Simulation Methodologies within Virtual Manufacturing Applied on Mechanical Cutting

PETER ÅSTRÖM

Department of Mechanical Engineering
Division of Computer Aided Design
Preface

The research work presented in this thesis has been carried out within the Polhem Laboratory at Luleå University of Technology, Sweden. The Polhem Laboratory is one of several competence centres funded partly by the university, by VINNOVA (Verket för innovationssystem) and by the participating companies in The Polhem Laboratory. The thesis work has been done in close cooperation with Volvo Aero Corporation. At Volvo Aero Corporation I especially want to thank Maria Nars, Dr Henrik Runnemalm and Prof. Bengt-Olof Elvström for their contribution and support.

Since Luleå University of Technology, and the department of Computer Aided Design, is where I do my every day work, I have a lot of people to thank there. A great thanks to all my present and former colleagues within the department, for making it a pleasant working environment with both work related and non-work related discussions.

Further I would like to send a special thanks to Dr Mats Näsström, my supervisor during almost three years of PhD studies, for making these years a great time both when it comes to research work and time off work.

Finally, I would like to express my appreciation to my family: Magdalena, Christoffer and Emilia: Thank you for being there!

Luleå November 2001

Peter Åström
Abstract

Virtual manufacturing, that is simulation of welding, heat treatment, cutting and other manufacturing processes, is becoming more and more widely used as a tool for prediction of material- and mechanical properties in modern industry. By simulations we refer in this case to FE-simulations of the thermo-mechanical effect of the manufacturing process on the component in question.

Despite the fact that simulations are becoming more widely used, there is a lack of integration of simulations of manufacturing processes in the sense that most work focuses on an individual process being simulated. It is only when a complete chain of manufacturing processes can be simulated the real benefits, of using virtual manufacturing as a tool within product- and process development, will become evident.

This thesis focuses on simulation methodologies within virtual manufacturing, and specifically methodologies for cutting simulations. Simulation of mechanical cutting has been identified as a key area where computational difficulties arise when attempting to simulate a sequence of manufacturing processes involving some form of cutting operation.

A distortion problem during manufacture of a shaft front to a RM12 engine has been analysed. At one time, distortions arised during the later stages of the cutting sequences involved in the manufacture of the shaft front. The ambition was to simulate both cooling from solution heat treatment temperature and the cutting sequence. The result from the cooling sequence however show that the cooling does not cause residual stresses that in turn cause distortions in subsequent cutting sequences, and hence only results from the cooling procedure is presented.

A test case was constructed to ensure that residual stresses would be present causing distortions during subsequent cutting. The experimental set-up with both a forming operation and subsequent cutting is used for validation of the mechanical cutting simulations using an element deactivation technique. The results show that the technique developed can be a useful tool for simulation of mechanical cutting when interested in distortions on component level.

Another necessity when performing analyses of a sequence of manufacturing processes is a system for exchange of Engineering Analysis Data (EAD) between each of the simulations. Further, a system for handling the increasing amount of EAD in the product- and process development process is also needed. Most engineering software is today used to solve engineering problems within a single, limited domain. Efforts have been made to develop standardised formats such as IGES and STEP for EAD exchange both within and across domains. However, by limited implementation in commercial software the user is often forced to either program translation routines that enables data sharing or even recreate meshes, boundary conditions etc. A system has been developed that supports the management of computer-based simulation information. The paper describes how information modelling and database technologies can bring new dimensions to the effective use of engineering simulations in product- and process development.

Keywords: Virtual Manufacturing, FE-simulations, Manufacturing Processes, Methodologies, Mechanical Cutting, Solutioning Heat Treatment, Forming, Aerospace Engineering, Engineering Analysis Data.
Table of Contents

1. INTRODUCTION .................................................................................................................. 1
   1.1 BACKGROUND .................................................................................................................. 1
   1.2 ABOUT VIRTUAL MANUFACTURING .............................................................................. 2
   1.3 AIM & SCOPE OF WORK ................................................................................................. 2

2. SIMULATION OF MANUFACTURING SEQUENCES .......................................................... 3
   2.1 CUTTING .......................................................................................................................... 3
      2.1.1 MECHANICAL CUTTING PRINCIPLES .................................................................. 4
      2.1.2 NUMERICAL ASPECTS IN SIMULATION OF MECHANICAL CUTTING .......... 4
          Explicit vs. Implicit time integration schemes ...................................................... 5
          Lagrangian, Eulerian or mixed formulations ....................................................... 5
          Material models ........................................................................................................ 5
          Thermo-Mechanical coupling .............................................................................. 6
          Contact- and Friction Modelling .................................................................... 6
          Chip separation criteria's .................................................................................... 8
          Mesh adaptivity and regeneration ................................................................... 9
      2.1.3 SIMULATION TECHNIQUES FOR CUTTING SIMULATIONS ....................... 9
          Contact analysis ...................................................................................................... 10
          Element deactivation techniques .................................................................... 11
          Combination techniques ................................................................................... 13
   2.2 HEAT TREATMENT ....................................................................................................... 13
   2.3 WELDING ...................................................................................................................... 14
   2.4 DATA TRANSFER .......................................................................................................... 14

3. SIMULATION METHODOLOGIES WITHIN VIRTUAL MANUFACTURING 14

4. SUMMARY OF RESULTS .................................................................................................. 21
   4.1 PAPER A ....................................................................................................................... 21
   4.2 PAPER B ....................................................................................................................... 21
   4.3 PAPER C ....................................................................................................................... 21

5. DISCUSSIONS & FUTURE WORK .................................................................................. 21

6. REFERENCES ..................................................................................................................... 22

Appended Papers

Paper A The Effect of Convective Heat Transfer Coefficient on the Residual Stresses After Cooling from Solution Heat Treatment

Paper B FE-simulation of Forming and Subsequent Cutting by use of an Element Deactivation Technique

Paper C A System for Information Management in Simulation of Manufacturing Processes
J.P. Åström, *Simulation Methodologies within Virtual Manufacturing Applied on Mechanical Cutting*

1. Introduction

The concept "Virtual Manufacturing" is a commonly used word within the field of manufacturing engineering. There are many definitions of the concept as such, for example:

"Virtual Manufacturing (VM) is an integrated, synthetic manufacturing environment exercised to enhance all levels of decision and control"

*(The Institute for Systems Research/ISR -97)*

More specifically, what is being referred to as virtual manufacturing (VM) in this thesis, is what we can call design- and production-centred VM. In other words this means that:

VM incorporates the modelling and simulation tools, the environment and the logics or methodologies to enable the development of a product, including its manufacturing processes, to be simulated in the computer.

By simulation methodologies, we refer to methodologies that support the use of finite element software to simulate manufacturing processes such as welding, mechanical cutting and heat treatment.

1.1 Background

The finite element method theories emerged mainly during the 1950's and 60's, while under the 1970's through the 80's theories and methods were further developed and implemented in CAE software. Today, FE-simulations are widely used within industry for both design purpose (both linear and non-linear structural analysis) and also for evaluation of the effect of the manufacturing process on the product being manufactured (VM).

In the area of research, most work and most publications focus on one individual process being simulated [4]. As much as this research is needed, there is also a need to study a sequence of manufacturing processes. It is only then the real benefits of using simulations, as a tool within process- and product development, will become evident. An integrated simulation approach, with simulation of all manufacturing processes incorporated in a manufacturing sequence will permit optimisation of process parameters for all operations as opposed to a single operation. It may be facts that a change in a process parameter in a process located in the beginning of the manufacturing sequence not only affects the current process but almost certainly also processes several operations away in the sequence. To enable optimisation of the overall effect of this process parameter on the product, simulation of the entire manufacturing sequence is essential.
Selection of process parameters is a complex task, and definitely a field where choices and decisions are made based on prior knowledge and experience of the process in question. Using simulations as a tool for process parameter evaluation will not replace the need for this knowledge and experience but rather serve as a support in determining process parameters [15].

It is with this background it has been recognized that there exists a need for simulation methodologies within virtual manufacturing when attempting to simulate a sequence of manufacturing processes. What are also needed are computational techniques to perform these simulations in a way that sufficient accuracy is gained within reasonable computational time.

1.2 About Virtual Manufacturing
There have been many revolutions in the area of manufacturing science during the last couple of decades such as, the evolution of laser technology, the introduction of robotics, use of advanced tool materials in cutting processes and the use of modern composite materials [25]. Virtual manufacturing, which is the topic addressed here, is predicted by many to be the next revolution within manufacturing technology and the question is: Has it already started? The gains of using VM are many, and an effort to outline some of these are presented below.

*Reduced time to market*

The lead time can be shortened due to that extensive analyses can be done in a relatively short time. Another time reducing factor is that by enabling parallel activities during the product development process, or what is by other words known as integrated product- and process development (IPPD), the time to market for a product is shortened. Virtual manufacturing essentially serves as a tool enabling simulations and predictions of process parameters to be determined in advance of design of the manufacturing process.

*Reduced tooling cost*

Prediction of material shapes after a manufacturing step enables redesign of tooling to be done virtually, which in turn leads to fewer tool prototypes to be made. This has a great impact on the tooling cost, which often is a leading cost in manufacturing industry.

*Improved quality*

By enabling optimisation and iterative design loops to be done virtually with in comparison to making physical prototypes no increase in cost, the quality of the manufactured products will also benefit [13].

1.3 Aim & Scope of Work
The aim of the work done in this thesis has partly been to enable simulations of a sequence of manufacturing steps to be done, in order to establish methodologies for how simulation activities like this can become an effective tool within product- and process development [7].

Three of the most common manufacturing sequences in many manufacturing industries are welding, heat treatment in some form and mechanical cutting. Of these three, simulation of mechanical cutting has been identified as the operation often being an obstacle when attempting to perform simulations of a sequence of manufacturing steps. The reason for this is that mechanical cutting simulations are very computationally demanding [6]. Simulation of cutting is complex due to a number of factors, mainly due to large plastic deformations, high strain rates, plastic heat generation in the tool-workpiece interface and complex changing
contact conditions. Taking all these aspects into account can result in computational times in 
the order of months if this type of contact analysis is to be performed on component level. 
In order to be able to simulate mechanical cutting on component level, simplified methods 
thus are needed. In this thesis methods for simulation of cutting are investigated, and 
recommendations of when to use which method are suggested.

Another topic essential for the integrated simulation approach is the sharing of analysis data, 
with others whom are performing the next analysis in the analysis sequence [21]. An 
understanding of what type of analysis data, in what format and when it is needed are all 
essential questions to ask. The thesis also presents a system for this type of information 
management within IPPD. This type of system not only enables analysis data sharing but also 
offers effective information management such as transformation between formats, trace- and 
search ability within product analysis data and other database capabilities.

To summarize the aim and scope of the thesis, it can be said that the work so far has been 
focused on investigation and development of simplified methods to simulate cutting and 
outlines when these are appropriate to use. These methods will be used as tools to simulate 
cutting on component level, when attempting to simulate a sequence of manufacturing steps 
including welding, heat treatment and cutting. All these simulations are intended to be 
performed in the type of system for engineering analysis data management also described in 
this thesis.

2. Simulation of Manufacturing Sequences

This section will outline simulation aspects regarding simulation of mechanical cutting. Some 
words will also be mentioned about simulation of welding and heat treatment, even though 
these areas are areas for further work. In addition an introduction of the physical aspects of 
mechanical cutting will be done. Finally, the data transfer issue is addressed.

2.1 Cutting

Mechanical cutting is defined as a number of methods to separate material from a workpiece 
in form of a chip. Methods included in this definition are for example milling, turning, drilling 
and grinding. The cutting methods studied in this thesis are milling and turning. Mechanical 
cutting, and primarily turning operations are very common in the manufacture of aerospace 
components, due to the fact that most components are rotational symmetric, see figure 1. 
Components that have a main geometry that is axisymmetric but also features that are non-
symmetrically placed in the circumference, like in figure 2, normally are subject to a number 
of additional milling operations.

Figure 1: Axisymmetric compressor spool

Figure 2: Diffuser case
2.1.1 Mechanical cutting principles

By applying external forces to a workpiece by rotating either the workpiece or the tool while moving the tool or the workpiece in the direction of the material causes the formation of a shear zone (Primary deformation zone). The deformation is localised to this shear zone, and the formation of a chip is started. This principle is visualized in figure 3, together with the angle \( \phi \) indicating the shear plane.

![Figure 3: Mechanical cutting principle](image)

There are also other zones in the vicinity of the tool that are extensively affected in the cutting operation. The zone labelled A in figure 4 is the secondary deformation zone where heat is generated due to both plastic deformation and friction between the chip side of the tool and the workpiece. In zone B, heat is generated due to friction between the clearance side of the tool and the workpiece.

![Figure 4: Deformation- and friction zones during cutting](image)

![Figure 5: Energy distribution into different physical processes during cutting](image)

In an observation of the energy transformation in the cutting region, the energy is distributed accordingly to figure 5. Of the total amount of heat generated in the cutting process approximately 80% of the heat is removed with the chip, while 20% is divided approximately equal between the tool and the workpiece.

2.1.2 Numerical aspects in simulation of mechanical cutting

A number of computational issues are important to address in the field of simulation of mechanical cutting. This section shortly describes computational aspects to consider.
Explicit vs. Implicit time integration schemes

An implicit time stepping scheme implies that a coupled system of equations is solved and hence convergence in the previous time step is necessary for the solution to continue. On the other hand, explicit time stepping schemes where no iteration procedure is required allows for solution of problems with high non-linearity, complex changing contact conditions and other high-speed phenomena. The explicit time stepping scheme also put an upper bound on the time step size in order to maintain stability in the solution.

When dealing with high strain rate phenomena, rapidly changing contact conditions and physical processes in general that are rapid in nature, convergence problem will arise if using an implicit time stepping scheme [14]. This is where explicit time stepping schemes are favourable. The main drawback with explicit time stepping schemes is that restrictions are placed on the maximum time step length. In smooth processes implicit schemes therefore are to prefer. In practise the discussion above means that implicit schemes are recommended when the simulation involves continuous chip formation and non-complex contact conditions and explicit schemes when dealing with complex geometry- and contact conditions such as discontinuous chip formation or in the case of high-speed machining.

Lagrangian, Eularian or mixed formulations

In a Lagrangian formulation the mesh is fixed to the material, which means that the mesh follows the material deformation path. Using an eularian formulation means that the mesh is fixed in space and the material is allowed to flow through the discretized area.

Both have been used in simulation of mechanical cutting but generally Lagrangian formulations are preferred, due to that if a fixed mesh is to be used (Eularian) the chip geometry must be known in advance to allow for the discretization. Eularian formulations are hence not recommended when dealing with discontinuous chip formation. The chip geometry also changes during the cutting process due to for example changing rotational velocity when the radius of the workpiece in a turning operation decreases. The advantage of using an Eularian formulation is definitely that problems with element distortions are avoided. This is not the case when using a Lagrangian formulation. Simulation of cutting using a Lagrangian formulation places great demands on the mesh adaptivity and regeneration.

Material models

When simulating mechanical cutting it is possible to use both rigid-plastic and elastic-plastic material models, depending on how the representation of the elastic part of the deformation is to be considered. Further, both rate dependent and rate independent material models has been used by a number of researchers.

Since springback is an elastic phenomenon and often is a problem area in turning operations, especially with thin-walled structures, elastic material models are often used. If using a rigid material model, it is not possible to predict springback phenomena in cutting simulations, nor is it possible to predict thermal strains or residual stress states.

The difference between a rate dependent and a rate independent material model is that the plastic strain rate is incorporated in the constitutive equation of the former, as opposed to the latter. Since high strain rates occur in all cutting operations, strain rate dependent models are preferred, however, obtaining this dependency experimentally is a costly and tedious task and hence simplifications using strain rate independent material models also are common.
A physical phenomenon called shear banding can appear under certain cutting conditions. The phenomenon has its origin in that the material experiences a negative tangent modulus during deformation. This is also called strain softening and is associated with localized growth of the deformation in materials with low diffusivity or in high-speed processes, typically when machining titanium alloys. The deformation mode in this zone is usually shear, thereby the name [8]. Efforts to capture this phenomenon in computational models have been done by introducing parameters that can describe the onset of failure and the energy released during the softening process.

**Thermo-Mechanical coupling**

Two types of thermo-mechanical couplings are common when simulating mechanical cutting, namely adiabatic heating and complete coupling. An adiabatic thermo-mechanical coupling means that an assumption is made that the heat generated during the cutting process due to plastic work and friction remains localized. In a completely coupled thermo-mechanical model heat conduction within tool and workpiece is accounted for. Depending on the type of process to be modelled, and the type of workpiece material to be analysed, both of the above couplings are valid. In a high-speed process where there is no time for heat conduction to take place, or if a material with low thermal conductivity is used as workpiece material the adiabatic assumption can be used. On the other hand if a high conductivity material is used or if the process is a low-speed process, a completely coupled thermo-mechanical model is preferred.

Some form of thermal conductivity model usually models heat conduction between the tool and the workpiece. Researchers have adopted a number of different heat conduction models where the difference is how the amount of heat transferred, to the tool and the chip respectively, is calculated. One method is the heat conduction continuity method, which assumes equal heat flux between the tool and the chip respectively. Another approach is to assume that the tool is isothermal, that is, the temperature of the tool does not change as opposed to the chip. Some works have adopted the first law of thermodynamics in determining the interface temperature, after which the heat transfer to the tool is computed separately.

**Contact- and Friction Modelling**

One of the most important aspects in many manufacturing simulations is the contact model, which describes what occurs in the region of two bodies in contact. Examples of processes where contact and friction modelling are important are metal forming processes and mechanical cutting processes. Numerical modelling of contact is essentially a constraint prohibiting two bodies to penetrate each other. There are a number of numerical methods commonly used to pose these prohibitions. One can divide these numerical methods into a number of groups as below:

- Lagrange multiplier methods
- Penalty methods
- Mixed methods
- Method of direct constraints
Lagrange multiplier methods
In the Lagrange multiplier method, minimization of the potential energy of the system is done by introduction of Lagrange multipliers. This results in, even for smooth problems, a non-positive definite mass matrix, which in turn often leads to numerical difficulties in solving the system of equations. Techniques exist to deal with this problem but often to a high computational cost. There is also no mass term associated with the Lagrange multiplier (A zero in the mass matrix), which makes the mass matrix non-invertible and hence non-suitable for explicit dynamic simulations.

Penalty methods
In the penalty method, instead of introducing Lagrange multipliers, multiplying the square of the constraints with a penalty parameter enforces the constraints. In other words this means that the magnitude of the penalty parameter is chosen large enough to minimize the penetration of the two bodies. Choosing this penalty factor to be very large results in a realistic contact modelling but introduces numerical difficulties in that the mass matrix will be ill-conditioned. The method is often implemented in solution of explicit dynamic systems but may result in an over-stiff system since the contact pressure is assumed to be proportional to the point wise interpenetration.

Mixed methods
Often, when there exists a number of ways doing the same thing, each way of doing it has its own drawback. The potential of combining such methods to gain from the advantages of each of the methods is also used within contact modelling. Mixed methods refer to methods such as the augmented Lagrangian method, which essentially is a combination of a Lagrange multiplier method and a penalty method. Choosing parameters in the augmented Lagrangian methods adequately will reduce it to a penalty method. The benefit of mixing the methods like this is that since the Lagrangian multipliers are present, the magnitude of the penalty parameter can be chosen smaller, resulting in a better conditioned system as opposed to not including the Lagrangian multipliers.

Method of direct constraints
The method of direct constraints can be described as a method where the motion of the two bodies are tracked, and when contact occurs direct constraints are placed on the motion. This results in an accurate contact procedure if the motion of the bodies can be adequately tracked. Another advantage of this technique is that complex changing contact conditions can be handled, since no in-advance knowledge of where contact occurs is necessary.

Depending on which time stepping scheme that is chosen, the search for contact is treated differently. In a fixed time stepping scheme, the time increment is subdivided into half the time step length, resulting in a node either almost in contact or else with a certain amount of penetration, at the end of the time step. Another method is to treat the contact update within the Newton-Raphson iteration loop, where the incremental displacement is scaled so that the contacting node reaches the contact segment exactly. This results in a more accurate contact model. The third way of performing the contact search is when adaptive time stepping is used. The time step length is reduced so that the node just is in contact after which constraints are placed on the motion of the node. The new time step length is then calculated based on the convergence criteria. This procedure reduces the speed of the solution, in the contact search, but just to the extent that is necessary in order to get accurate contact modelling.
Friction modelling

Authors in the field of mechanical cutting simulations have implemented a number of friction models. The simplest is the well-known Coulomb friction model where it is assumed that the frictional tangential stress is proportional to the normal stress by a friction coefficient, often denoted $\mu$, perpendicular to the normal of the contact plane. The Coulomb friction model in its original formulation assumes either stick or slip behaviour. If the tangential stress is larger than $\mu$ times the normal stress slip is anticipated, otherwise there is no relative motion in the contact, e.g., stick behaviour. This abrupt change in contact behaviour can cause numerical difficulties and therefore modified Coulomb friction models exist. In some of these the stick-slip behaviour can be smoothened out so that the value of the relative velocity in the contact can be changed. In addition, some modified Coulomb friction models accounts for the difference between dynamic and static friction coefficient. Here, an overshoot parameter can be specified to take care of this physical behaviour.

Experimental models, which have their basis in experimental observations of the physical behaviour, also exist. These will however not be addressed here.

Further, models that do not use a relation between normal- and tangential stress have been proposed. Examples of such models is a model used by Eldridge et al. that relates shear stress to the yield stress in shearing mode. Shear friction models are favourably used when the normal forces in the contact are large. In these cases Coulomb friction models often predict a higher frictional stress than what is observed in reality.

However, in discussing friction models and the advantages and disadvantages of different models, there is no clear view of what model is the most suitable for cutting simulations. This is most likely because friction is a very complex phenomenon not yet completely understood.

Chip separation criteria's

In performing a contact analysis of a cutting operation, some form of criteria of when the chip is going to separate from the workpiece is needed. Two main categories can be defined, geometrical or physical [6]. Within these there exist a number of methods to account for chip separation. A path together with a criterion of when the separation will occur can be specified. A common measure is to use the equivalent plastic strain as an indicator of when the chip will separate, use a predefined distance from the tool tip to the nearest node to trigger the separation [12] or to use some form of fracture criteria. Fracture criteria's can be based on for example void growth models or the materials fracture toughness, depending on if the fracture is brittle or ductile.

To summarize, it can be stated that if cutting simulation of a multi-fracturing material is to be performed, a chip separation criteria that takes into account an actual break-away of the chip from the workpiece is to be preferred. If the aim of the analysis is to predict surface roughness, a chip separation criterion where the separation can take place outside a predefined cutting path is essential.

Using equivalent plastic strain as an indicator of when to separate the chip from the workpiece along a cutting path can be dangerous if interested in phenomena close to the cutting edge. This is due to the fact that the duplication of nodes and finally separation along the cutting path propagates more rapidly than the actual cutting tool speed, and hence a long open crack forms in front of the cutting tool, removing the possibility to accurately study the effects close to the cutting edge.
Due to computational difficulties in dealing with a chip actually breaking away from the workpiece, most cutting simulations have so far focused on continuous chip formation.

**Mesh adaptivity and regeneration**

There are a number of reasons why remeshing is used within the field of FE-simulations. One can be that a higher accuracy is needed in regions where large gradients or singularities exist, for example a sharp corner. This is referred to as geometrical singularities. Other types of singularities are point loads causing the stress to approach infinity at that location. Here, a denser mesh normally also is needed.

In the field of non-linear finite element simulations where large plastic deformations are present, the need for remeshing often is due to severe element distortions causing the accuracy of the solution to decrease. Another reason for using remeshing can be to capture the chip formation in a cutting operation more accurately [14] or to enable for alternating breakage paths for the chip. Remeshing can be divided into three main categories namely, H-adaptivity, P-adaptivity and R-adaptivity [6]. If H-adaptivity is used the size of the finite elements are changed, normally reducing the size in order to more accurately capture a physical phenomena. In P-adaptivity, the interpolating polynomials of the finite element are changed to a higher degree, allowing for more accurate representation of gradients in the mesh. Finally, the main idea of using R-adaptivity is to relocate nodes to a more favourable position that reduces the element distortion.

What is most commonly used in mechanical cutting simulations is a combination of H- and R-adaptivity. Different criteria when to start remeshing has been proposed by a number of authors. Sekhon and Chenot (1993) suggested a method based on element distortion for the start of the remeshing algorithm. This is suggested on a local level of refinement, but is also normally used in global remeshing schemes when local refinement is insufficient. Maurish and Ortiz uses the plastic work rate as an indicator to start remeshing, while Kalhori et. al uses both the plastic work rate and a posterior error estimate based on the gradients in the mesh [6].

Irrespective of what technique is used, the need for both local and global refinement is clearly needed in simulation of mechanical cutting, when interested in for example effects on a micro-level scale or in prediction of cutting forces.

**2.1.3 Simulation techniques for cutting simulations**

When intending to simulate mechanical cutting, there are several different ways of doing this depending on what the focus of the analysis is. The alternative ways of simulate mechanical cutting are visible in figure 9 and an outline of each of the methods is given below.

All techniques described in this section sorts under the finite element method, but the focus differ with the different techniques. The choice of computational technique can depend on where in the product-/process development cycle the analysis is to be performed. In the early stages of a product development process, see figure 6, little information about the process and also the product has been gathered. If an evaluation of a cutting process is to be performed at this stage, an element deactivation technique can be considered, see chapter 2.1.3.2. This does not mean that this type of analysis is unmotivated in other stages of a product- or process development chain.
Other motivations to use element deactivation methods can be the time available for an evaluation of a process or a concept, there is just not enough time to do an advanced contact analysis, with all the work and information gathering that such an analysis incorporates, see chapter 2.1.3.1. What also acts as an obstacle in performing a contact analysis, when interested in simulating longer periods of cutting on a component level, is the computer hardware performance of today. As mentioned in section 1.3, mechanical cutting simulations in the form of a contact analysis are very computationally demanding. Despite of the evolution of computer hardware, and a doubling of the processor speed every 6 months, there is still a lack of computer performance when aiming at these types of analyses.

Finally, when production is up and running, trouble in the manufacturing process whatever the causes may be, is a costly problem. Not only due to the fact that every hour the machine on the shop floor is not running, manufacturing costs increase, but also because of the fact that in aerospace industry, a single component to an aerospace engine has a manufacturing cost compatible with a complete truck, which means that waste production must be held at lowest possible level. Simplified methods for cutting simulations can in the case of production problems serve as a trouble-shooting tool.

**Contact analysis**

What is normally associated with simulation of mechanical cutting is a contact analysis. A definition of a contact analysis could be:

An analysis where one or more contact bodies are defined, where at least one is discretized in the form of finite elements. The body/-ies can potentially contact themselves or the other body/-ies in a way that no penetration between elements or analytically described geometry can occur.

As described in section 1.3, simulation of cutting using a contact analysis is computationally demanding and often acts as an obstacle in performing a sequence of manufacturing simulations.
If the aim of the analysis is to capture effects or phenomena on a micro-level scale, contact analysis is the way to progress. Effects and phenomena possible to study are:

- Cutting forces and their relationship to material parameters
- Residual stresses caused by the cutting procedure itself, often in the surface of the workpiece
- Surface roughness and its relation to process parameter changes
- Design and evaluation of cutting insert geometry
- Heat effects in general
- Chip formation and chip fracture

The use of a contact analysis is also motivated by that it serves as a tool to study and learn the cutting process and its physics.

**Element deactivation techniques**

A simplified method to simulate cutting is to deactivate or kill elements corresponding to the material to be removed. The use of such techniques is motivated in section 1.3. In this work, element deactivation techniques has been implemented in 2-D. Element deactivation techniques can be divided into two categories, one where the deactivation of all the elements corresponding to the material to be removed is done simultaneously, and one where elements are deactivated one-by-one. The latter will be described more in detail in the following sections.

Deactivating all elements corresponding to the material to be removed at once is the simplest way of using element deactivation. By defining two domains, one incorporating the elements to be removed and one including those to be kept, all the elements in the domain to be removed are deactivated, see figure 7. Using this technique, it is not possible to predict the influence of cutting order nor is it possible to predict varying chip thickness and a non-uniform thickness of the workpiece as a consequence.

![Figure 7: Static element deactivation principle](image)

An enhancement of the technique would be, as is done in this work, to implement this technique in a time stepping scheme with geometry updating in each time step. In this way, the above mentioned drawbacks of deactivating elements "all at once" can be avoided. We
will refer to this method as the method of dynamic element deactivation. Dynamic element deactivation thus has the features of predicting the influence of cutting order and varying chip thickness. This makes the technique useful as a tool in process parameter design and also allows for its use as a trouble-shooting tool during production.

Physical assumptions in the use of element deactivation
The use of a simplified technique, as described above, incorporates several assumptions regarding the cutting process, as can be seen below.

- There is no frictional heat generation in the cutting process
- There is no introduction of stresses due to the cutting forces and there is no plasticity introduced, which also means there is no plastic heat generation
- The geometry of the tool or the insert has no effect on the result
- Only the contribution of the deactivated elements to the stiffness of the structure is considered

Dynamic element deactivation scheme
First, when using dynamic element deactivation, the cutting paths for the process must be defined, see figure 8.

These are defined analytically, and each path is defined independently of the next. The feeding speed along the cutting path is defined after which the position along the cutting paths can be calculated at any instance of time.

The analysis is initialised, and the first time step is taken. If the tool, which is thought of as a point moving along the cutting path, is located within an element of the mesh, two of the nodes of this element are moved onto the cutting path, see figure 9. This element now has one of its boundaries positioned along the cutting path, and is ready to be deactivated. When it is deactivated, the stresses and strains of that element are set to zero, and the structure reaches a new equilibrium state causing a small distortion of the mesh. In the next time step, the nodes of the next element are moved onto the cutting path (including the shared node with the previous element) after which the element is deactivated a. s. o. The procedure is visualized in figure 9, where the cutting path is represented as the dotted line.
Combination techniques

As mentioned in section 2.1.3.2, a number of physical aspects are discarded when using the element deactivation technique. Among these, one of the more important aspects, especially if the cutting conditions are not perfect, are the heat generation due to both frictional- and plastic work. Combination techniques refer to mechanical cutting computational techniques that use a combination of methods to account for physical aspects. Two main combinations can be defined, one which combines the use of a deactivation scheme in parallel with a moving heat source. The moving heat source will account for the thermal effects induced by both friction and plastic work.

Another possible combination of techniques, especially if attempting to increase the accuracy in using an element deactivation technique for prediction of global distortions, is to start off with a contact analysis. The contact analysis is run until a steady-state solution is found (normally just a few millimetres of mechanical cutting). This steady state of stresses is then mapped onto the new surface resulting from use of an element deactivation technique. This combination of techniques is favourable if the cutting conditions are somewhat constant. For cutting processes where cutting speeds and feeding speeds are continuously changed, an update of the contact analysis may be needed to reflect the changes in cutting parameters and the effect that they have on the result.

2.2 Heat treatment

Heat treatment processes can be divided into several categories where the aim of the heat treatment process differs. In aerospace industry, stress-relieving heat treatments are common due to the fact that residual stresses affect the in-duty behaviour of a component negatively. Quench processes are also common in aerospace industry, especially in the beginning of a manufacturing sequence. Quench processes are used to control the physical- and mechanical properties of for example a forging.
In an effort to analyse or simulate a heat treatment process, depending on the type of heat treatment process, various demands are put on the computational model. Since in a stress-relieving process the driving physical phenomenon is creep, a computational model of such a process must incorporate a material model that takes creep into account. On the other hand, in a quench process an important issue is the modelling of the heat transfer to the surrounding. It may be a fact that a computational model of a quench process must incorporate both radiational, convectional and conduction heat transfer as well as phase transformation modelling.

2.3 Welding

The main focus of many analyses incorporating welding, as a manufacturing process, is to determine either welding residual stresses or distortions caused by the welding process. These results are in turn often used as input in lifetime prediction analyses. Another common reason for numerical analysis of welding procedures is to determine process parameters to achieve wanted properties in the actual product. This type of analysis is often iterative in nature. As in the case of analysis of mechanical cutting, many computational issues must be considered in order to be able to extract the wanted information from such a computational model. The first question to be answered is: What is the scope of the welding analysis to be performed? Depending on the answer to this question, a definition of what type of welding model to use can be done. This way of categorizing computational aspect can be brought further to incorporate other physical phenomena, computational issues and other parameters important for the analysis of a welding procedure [26].

2.4 Data transfer

In a product- or process development process, where staff from different engineering fields cooperates across what can be seen as traditional boundaries, the sharing of analysis data is becoming more and more necessary. Unfortunately many engineering software does not support the sharing of analysis data, even between analyses done in the same software, in an easy way. One reason to this is limitations in the standards used to describe this type of analysis information. The standards of today are well suited for translation of mainly geometry and discretization information but when it comes to translation of boundary conditions, contact bodies and both nodal- and gauss-point information such as displacements, residual stresses and so on, there is still a lack of functionality.

In a company where analyses in a wide spectrum of domains are performed, a system for translation of analysis data between different software or even between different analysis domains is needed. This type of system does not only serve as a translator between formats but also as system for information management and storage where features such as search ability within analysis data is supported.

3. Simulation Methodologies within Virtual Manufacturing

In sections 1 and 2 above a number of issues concerning simulation of cutting have been addressed. In this section, an effort has been made to gather these. Issues are gathered in a scheme that will serve as a comprehensive map or guideline for how to progress when attempting to simulate mechanical cutting. The scheme are not intended to be interpreted as the absolute truth of how to perform mechanical cutting analyses, since there probably are other ways to progress and reach the same finish line. They will rather serve as a mind-map for experienced users and as a way for users fresh to mechanical cutting simulations to quickly get an overview of the obstacles involved in performing these analyses.
What will not be addressed however are similar maps for heat treatment analyses and welding analyses, since they are subjects for further work.

In figure 10 and in the text following the figure, a comprehensive description of the main routes in the map is given while in figure 11 and 12 the complete map is presented. In the cases where no clear agreement among researchers within the field of numerical analysis by finite elements is made, possible choices are still indicated, but no advice which method or principle to be used is given.

![Simulation Methodologies within Virtual Manufacturing Applied on Mechanical Cutting](image)

**Figure 10: Methods for simulation of cutting**

A. **Static element deactivation**

Suitable for concept evaluation and other applications where demands on short time for result generation is a fact. Definitions of element domains are needed. No possibility for prediction of varying chip thickness- or influence of cutting order on result. In reality this means that process parameter effects cannot be predicted. Time-response analyses are not possible, since the solution is a one-step solution. Can be helpful for behaviour studies, in situations where interested in for instance distortion effects of geometry changes or material changes in a component. Method with the shortest computational time.

B. **Dynamic element deactivation**

Dynamic element deactivation is a method that allows for time-response analyses, since element deactivation here is incorporated in a time stepping scheme. As a result, effects of cutting order can be predicted. Varying chip thickness due to continuous distortion is also possible to predict. Definitions of cutting paths are necessary. Useful for behaviour studies and as a trouble-shooting tool in production since effects of certain process parameters such as cutting order or the placement of the final geometry within the bulk material is possible. Process parameters such as cutting tool geometry, feeding- and rotational velocities and their influence are not incorporated in this type of analysis. No thermal effects due to frictional- or plastic heat generation is accounted for. Therefore, in situations where severe cutting conditions is a fact and hence a lot of heat is generated, the method's applicability can be questioned.

C. **Contact analysis**

Performing a contact analysis is the most general way of simulating cutting. Most physical phenomena are possible to include, and the results can be very accurate. Computational times are the main drawback, since analyses of cutting sequences with a duration in real-time in the order of minutes results in computational times in the order of weeks and sometimes months. A contact analysis enables prediction of cutting insert geometry effects, heat effects due to frictional heat generation, effects of plastic work generation, prediction of surface roughness,
design of tool geometry [11], prediction of cutting forces and so on. For research and design purposes in the field of cutting tools, contact analyses are the way to progress.

**D. Combination techniques**

These can be described as a series of methods taking advantage of each of the techniques mentioned above. An analysis where the focus is to study the cutting operation's effects on the components geometry, and not study the effect on either tool itself or to predict cutting forces, these techniques can be favourable. If the aim of the analysis is to predict distortions accurately, especially in thin wall components [13], the residual stress field introduced in the cutting operation by the tool is preferably included. A combination of a dynamic element deactivation method and a contact analysis is in this case recommended. It may also be the case that heat effects are a cause to distortion during cutting. In this case a combination of an element deactivation technique together with a moving heat source, to account for the thermal effects, may be the right choice.

![Mind map for computational choices within the field of simulation of mechanical cutting.](image)

In figure 10 above only the parts of the map incorporating the low- and high computational effort routes are presented. The continuation of the map incorporating the medium computational route is presented in figure 11.
When an analysis appropriate for the purpose is chosen, there exist a number of computational choices depending on computational aspects described in section 2.1.2. These are presented graphically in figure 12, 13 and 14. Some of the aspects are applicable independently of analysis type chosen, while some only refer to a specific analysis type. An arrow in the figure indicates a one-way path.
Figure 13: Computational aspects for simulation of mechanical cutting.
Strain rate in process?

High | Low
--- | ---

Rate dependent material model | Rate independent material model

Low diffusivity/high speed process?

** Failure model may be included if there is risk for shear-banding, see section 2.1.2.3.

High/Low speed process

High | Low
--- | ---

Adiabatic heating

Low diffusivity material?

High

Complete coupling

Low

Workpiece/tool thermal contact model?

Heat conduction continuity

Isothermal tool

Thermal equilibrium

* Simplifications using rate independent material models despite high strain rates are common. see section 2.1.2.3.
Figure 15: Computational aspects for simulation of mechanical cutting (Cont.).
4. Summary of Results
The results of the work described in each of the appended papers are described briefly below.

4.1 Paper A
The effect of convective heat transfer coefficient on the residual stresses after cooling from solutioning heat treatment is investigated by use of the finite element method. Both effects of magnitude variations in the heat transfer coefficient as well as effects of asymmetric cooling are investigated. The result show that variations in heat transfer coefficient magnitudes reasonable for an air cooling procedure do not cause residual stresses that can have considerable effect on the following operations in the manufacturing sequence.

4.2 Paper B
This paper presents FE-simulations of a forming operation followed by simulation of mechanical cutting using dynamic element deactivation techniques. Experiments are performed to validate the analyses. A comparison between the analyses and the experiments show that the behaviour of the workpiece during milling can be captured using dynamic element deactivation techniques, and hence dynamic element deactivation has a potential as a tool for simulation of mechanical cutting. Causes to the discrepancies between experiments and the analyses are also discussed.

4.3 Paper C
The paper presents a system for analysis information management within process- and product development. By use of an information model described in the information modelling language EXPRESS, and an embedded object oriented main-memory database management system, the solution will provide analysis data sharing, effective information management such as transformation between formats, trace- and search ability within product analysis data and other database capabilities.

5. Discussions & Future Work
The work presented in this thesis has been focused on performing FE-analyses of a sequence of manufacturing steps and draw conclusions and make recommendations of how such simulations can become an effective tool within process- and product development. Simulation of mechanical cutting has been identified as an activity which often acts as an obstacle when trying to perform analyses of several manufacturing steps. This is mainly due to high computational costs when using contact analyses to simulate cutting. Therefore investigations of dynamic element activation as a tool for simulation of cutting have been investigated. A methodology, or mind-map, has been created to help analysts to get an overview of the aspects and choices that must be considered when performing these analyses. So far this methodology covers simulation of mechanical cutting, but in the future simulation of other processes such as inertia welding will be addressed in the same manner.

Further investigation and development of simplified techniques, such as dynamic element deactivation, as tools for simulation of cutting is also an area that will be addressed. Several issues important to make simplified methods more generic and user-friendly have been identified. Among these issues, mesh logics and updating strategies as well as implementation in adaptive time stepping schemes are important.
Together with simulation methodology issues, an important area to make FE-analyses an effective tool, is the information management issue. Cooperation with researchers focused on data communication and data sharing in information management systems will be crucial in the continuation of this work.

6. References


The effect of convective heat transfer coefficient on the residual stresses after cooling from solution heat treatment

J.P Åström & M.O Näsström
The Polhem Laboratory, Division of Computer Aided Design, Luleå University of Technology, SE-971 87 Luleå, Sweden

ABSTRACT: The influence of convective heat transfer coefficient on the residual stresses in a jet engine component is investigated by use of the finite element method. The component is heated to solutioning temperature 980 °C and is held at that temperature a certain time to relieve the residual stresses introduced by the previous forging operation. The aim of the study is to predict the residual stresses in the component introduced by the cooling from solutioning temperature to room temperature and also to estimate the sensitivity to changes in the convective heat transfer coefficient and asymmetry in the convective boundary condition. The results show that the residual stresses are not influenced considerably by changes in convective heat transfer coefficient, assuming the convective heat transfer coefficient is held within what is reasonable for an air cooling procedure. Also the asymmetry in the convective boundary condition does not influence the residual stress pattern much.

1 INTRODUCTION

In most manufacturing processes the workpiece material is in some way thermally or mechanically affected. Residual stresses in the workpiece due to large thermal gradients or plastic deformation during the operation is often the case after a manufacturing process (Chandra et al. 1992).

Especially in aerospace industry where residual stresses in a component can be a source to crack initiation and propagation and later cause severe failure during running it is important to relieve residual stresses after they are introduced (Wallis et al. 1989). Hence, a number of heat treatment processes are common in the manufacturing chain of an aerospace component (Röhl & Shesh 1997). Failure to remove residual stresses in the heat treatment operation or the fact that new stresses are introduced in the subsequent cooling procedure will cause unwanted distortions in processes later on in the manufacturing chain (Ramankrishnan 1992).

One occasion when the distortions appear is when material is removed by milling or turning. These distortions sometimes cause tolerances to be exceeded, and the component is wasted. Both due to the extensive material cost and the many and rigorous controls a great deal of money often have been invested in such a component. It is therefore interesting to investigate the influence of cooling from solutioning temperature to room temperature and the effect that this cooling has on the residual stresses in the component.

The studied component is a forged axisymmetric jet engine component. It is made of titanium 6-2-4-2, which is a creep resistant high strength titanium alloy most frequently used for hot applications in jet engines. The component can be seen in figure 1.

Figure 1. Forged axisymmetric component.

The cooling procedure is characterized by three phases. The first phase corresponds to the moving of the forging from the furnace to the cooling table. In the second phase the forging is fan cooled for a period of time and in the last phase the forging is allowed to air cool to room temperature. This is simulated by defining three different loadcases where the convective heat transfer coefficients are chosen according to what is reasonable for forced- and free convection respectively.
The calculations have been performed using the finite element software MARC™. The model used in the simulations is an axisymmetric FE-model with 4-node isoparametric elements written for axisymmetric applications. The mesh consists of 854 elements. Principal dimensions of the forging can be seen in figure 2 along with the mesh used in the simulations.

Figure 2. FE-model with principal dimensions.

An initial condition is specified so that the forging has an initial temperature at the start of the cooling procedure of 980 °C. Since the component has been held at the solutioning temperature, to relieve residual stresses, for a period of time it is reasonable to assume that there are no residual stresses present at this stage. The simulation hence start with a zero stress state. Two types of thermal boundary conditions are used in the model, convective and radiative. A fixed displacement restraint is added to one node in the model to prevent rigid body motion. The node is restrained in the x-direction (axial).

2.1 Convective boundary conditions

The convective boundary condition is split into two parts, inner and outer convective boundary condition according to figure 3. This is due to the fan cool phase where it can be considered that the inside of the forging is left unaffected by the increase in air speed and hence the inside has the same convective heat transfer coefficient during the whole process. The outer convective heat transfer coefficient varies according to figure 4 during the process. Figure 4 shows the three phases of the cooling procedure where the duration in time of the first level is 40 seconds. Level two which corresponds to the fan cool phase has a duration of 600 seconds and finally the third phase lasts until the forging has reached room temperature \(T_{\text{final}}\), which depends on the magnitude of the convective heat transfer coefficients used. No magnitudes of the convective heat transfer coefficients are present in figure 4. These are instead defined for each of the runs in Table 1. The magnitudes of the heat transfer coefficients in level one and three are equal. In the simulation model the convection is modeled using an edge film coefficient and a surrounding temperature of 25 °C, which is assumed to be constant at all times.

Figure 3. Convective boundary conditions on the inside and outside of the forging respectively.

Figure 4. Outer convective heat transfer coefficient during cooling cycle.

2.2 Radiative boundary conditions

The heat losses due to radiative heat transfer is modeled by edge radiation assuming a constant surrounding temperature of 25°C and by calculating radiation viewfactors using the Monte Carlo-method (MARC Analysis Research Corporation, 1997) with 1000 rays emitted per object. In the Monte-Carlo method the rays are emitted randomly from the element surfaces. The percentage of these rays that hit another surface is the viewfactor between these surfaces. This is done automatically in the code and hence shadowing effects between different parts of the model is accounted for. The radiative boundary condition is applied on the whole circumference of the model.
2.3 Material data

The material is assumed isotropic with isotropic hardening and temperature dependent mechanical and thermal properties. Von Mises yield criterion has been used along with temperature dependent yield strength. In the temperature interval simulated no phase changes occur in Tn-6-2-4-2 and hence no latent heat is needed. The temperature dependence of the material properties used are shown in figure 5.

![Material data temperature dependence.](image)

2.4 Analysis of the cooling procedure

A total number of 4 analyses have been performed with different convective heat transfer coefficients on the inside and outside of the forging according to table 1. Level one, two and three refers to different levels of convective heat transfer coefficients on the outside of the forging during the cooling procedure, see section 2.1 and figure 4. h_{inside} represents the convective heat transfer coefficient on the inside of the forging. Analysis number 4 represents the asymmetric case where the inside and outside of the forging are assumed to have different free convection heat transfer coefficients.

The analyses are coupled thermo-mechanical quasi-static analyses with adaptive time stepping with an initial time step of 0.001. A finish criteria is specified so that the analysis stops when the complete structure has reached a temperature below 300 K.

![Definition of result plotting locations and paths.](image)

Table 1. Convective heat transfer coefficients used in analysis [W/m^2*K].

<table>
<thead>
<tr>
<th>Analysis #</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>h_{inside}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>50</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>200</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>1000</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1000</td>
<td>200</td>
<td>12</td>
</tr>
</tbody>
</table>

3 RESULTS

A comparison of axial, radial and hoop stress between runs with different convective heat transfer coefficients has been made along the paths defined in figure 6. Since the temperature gradients in the forging are small, only the temperature distribution through the thickness in path I is plotted in figure 10. Path I represents the location where the temperature gradients are the largest. Only temperature distribution for analysis #4 is plotted since this run is the one that gives the largest temperature gradients. In addition the temperature history for the nodes shown in figure 6 are plotted in figures 11-14.

![Axial stress along path I.](image)

3.1 Stress distribution

The stress distribution along the paths defined in figure 6 are plotted in figure 7, 8 and 9. The stresses are plotted as a function of radial distance from the axis of symmetry. The first graph in each figure displays results from path I while the second graph displays results from path II.
Figure 7 (Continued). Axial stress along path II.

Figure 8. Radial stress along path I and II respectively.

Figure 9. Hoop stress along path I and II respectively.

3.2 Temperature history

The temperature variation along path I for analysis #4 as a function of radial distance is shown in figure 10 for different times. Note the effect of the difference in radiative heat losses between the inside and the outside of the forging. This is visible in figure 10 as a difference in temperature between the inside and the outside of the forging, and is a result from the automatic viewfactor calculation where a greater radiative heat exchange between surfaces located inside the forging is a fact.

Figure 10. Temperature versus radial distance in run #4.
Temperature history for nodal locations defined in figure 6 is shown in figures 11-14 below, from start of cooling until 600 seconds. At times greater than 600 seconds the temperature difference between different nodal locations is of such low amplitude that plotting is unnecessary.

3.3 Discussion

As can be seen in figures 7-9 the stresses due to air cooling from solutioning temperature to room temperature are very low, especially in the first analysis. Increasing the convective heat transfer coefficient (run #2 and #3) increases the stress magnitude but not to the extent that the residual stress field can be considered to have significant influence on manufacturing processes later on in the manufacturing chain.

It is therefore believed that any residual stresses in the workpiece arise from failure to remove the residual stress field during solution heat treatment and not from the cooling procedure. Selecting an appropriate air cooling procedure is then more a question of selecting the right procedure to achieve the wanted microstructure in the workpiece rather than trying to keep the residual stresses at an appropriate level.

Figure 7-9 also shows that the maximum magnitude of the radial stresses are lower while the axial- and hoop stresses are higher. Another tendency is that the stresses (all components) are reduced on the inside of the forging when an asymmetric boundary condition is applied (analysis #4). Since when applying an asymmetric boundary condition the stress components changes direction (from tensile towards compressive or vice versa) this is a parameter for investigation when trying to minimize the residual stress field resulting from the cooling procedure.

Figures 11-14 are also in agreement with the stress pattern, since the temperature history curves from nodes on the interior and on the surface of the workpiece show that the temperature gradient is maximum in the order of 100 °C for analysis #4, which is not enough to give rise to any residual stresses. It is also worth noting that the asymmetric boundary condition in analysis #4 cause greater temperature gradients in the workpiece and still both the axial- and radial residual stresses on the outer surface of the forging are reduced while on the inside of the forging the stresses change sign towards compressive. This implies the complex nature of interaction between convective
heat transfer coefficients, workpiece geometry, asymmetry in the boundary condition and the resulting residual stresses.

REFERENCES


FE-simulation of forming and subsequent cutting by use of an element deactivation technique

J.P Åström & M.O Näsström
The Polhem Laboratory, Department of Mechanical Engineering, Division of Computer Aided Design, Luleå University of Technology, 971 87 Luleå, Sweden
mailto:peter.astrom@cad.luth.se

Simulation of manufacturing processes, so called virtual manufacturing, is becoming more widely used as a tool for prediction of mechanical and geometrical properties when a product is fabricated. In many manufacturing sequences, cutting operations in some form are common. This paper describes the simulation of a forming operation followed by simulation of cutting by use of an element deactivation technique. A stepping algorithm is implemented where the FE-mesh is continually updated so that the nodes, of the element to be deactivated, are always located on the cutting path. Using the technique enables for instance prediction of effects of cutting order on the final geometry, with a computing effort that enables simulation of cutting on component level. The paper investigates if the method of element deactivation could be a useful tool to simulate cutting in product- and process development. This is done by comparing results from simulations with experiments. The result shows that the stepwise deactivation technique could be a useful tool in product- and process development.

1 Introduction

Simulation of manufacturing processes, so called virtual manufacturing, is becoming more widely used as a tool for prediction of mechanical and geometrical properties when a product is fabricated. However most research work and most publications focus on one individual manufacturing process being simulated. It is of course important to know the effect of each process on the product but the real benefits of using virtual manufacturing as a tool in product- and process development will be visible when the whole manufacturing chain of a product is analysed. One of the more frequently used computational methods for this purpose is the finite element method, and in this paper this is the method used in the simulations.

By cutting we refer to mechanical cutting such as milling and turning. In order to be able to simulate a sequence of manufacturing steps, a computational tool for the simulation of cutting is necessary.

One of the more computationally demanding processes to simulate is cutting. The process is complex to simulate due to large plastic deformations, heat generation due to contact friction which in turn often leads to local surface hardening. In addition there are demands on the adaptive mesh generation in order to capture the phenomena close to the cutting tool. All of these phenomena result in significant computational time. When interested in simulating the entire cutting process of a component and when interested in the effect on the component this type of contact computational model for cutting simulation often is too hardware demanding to realize.
This paper therefore investigates a less computationally demanding technique to simulate cutting, namely the method of element deactivation. The main idea is to deactivate elements corresponding to the material to be removed. The contribution of the deactivated elements to the stiffness of the structure then reflects in a distortion of the component when they are removed.

The simplest form of element deactivation technique is to deactivate all elements, corresponding to the material to be removed, at once. The main drawback of this method is that varying chip thickness due to continuous deformation during the cutting process cannot be predicted. Another drawback is that the effect of altered cutting order is not possible to predict.

An enhancement of this method would be to eliminate these drawbacks, by using element deactivation in a time stepping scheme. In practice this means that a cutting path is defined and the first element on this path is deactivated. The structure then deforms, reaches a new equilibrium and nodes of the next element are moved onto the cutting path and data is mapped after which this element is deactivated aso. This method will enable effects of altered cutting order and varying chip thickness to be predicted.

The paper investigates if the method of element deactivation could be a useful tool to simulate cutting in product- and process development when interested in distortions on component level. This is done by comparing results from simulations with experiments.

To enable investigation of the method itself, a simple geometry has been used. The plate used has first been deformed to introduce a residual stress field after which a cutting sequence on the deformed plate has been investigated. The plate can be seen in figure 1.

![Figure 1: Test plate dimensions and location of strain gauges during forming experiment.](image-url)
2 Simulations

Calculations of both the forming operation and the subsequent cutting has been performed using the FE-software MARC™. MARC™ is an implicit FE-code supplied by MSC Software. A 2-D plain strain model with a total of 476 elements has been used in both simulations, see figure 2. The elements are four-node, isoparametric, arbitrary quadrilaterals with four integration points written for plain strain applications. Between the simulation of the forming and the cutting data is transferred, more specifically the stresses, the displacements and the equivalent plastic strain.

![Computational model with discretized workpiece and rigid tools.](image)

2.1 Forming simulation

To prohibit strain rate effects a low velocity for the indent was chosen. To make sure no local plasticity is introduced the tooling was designed so that a gap of 0.2 mm is present when the upper and lower part of the tools are in contact. The tooling can be seen in figure 6.

Material data in forming simulation

The material used for the test plates is Sandvik SANMAC 316L, which is a molybdenum-alloyed austenitic chromium-nickel steel delivered in solution heat treated condition. Mechanical properties are listed in table 1. In addition a tensile test has been performed with tensile test specimens taken from the same bulk material as the test plates, and the stress strain curves from this tensile test are found in figure 3. The strain rate of the uniaxial tension test was chosen to coincide with the strain rate used in the forming operation.
### Table 1: Mechanical properties for Sandvik SANMAC SS316L

<table>
<thead>
<tr>
<th>PROOF STRENGTH, $R_{p0.2}$ [MPa]</th>
<th>TENSILE STRENGTH, $R_m$ [MPa]</th>
<th>ELONG, A[%]</th>
<th>CONTR, Z[%]</th>
<th>HARDNESS, [HB]</th>
<th>YOUNG'S MODULUS [MPa]</th>
<th>POISSON'S RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>min 205</td>
<td>min 240</td>
<td>min 40</td>
<td>min 50</td>
<td>~170</td>
<td>14</td>
<td>0.3</td>
</tr>
</tbody>
</table>

An elastic-plastic isotropic material model was used in the analysis. The plastic behaviour is obtained from the stress-strain curves visible in figure 3. The yield behaviour is described by Von Mises yield criterion with isotropic piecewise linear hardening.

![Stress-strain curve for Sandvik SANMAC SS316L obtained from uniaxial tensile test.](image)

Figure 3: Stress-strain curve for Sandvik SANMAC SS316L obtained from uniaxial tensile test.

**Boundary conditions and model input data for forming simulation**

A rigid to deformable contact model with both tools modelled as rigid bodies has been used to simulate the forming. The rigid tools and the deformable workpiece are visible in figure 2. In the paper the upper tool will be referred to as the punch, while the lower tool will be referred to as support. The validity of using rigid tools has been verified against the same simulation using a deformable to deformable contact model, with no variation in results. Two types of friction models has been implemented. Between the punch and the workpiece a glue model has been found appropriate. The glue model imposes that there is no relative tangential motion between the punch and the workpiece. Between the workpiece and the support a Coulomb friction model has been employed with a friction coefficient of 0.3.

A fixed displacement restraint has been added to one node in the model to prevent rigid body motion.

A contact detection feature has been used in the simulations. The feature allows for specification of an initial velocity which is used in increment zero to position the rigid bodies
in contact with the deformable body. The numerical procedure used for the contact is the method of direct constraints [1]. In this procedure the motion of the bodies is tracked and when contact occurs direct constraints are placed on the motion. The method allows for complex changing contact conditions since no a priori knowledge of where contact occurs is necessary.

**Forming analysis**

The analysis is a mechanical static analysis, with adaptive time stepping using an modified Riks-Ramm arc length method. The initial time step is set to 0.01 while the maximum is set to 1. A full Newton-Raphson iterative procedure is used with a maximum of 50 recycles per increment. The time for the indent in the forming operation was 7.92 seconds while the release time was 0.1 seconds with gradual force removal during this stage.

### 2.2 Cutting simulation

To implement the stepwise element deactivation scheme used to simulate cutting, user coding has been input through user subroutines in MARC™. These subroutines have a predefined structure and acts as the interface in which variables and data can be interchanged with the FE-code. In addition to the subroutines available in MARC™ a number of routines are needed for functionality not supplied by MARC™. These routines stand alone but are connected via one or more of the user subroutines.

The start geometry for the cutting simulation is obtained by reading the displacements from the last increment in the previous forming analysis. At this stage the punch has been released so that a certain springback is obtained. The starting geometry for the cutting simulation is hence the geometry after springback in the forming simulation. The starting geometry is visible in figure 5 together with the cutting paths along which elements will be deactivated. Five cutting paths have been defined and the end of each cutting path is marked in figure 5 with a dot. In each time step one element is deactivated. This element is found by a search routine implemented in user subroutines. The intercept between the element edges and the cutting path is calculated after which the nodes of the current element is moved onto the cutting path and data is mapped. The procedure is then repeated until a whole layer of elements is removed. A total of 5 layers are removed which corresponds to half the thickness of the workpiece. The length of the first cutting path is 3/4 of the length of the plate, and this length is then reduced with the feeding distance in the removal of every next layer of elements.

Stresses and equivalent plastic strains are also read from the last increment in the previous forming analysis.

**Material data in cutting simulation**

In order to capture some of the effects caused by heat generation due to friction between the cutting tool and the workpiece, material data for a higher temperature (400°C) has been used in the cutting simulation. A Young's modulus of 172 GPa and a Poisson's ratio of 0.3 has been adopted. The plasticity behaviour used is shown in form of a stress strain curve in figure 4.
Boundary conditions and model input data for cutting simulation
A displacement restraint is applied on the clamping area of the plate. These nodes are restrained in both x- and y-direction. Except this displacement restraint the plate is free to move in all directions. The restraints can be seen in figure 5.

Cutting analysis
The cutting analysis is a mechanical-static analysis with fixed time stepping. Since the stepwise element deactivation scheme is time independent, the length of each increment has been chosen to 1 second. A total of 230 elements are deactivated in a total simulation time of 230 seconds. A full Newton-Raphson iterative procedure has been used with a maximum of 50 recycles per increment.
3 Experiments

The experiment consists of two parts, one where a residual stress field is introduced in the test plates, i.e. the forming operation, and one where the cutting is performed.

3.1 Forming experiment

The introduction of the stress field is done by pressing the plates in a tool upset with a constant radius. The tooling can be seen in figure 6, along with principal dimensions of the tools. The upper tool (i.e. the punch) is moved with a constant velocity of 0.00074 m/s in the negative y-direction during 7.92 seconds which results in a total displacement of 5.86 mm. When this displacement is achieved the punch and the support are in contact. At this time there is still a gap of 0.2 mm between the plate and the support to ensure that no local plasticity is introduced in the plates. The resulting residual stress pattern has tensile components on one surface and compressive on the other.

![Figure 6: Tooling set-up for forming experiment.](image)

The test plates also have a small ledge, see figure 1, that is unaffected in the pressing operation. This ledge will serve as a clamping area in the following cutting experiment. During forming strain is measured with strain gauges at both the front and back surface of the test plates. The position of the strain gauges can be seen in figure 1 along with the dimensions of the plate. The measured values of strain will be used as a verification measure between the FE-simulation of the forming operation and the experiment.

3.2 Cutting experiment

Verification of the cutting simulation has been made by performing milling experiments on test plates in the experimental set-up visible in figure 7. The workpiece is clamped on the ledge previously mentioned and is prohibited to move in other directions than in the y-direction by a support, see figure 7. In the holes in the support, balls from a ball joint bearing are adjusted into contact with the workpiece. The balls serves as both support for cutting forces in the cutting direction and also as vibration prohibitors during cutting. The complete experimental upset is screwed onto the milling table as can be seen in figure 7. Distortion in
the y-direction is measured by micrometer gauges with a resolution of 0.01 mm. Four mill passes are made after which the screws to the cutting force support ball joints are loosened to ensure that the plate is free to move in y-direction and the micrometer gauges are read.

Figure 7: Experimental set-up for cutting experiment.

A total of three gauges are placed in the z-direction of the workpiece to verify that the plate is in a symmetric stress state, and hence gauges located on the edges are expected to show the same distortion. Possible discrepancies will then mainly be between near-edge gauges and the middle gauge. For location of micrometer gauges, see figure 8.

Figure 8: Locations of micrometer gauges during cutting experiment.

4 Results

Results are presented for simulations of both the forming- and cutting simulation. The results are compared with experimental results of the same operations.

4.1 Forming

Figure 9 shows a comparison between strains measured during the forming experiment and the same strains obtained from the analysis. The red and the blue line indicates values of strain from the two strain gauges located according to figure 1 on both sides of the test plates.
Figure 9: Comparison of experimentally and computationally obtained strains during forming.

4.2 Cutting

Figure 10 shows a comparison of displacement in y-direction, defined according to figure 7, between the cutting simulation and the experiment.

Figure 10: Comparison of experimentally and computationally obtained y-displacement during cutting.
5 Discussion and Conclusions

In a comparison of results from the forming simulation and the forming experiment discrepancies arise predominantly during the beginning of the process. The final value of strain reached correlates quite well with experimental values. Possible causes to this discrepancy could be that the test plates are not stress free at the beginning of the process. Despite of that the results from the cutting simulation show a good correlation in behaviour. Especially during the later stages of mill pass 1 and 2, that is around deactivation cycle 10 and 20 respectively, discrepancies are found that cause the result to differ from that point on. If the results would correlate better at the end of mill pass 1 and 2 the final result after milling would be excellent. This points to that the main error originates from an incorrect residual stress pattern in the surface of the test plates. That the errors become larger in the end of mill pass 1 and 2 are natural since an error at the end of each pass becomes more evident when measuring distortions at the other end of the test plate.

It could also be so that new stresses are introduced during the milling due to cutting forces in the cutting direction. Neglecting the thermal contribution caused by friction between the tool and the workpiece seem to have less significance in the cutting experiment. If the workpiece is allowed to cool to room temperature, no significant change in distortion is notable.

Returning to the forming experiment it is also unsure if using a strain gauge, as it was used here, is a good choice in the type of bending mode that the test plates were subjected to during the forming operation. It could be more valuable to use the hole drilling method for determination of residual stresses on a surface centred line along the curvature of the test plates after the forming operation.

Various friction models have been tested in the forming simulation with no considerable change in result. In this type of forming process which almost is a bending process this could be expected. In addition, kinetic hardening has been tried to ensure that an incorrect hardening rule is not the reason for the errors.

Despite of the discrepancies, it is believed that the stepwise method of element deactivation is a very useful method to simulate cutting when interested in distortions on component level. The information gained through this type of simulation is more useful compared to the method of deactivating all elements at once, since the distortions caused by the cutting operation can be followed in time. In addition effects of cutting order, cutting depths and other cutting parameters can be estimated. The experiments showed that the method also is useful for prediction of varying chip thickness.

To make the time stepping element deactivation technique used here more useful for industrial purposes, several problem areas need to be resolved. In order to make the method more generic, mesh logics need to be refined. In particular, it would be desirable to be able to define cutting paths independently of the mesh, which is not the case today. Another task to solve is to connect the deactivation routines to the FE-code so that running with adaptive time stepping is possible. The above mentioned issues are two possible areas that could be subjects for further work.

The deactivation scheme will in the future be tested in an industrial application on an aerospace component, where it will be used to evaluate design solutions for a motor bracket.
6 References


A SYSTEM FOR INFORMATION MANAGEMENT IN SIMULATION OF MANUFACTURING PROCESSES

Henrik Johansson*, Peter Åström*, Kjell Orsborn*

*Department of Mechanical Engineering, Luleå University of Technology, Luleå, Sweden
+Department of Information Science, Uppsala University, Uppsala, Sweden

Abstract

A system has been developed to manage information associated with the simulation of different manufacturing processes. The system focuses on information, such as mesh information, boundary conditions and process parameters, required for numerical simulations. The present work concerns non-linear simulations of processes such as plastic forming and cutting. The goal is to enable information exchange between the different manufacturing simulations to be performed so as to make it possible to predict how a change in one manufacturing process affects the whole chain of manufacturing processes, and thereby the final product.

The system uses an information model described in the information modelling language EXPRESS and uses an embedded object oriented main-memory database management system called AMOS II to store and retrieve information via a query language. The system is written in Java and communicates with the database by using an object oriented query language.

The system allows import and export of information from different simulation codes. Results from one simulation can thus be used as initial conditions for the next simulation. Independent storage and database techniques enable the system to use and manipulate information independent of any specific simulation tool. The system has been used to predict the possibility of a simulation succeeding by using mesh information and process parameters for a cutting process.

Keywords: information management, simulation support, manufacturing simulation, database technique, finite element method
1 Introduction

The use of virtual prototyping is one of the things that have had the greatest impact on the product development process during the last decade. Virtual prototypes are now being used at all stages of the product development process and the importance of the technology is increasing, indeed, many leading companies have suggested that virtual prototyping will be a “must have technology” in the next decade [1].

The success of virtual prototyping is highly dependant on the ability to share and communicate information between the different people involved in the development process. It is often the case that a given analysis depends on the results from earlier analyses, which makes it important for information to be carefully managed to make it accessible and available for use throughout the development process. Even simulations that are not directly dependent on previous results invariably require access to information generated by other sources, such as features of the solid model, boundary conditions and external process data. The purpose of this project is to develop tools and techniques for efficient information management to support simulation of manufacturing processes.

1.1 Usage of virtual prototypes

The use of 3D solid models allows developers to obtain a better understanding of a product when they using standard off the shelf software. These software often include simple simulation features that the users can use to perform simulation tasks, such as simple stress calculations or simple simulation of the dynamic behaviour of a component or system [2].

Some of the time and cost savings associated with the use of virtual prototyping comes from reducing the number of physical prototypes that have to be made. The real advantage and big savings are that the number of iterations can be reduced. To have the physical prototype right first time is the key gain from using virtual prototypes. The advantages are not just limited to product development; virtual factory planning allows the layout of a manufacturing or assembly facility to be assessed against a given product. Conflicts and other problems, with respect to both manufacture and the product itself, can be solved at an early stage of the development process. Any changes required due to manufacturing or assembly issues associated with the product, and also from a logistic, safety or ergonomic point of view can be incorporated before expensive plant of buildings have been commissioned. [3]
1.2 Simulation of the manufacturing processes

How a product is to be manufactured must be considered and planned for at the same time as the product is being developed. The product and its manufacturing process must be designed to produce the product in the best and most cost-effective way. Not taking manufacturing into account can lead to late changes to the product being necessary in order to overcome manufacturing problems. Such changes can significantly affect the product’s geometric and material properties considered during the development process resulting in the need for time consuming and expensive design changes.

Virtual prototyping allows simulation of different manufacturing processes. Simulating the manufacture of a product using, for example cutting, welding and heat treatment, see figure 1, is not always a trivial task and can require non-linear analysis.

1.3 Information access

The amount of information generated during the development process is increasing, due in part to faster computers and more advanced and complex programs. In some cases the volume of information generated becomes a burden on the developers instead of being an asset. Keeping track of all the information used and generated during design and analyses can be a tedious task.

1.4 Information standardisation

Management and distribution of information produced at different stages of the development process or in different engineering domains is a complex task. Most engineering software is used to solve problems within a single, limited, domain. Such software only use the information necessary for solving problems within their particular domain and often have little or no possibility of exchanging input data or results with software used in other domains. Even the possibility of exchanging data between software used in the same domain is limited.
Significant efforts have been made to develop standardised formats, such as IGES [4] and STEP [5], for presenting product information, both within domains and across domains. By defining product data in a standardised format it becomes easier to communicate and share information between different domains within the development process. Standardisation and effective data sharing also gives users the possibility of choosing the software that best performs a given analytical task, as long as it can exchange information with other software based on the standardised format. However, due to limitations in current standards coupled with their limited use and implementation by system developers within many domains, product developers are often forced to either use software that is closely coupled to upstream data sources, e.g., CAD or that supports existing or implemented standards such as IGES or STEP. In some cases, it may even be necessary to recreate the geometry and boundary conditions from scratch thereby leading to duplication of information and the possibility of errors.

2 Background to the system

When a product is manufactured it goes through a series of different manufacturing processes such as welding, heat treatment and machining called the manufacturing process chain. The chain will depend on the actual product and can range from one simple process to a large number of highly complexity interrelated processes. Planning for and optimising these individual processes requires information, which is to some extent based on common product data such as geometry and material data.

The goal with the project described here is to demonstrate simulation of a series of processes carried out as a manufacturing process chain, where the results from one simulation form part of the input to the next. Enabling the exchange of information between the different software used to simulate the individual manufacturing processes makes it easier to produce valid analyses of the outcome of the entire process chain. This makes it possible to easily and reliably predict how a change in one process will affect the final product.

Development of data exchange, distribution and management technologies is a key activity within the Department of Mechanical Engineering and the Polhem Laboratory at Luleå University of Technology. These technologies are then applied in ongoing research projects; the current project aiming to simulate the manufacturing process chain associated with a Spool/Drum manufactured at Volvo Aero Corporation in Trollhättan, Sweden. The process chain studied consists of three processes, i.e., welding, heat treatment and machining. The welding process is friction welding whilst the machining operation is turning. The focus of this work has been to investigate the impact of residual stresses caused by plastic deformation during machining.
2.1 Project co-operation

This paper represents the results of two research projects, “Methodology for Simulation of Manufacturing Processes within Product- and Process Development” and “Management of Computer Based Simulation Information in the Product Development Process”. Both of these projects are part of the research portfolio of the Polhem Laboratory at Luleå University of Technology.

The first project focuses on simulation of the individual processes whilst the second addresses information management between the development and analytical activities associated with each process.

![Diagram showing different simulations and information management project](image)

Figure 2. The focus of the two projects

The findings described in this paper are mainly the result of the information management project, where the goal is to support the sharing, management and use of information associated with computer based simulation used in product and process development. For this reason the specific results from the simulations are not discussed in this paper.

The system described in this paper has been developed to support the management of computer-based simulation information used within different domains during product and process development. The paper does not describe the information model required for the individual simulations but rather shows how management of simulation information can help the users of simulation tools and to show how information modelling and database technologies can bring new dimensions to the effective use of engineering simulations in product and process development.
3 The system

3.1 System overview

The system developed uses an object oriented database management system [6,7] (OO-DBMS), AMOS II [8,9], to support the management of information during product development; in this case information concerning manufacturing process simulations. The information needed for these simulations is mesh information, boundary conditions, process parameters and material data [10]. Central to the system is mesh information, such as nodes and elements. Boundary condition and process parameter data have been incorporated into the system based on the specific requirements of the individual simulations. This allows, for example, the input boundary conditions to be part of the results from the simulation of an earlier process in the manufacturing chain.

![Schematic figure of the prototype system](image)

**Figure 3. Schematic figure of the prototype system**

The system uses the platform independent Java 3D API [11] to give the user a graphical overview, including rotation and zoom capabilities, of the nodes and elements stored in the database. This information visualisation capability makes it easy to verify that the correct information is available for the simulations.

Data Management and Storage

The system also has functions for importing and exporting data in ASCII based STEP Part 21 files [12], defined by the STEP standard and described using EXPRESS schema [13]. In this case the system uses the EXPRESS schema “Engineering Analysis Results” (EAR), developed at Volvo Aero Corporation (VAC).
The system also contains an interpreter for SDRC’s open Universal File format [14] which is a de-facto standard within the simulation community. The system interpreter can take Universal Files and convert them to Part 21 files that are compliant with the EAR schema. Many simulation and mesh generating tools support the Universal File format which makes it possible to import information from many different sources. Information from sources not supporting Universal Files can also be imported and exported as VAC has developed import/export routines for numerous in-house and commercials codes.

![Information Model](image)

**Figure 4. The input of Universal files to the system**

The embedded object oriented database management system AMOS II is used by the system to store information. The information in the database is managed by extensions to the database and queries that are implemented into the system or posed by an interactive user. The system communicates with AMOS II via the AMOS Java API. AMOS II supports the import of EXPRESS schema and corresponding Part 21 files via the extension ST-AMOS.

**Database Modelling and Content**

The key information that was to be transferred was determined with the help of the simulation software users for each of the different processes. This was found to be:

- Nodes
- Elements
- Stress, strain, temperature, plastic strain, etc.
- Boundary conditions
- Material data
- Process parameters
Material data and process parameters were excluded at this initial stage of development of the system; only the information crucial for the simulation of the actual cutting process was managed in the system. However, material data and process parameters are clearly central to any simulation and must be included in the completed system.

**Figure 5.** Identified need of information exchange in a Spool/Drum manufacturing simulation

**Simulation Engine**

The manufacturing simulations are performed using the simulation tool MARC [15] it is capable of solving non-linear structural dynamic equations required for simulations of manufacturing processes such as welding, heat treatment and machining. The system uses MARC’s subroutines to import information to MARC. To do this, the system exports a data file and a subroutine parameter file. When the MARC import subroutine is run, it reads the information from the data file and imports the data into MARC. The process parameters required for the different simulations are incorporated into the data and parameter files by the system according to MARC’s definitions.

**Figure 6.** Export from the system to MARC by using subroutine and data files.
To simulate the welding of the Spool/Drum, see figure 6, the information needed were process parameters, boundary conditions, result sets, material data and geometry information. The results from this simulation were then stored and the information needed for the next simulation extracted from the system together with a subroutine file that suits that simulation.

### 3.2 Information model used in the system

An information model described using the EXPRESS language was used to define the information used by the system. EXPRESS is an object oriented information modelling language that was developed as part of the STEP standard to provide a computer parsable representation of the product data encompassed by STEP.

The information model used was developed at Volvo Aero Corporation. This is known as the Engineering Analysis Results (EAR) schema and encompasses the information associated with, for example, structural dynamics and computational fluid dynamics, CFD simulations. These engineering domains use similar data structures. Both divide the component geometry to be analysed into a mesh with nodes and elements which is used as the basis for common analytical techniques such as the finite element method, FEM.

The EAR schema has been developed specifically to suit VAC’s needs and incorporates information required by an aeroplane manufacturer for simulation as well as data management and verification of results. External modelling experts have, along with the simulation experts, verified the correctness of the rules in the EAR schema and that it support the requirements of the users.

In addition to better understanding database and computer science aspects of managing engineering data, the current work has a specific focuses on assessing how well the schema suits the information exchange needs when simulating a number of different, but dependant, processes in a manufacture process chain. The EAR schema is currently proprietary to VAC and has not as yet been published. It is therefore impossible to go any deeper into the details of the schema at this time.

### 3.3 Interfaces to different formats

For the system described in this paper, data import use input files based on the Universal File format whilst data export is in a format suited for input to MARC. The data export routines have been written to provide the data required for manufacturing simulation in MARC, and both result sets and mesh information are exported. As mentioned earlier, the result sets and mesh information are imported to MARC using its own internal subroutines which are accessed using Fortran programs.
The system is not limited to data input from Universal Files or export of data for simulation in MARC. Different input and output filters written at Volvo Aero Corporation can also be used allowing import and export of data from other commercial programs as well as VAC in-house developed programs. Indeed, data from any Part 21 file based on the EAR-model can be imported to the system allowing, for example, data visualisation to be carried out.

### 3.3.1 Universal file format

The system imports information following the Universal File format, a well documented, open, ASCII file based de-facto standard developed by SDRC. This format is widely used within the simulation community and many simulation programs can export and import information based on this format. The Universal File format supports features such as finite element information, boundary conditions and result sets. The features of the Universal Files that are implemented in the present system is currently limited to nodes, common element types and result sets, such as stresses and plastic strain.

### 3.3.2 The simulation tool MARC

MARC is a commercial simulation engine used for solving linear and non-linear problems. In this project, the non-linear capabilities are used. MARC offers state of the art functionality including automated contact, automated mesh enrichment and is capable of handling large problems. It is also possible to run MARC on parallel computers to speed up solutions. Only a small portion of MARC’s functionality is used in this project.

MARC has been continuously developed since it was first released in 1971, and is used in a wide range of industries including aerospace, automotive and manufacturing companies.

The developers of MARC have recognised that many users require capabilities that the standard software does not support. To solve this problem, user subroutines can be incorporated into the MARC analysis software to extend the capabilities of the software. The user subroutines, written in Fortran, allow, for example, complex material properties or friction coefficient to be represented. The possibilities are limited by the users needs and programming skills.

In this project, subroutines are used to import mesh information, process parameters and residual stress data. The residual stresses are the result of deformation of the product in an earlier manufacturing process and must be included to allow accurate simulation of the manufacturing process chain. Subroutines are also used to deactivate elements in the simulation of the cutting process, (see section 5.2).
3.4 Development of the system

The system has been developed to allow information to be stored in an object-oriented database following an information model described in an open and generalised format. Using an open and generalised information model ensures that the system remains independent of specific system or propriety data formats. The information model, described using EXPRESS, also supports standardised information transfer based on Part 21 files.

For development of the input routines for data based on the Universal File format, the commercial parser ST-Developer was used to parse the EXPRESS data model into useful C++ classes. These classes were then used as the basis for the Universal File import routines. Universal files are first read into ST-Developer’s internal database and then exported as Part 21 files that can be imported into the system database.

![Diagram](image)

**Figure 7. Parsing the EXPRESS schema to C++ classes using ST-Developer**

To make the system platform independent it was developed in Java. Using Java also offers the long term possibility to support access to the system via applets via web browsers, making it possible to run the system over a company intranet. Since web browsers and corporate intranets are now almost ubiquitous, this makes it easier for product developers to share ideas and simulation results with other departments in the company.

Routines written using the Java 3D application programming interface (API) are used by the system to display mesh information, such as nodes and elements. Since the Java 3D API is a high level API, the application developer does not have to be a graphical or rendering expert to create 3D visualisation applications.
AMOS II, developed at Uppsala University, Sweden, was selected as the database management system since it can import and export information based on Part 21 files and supports data access using an object oriented query language, AMOSQL. AMOS II also has a Java API so the system, which is written in Java, can access and manipulate information easily by posing queries using this API.

4 Database management

AMOS II is a main memory database and works as an object relational database allowing it to support data described in the object oriented modelling languages. In the current implementation, AMOS II is used as an embedded database and can handle queries posed by the system using the AMOS II Java API.

AMOS II can handle data from many different sources and in different formats. As well as importing and exporting information, AMOS II can also be used as a mediator of information between different data sources. AMOS II can also be run as a distributed database.

![Figure 8. AMOS II Architecture](image-url)
4.1 ST-AMOS

AMOS II has an extension called ST-AMOS, which allows import of information in the STEP Part 21 file format. A corresponding information model defined by an EXPRESS schema describes the information that the file contains. The internal structure of the database follows the structure of the EXPRESS schema.

![Diagram of AMOS II Information Model](image)

**Figure 9.** The input of data into the system using ST-AMOS

4.2 AMOS II Java API

The system also uses the ability to extend and posing queries to the database using AMOS Java API.

![Diagram of Calling AMOS II Java API](image)

**Figure 10.** Query from the system to AMOS II by using AMOS II Java API

It is also possible, using the Java API, to access AMOS II sources on the Internet, or within a corporate intranet. This means that the system need not be running on the same computer as the database. However, this feature is not implemented in the current system because the simulations performed are limited to one site.
Allowing simple access to foreign data sources is useful if the system is implemented in an engineering environment where numerous design tools and simulation codes are used. Exchange and sharing of information between different domains, which may contain information based on different information models, can be mediated by AMOS II. This effectively eliminates duplication of information since the mediated information remains at the original data source.

5 Examples of the system

Two examples of how the system developed can be used are given below. The first example shows how mesh information can be extracted from the database and visualised. The second uses the system to extract information from the database to estimate the probability of success of a simulation. The simulation data used in the examples is 2D; although the system can equally easily handle 3D data.

5.1 Choosing the mesh to extract

The first example shows one of the simplest tasks that the system can perform; the visualisation of nodes and elements stored in the database. Data is extracted using embedded database queries, posed by the AMOS II Java API. The relationship between elements and nodes is described in EXPRESS-G, see figure 10.

Figure 11. The EXPRESS-G view of Element domain, Node domain position, Id numbers and Position in space
The system then uses the Java 3D API to present the extracted information on screen. The user interface allows the user to zoom, pan and rotate over the visualised mesh allowing interesting parts to be examined more closely. This makes it easier for the user to confirm that the correct mesh has been selected for the next simulation.

Retrieval of node positions connected to an element is done using the three user developed functions presented below:

```sql
create function get_element_nodes(integer j) -> vector of st_node as
select nodes(e)
from st_element e, st_element_domain ed, st_domain_id_numbers din,
integer i
where elements(ed)[i] = e and for_domain(din) = ed and id(din)[i] = j;
create function position_of_node(st_node n) -> vector of real as
select values(positionsaidpf[i])
from st_node_domain_positions ndp, st_node_domain nd, integer i
where nodes(nd)[i] = n and for_node_domain(ndp) = nd;
create function position_of_element_nodes(integer i) -> vector of real as
select position_of_node(get_element_nodes(i)[j])
from integer j;
```

The system uses the same data access functions to extract mesh and node information needed for simulation in MARC. Input to MARC is currently a manual, file based activity requiring mesh information and a subroutine file. The subroutine file is then run to import the input file and perform the simulation.

![Figure 12. Export to MARC from the system](image)
5.2 Using the data stored in the database

By extending the database and posing queries on this information it is possible to implement features and perform tasks that are difficult or impossible with a simulation tool.

A limitation to the cutting simulation is that it must be done on a geometry meshed as four node elements and that the cutting path must go through opposite element edges. In other words, there must be two element corners between the cutting path and the edges it is cutting through. If the cutting path crosses two edges that share one corner an error occurs and the simulation halts.

The simulation is also sensitive for cutting paths that are near corners because the relaxation of the residual stresses deforms the mesh. Since the elements “move” during the simulation, it is possible that the cutting path will share a corner, and the simulation fail, even if the original mesh and cutting path did not.

A program has been developed that retrieves element and node information from the database and uses the imported cutting path to establish whether the simulation may succeed. It also shows how far from the nearest comer the cutting path goes, allowing an estimation of the success ratio of a simulation with the element “movement” due to relaxation of residual stresses to be given.

The database was extended with a user defined function that retrieved elements that a given element shares two nodes with. In figure 12, the cutting path is at element nr 8, which shares two nodes with elements 3, 7, 9 and 13. Using the user defined function allowed the possible “next” elements that the cutting path enters to be found. The functions are defined as:

![Figure 13. Cutting path and deactivation of elements](image-url)
create function how_many_common_nodes(st_element e1, st_element e2) -> integer as
    select count ( select i
    from integer i, integer j
    where nodes(e1)[i] = nodes(e2)[j] );

create function which_elements_share_two_nodes(st_element e) -> vector of st_element as
    select elements(ed)[i]
    from st_element_domain ed, integer i
    where how_many_common_nodes(e,elements(ed)[i]) = 2;

6 Results

The system uses the AMOS II database to store and exchange simulation information between different manufacturing simulations. The database structure is based on the EAR EXPRESS schema, which describes simulation information, such as meshes and result sets. Results and meshes from one simulation can be imported into the system via the STEP Part 21 interface to AMOS II and subsequently extracted to be used as part of the input data for the next simulation. The system is capable of managing information from many different kinds of simulations, although only information related to simulation of manufacturing processes has been implemented within the project.

The system can use and manipulate information independent of its origin. This separates the data from the simulation tools allows data manipulation tasks to be performed even if the simulation tool is changed. For example, if the deactivation of elements is to be performed in a simulation code another than MARC, the probability of success routine will still be valid. Even tasks that are today carried out by the simulation tools can be generalised and incorporated in the system, such as user written codes.

The import and querying of information from large datasets is currently a time consuming task within the system which must be speeded up and optimised.

7 Summary and future work

Although virtual prototyping has evolved considerably, its full potential is far from fully explored. One area which offers considerable scope is the ability to carry out a connected chain of simulations representing a chain of manufacturing processes.

The system presented in this paper will allow further development of database techniques for application within the engineering domain. Being able to query and process information will help streamline the product development process whilst the mediation function of the system will act as a foundation for combining information from different domains without duplication.
Structuring process parameters to fit the different simulation which may be carried out is still an issue since input of process parameters is not yet standardised. Nearly every tool uses its own proprietary format for data import and it will become increasingly important in the future to describe process parameters in a standardised and general way thereby making it easier to link other simulation tools.

It should be possible to solve the performance issues associated with import and querying of information in the current system by using a different data structure within the database, rather than the EXPRESS schema’s structure. Even though the EXPRESS schema describes all the information needed it is not certain that this is the best structure for holding the data internally in the database. Performance is also affected by how queries are formulated and the speed with which these queries are handled. The C++ version of AMOS II, which is many times faster than the Java API, offers one possibility to speed up the system.

It is important to develop and document a methodology describing how to work with the system if it is to be implemented at a company. The users of the system must develop basic knowledge of query languages in order to be able to develop the full potential of the system and to develop their own queries to ease their work. Common tasks or queries that many users require should be incorporated as a feature within the system on an ongoing basis. What to incorporate and what to leave out must be decided by the users of the system in the light of the cost of incorporating new functionality into the system.

7.1 Future work

A further development of predicting of likelihood of the cutting simulation succeeding using information extracted from the database is to analyse the mesh after every element deactivation and thereby predict the accuracy of the mesh. If the mesh becomes distorted, it would then be possible to interrupt the simulation. To do this, the system must interact continuously with the simulation software during the simulation and calculate the mesh correctness.

The system will be further developed during the current project to further enhance the simulation of manufacturing processes associated with the Spool/Drum at Volvo Aero Corporation. Further requirements that emerge from the simulation environment will be incorporated into the system, such as support for more element types and result sets. It is hoped to develop the system to allow it to cater for simulation information covering the full range of manufacturing process simulation carried out at Volvo Aero Corporation.
8 References


[14] I-DEAS, Structural Dynamics Research Corporation, 200 Eastman Drive, Milford, Ohio 45150-2789, USA
[15] MSC.MARC, MSC.Software Corporation, 2 MacArthur Place, Santa Ana, CA 92707 USA
Virtual manufacturing, that is, simulation of welding, heat treatment, cutting and other manufacturing processes is becoming more and more used as a tool for prediction of material- and mechanical properties in modern industry. By simulations we refer in this case to FE-simulations of the thermo-mechanical effect of the manufacturing process on the component in question.

Despite the fact that simulations are becoming more widely used, there is a lack of integration of simulations of manufacturing processes in the sense that most work focuses on an individual process being simulated. It is only when a complete chain of manufacturing processes can be simulated the real benefits, of using virtual manufacturing as a tool within product- and process development, will become evident.

The thesis focuses on simulation methodologies within virtual manufacturing, and specifically methodologies for cutting simulations. Simulation of mechanical cutting has been identified as a key area where computational difficulties arise when attempting to simulate a sequence of manufacturing processes involving some form of cutting operation.

A distortion problem during manufacture of a shaft front to a RM12 engine has been analysed. At one time, distortions aroused during the later stages of the cutting sequences involved in the manufacture of the shaft front. The cooling from solution heat treatment temperature and the cutting sequence .... (cont.)