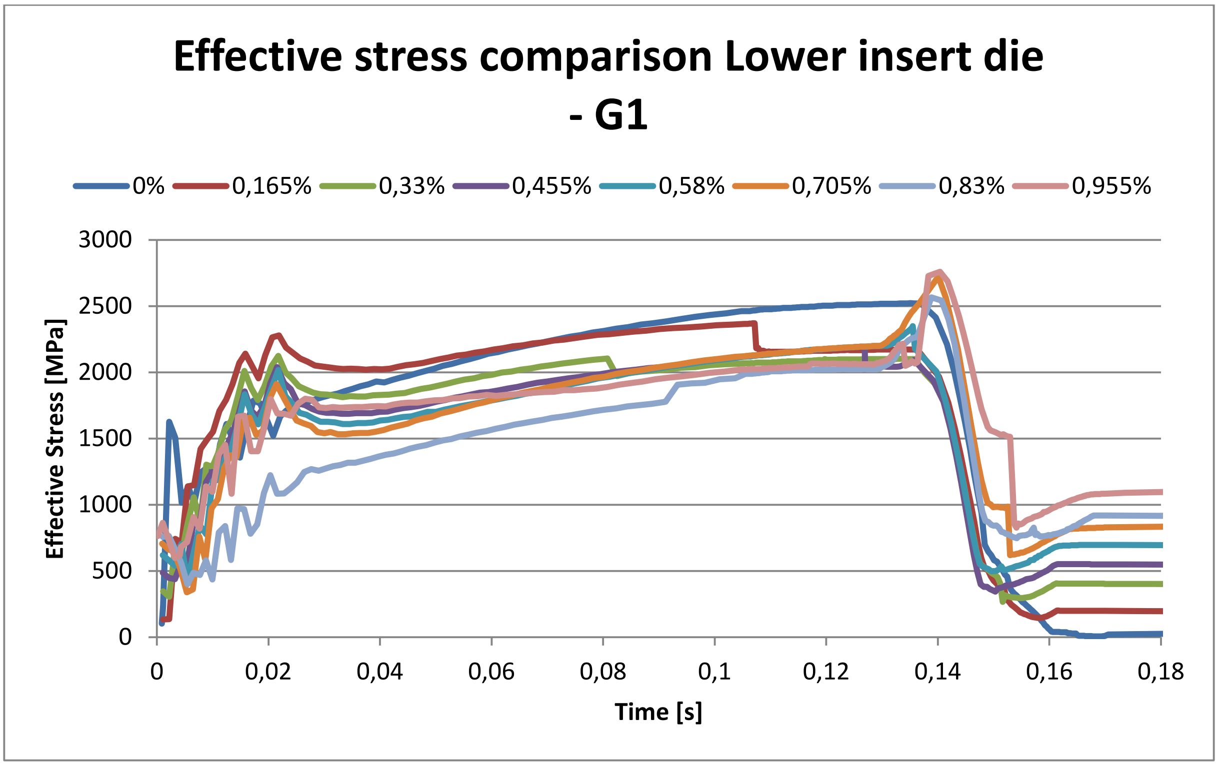


Figure 56 – Node with highest effective stress – Lower insert die - Product variant G1

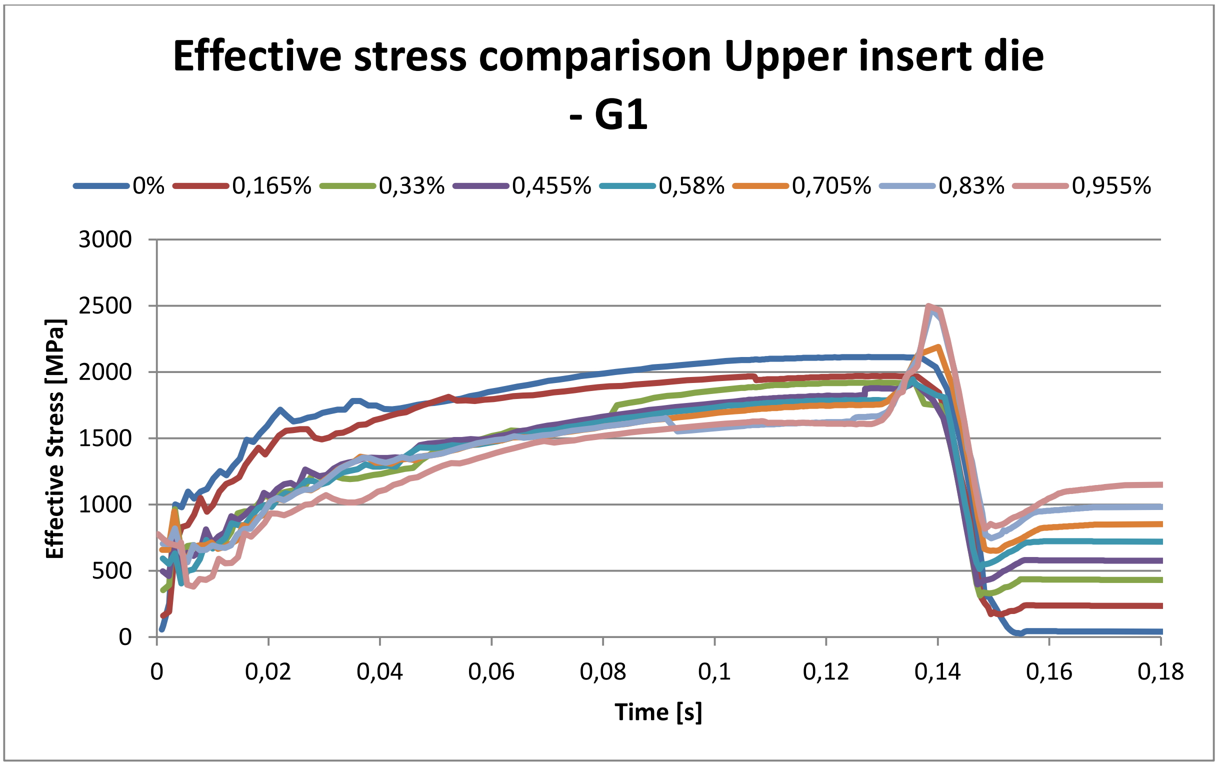


Figure 57 – Node with highest effective stress – Upper insert die - Product variant G1

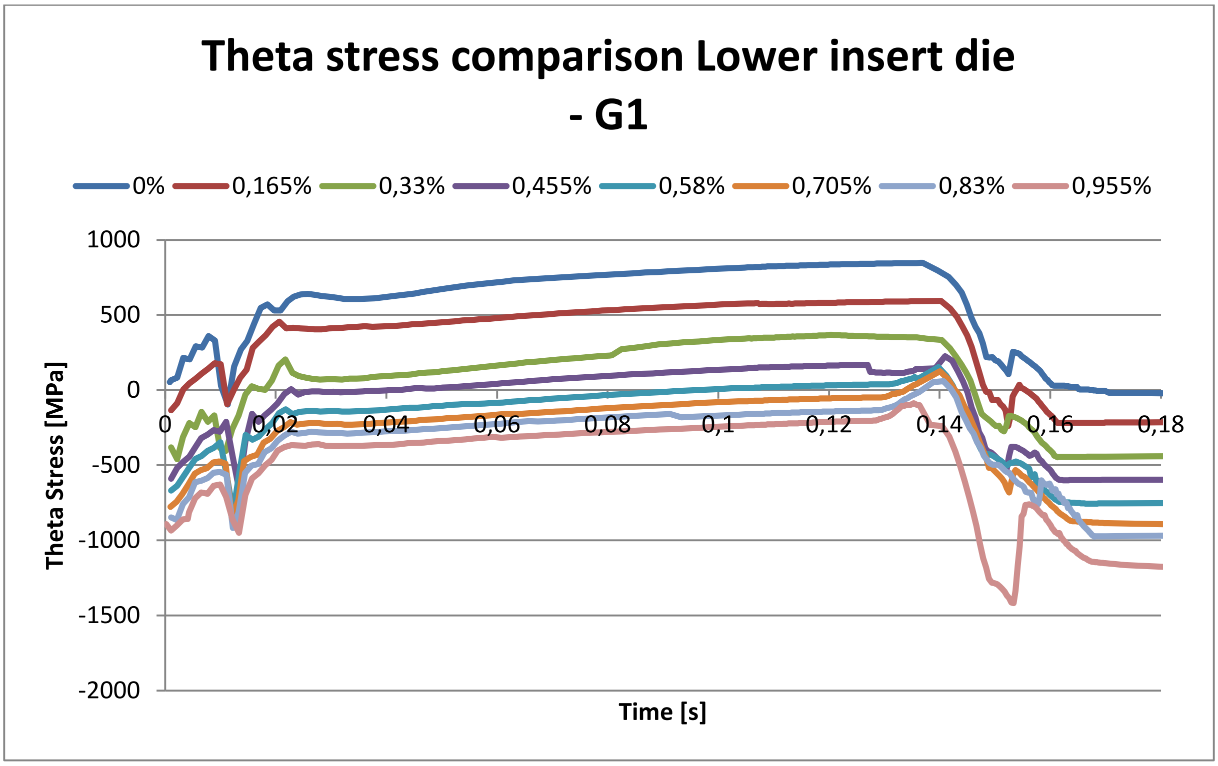


Figure 58 – Node with highest theta stress – Lower insert die - Product variant G1

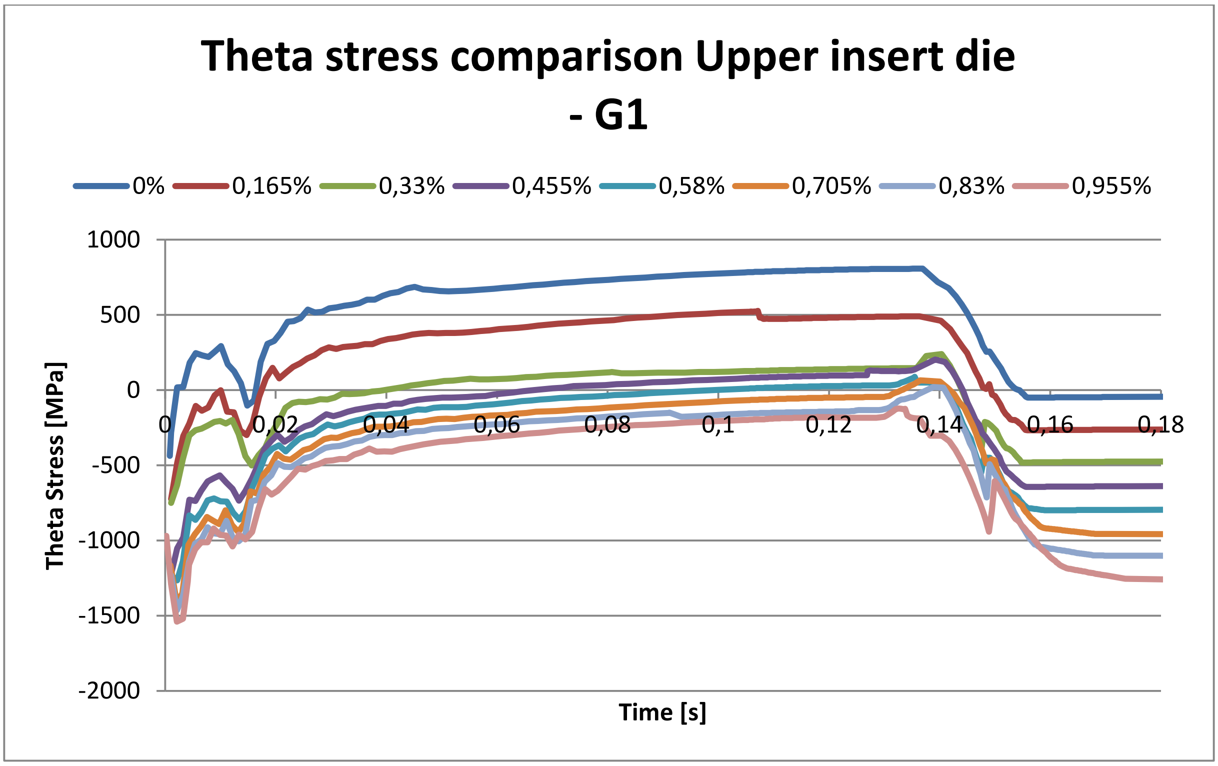


Figure 59 – Node with highest theta stress – Upper insert die - Product variant G1

4.2.3 Optimization with axial pre-stress

To investigate if an axial pre-stress of the insert dies will effect the service life three simulations were performed. Optimization of axial pre-stress was performed on product variant D1 with a shrink fit ratio of 0.58%. The results can be seen in figure 60. From the simulation result an axial pre loading could result into a doubling in the service life from an already optimized product variant.

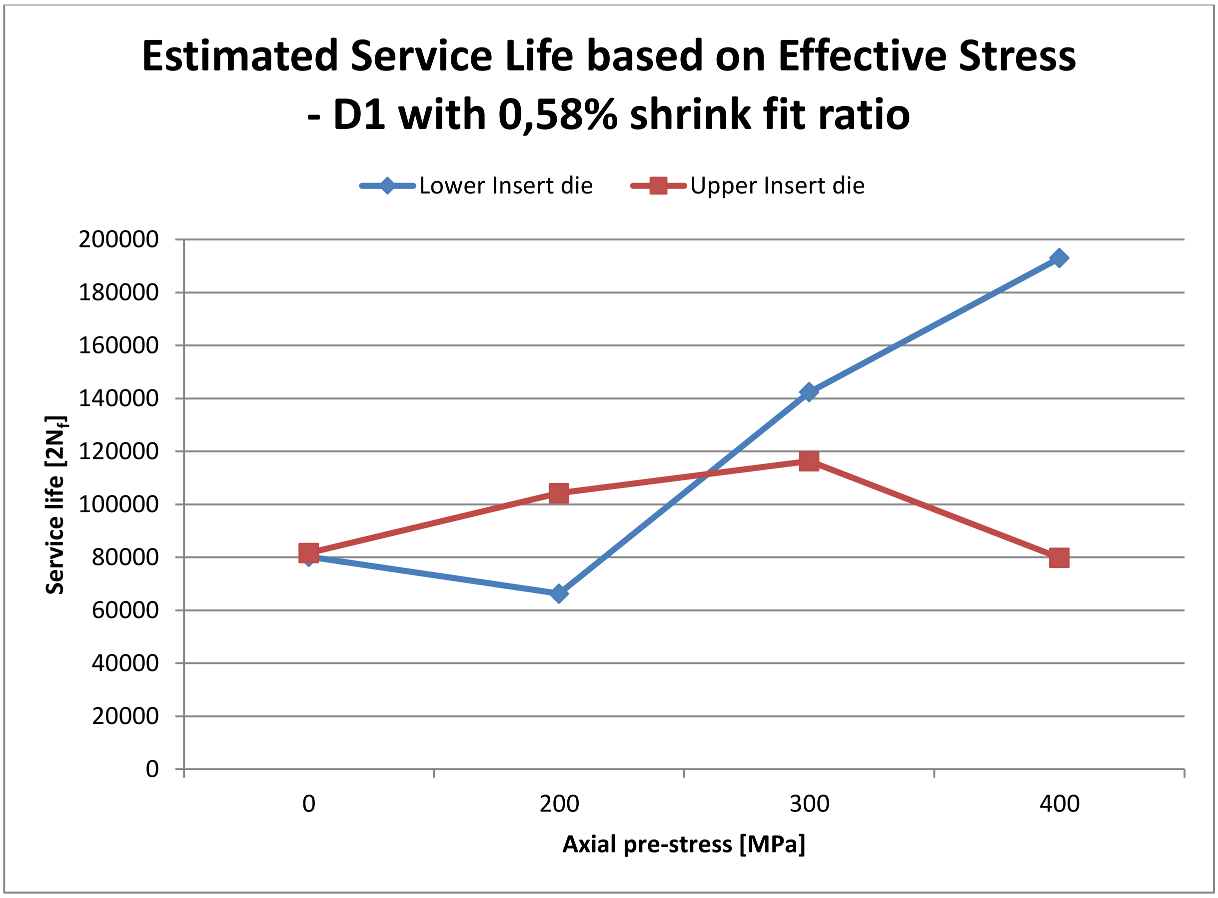


Figure 60 - Estimated service life for product variant A1 with axial pre-stress

4.3 Validation

To validate if the DEFORM is performing as the reality two test was conducted. Test one was to control if the displacement of an object during load is the same in reality and in the simulation. Test two was to control if the heat generation during the press operation is the same in reality and in the simulations. These tests result are presented below.

4.3.1 Test one - Displacement

In figure 61 and 62 the points that the CMM measured before and after the assembly of the insert die and shrink fit container. In Table 1 the results from the CMM and the simulations are presented. When taking into account the tolerance of CMM the simulations could be considered as good representation of the reality.

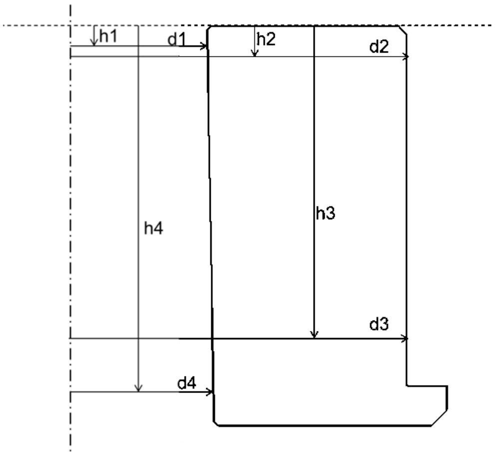


Figure 61 – Lower shrink ring

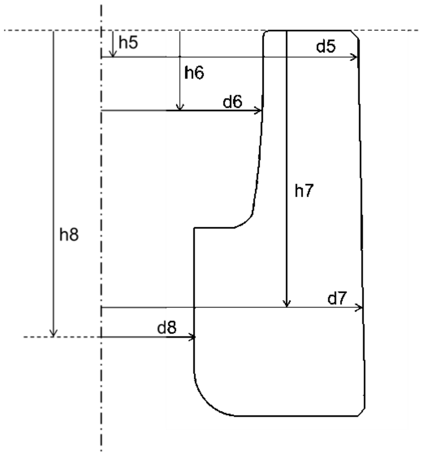


Figure 62 – Lower insert die

Table 1 – Displacement measurements

Measurement	Measured	Modeled	Measured	Simulated	Difference
	<u>Before assembly</u>		<u>After assembly</u>		
d1	59,829	59,829	-	-	-
d2	109,717	109,717	109,842	109,8416	0,0004
d3	109,722	109,722	109,845	109,8652	-0,0202
d4	61,330	61,330	-	-	-
d5	61,255	61,255	-	-	-
d6	35,128	35,128	35,012	35,024	-0,012
d7	60,258	60,258	-	-	-
d8	17,125	17,125	17,063	17,0609	0,0021
Accuracy of the CMM ~5µm on 100mm					

4.3.2 Test two – Heat generation

Results from the heat generation test are presented in table 2. The simulation and the measured values are close together and it indicates that the software's heat generation estimation performs well.

Table 2- Heat generation

Temperature – Product variant G1			
Part	Measured value	Simulated value	Comment
Blank	21.5 ºC	-	Stored >24h inside
Roller	49,3 ºC	50,3 ºC	Mean from 5. ~15 sec cool down
Upper Insert die	33,7 ºC	-	>1h running. ~15 sec cool down
Lower Insert die	37,3 ºC	-	>1h running. ~15 sec cool down
~7000 cycles before measuring			

In appendix C an investigation of how an elevated temperature would effect the shrink fit ratio. The outcome was that an elevated temperature of $60\ ^{\circ}C$ wouldn't effect the shrink fit ratio substantially.

4.4 Production test

A production endurance test was performed on product variant E3 with a changed shrink fit ratio to 0.58% from 0.33%. This resulted in a service life of 19000 for the upper insert die and at least 14000 for the lower insert. In the beginning of the test the lower insert failed after 500 cycles. The reason is not known but it suspects to be either due to a blank with geometry outside the specification or that the insert die had material defects. These results were in line with the calculated service life. The service life calculation predicts that the service life should be unchanged. It can also be noted that the estimated force need for the forming operation was close to the measured force during the test. Simulation predicted 90 ton of force and the measurement equipment attached to the machine showed the force of 88 ton.

4.5 DOE evaluation

To present and evaluate the usefulness with the new DOE module for designing the press operations two scenarios were created. Scenario one was to optimize the blank height to make a complete fill of an insert die. Scenario two was to examine the influence of the movement speed and the friction has on the maximum effective stress. The results of these scenarios are presented below.

4.5.1 Scenario one

In order to optimize the blank height the software first needed one simulation as a starting point. Here one makes an initial guess what height the blank should have and run the simulation as usual. When the simulation was completed a DOE study was added to the simulation. In this study it was possible to change many of the ingoing parameters of the simulation to see their impact on for example stress levels or die fill. In this case the only parameter of interest was the height of the blank. This parameter was easily changed. Only to click on the nodes that should be move and specify the distance. This can be seen in figure 63. In this step it was possible to specify an upper and lower limit of the displacement of the nodes. When the geometry was defined it was time to define the area that should be filled. In this case an area close to the top of the lower insert die was chosen to be examined to see if the different blank heights were able to fill it, figure 64. It was also possible to import the geometry of a product variant to check if the blank fills it completely. This can become difficult to work properly due to the displacement of the press tools and the shape of the roller. Therefore an approach like the one that was used in this project would be favorable. An experienced tool designer would know if a certain area was filled in a press tool there was also likely the rest of the tool is completely filled.

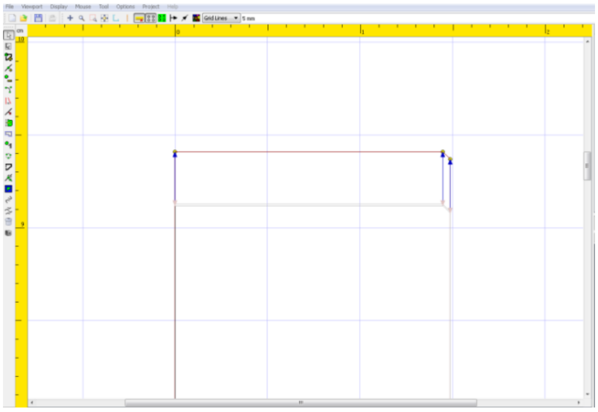


Figure 63 – Defining Geometry

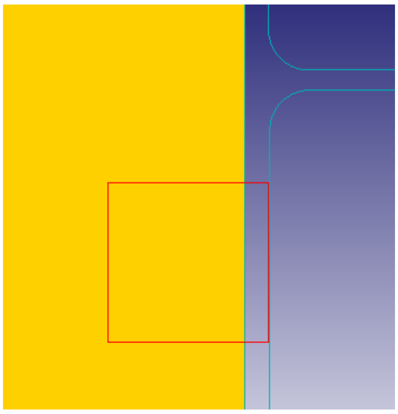
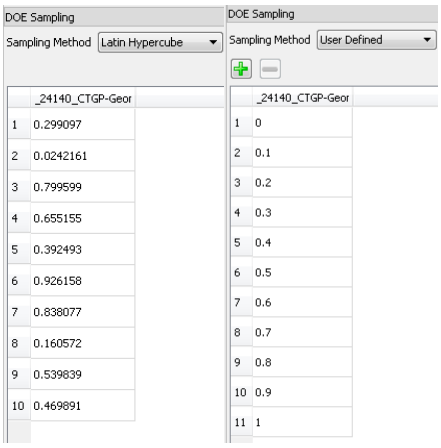


Figure 64 – Area of interest

Next was to define is how many different geometries that should be simulated. This can be made either to set a number of samples with random intervals between or with specified intervals, figure 65. If the intervals were specified manually they can be set to the same range as the tolerances of the blank. When the sample size was defined it's time to start the DOE simulation. When it was completed a table was created and showing clearly which heights of the blanks meets the criteria of filling the area of interest, figure 66. This approach can be also extended to take in account in change of the diameter of the blank. It was also possible to extend the result from only looking for a complete fill to also minimizing stress in selected areas.


DOE Sampling

Sampling Method: Latin Hypercube

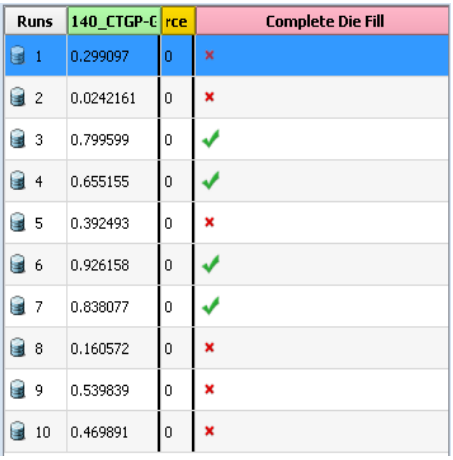
	_24140_CTGP-Geor
1	0.299097
2	0.0242161
3	0.799599
4	0.655155
5	0.392493
6	0.926158
7	0.838077
8	0.160572
9	0.539839
10	0.469891

DOE Sampling

Sampling Method: User Defined

	_24140_CTGP-Geor
1	0
2	0.1
3	0.2
4	0.3
5	0.4
6	0.5
7	0.6
8	0.7
9	0.8
10	0.9
11	1

Figure 65 – DOE Sampling

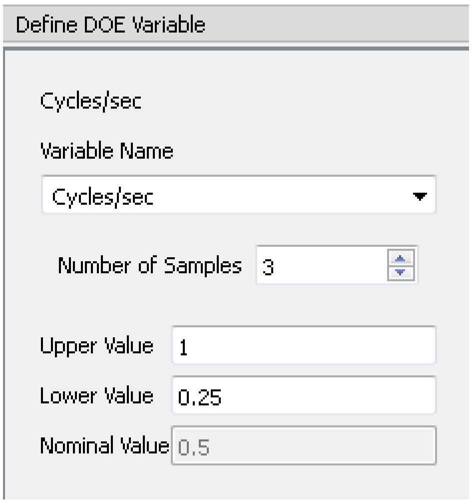


Runs	140_CTGP-C	rce	Complete Die Fill
1	0.299097	0	✗
2	0.0242161	0	✗
3	0.799599	0	✓
4	0.655155	0	✓
5	0.392493	0	✗
6	0.926158	0	✓
7	0.838077	0	✓
8	0.160572	0	✗
9	0.539839	0	✗
10	0.469891	0	✗

Figure 66 – Table of result

4.5.2 Scenario two

As scenario one an origin simulation was needed to be able to run a DOE simulation. When the origin simulation was completed a DOE study is added to the simulation. Next was to add DOE variables to the simulation. In this case the movement speed of the forming operation and the friction were set as variables. In figure 67 it can be seen how the movement speed was defined. It was only to define the upper and lower limit for the movement speed and how many samples that should be within this range. The same approach goes for defining the friction.



Cycles/sec

Variable Name: Cycles/sec

Number of Samples: 3

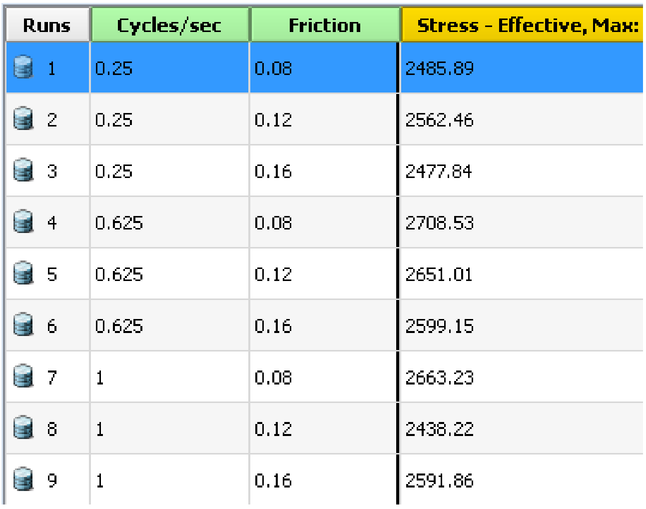
Upper Value: 1

Lower Value: 0.25

Nominal Value: 0.5

Figure 67 – Define DOE Variable

Next step of the DOE simulation was to define which parameters that should represent the result. In this case the maximum effective stress in the critical area was selected as the resulting parameter. When this was defined it was just to start the simulation. When the simulation was completed the results were presented either in a table like in figure 68, as a response surface as in figure 69 or in a sensitivity plot like in figure 70. In the table the different runs results are presented. It also shows if some of the runs have failed during the simulation. The response surface can be either linier, quadratic or Gaussian. In this case the results are presented as a quadratic surface.



Runs	Cycles/sec	Friction	Stress - Effective, Max:
1	0.25	0.08	2485.89
2	0.25	0.12	2562.46
3	0.25	0.16	2477.84
4	0.625	0.08	2708.53
5	0.625	0.12	2651.01
6	0.625	0.16	2599.15
7	1	0.08	2663.23
8	1	0.12	2438.22
9	1	0.16	2591.86

Figure 68 – Table of result

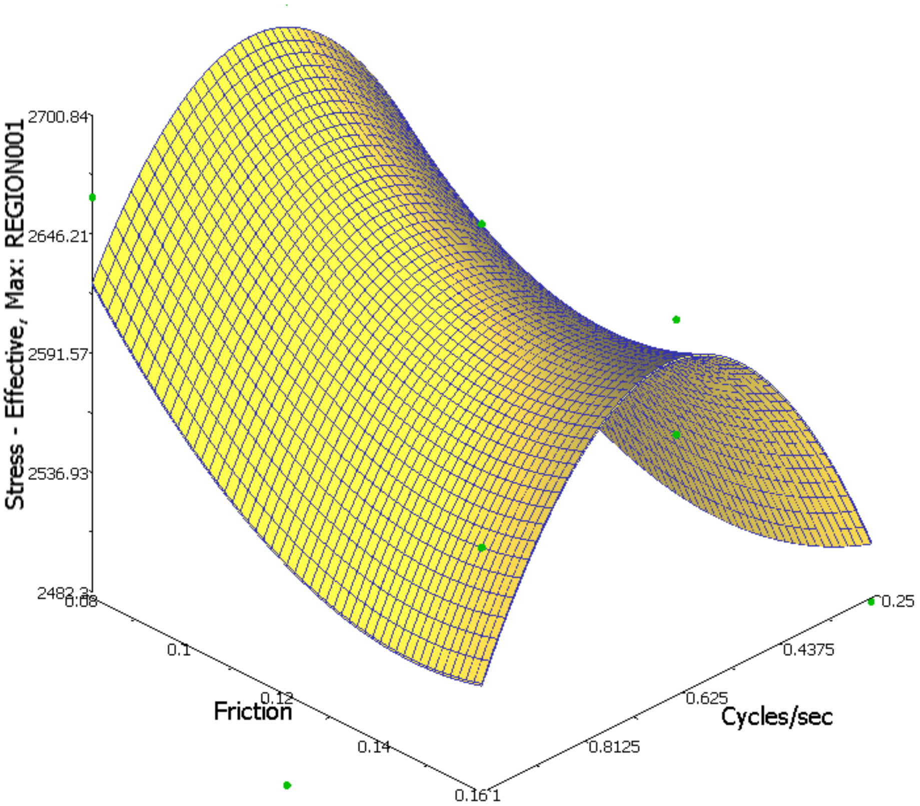


Figure 69 – Quadratic response surface

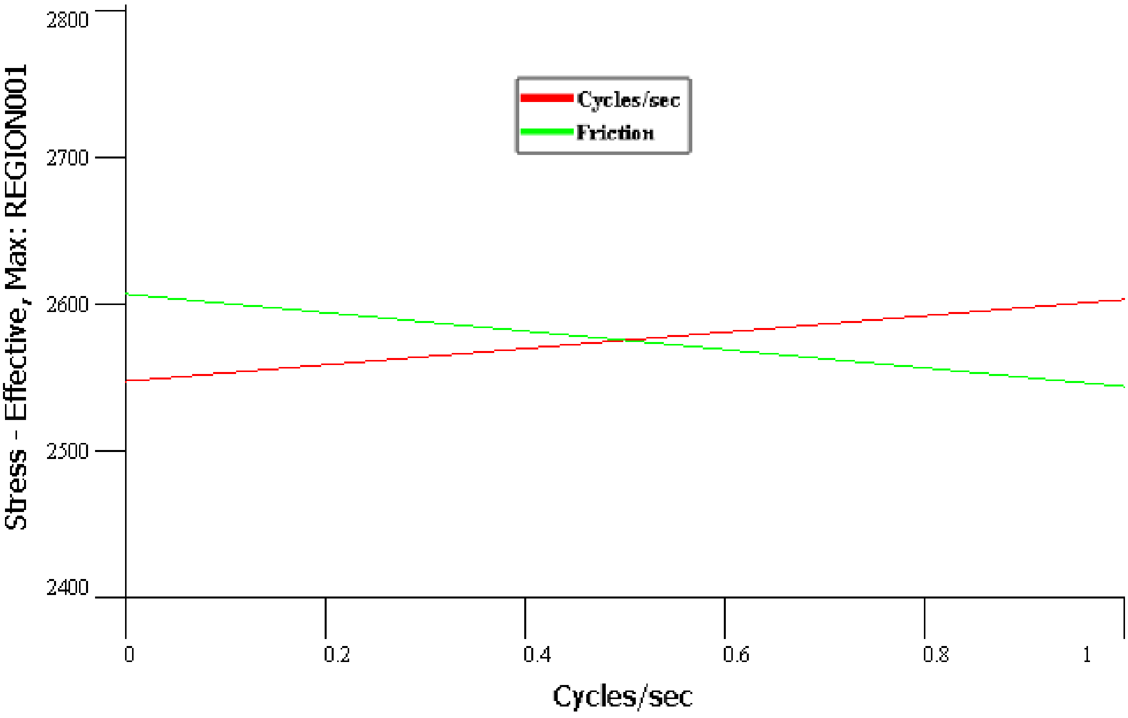


Figure 70 – Sensitivity plot

5 Analysis

The results from the *information study, simulation* and *practical test* are analyzed below.

5.1 Information study

An analyze about the ingoing parts of the information study are presented below

5.1.1 Production study

Result from the production data collection showed that many of the product variants consumes more tools per order than the set target. But due to the reliability of the data was low the calculated mean service life of the tools should be seen more as a guideline than an absolute number.

One earlier test with a changed shrink fit ratio had been performed with promising results. Type of failure had changed from fatigue cracks to wear. This could be set as a new target when designing new tools. It was now known that with an optimized shrink fit ratio the service life of the insert dies can be extended to a new level. A level when the service life was determined by wear instead of fatigue cracks.

5.1.2 Literature study

The literature was united that an optimized shrink fit ratio is beneficial for the service life of press tools. Many of the authors report an increase of the service life by at least twice when optimizing the shrink fit ratio. Something that was noteworthy was that in the literature when the shrink fit ratio was changed and an increased service life obtained it was never mentioned that the geometry of the tool is changed to compensate for the compression of the tool.

In order to estimate the service life with Morrow's stress/strain approach was widely used. The sort of stress/strain that should be used to was not defined. It was up to the user to choose one for the specific case.

5.1.3 Design study

Because there were no guidance or templates of how to design a new shrink fit container at the design departments disposal there was no starting point. This allows this work to be a template when designing new tools.

5.2 Simulation

An analysis of the simulation results for *Simulation of product variants with original shrink fit ratio, optimizing process* and *DOE evaluation* are presented below. There will also be presented the project's thoughts about the software's ability to perform as a production tool.

5.2.1 Simulation of product variants with original shrink fit ratio

Simulations with the original shrink fit ratio shows that the effective stress levels were in the region where the material starts to plasticize. This means there were probably some small plastic deformations in the tools. But it assumes to be much smaller than the elastic deformation and thus the service life calculations can neglect the plastic part of the formula.

When searching for a common material parameter it become clear that the service life equation was very sensitive. Thus it was impossible to find one parameter that makes the calculated values corresponds to the production data.

Service life estimation is largely dependent on the maximum effective stress level and from that the search of trends between the different product variants were conducted. After comparing the different attributes of the product variants to their maximum effective stress it could be concluded there were no visible trends. Attributes of the product variant seems to have little influences on the stress levels. Thus the control of the stress levels lays in the design of the tools and not in a specific attribute.

5.2.2 Optimization process

When trying to optimize the shrink fit to gain a higher service life it became clear that in most of the cases the optimum lays close to the original shrink fit. It can be also observed that if the design of the tools allows a higher shrink fit the service life increases rapidly. Another observation is that even if the tools become overfilled due to the shrink fit ratio the theta stress stays as compressive during the whole press process when the ratio exceeds $0{,}455\%$.

No common material strength exponent was found between the product variants. But the ones that were used to calibrate the variants in the optimization process were found to be close to each other and within the guideline given be Morrow.

Adding pre-stress in the axial direction of the tool gives promising results. From an already optimized product variant an axial pre-loading estimates to increase the service life further with a factor of two for the lower tool.

In this case an optimized shrink fit was closely related to the design of the tool. Therefore to get the benefits from shrink fitting the tools should be designed when a shrink fit ratio is set.

5.2.3 DOE evaluation

Scenario one shows in a simple way how useful the DOE module could be when designing blanks to completely fill the tools. Only a few additions to a normal simulation, the possibility to set the interval of the blank height and a clear visualization of which heights passes the filling criteria make the DOE module very useful.

Scenario two demonstrates how the DOE module could be used to investigate process parameters influences on the forming operation. The results are easily accessed and presented in a clear way. Therefore the DOE module would be useful in this kind of process investigation.

Something that was not critical for the usefulness but would be a good edition to the DOE module would be the possibility to investigate more than one object in one DOE project. Today it needs to be run two separate DOE simulations to be able to see the effect of a certain parameter has on the lower and upper tool at the same time.

5.2.4 DEFORM's performance

DEFORM is a software that has a low entry level to start to simulate problems. With this easy access comes also that many parameters has a default setting and don't needed to be changed for a simulation to be able to run. In this way it is easy to oversee critical boundary conditions and/or choosing the wrong type of calculation method. Thus if something is overseen or missing the results could be irrelevant (Ottosen & Petersson, 1992).Therefore it is not only the input data that effect the quality of the results but also how the results is produced. Moreover in this version of DEFORM there are issues with the reliability of modeling and running the simulations. To mention two issues, one is memory leaks that causes the simulation to stop and second there are sometimes when DEFORM believes that some elements in a mesh have a negative area but clearly has a positive one. There are tweaks to go around these problems but in this type of premium software problems like this should not exist.

5.3 Practical test

Below the analysis of the results from the practical tests are presented

5.3.1 Displacement

When comparing the results from the CMM and the simulations the conclusion can be drawn that the simulation software represents accurately the reality. Thus when the task is to simulate displacements the software can be trusted.

5.3.2 Heat generation

The differences in the results between the simulation and in reality are small. From this the conclusion can be drawn that the software estimates the temperature increase due to the deforming with good precision.

5.3.3 Endurance test

Even if the lower insert die failed already after 500 cycles the upper insert die lasted for 19000 cycles. When the lower insert die was changed it was still functional after 14000 cycles. This was in the same range as the service life estimations and thus there was an indication it is possible to calculate the service life from the simulation results. When it comes to the premature failure of the lower insert die the reason behind it should to be investigated further.

6 Conclusion

The aim with this project was to evaluate the impact of the shrink fit ratio has on the service life for press tools with the assistance of simulation. Questions that were defined in chapter 1.2 are answered below.

An optimized shrink fit ratios increases the service life only if the current tool design allows it. With todays tool design is most likely that a changed shrink fit ratio will effect at best a service life to the same range as the original shrink fit ratio. In some cases a considerably lower service life will be achieved. But if the tool design allows a changed shrink fit the service life can increased with at least a factor of two. This conclusion is supported both by simulation and practical test.

An attribute based selection of an optimized shrink fit ratio is not possible today. This because there could not be found any trends between the different product variants and their maximum effective stress.

If the insert die design allows a changed shrink fit ratio the service life will reach acceptable levels. If the service life needs to be raised even further the simulation shows a potential to increase it further with axial pre-stressing. This approach estimates to increase the service life additional with a factor two. However if this approach is possible in reality the project doesn’t address.

The DOE module would be suitable to design press operations. In a few easy steps the height of a blank could be determined to be able to completely fill the tools. Also it would be useful to determine what the influences different process parameters such as movement speed and friction has on the stress levels in the press tools.

6.1 Future work

Topics that would be beneficial to continue work with are presented below

- Residual stresses
  How big are the stresses and do they work in favor of the service life?

- Design tools with an higher shrink fit ratio
  With a tool design optimized for a higher shrink fit ratio how much would that increase the service life?

- Axial pre-load of insert die
  Promising simulation results but is it possible to recreate in reality?

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Appendix

A. Derivation of Morrow’s local stress formula

$$\Delta\epsilon = \Delta\epsilon_e + \Delta\epsilon_p \qquad [A.1]$$

$$\Leftrightarrow$$

$$\frac{\Delta\epsilon}{2} = \frac{\mathrm{\sigma}}{2\mathrm{E}} + \frac{\Delta\epsilon_\mathrm{p}}{2} \qquad [A.2]$$

$$\sigma_a = \frac{\Delta\sigma}{2} \qquad [A.3]$$

$Assuming\ plastic\ strain\ is\ near\ zero\ \Rightarrow$

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_a}{E} \qquad [A.4]$$

Morrow’s local strain approach

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_f' - \sigma_m}{\mathrm{E}} \cdot \left(2 \cdot N_f\right)^b + \epsilon_f' \cdot \left(2 \cdot N_f\right)^c \qquad [A.5]$$

$Assuming\ plastic\ strain\ is\ near\ zero \Rightarrow$

$$\frac{\Delta\epsilon}{2} = \frac{\sigma_f' - \sigma_m}{\mathrm{E}} \cdot \left(2 \cdot N_f\right)^b \qquad [A.6]$$

$$\Leftrightarrow$$

$$\frac{\sigma_a}{E} = \frac{\sigma_f' - \sigma_m}{\mathrm{E}} \cdot \left(2 \cdot N_f\right)^b \qquad [A.7]$$

$$\Leftrightarrow$$

$$\frac{\sigma_a}{\sigma_f' - \sigma_m} = \left(2 \cdot N_f\right)^b \qquad [A.8]$$

$$\Leftrightarrow$$

$$2 \cdot N_f = \left(\frac{\sigma_a}{\sigma_f' - \sigma_m}\right)^{1/b} \qquad [A.9]\ \ ([3])$$

(Bannantine, et al., 1989)

B. Calculate intersecting point to define curve

In order to transfer a curve from a drawing to the software one need to know the intersecting point of the two tangents of the two points on a circle. A drawing defines a curve with two points and a radius between them, figure B.1. The software wants also the point (x_r, y_r) to be able to define a curve, figure B.2. This point can be derived from figure B.3 and with the equations B.1 and B.2. When combining these equations it is possible to calculate a and b, equation B.3 and B.4. When a and b are known it is possible to calculate $K_1$and K_2 with equation B.5 and B.6. From this it is than possible to calculate $X_r and\ Y_r$ by combining equations B.7, B.8, B.9 and B.10 to equation B.11 and B.12.

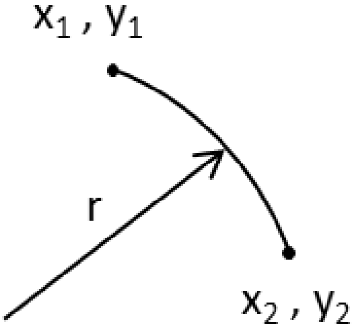

Figure B.1 – Radius between two points

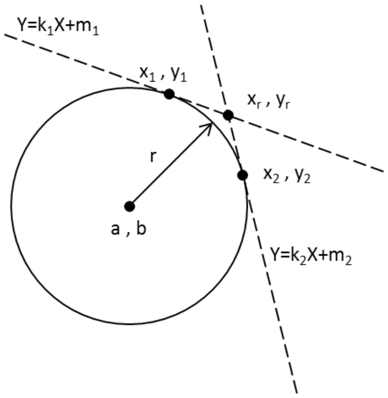

Figure B.2 – Define intersecting point behind curve

$$(Y_1 - b)^2 + (X_1 - a)^2 = r^2 \qquad [B.1]$$

$$(Y_2 - b)^2 + (X_2 - a)^2 = r^2 \qquad [B.2]$$

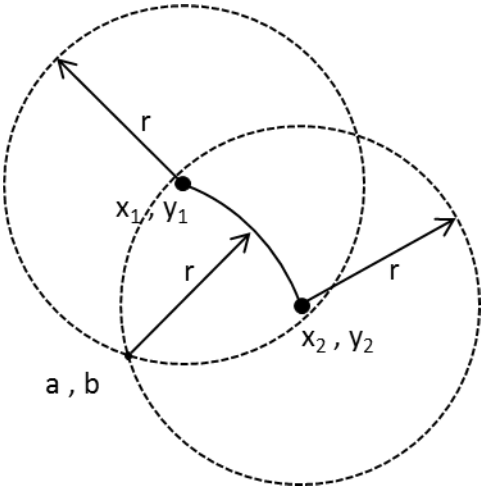

Figure B.3 – Derivation of origin of circle

$$\begin{aligned} a = ((-\surd\,((&-4 \cdot \mathrm{X}_1^3 + 4 \cdot \mathrm{X}_1^2 \cdot \mathrm{X}_2 + 4 \cdot \mathrm{X}_1 \cdot \mathrm{X}_2^2 - 4 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_1^2 + 8 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 - 4 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_2^2 - 4 \cdot \mathrm{X}_2^3 - 4 \\ &\cdot \mathrm{X}_2 \cdot \mathrm{Y}_1^2 + 8 \cdot \mathrm{X}_2 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 - 4 \cdot \mathrm{X}_2 \cdot \mathrm{Y}_2^2\,)^2 - 4 \cdot (4 \cdot \mathrm{X}_1^2 - 8 \cdot \mathrm{X}_1 \cdot \mathrm{X}_2 + 4 \cdot \mathrm{X}_2^2 + 4 \cdot \mathrm{Y}_1^2 \\ &- 8 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 4 \cdot \mathrm{Y}_2^2\,)\ \ \cdot (-4 \cdot \mathrm{X}_2^2 \cdot \mathrm{Y}_1^2 + 8 \cdot \mathrm{r}^2 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 - 4 \cdot \mathrm{r}^2 \cdot \mathrm{Y}_2^2 + \mathrm{X}_1^4 - 2 \cdot \mathrm{X}_1^2 \cdot \mathrm{X}_2^2 \\ &+ 2 \cdot \mathrm{X}_1^2 \cdot \mathrm{Y}_1^2 - 4 \cdot \mathrm{X}_1^2 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 2 \cdot \mathrm{X}_1^2 \cdot \mathrm{Y}_2^2 + \mathrm{X}_2^4 + 2 \cdot \mathrm{X}_2^2 \cdot \mathrm{Y}_1^2 - 4 \cdot \mathrm{X}_2^2 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 2 \\ &\cdot \mathrm{X}_2^2 \cdot \mathrm{Y}_2^2 + \mathrm{Y}_1^4 - 4 \cdot \mathrm{Y}_1^3 \cdot \mathrm{Y}_2 + 6 \cdot \mathrm{Y}_1^2 \cdot \mathrm{Y}_2^2 - 4 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2^3 + \mathrm{Y}_2^4\,)\ \ ) + 4 \cdot \mathrm{X}_1^3 - 4 \cdot \mathrm{X}_1^2 \cdot \mathrm{X}_2 \\ &- 4 \cdot \mathrm{X}_1 \cdot \mathrm{X}_2^2 + 4 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_1^2 - 8 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 4 \cdot \mathrm{X}_1 \cdot \mathrm{Y}_2^2 + 4 \cdot \mathrm{X}_2^3 + 4 \cdot \mathrm{X}_2 \cdot \mathrm{Y}_1^2 - 8 \cdot \mathrm{X}_2 \\ &\cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 4 \cdot \mathrm{X}_2 \cdot \mathrm{Y}_2^2\,))/\ (2 \cdot (4 \cdot \mathrm{X}_1^2 - 8 \cdot \mathrm{X}_1 \cdot \mathrm{X}_2 + 4 \cdot \mathrm{X}_2^2 + 4 \cdot \mathrm{Y}_1^2 - 8 \cdot \mathrm{Y}_1 \cdot \mathrm{Y}_2 + 4 \\ &\cdot \mathrm{Y}_2^2\,)) \qquad [B.3] \end{aligned}$$

$$b = \frac{(X_1 - a)^2 - (X_2 - a)^2 + Y_1^2 + Y_2^2}{2 \cdot Y_2 - 2 \cdot Y_1} \qquad [B.4]$$

$$k_1 = -1 \cdot \frac{X_1 - a}{Y_1 - b} \qquad [B.5]$$

$$k_2 = -1 \cdot \frac{X_2 - a}{Y_2 - b} \qquad [B.6]$$

$$Y_1 = K_1 X_1 \cdot m_1 \qquad [B.7]$$

$$Y_r = K_1 X_r \cdot m_1 \qquad [B.8]$$

$$Y_2 = K_2 X_2 \cdot m_2 \qquad [B.9]$$

$$Y_r = K_2 X_r \cdot m_2 \qquad [B.10]$$

$$X_r = \frac{k_1 \cdot X_1 - k_2 \cdot X_2 - Y_1 + Y_2}{k_1 - k_2} \qquad [B.11] \quad ([6])$$

$$Y_r = k_1 \cdot (X_r - X_1) + Y_1 \qquad [B.12] \quad ([7])$$

C. Effect on shrink fit ratio due to elevated temperature

To see if the shrink fit interference changes due to elevated temperature during the press operation the following equation was used

$$I = \Phi\lambda_a \Delta T + \Delta d_a + \Phi\lambda_n \Delta T - \Delta D_n \qquad [C.1]$$

$$\Phi = Common\ diamter\ between\ D_n and\ d_a$$

$$d = Actual\ inner\ diameter$$

$$D = Actual\ outer\ diameter$$

$$\lambda = Therminal\ expansion\ coefficient$$

$$T = Temperature$$

$$a = Shrink\ fitting\ contanier$$

$$n = Insert\ die$$

(Bocchini, et al., 1996)

Were the parameters are

$$\Phi = 60mm$$

$$\Delta d_a = \Delta D_n = 0.1mm\ ^*$$

$$\lambda_a = 11{,}7 \cdot 10^{-6}$$

$$\lambda_n = 12 \cdot 10^{-6}\ ^*$$

$$\Delta T = 40℃$$

$^*assumed\ values$

This resulting into an increase of the interference between the insert die and shrink ring with $\sim 7\mu m$. This range of increase of the interference is very small. It would increase the shrink fit ratio with 0.01% and thus can be neglected.