CAD Implementation of Design Rules for Aluminium Extrusion Dies

Gijs van Ouwerkerk

CAD IMPLEMENTATION OF DESIGN RULES FOR ALUMINIUM EXTRUSION DIES

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CAD IMPLEMENTATION OF DESIGN RULES FOR ALUMINIUM EXTRUSION DIES

PHD THESIS
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Summary

Aluminium extrusion is an industrial forming process that is used to produce long profiles of a constant cross-section. This cross-section is shaped by the opening in a steel tool known as the die. The understanding of the mechanics of the aluminium extrusion process is still limited. The flow of aluminium within the die is governed by tribomechanical and rate- and temperature-dependent effects that have not yet been fully mathematically modelled. As a result, it is difficult to design the die geometry in such a way that the aluminium profile complies with high customer demands regarding dimensional accuracy and surface quality. Die design has to a large extent been empirically based. This, along with a low level of automation, causes a large variation in the performance of dies. This often necessitates corrections to the die and results in a high percentage of scrap production.

This dissertation is a continuation of a research project that has existed since 1991. In cooperation with the aluminium extrusion company Boalgroup, researchers at the University of Twente have worked to gain more insight into the extrusion process. With the help of finite element simulations this has led to the formulation of design rules and approaches that are based on a more fundamental understanding of the process than the existing empirical knowledge. A design method was devised that balances the exit velocity of flat dies by using a combination of variable sink-in and bearing geometry. This leads to die designs that exhibit a more stable and predictable flow balancing behaviour than traditional designs based on length variations of parallel bearings alone. In addition, a formula is given that estimates the pressure acting on the die, so that the calculation time of finite element analysis of the die deflection is drastically reduced.

Along with making a contribution to the developments mentioned above, the work presented in this thesis focuses on the implementation of these design rules and approaches into CAD tools. The provided automation of these design tasks significantly accelerates the design process and increases the consistency of the results, without removing the control of the human designer. By taking constraints of the manufacturing process into account while generating the geometry, the risk that the die manufacturer has to make unexpected changes to the die design is reduced. The reduction of design time that was achieved has enabled Boalgroup to greatly increase the number of in-house die designs. Since the majority of these new designs is showing a significant performance increase, the company’s overall productivity has increased steadily, helping them to deal with the ever rising labour and energy costs.

SAMENVATTING

Aluminiumextrusie is een industrieel omvormproces voor het produceren van lange profielen met een constante dwarsdoorsnede. Deze dwarsdoorsnede wordt gevormd door een opening in een stalen gereedschap dat een matrijs wordt genoemd. De kennis van de mechanica van het aluminiumextrusieproces is nog beperkt. De stroming van het aluminium in de matrijs wordt beheerst door tribomechanische en temperatuurs- en reksnelheidsafhankelijke effecten die nog niet volledig wiskundig beschreven zijn. Hierdoor is het moeilijk om de matrijsgeometrie zo te ontwerpen dat het aluminiumprofiel aan de strenge eisen van maat- en oppervlaktenauwkeurigheid voldoet. Het ontwerpen van matrijzen verloopt nog voor een groot deel empirisch. Samen met de lage mate van automatisering zorgt dit voor een grote variatie in de prestaties van matrijzen. Hierdoor zijn vaak correcties aan de matrijs nodig en bestaat een hoog percentage van de productie uit schroot.

Dit proefschrift beschrijft de voortzetting van een onderzoeksproject dat al sinds 1991 bestaat. In samenwerking met extrusiebedrijf Boalgroup hebben onderzoekers aan de Universiteit Twente geprobeerd meer inzicht te krijgen in het extrusieproces. Met behulp van eindige elementensimulaties heeft dit geleid tot het formuleren van ontwerpregels en ontwerpmethodes voor matrijzen die gebaseerd zijn op een fundamenteler begrip van het proces dan de bestaande empirische kennis biedt. Er is een ontwerpmethode ontwikkeld die zorgt voor een uniforme uitstroomsnelheid bij vlakmatrijzen door het gecombineerde gebruik van een voorkamer (*sink-in*) met variabele breedte en uitstroomkanalen (*bearings*) met variabele lengte. Vergeleken met traditionele matrijsontwerpen waarbij slechts de lengte van het parallelle uitstroomkanaal wordt gevarieerd, is dit een stabielere en meer voorspelbare manier om uitstroomsnelheidsverschillen te vereffenen. Bovendien wordt een formule gepresenteerd waarmee de druk op de matrijs kan worden voorspeld. Hiermee kan een eindige elementenberekening van de doorbuiging van de matrijs aanzienlijk worden versneld.

Het onderzoek dat wordt behandeld in dit proefschrift levert een bijdrage aan de hierboven genoemde ontwikkelingen en is toegespitst op de implementatie van deze ontwerpregels en –methodes in CAD-gereedschappen. De automatisering van deze ontwerptaken versnelt het ontwerpproces aanzienlijk en verhoogt de consequentheid van de resultaten, zonder de menselijke ontwerper buitenspel te zetten. Door bij het genereren van de matrijsgeometrie rekening te houden met de beperkingen van het productieproces wordt het risico van onverwachte aanpassingen door de matrijzenmaker verkleind. De behaalde verkorting van de ontwerptijd stelt Boalgroup in staat om meer zelf ontworpen matrijzen in te zetten in de productie. Omdat de meerderheid van deze nieuwe ontwerpen sterk verhoogde prestaties vertoont, stijgt de algehele productiviteit van het bedrijf gestaag. Dit helpt Boalgroup om om te gaan met de alsmaar stijgende arbeids- en energiekosten.

PREFACE

The possibility of taking on a PhD project had never really crossed my mind. After finishing my masters project and continuing that work for another year after obtaining my degree, I was looking to move west and start work at a hi-tech company of some kind. I went to see Professor Van Houten to ask if he had any contacts at such companies that could help me find a job. This is when the option of this PhD project was brought to my attention. This offer was, at least on paper, very different from the image of PhD projects that existed in my mind. When I thought of PhD students I thought of people that are much smarter than me, but get paid a lot less, working long hours pondering over mind-blowing differential equations. In fact, two of my friends that were PhD students fit this description pretty well. However, reading the very practical and accessible dissertation written by Tom Vaneker, whose work I was asked to continue, I started to feel that I might be up to the task. Here was a project that was very similar to the development of CAD/CAM solutions that I had worked on before, only this time I would be the captain of the ship. I took the plunge and never looked back.

During the four-and-a-half year period of working on this thesis I never felt alone. The close cooperation with Boalgroup in De Lier, The Netherlands, the group of Applied Mechanics at the University of Twente and the various master students and programming aids from my own group has always made me feel like a team player. Many thanks to Kjell Nilsen and Peter Koenis at Boalgroup for being a source of invaluable information and undying support for the project. I also would like to thank the people at Phoenix International in Italy and The Netherlands, Sapa in Drunen and Matec in Belgium for welcoming me with so much hospitality and expanding my horizon in this project.

I was very fortunate to have Bert Koopman, a fellow PhD student at the group of Applied Mechanics, working with me on the same project. We shared ideas, experiences and insights and had great times visiting some conferences together. We must have played that Herman Finkers CD a hundred times! From his group I also want to thank Professor Han Huétink, Bert Geijselaers and Wissam Assaad for their companionship and contribution to the project. The software that was developed in this research would never have worked without the help of Hartwin Lier and Krijn Woestenenk. Without you guys I would probably still be breaking my head over the code, trying to find out why those damn arcs are being drawn backwards. Valuable contributions to this project were also made by students Erwin Sluiter, Kees Durk van der Kooi, Johan van Ravenhorst and Bastiaan Holm. It was a joy working with you. My supervisor Professor Fred van Houten did a great job of making me stop despairing too much about small details and keeping a clear view of the big picture. The bulk of the supervision was carried out by assistant supervisor Tom Vaneker. His well-written thesis was a jumpstart introduction into the subject of aluminium extrusion die design and throughout the duration of my research he has been a knowledgeable and ever-available source of inspiration. Tom's dedicated involvement during the writing of this dissertation has had a tremendous impact on its quality. Many thanks, Tom!

I greatly enjoyed being part of the group of Design, Production and Management. The tutoring of Industrial Design and Mechanical Engineering students that I performed alongside my research was a fun and rewarding experience. It provided some much needed breaks from my research, but was never a distraction. Coffee breaks and lunches with fellow group members were always a great excuse to get my eyes off the monitor for a short while. Especially the trips and dinners that were organised by the group have left behind fond memories. Special thanks are in order for the great people that have shared room N-211 with me over the years. Our crowded and lively office was not always the best catalyst for productivity, but always a strong motivation to come to work. I will greatly miss the laughter, the hell raising (“toeter mee met de Turken”), the visits from Mr. Zaagmans and Wouter “lunch guy” Schotborgh and the impersonations of cartoon and movie characters. I’ll really miss you guys! ... Nah, scr*w you guys!

A final and very heartfelt word of thanks goes out to my parents Kees en Tineke and brother Pieter. I’ve never sufficiently expressed my appreciation for your undying love and support. You’ve always encouraged me to choose my own path, no matter how radically I changed course, with only my happiness on your agenda. I love you dearly and consider myself incredibly lucky to have been raised by such great parents and grown up alongside such a cool brother!

-Gijs-

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Chapter 1

Introduction

CHAPTER 1: INTRODUCTION

This thesis will discuss the improvement of aluminium extrusion die design through the derivation of design rules and their implementation into a software based design tool. In this chapter a brief introduction will be given to the aluminium extrusion process, the challenges faced by the extrusion industry and the role of die design. Furthermore the project that this work is part of is introduced and finally an outline of the thesis will be given.

1.1 Aluminium extrusion

Aluminium extrusion is an industrial forming process to produce long profiles of a constant cross-section. Aluminium rods (billets) are heated and pressed through a die to obtain the product's cross-sectional shape. The most common type of extrusion is direct extrusion, where the ram of the press pushes the aluminium billet through a stationary die. The most common type of press for this process is the horizontal hydraulic press. Press capacities vary according to the size of the dies used, which can have diameters between 100 and 1000 mm. For the most common extruded products, dies of 175 to 250 mm in diameter are used. For these die diameters presses with capacities between 1500 and 2000 metric tons are required. A schematic detail of an extrusion press is shown in figure 1.1.

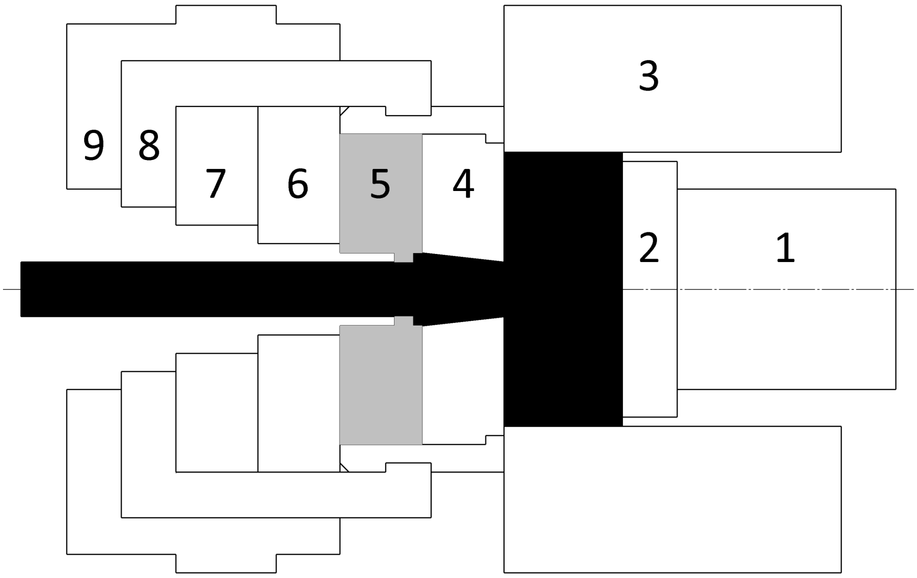

Figure 1.1 The extrusion press (reproduced from [1])

The ram (1) is fitted with a steel dummy block (2) that fits tightly into the container (3) and prevents aluminium (shown in black) from leaking backwards. The die (5) is part of a die assembly or tool stack, made out of tool steel. The backer (6), bolster (7) and the die holder (8) and its carrier (9) are supporting the die under the extrusion load. A feeder plate (4) may be used before the die to spread out the flow from the container to a larger area on the die. In direct extrusion no lubrication is used, so that the outer layer of the billet is sheared off by friction with the container wall. This is beneficial, because this layer contains coarse iron-rich intermetallics and Mg_2Si precipitations that are not suitable for extrusion [2]. These contaminations accumulate in the back of the billet at the end of the press stroke and are often referred to as the back end defect. This part of the billet is cut off before a new billet is loaded into the press. The aluminium from the new billet welds onto the material left in the die at the next press stroke, causing a continuous product to exit the die. This so called transverse weld is still visible in the extruded product. Due to the reduced mechanical properties and surface quality this section is usually sawed off and scrapped [3].

To ease the deformation process and to minimise the occurrence of work hardening, the aluminium billet is heated to about 400-500°C (depending on the alloy) before it enters the press, causing it to enter a plastic (not liquid) state. The container and the die are also heated to prevent the billet from cooling down. The die opening is made slightly wider than the intended profile dimensions, because the aluminium shrinks more than the tool steel as it cools down.

The most widely used types of dies are flat dies and porthole dies. Flat dies consist of only one piece and can be used to extrude solid profiles (figure 1.2a). Porthole dies are made up of two pieces, a plate and a mandrel. This allows the extrusion of hollow (figure 1.2b) and semi-hollow (figure 1.2c) profiles. Dies of either type may have multiple cavities, so that multiple instances of a profile can be extruded at once.

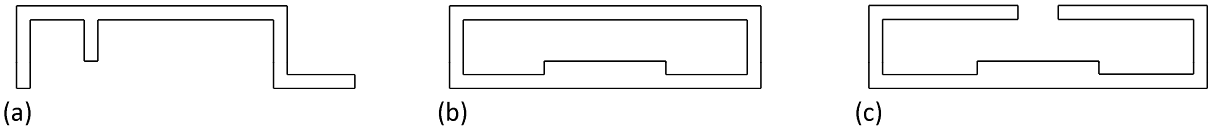

Figure 1.2 Three types of extrusion profiles

A flat die is shown in figure 1.3. The most important features are the sink-in (1), which is an optional pocket, the bearing (2) and the die relief (3). The bearing is the area that gives the aluminium its final shape. To minimise the required extrusion force the bearing does not extend over the entire die thickness, but has a length of 15 mm or less. The function of the die relief is to provide adequate support to the bearing without making contact with the aluminium. This means that it angles out at about 5 degrees and usually has some clearance just below the bearing. The sink-in's function is to protect the fragile bearing when the back end of the billet is sheared off and to facilitate the transverse welding of one billet to the next [4]. Additionally it can be used as a means to control the flow of the aluminium (see chapter 3).

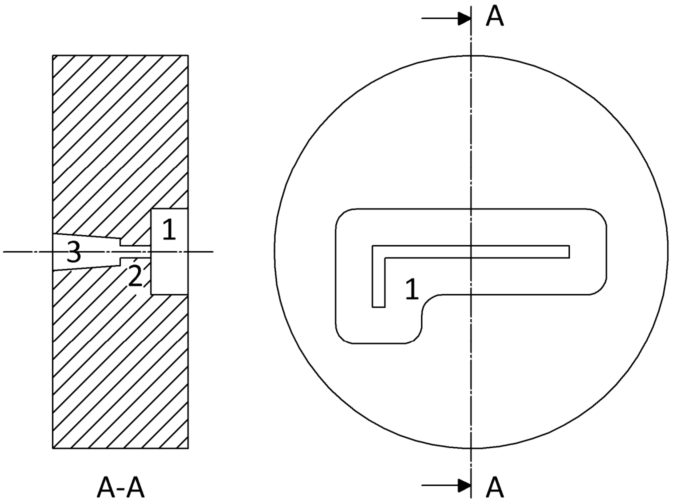

Figure 1.3 Flat die

Figure 1.4 shows a porthole die. As mentioned it consists of two parts, the plate (a) and the mandrel (b). The mandrel has one or more cores (1) with bearings that shape the inner contour(s) of the profile. The cores are attached to the rest of the mandrel through legs (2). The aluminium flows around these legs through feeder holes (3) and rejoins in the welding chamber (4). The final shape is then formed where the bearings of the mandrel and plate combine (5).

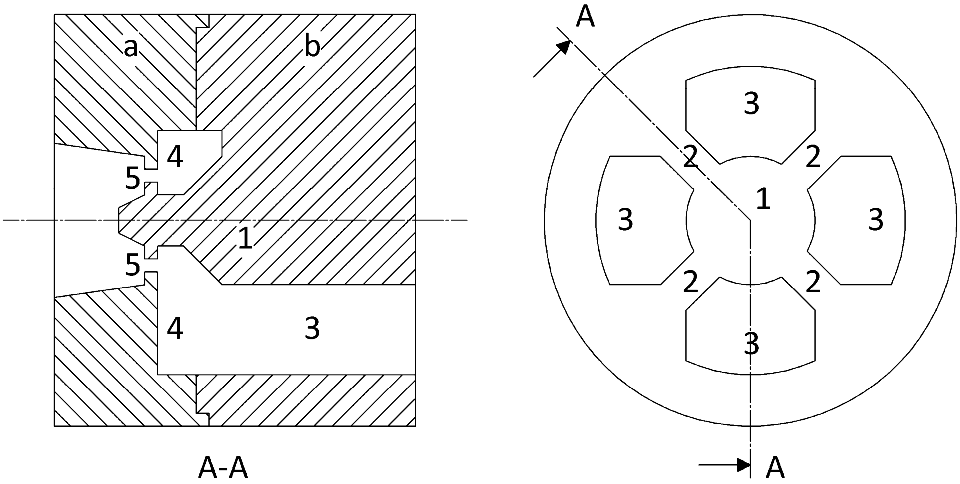

Figure 1.4 Porthole die

Extrusion dies, backers and bolsters are made from blanks sawed from steel cylinders. The dies first undergo turning and rough milling operations. Before the detailed areas such as the bearing and the back relief are machined the die is heat treated for stress relieving, hardening and tempering. The induced distortions from the heat treatment are removed by machining the two faces of the die again. Finally, the back relief and the bearing cavity are cut. The relief can be made by milling or by electro-discharge machining (EDM), depending on the accessibility. EDM is also used for the bearings. In flat dies EDM wire erosion is used for the narrow bearing opening.

1.2 The aluminium extrusion industry

The most important parties in the extrusion industry are the customers of extrusion products, the extruders and the die manufacturers. The users of aluminium extrusions most commonly supply the extruder with a profile design. Based on the profile design the extruder can quote a price and an expected delivery time to the customer. The profile design, which is sometimes modified slightly in agreement with the customer to enhance extrudability, is then sent to a die manufacturer. This manufacturer designs and makes the die and supplies it to the extruder. Some extruders have their own die shops, so they do not have to order dies from an external company. At the extrusion plant a test run is performed with the die to check if the product complies with the customer's specification. The customer often wishes to inspect this product sample. If the product is flawed, which is mostly due to non-uniformities in the exit velocity out of the die or due to problems with the surface quality, then corrections are made to the die. This is usually done by correctors working at the extrusion plant, who are equipped with measuring instruments and tools to make minor modifications to the die geometry. In case of bigger problems the die is sent back to the manufacturer. Multiple cycles of die trials and corrections may be necessary before it is established that the die produces a satisfactory product. At this point it is usually nitrided. This heat treatment involving diffusion of nitrogen increases the hardness of the die surface, making it more resistant to wear. This process is repeated every few hundred extrusion cycles, because the hardened layer deteriorates slowly due to diffusion of nitride to areas deeper beneath the surface of the die.

After production dies are stored in the extruder's facility in case the customer orders more of the product. The lifetime of extrusion dies is limited, however. Excessive wear in the bearing and fracture due to fatigue are the most common causes of failure. If demand for the profile continues to exist after the die has become unusable, then a repeat die is ordered from the die manufacturer. Some of the corrections that were made to the original die may already be incorporated into this new die. It is not uncommon that five or more repeat dies are ordered over time.

1.3 Controlling the aluminium flow

Aluminium extrusion is a difficult process to control. The ram speed and the billet and tooling temperatures are parameters that have an effect on process efficiency, die life and product surface quality, among other things. The focus of this thesis, however, is on the problem of balancing the exit speed of the aluminium through the die opening. For direct extrusion and a flat die with a constant bearing length, there are two main phenomena that introduce speed differences in the extrudate. The first is that the aluminium does not enter the die at a uniform speed. It was already mentioned that friction between the aluminium and the container wall shears off the outer oxidised layer of the billet. The aluminium is also stationary in the corners of the container and die, forming so called dead metal zones (see figure 1.5).

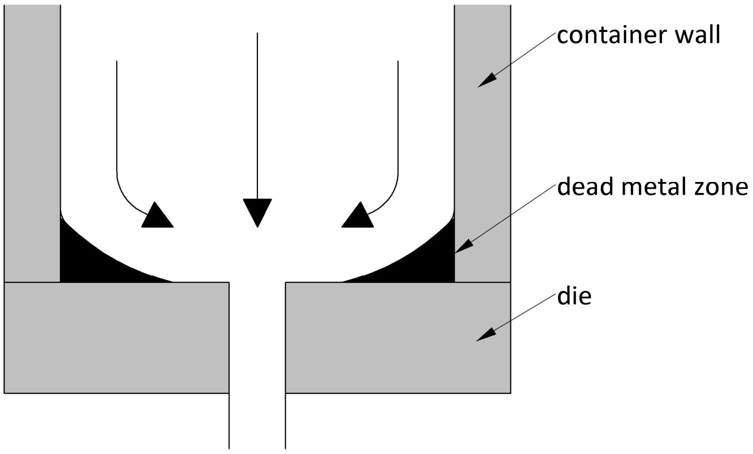

Figure 1.5 Dead metal zones in the interface between container and die

These effects cause the aluminium to flow faster in the centre of the die than towards the edges. It is sometimes called the *container effect*. As the billet becomes shorter during the stroke of the press, the friction decreases and the non-uniformity of the speed is reduced. It has also been shown that the dead metal zones change shape and size during each extrusion cycle [5, 6].

Variations in width of the profile opening also make the flow speed non-uniform. Wider openings provide a lower resistance to the flow than narrower sections. Deflection of the die under the extrusion load may also affect the flow resistance of the openings. If left uncorrected these effects combine with the container effect to introduce speed differences in the extrudate. This causes some parts of the profile to receive an excess of material and others a shortage. In mild cases the thicknesses will be out of specification. In severe cases surfaces may start to ripple (excessive feed) or tear (deficiency of material). Figure 1.6 shows an example of rippling of the profile.

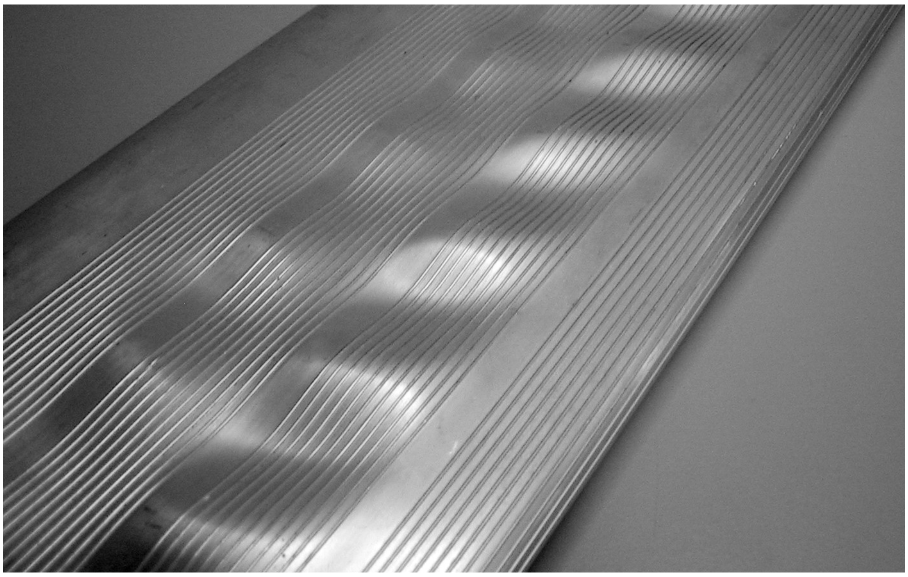

Figure 1.6 Rippling of an extrusion profile due to excessive feed in the middle

A good die design can counteract these speed differences. The most widely used method of controlling the flow is by varying the bearing lengths. A longer bearing has a greater resistance to the flow and therefore allows naturally faster sections of the cavity to be slowed down and vice versa. When using a porthole die, the shape and size of the feeder holes also has an effect on the speed distribution of the aluminium in the profile cavity. It can be used to the designer's advantage to (partly) even out the flow before it reaches the bearing area.

These corrective measures are mostly not based on the physical understanding of the aluminium flow, because this understanding is far from complete. The reasons for this will be discussed in chapter 2. Die design is therefore largely based on the experience of the die designer. In some cases this experience may be in the shape of explicit design rules, but it often just exists in the designer's mind and is difficult to transfer to another person. Trial and error also plays an important role as new dies are subjected to trial production runs and die correctors apply changes to the die to adjust the flow speed.

The challenges posed to extruders are becoming greater in recent years with the tendency of customers to demand more complex profile shapes. This added complexity is the result of the customers' wish to avoid assembly costs and integrate more functions into a profile. In addition they demand tighter tolerances on dimensional and positional accuracy and surface quality. This means that the dies must perform ever better and flow control becomes even more critical.

1.4 Economical considerations

As explained, strict demands are placed on the quality of the extrudate. Quality is therefore an important factor for consolidation and expansion of the extruder's customer base. The extruder must achieve this quality in a way that is economically feasible, however. Producing scrap or stopping production is very costly, because it wastes time, material, manpower and energy. Competition is fierce and the profit margin per kilogram of aluminium transformed into profiles is small. This margin remains fairly constant over time, whereas the costs of labour and energy increase every year. This can only be compensated by increasing the efficiency of the process, i.e. the net output of product per unit of raw aluminium and per unit of time.

One of the most important parameters that influence the net product output is scrap production. Some scrap cannot be avoided, such as the nose pieces (the first few metres of extrudate after the installation of a new die in the press), the back end defects and transverse welds. This loss is about 10% of the total aluminium used. Die design and the control of process conditions (e.g. ram speeds and temperatures) have a very limited influence on this portion of scrap [2]. They do, however, strongly affect the percentage of the extrudate that needs to be discarded because it does not comply with customer specifications. This is essentially downtime of the press, which is very costly. Compared to the influence of die design, the effect of process conditions is generally fairly well understood. The focus of this thesis is on the possibilities of improving the die design process to minimise scrap production.

A greater net production output can also be achieved by increasing the speed of extrusion, either by increasing the ram speed for a given extrusion ratio[1] or by increasing the number of cavities in the die. Aside from careful control of process conditions, the success of these measures also largely depends on the quality of the die design. If the extrusion speed is too high, the generated heat due to friction and deformation cannot be transferred away from the bearing fast enough and damage to the bearing ensues [7]. The lower the overall resistance to flow of the die, the lower the work performed on the billet will be. This will result in a decrease in the amount of heat produced [8]. This will allow a greater extrusion speed to be used.

Better control of die deflection may also allow for greater extrusion forces and/or higher speeds. Increasing the number of cavities poses a greater challenge to the die designer to balance the exit speeds.

1.5 Boalgroup

The industrial partner of this research is Boalgroup, an extrusion company founded in 1973 in The Netherlands. At present they have four locations; two in The Netherlands, one in Belgium and one in Great Britain. The majority of their presses are of medium size, with

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[1] The extrusion ratio is defined as the quotient of the cross sectional area of the billet and the combined cross-sectional areas of the die openings.

container diameters of 7, 8 and 9 inches. They execute direct extrusion of predominantly light alloys AA6060 and AA6063, as they are known in most literature about extrusion. Some material properties of these alloys are given in appendix A. Aside from producing profiles designed by their customers they also manufacture their own profile designs, particularly intended for greenhouses.

Most of the research and development is carried out at the company's headquarters in De Lier, The Netherlands. At this R&D department it is believed that improving the die design process is the key to increasing production efficiency and continuing to meet the customers' quality demands. Where other extruders tend to outsource the design of dies, Boalgroup aims to increase their level of control on the designs of dies that are supplied to them. By supplying the die manufacturers with their own designs they are no longer dependent on the variety of the die designs made between individual die manufacturers or individual designers at these companies. This means that their dies are constructed based on their own design strategy and vision, which can evolve over time as the production results are evaluated. Another advantage of this approach is that the time it takes to order a die is reduced. This translates itself into lower delivery times of the profiles to Boalgroup's customers, giving them an edge in order acquisition.

1.6 Project history

In May 1991 an aluminium extrusion research project was started as a cooperation between Boalgroup and two research groups at the Engineering Technology department of the University of Twente; Applied Mechanics and Design, Production and Management . At that time the project had a third partner; the Italian die manufacturer Phoenix International SpA. By 1995 the focus had shifted from die maintenance to the improvement of die design. Boalgroup and Phoenix supplied the practical knowledge and experience of the extrusion process. At the University of Twente the group of Applied Mechanics has been researching new ways of executing finite element simulations of aluminium extrusion. An important milestone was the development of the finite element code DiekA, which is very suitable for the simulation of forming processes with large deformations. The work of Mooi [9] and Lof [10] brought the simulation techniques up to standard to make them suitable for gaining insight into the extrusion process. This work is continued today by Koopman [11, 12]. In parallel with these researchers Lindeman [13, 14] and Vaneker [1] of the group of Design, Production and Management developed and partly implemented software to apply these insights into the design process of dies. This thesis reports on a continuation of that work.

1.7 Project focus

In order to improve the design of flat dies the following three causes of exit speed non-uniformity will be addressed within this thesis:

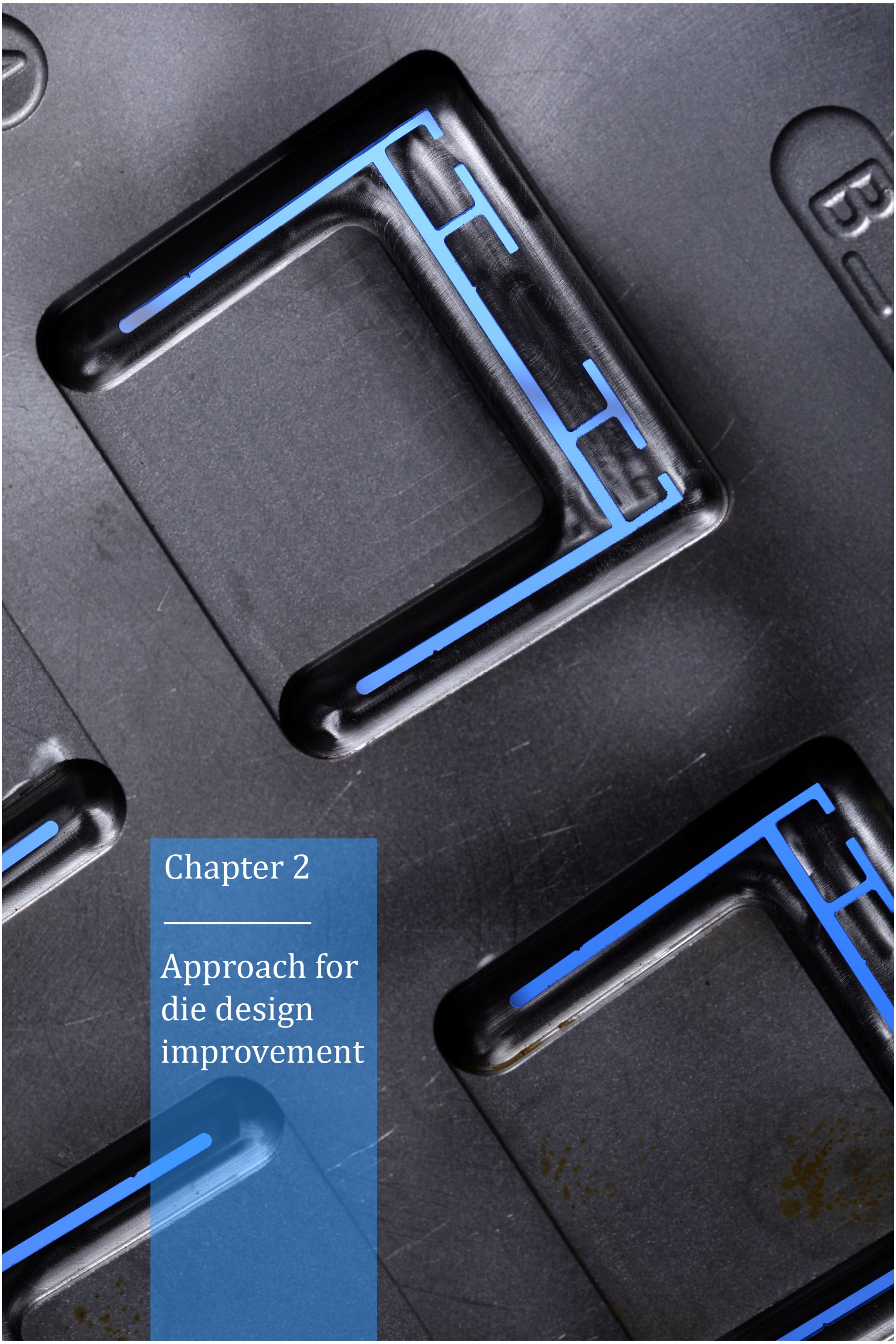
- Speed differences due to different profile opening widths.
- The container effect.
- The effects on the flow speed of die deflection under the extrusion load.

The influences of process conditions on the dimensional accuracy and surface quality of the extrudate will not be investigated. This includes deliberate or accidental variations in billet and tooling preheat temperatures, container diameter, the aluminium alloy and the speed of extrusion (a combination of extrusion ratio and ram speed). Since the production facilities at Boalgroup will be the testing ground in this project, the average conditions occurring there will be taken as the norm. Against this background the quality of the die and its design process will be addressed in the following areas:

- Correction for non-uniformity and improvement of predictability of the exit velocity.
- Prediction of die deflection and its impact on the aluminium flow.
- Speed and consistency of the creation of die designs.
- Manufacturability of the sink-in and bearing area of the dies to be designed.

1.8 Thesis outline

The next chapter will describe and motivate the project’s strategy for improving the die design process. Chapter 3 will discuss new insights related to the design of aluminium extrusion dies. Design rules have been derived and a designer’s best practice guide for flat dies will be provided. Chapter 4 describes the further development and implementation of the design methods into software tools. In chapter 5 the results will be discussed and chapter 6 provides conclusions and recommendations for further research.



Chapter 2

Approach for die design improvement

CHAPTER 2: APPROACH FOR DIE DESIGN IMPROVEMENT

In chapter 1 it was explained that die design is an important factor that determines scrap production and production speed. This influences the net production and efficiency of the process and therefore the profit margin of the company. This chapter will explain why despite much research the physics of aluminium flow have not yet been mastered to a level that die design can be transformed from an art to a science. Against the background of this complexity the merits of both empirical and FEM based design rule development will be investigated. It then proposes an approach to move towards a structural improvement in the performance of dies based on a more fundamental knowledge of the aluminium flow.

2.1 Complexity of the aluminium extrusion process

Aluminium that is being extruded is not in a liquid but in a plastic state. It therefore does not behave like a liquid, for which mathematical flow models exist. As explained in chapter 1 dead metal zones form where the aluminium is stationary. The occurrence and shape of these zones are not just determined by the shape of the die and the interface with the container. They are governed by the delicate balance between the frictional forces with the steel and the internal shear forces within the aluminium. Whenever the friction with some part of the die or container exceeds the internal shear stress, the aluminium will shear within itself and create stationary zones [5]. Most notably these dead metal zones occur at the container to die interface and within pockets such as the sink-in or the welding chamber [15]. As the billet progresses through the container the area of friction with the container wall is reduced. This changes not only the flow pattern towards the die, but also the shape of the dead metal zones [6, 16]. This is only the tip of the iceberg of the complexity of the aluminium extrusion process. The difficulty to control the process is illustrated in figure 2.1. The figure plots the most important adjustable input parameters of the process against some of the output parameters that reflect the quality of the product and process. Dependencies are marked by an ‘x’. This ‘dependency matrix’ applies to extrusion through flat dies. If porthole dies are used both the number of rows and the number of columns increase even further.

	Profile exit velocity uniformity	Profile dimensional tolerance compliance	Profile surface quality	Attainable extrusion speed	Die lifetime
Die geometry	x	x	x	x	x
Profile geometry	x	x	x	x	x
Container diameter	x	x	x	x	x
Billet length	x	x	x	x	x
Aluminium alloy	x	x	x	x	x
Ram speed	x	x	x	x	x
Container temperature	x	x	x	x	x
Die temperature	x	x	x	x	x
Billet preheat temperature	x	x	x	x	x

Figure 2.1 Dependency matrix of input parameters and output criteria

In the output parameters shown, exit velocity uniformity plays a key role. If the uniformity is low, then the adherence to dimensional tolerances and surface quality standards is very likely to suffer as well. The measures needed in the die design to assure exit velocity uniformity can also affect the surface quality, as for example strong bearing length transitions can result in marks on the extruded profile (see section 3.1) [17]. Furthermore, stronger corrective measures usually lead to greater overall flow resistance of the die, thus limiting the maximum attainable extrusion speed and potentially also the lifetime of the die. Therefore, if an input parameter can affect exit flow uniformity it can potentially also influence the other output criteria.

The profile geometry and the die geometry based on it influence where the aluminium will deform and how much resistance it will encounter. The container diameter is a measure of the size of the press and the diameters of the billet and the die. It influences, among other things, the effect of container wall friction on the aluminium flow and therefore the level of flow non-uniformity that needs to be corrected. Billet length has an even stronger effect on the non-uniformity of the aluminium flow towards the die as it influences the area of friction between billet and container [18]. Aluminium alloy composition was shown to influence the extent of flow speed non-uniformity too [18]. Ram speed had a strong effect on the flow non-uniformity in the Extrusion Benchmark 2007 [19] and greatly influences the heat generation in the bearing and therefore potentially affects surface quality and die life [7]. The container, die and billet preheat temperatures govern the ease of deformation of the aluminium and therefore have a strong relationship with the attainable extrusion speed. At temperatures that are too low the deformation requires more pressure from the press and the die is in danger of failure. If temperatures are too high, the surface quality and mechanical properties of the extrudate suffer greatly. Furthermore, the lifetime of the die is negatively affected due to the heat generation in the bearing. As the strain rate of the aluminium is temperature dependent [10] and temperature differences in the deformation zone are dependent on each of the three input temperatures mentioned, exit flow uniformity can also be affected.

In his so called Independence Axiom, Nam Su [20] refers to the column names in figure 2.1 as functional requirements and to the row names as design parameters. His axiom states that for a design process to be optimal, each design parameter must affect only a single functional requirement. This means that only the diagonal of figure 2.1 should be filled with dependencies, which is clearly not the case here. A process where only the area above or below the diagonal is filled with dependencies could still be completely controllable, but this is also not the case here. With only a few possible exceptions, modifying any physical property (design parameter) potentially affects all functional requirements.

To make matters worse the exact nature of the relationships between design parameters and functional requirements is often unknown. For example, Nagao [18] showed the dependence of flow speed non-uniformity on alloy composition, but his data was far too limited to derive a design rule to describe this relationship. Another problem is that design parameters often cannot be fully controlled as the above discussion suggests. The die geometry may differ from what the designer intends due to manufacturing inaccuracies beyond the designer’s control. These may be due to inaccuracies in the machines, operator and set-up errors, or even misinterpretation of the design drawings. The die is also prone to deflection during extrusion, which may negatively influence its function of flow control (see section 3.1). The aluminium alloy composition and the temperature distribution inside the press are variables that are also subject to uncertainty and unintended variation. Other matters that contribute to the complexity of the process are the strain rate, temperature and pressure dependencies of the material properties (both of the aluminium and the die). The die is subject to fatigue and creep behaviour over time [9]. Also not yet mentioned is the human factor; the variations in process conditions due to human involvement. This affects, for example, readiness to respond to problems that could damage the tooling or the extrudate.

2.2 Empirical design rules

The question arises how extruders deal with the staggering complexity outlined above. One of the ways in which they manage is to keep many of the design parameters as constant as possible. They will often work with only a small subset of the available aluminium alloys that are similar in properties. They will have presses of a certain diameter and length, thus restricting the dimensions of the billets. Temperature settings and the ram speed will be kept at their default values as much as possible. It is generally attempted to maximise the adherence to the functional requirements (see figure 2.1) for a given profile section by finding a matching die design. If during the process it is noticed that there is non-uniformity in the exit velocity of the profile, correctors use their experience to make adjustments to the die. Similarly, experienced press operators know how to adjust the ram speed if the surface quality of the extrudate is below standard. Die designers, correctors and operators work on the basis of empirical design rules. Some are explicitly stated, but many exist only in the personnel's heads. Even if design rules are stated explicitly, they very often will work only in the company that they are used. This is because many of the design parameters that have values specific to the company (such as alloy, temperatures, press characteristics, etc.) are implicitly included as constants. As a result design rules are not easily transferable between extrusion companies and often not even between locations of the same company.

A danger of using design rules based on everyday extrusion experience is that they are based on a questionable premise, but still give good results due to the circumstances in which they are used. Nieuwenhuis [21] provides an example of this situation, in which an empirical design rule for the dimensioning of feeder holes in porthole dies was tested by conducting finite element simulations. The empirical design rule, prescribing the relative size of the feeder holes, was based on the shape of the dead metal zones within these feeder holes. The simulations showed that these dead metal zones did not occur at all. However, the feeder hole sizes that the design rule prescribed did in many cases correctly balance the flow. Only when the height of the feeder holes was outside of a certain range of values most commonly used by the extruder, the design rule produce a large error. If, for example, the extruder had decided to increase the thickness of the mandrel (and with that the height of the feeder holes) in order to increase resistance to die deflection, they would have experienced quite unexpected results. Another example where empirically developed beliefs of die designers were shown to be questionable is given in section 2.5.2.

2.3 Extrusion experiments

Extrusion experiments can provide more insights into the relationships between physical variables and functional requirements in the aluminium extrusion process (see figure 2.1). One type of experiment is a parameter study in which the deformation inside the die is considered to be a black box and the relationships between inputs and outputs are investigated. An example of such an experiment is an extrusion benchmark [19] that studies the velocity differences between multiple die cavities that each have different geometries.

More challenging are experiments that aim to take measurements of the flow, because the inside of the die is difficult to reach and any measuring instruments will be subjected to very high temperatures and pressures. The formation and evolution of dead metal zones in the container have been studied by, for example, extruding plasticine billets or by analysing cross sections of (partially extruded) aluminium billets and analysing their microstructure [5, 6, 12].

Both types of experiments require sufficient access to an extrusion press and tooling. Only large extrusion companies will have the luxury of temporarily dedicating a press to scientific research and only a few universities have one. These studies usually identify some relationship between parameters and/or act as a validation of numerical simulations [12, 18, 22, 23]. Actual design rules derived from experiments are very rare in literature. An important reason is that it already takes a lot of effort to produce data about the relationship of a single input parameter (such as profile thickness) to a single output parameter (such as exit velocity). Even if a simple design rule can be derived, such as the bearing length formula by Lee and Im [24], its applicability at other extrusion plants is questionable, because the effect of parameters such as alloy composition and die radius is not included.

2.4 Finite element simulations of extrusion

The low accessibility of doing extrusion experiments on a real press has led many researchers to look for ways to model the process. For modelling aluminium extrusion analytically, methods such as the slip line method and the upper bound method are available [25, 26]. These methods are only possible for very simple geometry and not suitable for most profiles that occur in industrial practice [9]. In recent years the finite element method (FEM) emerged as the most common way to model aluminium extrusion problems. This numerical technique can represent complex geometry as a finite number of elements connected by nodes. Forces and boundary conditions can be applied to the nodes to simulate the forces and constraints exerted onto the geometry. The behaviour of the finite element model is then used as an approximation of the behaviour of the geometry under analysis. The increasing computer power in recent years has enabled the simulation of complex extrusion problems with industrial relevance. A biennial benchmark is held by a group of European researchers in order to test the accuracy of various FEM codes and simulation settings when compared with experiments on a real press [19]. Here is it shown that a combination of appropriate software and skilled engineering analysis can produce simulation results that are very close to these real experiments. However, the benchmark showed large variations in the results of different analysis teams. When predicting the exit speeds of the aluminium at four profile cavities with different geometries in the same die, both quantitative and qualitative errors in the results were observed [27].

FEM simulations can serve several purposes in analysing the extrusion process and optimising die design. They can replace or complement experiments on a real press when it comes to investigating relationships between parameters and investigating the nature of the flow inside the container and die. Simulations offer two important advantages over real experiments. Firstly, some parameters are much easier to measure than in experiments on an extrusion press. For example, dead metal zones are visualised with relative ease. This provides a valuable look into what otherwise often remains a black box. This information can help to offer physical explanations for the relationships between parameters that may be uncovered in the study. The deflection of the die is also very difficult to measure in a real experiment. In a FEM simulation it is fairly straightforward to determine stresses, strains and the deflection of critical areas in the die to great detail. Another important advantage of parameter studies using FEM is that the influence of parameters under investigation can be isolated by eliminating effects over which the researcher normally has limited or no control. For example, if a relationship between bearing length and exit velocity is investigated, a rigid die can be modelled so that the effects of die deflection are kept out of the equation. This is impossible in an experiment at a real press, where some die deflection will always occur, with unknown consequences for the parameter that is measured. Process variations such as temperature fluctuations also do not occur in numerical simulations. In this sense, the lack of realism of FEM simulations can be exploited to uncover relationships between the design parameters and functional requirements in figure 2.1 in a robust way. It therefore becomes easier to derive design rules from these experiments. Due to the elimination of uncontrolled process parameters and variations and the greater insight into the aluminium flow within the container and die, the danger of basing design rules on false premises (see section 2.2) is reduced.

However, it should be noted that any research can address only very small pieces of the dependency matrix (figure 2.1) at a time, and FEM simulations are no exception to that. The design rules that arise from this research are still not often transferable between companies, because too few parameters are included.

FEM can also be used as a validation tool for new die designs or a means to investigate dies that have demonstrated disappointing production results for unknown reasons. This way the performance of the die can be predicted or the causes of poor production results can be found. However, simulations of the complex dies and profiles used in production today still take hours [10, 19, 28]. Some companies have computer capacity to run these simulations while allowing the designer to move on to new designs. In order for this method to work a high degree of software automation is necessary to generate complex finite element models without much user input. This takes a lot of development effort. Furthermore, the company must be willing to wait many hours for a finite element validation of a die design to be completed. This is not compatible with a strategy that reduces the extruder’s time to market. At today’s level of computer power quick and complete analysis of the performance of every new die being designed is not yet feasible, especially for smaller extruders or die makers.

2.5 The approach of the Simalex project

As introduced in chapter 1, the Simalex project is a cooperation between the extrusion company Boalgroup and two groups at the faculty of Engineering Technology at the University of Twente. This cooperation is much older than its current incarnation known as Simalex, as it has existed since 1991. Using FEM techniques that are continuously being refined based on ongoing research, the department of Applied Mechanics has run many simulations to validate and update Boalgroup’s design rules. This has led to very useful insights and new approaches to aluminium flow control using the die geometry. Examples of this will be given in section 2.5.2 and in chapter 3. The chair of Design, Production and Management has sought to apply the new insights provided by the work of Applied Mechanics to the design of new dies. It has done so by developing and implementing design tools for use as part of Boalgroup’s CAD workflow. This thesis continues that work based on the latest FEM insights and aims to expand and improve the available design tools. The results of applying the design rules to dies used in extrusion practice are used to evaluate the validity of these rules.

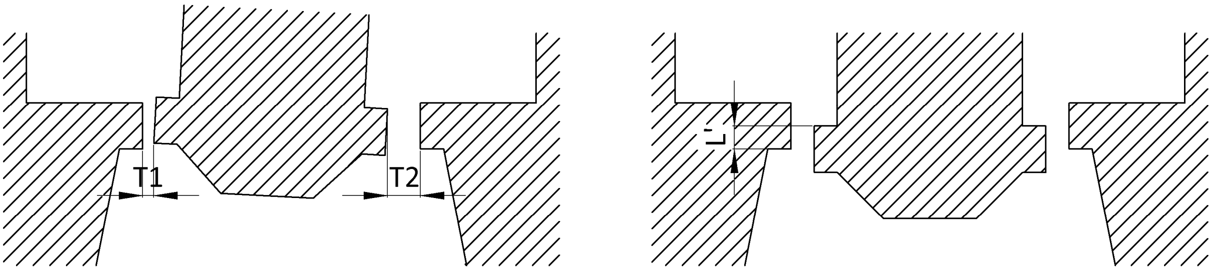
2.5.1 Dealing with the complexity of the extrusion process

When attempting to find formulas that describe the relationship between parameters in the aluminium extrusion process, the sheer number of dependencies and other complexities outlined in section 2.1 is a great obstacle. To deal with this, the project’s focus has been put mainly on the relationships between the die geometry and the output criteria shown in figure 2.1. Within these functional requirements the most emphasis is placed on the quality of the extrudate (exit velocity uniformity, adherence to dimensional tolerances and surface quality). Figure 2.1 may give the impression that die geometry is just a single parameter, but in truth it encompasses many parameters. It is therefore the most complex design variable and it has the largest influence on the exit velocity uniformity of all input variables.

The ‘proving ground’ for the developed design rules in this project has been Boalgroup’s plant in De Lier, The Netherlands. The range of press sizes, alloys and ram speeds is fairly small compared to the aluminium extrusion industry as a whole. This allows Simalex researchers to keep these parameters constant in their simulations without deviating too much from the realistic process conditions. Only when the performance of derived design rules is poor can the influence of these plant and process conditions be investigated further. This is likely to apply in particular when design rules that work well in the De Lier facility are tested in other Boalgroup extrusion plants.

2.5.2 Example of the project's success

The benefits of using finite element simulations in order to gain more insight into the extrusion process and to improve the design of dies can be illustrated by an example. In the design of portholes dies the shapes of feeder holes, legs and the welding chamber (see figure 1.4) work closely together to influence the uniformity of the exit speed of the aluminium, the extrusion force and the product's surface quality. There are some conflicting interests when designing these three features. For example, widening the legs increases the stiffness of the mandrel, but reduces the available space for the feeder holes. A smaller cross-sectional area of the feeder holes increases the necessary extrusion pressure. A greater welding chamber height generally improves the quality of longitudinal welds and therefore the surface quality of the product [29], but reduces the area of attachment between the legs and the core. Failure of porthole dies often occurs due to plastic deformation in the legs [30]. The displacement of the core due to the extrusion force also negatively influences the accuracy of the extrudate, as figure 2.2 illustrates. The core may be displaced laterally and/or longitudinally, changing the width, angle and alignment of the bearings in the mandrel and plate. This can have severe negative effects on the balance of the exit velocity and dimensional accuracy of the extrudate.



(a) (b)

Figure 2.2 The lateral (a) and longitudinal (b) shifting of the core due to deformation of the legs

With the intent of improving the ability to quantify some of the aforementioned effects, researchers at the Applied Mechanics group of the University of Twente used finite element simulations to investigate the influence of various leg shape parameters (shown in figure 2.3) on the extrusion pressure and the stresses occurring inside the legs [30].

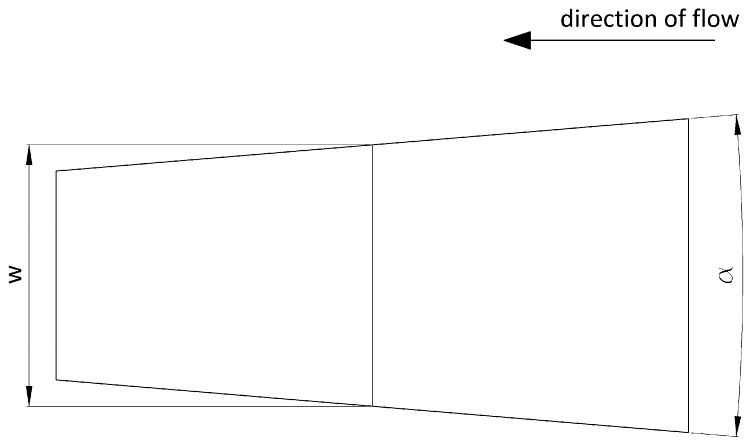


Figure 2.3 Leg shape parameters width *w* and angle *α*

Some remarkable results were obtained. First of all it was found that the increase of the leg width and the consequent reduction of the feeder hole area had a much smaller effect on the extrusion pressure than is commonly believed by die designers. Increasing the leg width from 23 mm to 40 mm only led to a pressure increase at any point in the die of 5% at the most [30]. This means that the strength of the legs can be increased at a relatively low increase in extrusion pressure. The leg angle *α* had almost no influence at all on the average extrusion pressure. Variation of α between -10° and 10° causes an extrusion pressure variation within 1% [30]. It was found that the stresses in the legs are greatest near the welding chamber and that the yield stress of the steel may locally be exceeded. Traditional leg shapes (figure 2.4a) are narrowest at these areas of high stress, because many designers believe that this reduces the resistance to flow. This FEM study showed that this effect is not significant. The insensitivity of the leg angle to the average extrusion pressure therefore inspired the researchers to suggest an alternative ”torpedo” leg shape (figure 2.4b).

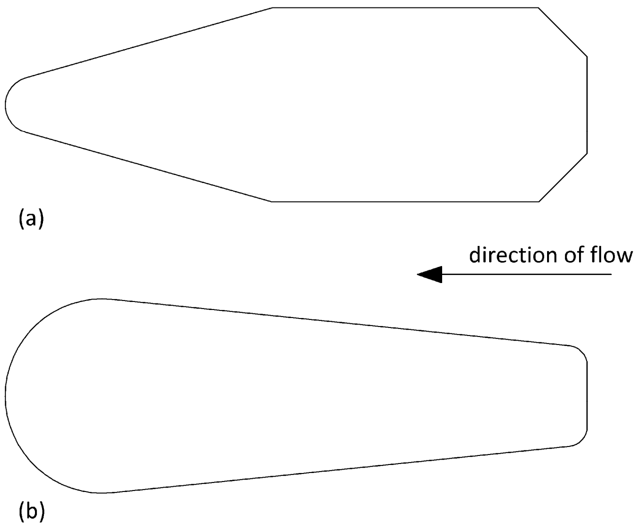


Figure 2.4 Leg shapes; (a) traditional; (b) torpedo shape

This torpedo leg shape offers the most support where the stresses are highest, therefore increasing the support to the core without significantly increasing the extrusion pressure. These leg shapes were also compared in extrusion practice for a circular tube profile. For the dies with traditional leg shapes permanent core displacements between 0.3 and 0.5 mm were measured [30]. No plastic deformation was visible on dies with torpedo shaped legs. This confirms that the torpedo shaped legs provide more support to the core. However, it was found that the height of the welding chamber needed to be slightly larger when using torpedo shaped legs, otherwise the surface quality of the profile would suffer. The impact of the use of torpedo shaped legs on the production results can be illustrated by figure 2.5.

Die repeat number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**1-5**	**6-8**
Production gross (kg)	3811	3596	1155	4625	3323	17719	19296	17771	3302	18262
Production net (kg)	2535	2753	598	2856	1551	13409	14666	13671	2059	13915
Scrap percentage (%)	33	23	48	38	53	24	24	23	38	24
Prod. rate gross (kg/h)	949	1233	1308	1084	968	1193	1249	1580	1108	1340
Prod. rate net (kg/h)	631	944	677	669	452	903	949	1215	675	1022

Figure 2.5 Production results for porthole die repeat orders. Repeats 1-5 use traditional legs and 6-8 use torpedo shaped legs. The rightmost columns show averages for the two leg shapes. Reproduced from [31].

The eight columns in figure 2.5 show the production results of eight repeat dies that were used for the extrusion of round tube. The production for each die is the amount of kilograms of material it produces (gross or net) before it has to be scrapped due to failure or excessive wear. The scrap percentage is the difference between gross and net production. The production rate is a measure of the speed of extrusion. Dies 1 through 5 featured a traditional leg shape (figure 2.4a) and dies 6 through 8 had torpedo shaped legs (figure 2.4b). The production results of the latter are significantly better. The average gross production per die increased by 550%, which indicates that the lifetime of the dies with torpedo shaped legs is much longer. The scrap percentage dropped by 14%. Gross production rate increased with 21% for the dies with torpedo shaped legs and the lower scrap percentage causes an even larger improvement of 51% in the net production rate.

The longer lifetimes of the dies with torpedo shaped legs can be attributed to this design's higher resistance to plastic deformation. This lowers the sensitivity of the legs to fatigue failure, which is a common mode of failure for porthole dies [32]. Lower deformation of the core also increased the accuracy of the produced extrudate, as demonstrated by the lower scrap percentage.

It should be mentioned that the better performing dies also had other new design features that arose from insights gained by the cooperative research between the University of Twente and Boalgroup. New design rules for balancing the flow through the feeder holes were applied and the average bearing length was decreased. These measures are also likely contributors to the success of dies 6 through 8. For example, better flow balancing decreases lateral forces on the core and the shorter bearings decrease the overall resistance of the die to the aluminium flow. The latter is most likely the main cause for the increase in gross production rate.

2.6 The scope of this thesis

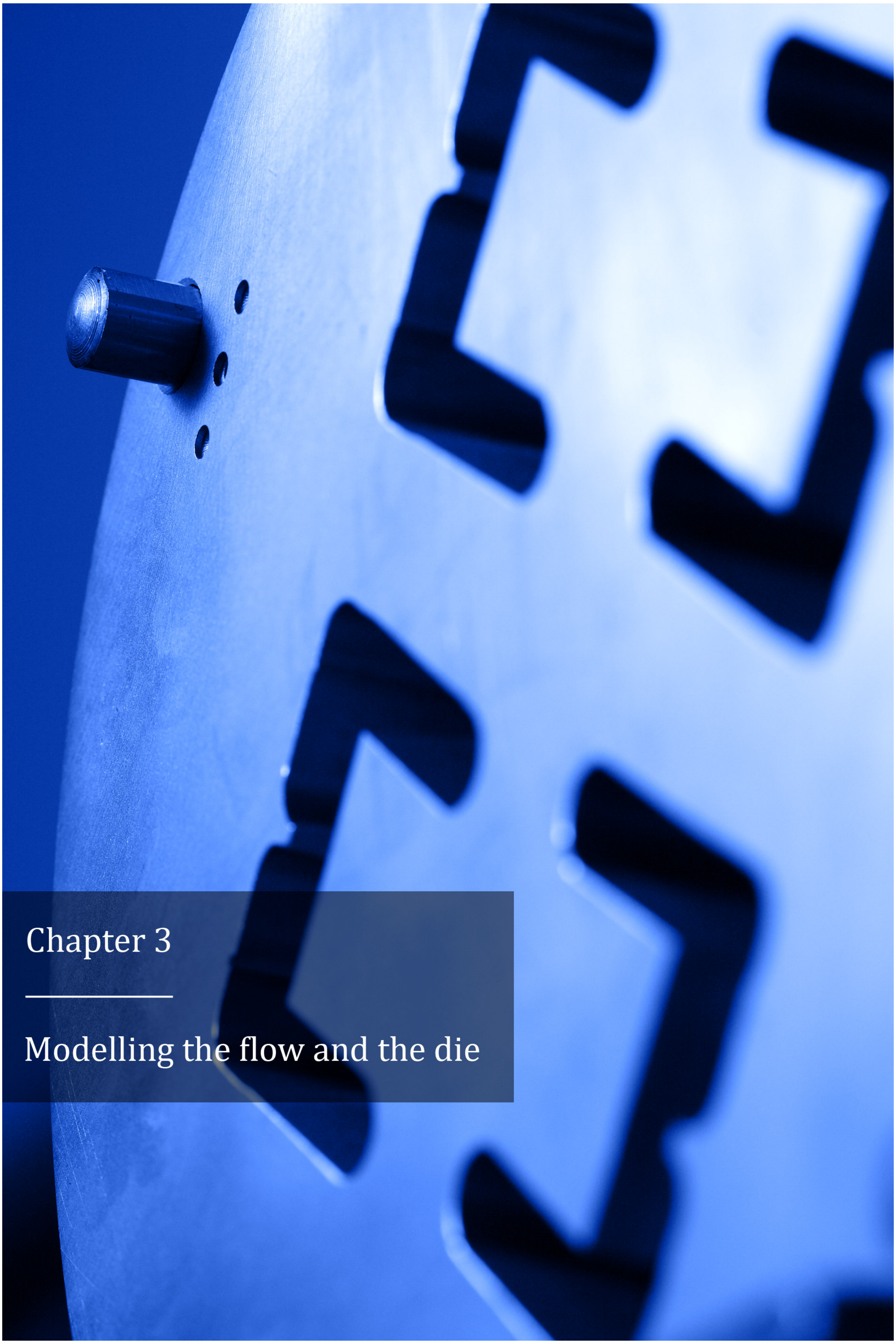
As mentioned in the previous section the Simalex project focuses on a subset of the dependencies that exist within the aluminium extrusion process. This subset is shown in figure 2.6.

	Profile exit velocity uniformity	Profile dimensional tolerance compliance	Profile surface quality	Attainable extrusion speed	Die lifetime
Die geometry	x	x	x	x	x

Figure 2.6 Dependencies covered in this thesis

More emphasis is placed on the quality of the extrudate than on the extrusion speed and die life, because the extrudate quality is more directly related to the level of scrap production. In order to achieve exit velocity uniformity of the aluminium, attention will be given to the effects of varying profile thickness, the container effect and deflection of the die under the extrusion load. The departure point of this research is the insight and the design rules that have been developed by the FEM research of the Applied Mechanics group. This chapter has made clear that, despite the effective approach chosen by the project to derive these design rules, the sheer complexity of the extrusion process remains an issue. The accuracy and the transferability of the design rules are not completely certain. Although not perfect, it is the premise of this thesis that the design rules can still greatly improve die design and help to reduce scrap in a significant way. While existing formulas are used to design new dies, ongoing research can regularly update them to improve their accuracy and transferability.

The die design rules that were derived as part of the Simalex project, covered in more detail in chapter 3, are too labour-intensive to apply to complex extrusion profiles without any computer support to the designer. An important part of this work is therefore concerned with the development of support tools that integrate the design rules into the extruder's CAD workflow. Speed and consistency of this part of the workflow are crucial to the acceptance of the new functionality on the extruder's work floor. Furthermore, the manufacturing of the die is taken into account, such that no unexpected changes need to be made to die geometry that was calculated and constructed based on the design rules.



Chapter 3

Modelling the flow and the die

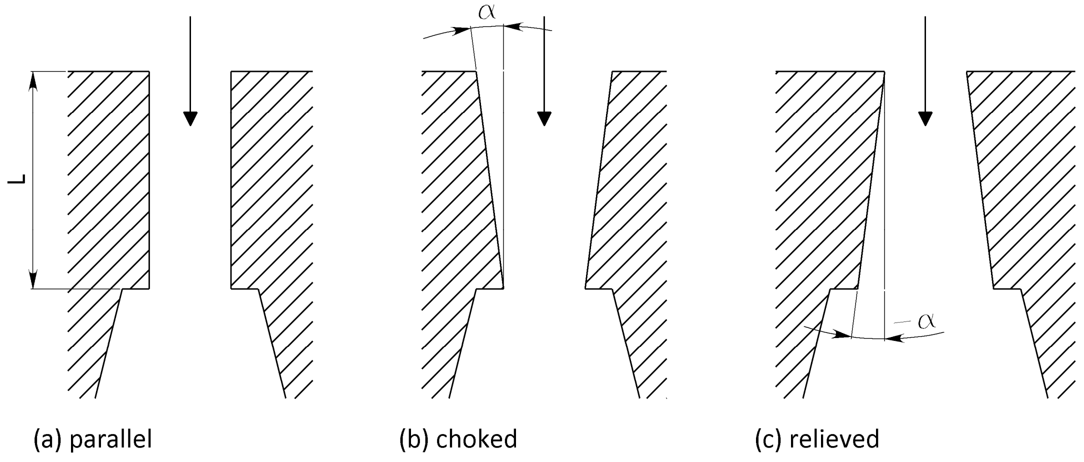
CHAPTER 3: MODELLING THE FLOW AND THE DIE

In the previous chapter it was demonstrated that finite element method simulations that investigate the influences of parameters can provide insights that lead to structural improvements in die design. An example was given regarding the design of porthole dies. The main focus of this thesis is on flat dies, so our attention will now shift to the results of FEM investigations into this type of dies. As explained in chapter 1, the friction between the aluminium and the container results in non-uniformity of the flow of aluminium towards the die. Together with the variation of wall thicknesses of the profiles and the deflection of the die under load this has been identified as one of the major causes for the non-uniformity of the exit velocity of the extrudate in flat dies [1, 33, 34]. To compensate for these sources of fluctuation modifications to the die geometry can be made. This chapter will investigate which of these changes to the geometry result in the best control of the exit velocity and present a finite element based design rule. The effects of die deflection on the flow and how it can be predicted and counteracted will also be addressed.

3.1 Controlling the flow using variable bearing geometry

A method most commonly used by designers to achieve a uniform exit velocity in extrusion dies is the variation of the bearing geometry. Increasing the length of the bearing channel increases the resistance to flow and therefore decreases the exit velocity [24, 33, 34]. Some simple design rules for bearing lengths are found in literature[24, 33]. Aside from the compensation for the container effect that they provide, they state that bearing length should increase linearly with profile width in order to achieve a uniform exit velocity. Lee and Im [24] even acknowledge that a shorter bearing is called for in places where there is a bigger bearing surface slowing down the flow, such as at the ends of legs of the profile.

An angle can also be introduced in part or all of the bearing channel. When a positive angle is introduced the bearing is said to be ‘choked’ and with a negative angle it is ‘relieved’ (figure 3.1).



(a) parallel (b) choked (c) relieved

Figure 3.1 Bearing angles

Bearing angle variations are most commonly used in situations where only a bearing length variation cannot adequately correct the flow speed differences. This is the case when bearing length variations would be required that are not manufacturable or would have such sudden transitions that marks will show up on the extruded profile [17]. Bearing angle variations are also a popular means for correctors at extrusion plants to fine tune a die, because with only a small amount of material removal sections can be sped up or slowed down. The angle variations may also be introduced, by the designer or by the corrector, in anticipation of die deflection. For example, in a situation where the bearings are intended to be parallel, a slight choke may be applied to certain parts of the bearing that are expected to deflect.

3.2 *Sensitivity of bearing parameters*

The sensitivity of bearing angle variations on flow resistance was investigated by Lof [10]. In finite element simulations he varied the bearing angle and expressed the flow resistance as an average inflow pressure. A schematic of the model is shown in figure 3.2. In this series of simulations a round tube of 80 mm in diameter and with a wall thickness of 2 mm was extruded. The average inflow pressure is calculated on an imaginary surface in the aluminium just before the bearing (surface *s*). Temperature variations were not taken into account and a stationary isothermal simulation was executed. An Arbitrary Lagrangian-Eulerian (ALE) formulation was used such that the mesh can only move normal to the surfaces at the outflow end and at the aluminium-die interface. At the latter surface (surface *c*) contact elements were used in order to allow some slipping friction in the bearing area (see appendix B.6). In these simulations the Coulomb friction law is used with μ = 0.5. The ALE description also allows the aluminium to lose contact with the bearing surface. To initiate contact a small back pressure was applied in the reverse extrusion direction. More information about the considerations that have led to this model and other models used for simulations as part of the Simalex project can be found in appendix B.

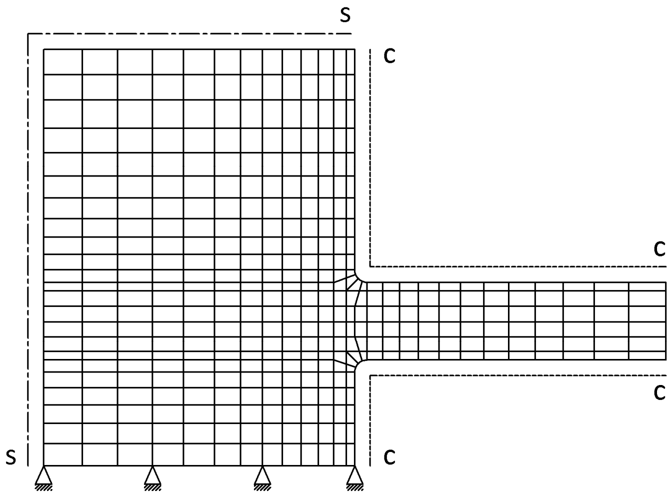


Figure 3.2: FEM mesh for the simulation of the bearing behaviour. Reproduced from [10]

The aluminium was meshed with four node axisymmetrical elements. Reduced integration was applied to prevent volume locking. Because Lof wanted detailed information about stresses and strains within the aluminium in the bearing area, he did not use his equivalent bearing model (see appendix B.7), but applied a fine mesh and a small radius at the bearing channel entrance (the figure shows a coarser mesh for clarity). As initial simulations with a parallel bearing clearly showed that elastic effects have a significant influence on the resistance in the bearing channel, an elasto-viscoplastic material model was used (see appendix B.5).

The results of the bearing angle variation are shown in figure 3.3.

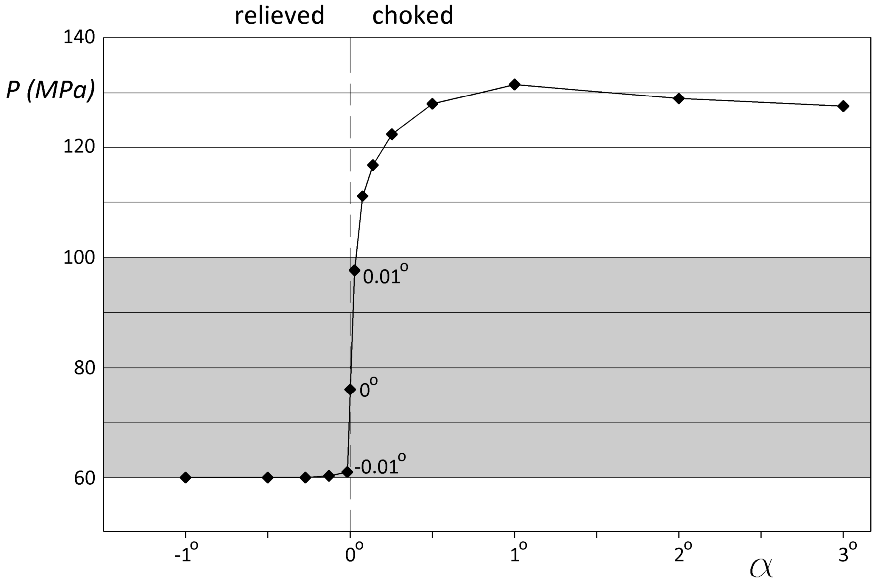
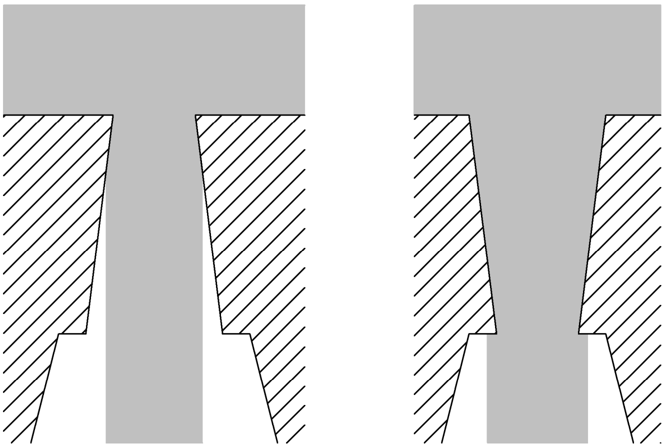


Figure 3.3 Average inflow pressure P versus bearing angle α for a bearing channel 2mm wide and 5 mm long. Reproduced from [10].

It can be seen that a negative bearing angle (the relieved bearing) has a low resistance to flow that remains stable as the negative angle varies. Just before the parallel state the pressure then shoots up, only to stabilise again at a positive bearing angle of around 0.5°. This behaviour can be explained as follows. In a relieved bearing the aluminium only touches the entry of the bearing channel and loses contact immediately after (see figure 3.4a). An increase of the angle, or indeed of the bearing length, is then irrelevant to the resistance to flow. Similarly, a choked bearing forces contact of the aluminium along the entire bearing length (see figure 3.4b). A small variation of the angle at which this full contact occurs will then be relatively insignificant to the flow velocity. Around 0° the transition from almost no contact to full contact takes place. The sudden increase in friction that this generates can be the explanation for the sudden jump in the graph. This behaviour was also observed by Akeret and Strehmel [15] in experiments on a real extrusion press and by the analytical work of Hardouin [35].



(a) relieved (b) choked

Figure 3.4 Contact between the aluminium and relieved and choked bearings

In practice, bearings are usually designed to be parallel. However, this angle may differ slightly due to the manufacturing inaccuracy generally not exceeding 0.05° [1, 36] and deflection of the die under the influence of the extrusion pressure. Given the large amount of flow resistance variation that is possible within this range of angles according to figure 3.3, controlling the exit velocity by varying bearing geometry is an important source of the unpredictability of the extrusion process [1, 10].

If the designer wishes to control the flow by varying only the bearing geometry, the use of sufficiently choked bearings with varying lengths is recommended. This ensures full contact with the aluminium, despite manufacturing inaccuracies and the influence of die deflection. Lof's simulations [10] showed that, in a state of full contact, flow resistance increases predictably with the bearing length. When using relieved bearings, where contact is minimal, the bearing length has little effect on the flow resistance. Therefore, despite the benefits of low overall resistance during extrusion, relieved bearings cannot be used to control the exit velocity. They are only recommended in situations where this control is not necessary. This is the case when the die is perfectly symmetrical and of uniform profile cavity thickness or if there is some way in which the flow can be controlled without using the bearings.

3.3 Controlling the flow using variable sink-in geometry

A possible way to control the exit velocity of the aluminium without altering bearing lengths and angles is the use of a pocket of variable offset before the bearing [37, 38]. This pocket, which will be referred to as a *sink-in* in this thesis, essentially pre-forms the aluminium before it enters the bearing. In doing so, it exerts a pressure on the material that depends on the shape of the pocket. By adjusting this shape according to the expected flow resistance of the different profile sections, the exit velocity of the aluminium can be levelled. It will be shown that this method of flow control is much less sensitive to the effects of die deflection and manufacturing or correction inaccuracies than the method of varying bearing lengths and angles.

In a manner very similar to his investigation of the influence of bearing angle, Lof [38] conducted a study of the influence of sink-in parameters and the profile cavity thickness on the resistance to flow. A short relieved bearing was modelled to ensure a constant low resistance to flow in the bearing. The parameters are indicated in figure 3.5.

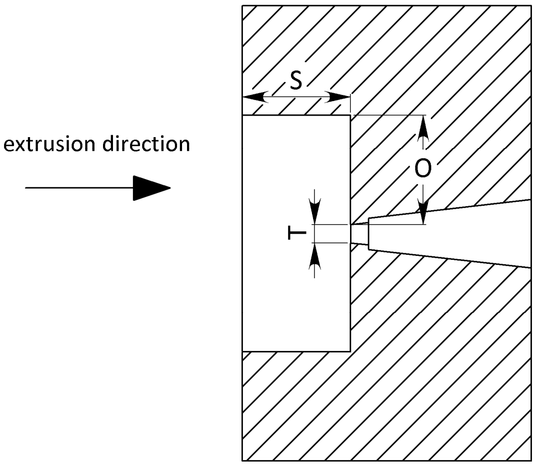


Figure 3.5 The definitions of sink-in depth (*S*), width (*O*) and profile cavity thickness (*T*)

A large number of simulations were run varying thickness *T*, depth *S* and offset *O* and determining the average inflow pressure *P* (see section 3.2 and figure 3.2). The finite element model is similar to that investigating the effect of bearing angle (see section 3.2), which involves stationary isothermal simulations of the AA6063 alloy with an ALE description. Lof complemented this research by investigating the influence of the container effect (the distance of the profile cavity to the centre of the die). He showed that this effect is independent on the variation in cavity thickness *T*. Out of the data the following relationship was found:

$$P(O,R,S,T) = c_1 T^{n_1} + c_2 R^{n_2} + \underbrace{c_3 S T^{n_3} O^{c_4 T^{n_4}}}_{\sin k-in} \tag{3.1}$$

R is the distance of the point on the profile to the centre of the die, measured in the plane of the front face. The constants $c_{1\ldots4}$ and $n_{1\ldots4}$ were fitted to the numerical results.

Not included in this formula are parameters such as billet preheat temperature, die diameter, extrusion ratio, ram speed and bearing length, to name a few. This formula can therefore not be used to reliably determine the average inflow pressure *P* in an absolute sense for any given die and process. Instead, it was intended to evaluate pressure *differences* between points on the profile cavity. The underlying premise is that the exit velocity of the aluminium will be uniform if the inflow pressure is the same for all points on the profile cavity [35, 38]. The points' locations (*R*) and cavity thicknesses (*T*) can introduce a relative pressure difference and the sink-in parameters (*O* and *S*) can be used to remove these differences, while using a fast flowing short and relieved bearing.

It is the most practical to keep the sink-in depth constant and vary only the offset of the sink-in pocket. Varying the sink-in depth makes the pocket or the die as a whole more difficult to manufacture and correct. An example of a flat die for which the flow speed differences were overcome using a variable sink-in offset is shown in figure 3.6. Notice that the sink-in offset (*O*) is larger where the profile cavity thickness (*T*) is smaller and the distance (*R*) is larger.

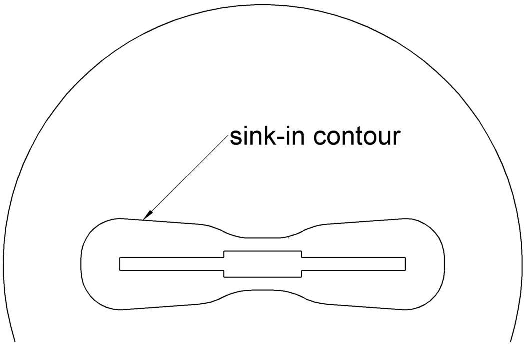


Figure 3.6 Profile cavity with variable sink-in

3.4 Sink-in model evaluation

The main goal of the adaptation of flow control using a variable sink-in is to greatly reduce the instability of the flow speed due to manufacturing or correction inaccuracy or deflection of the die. To this end it is relevant to consider the effect of varying the sink-in parameters on the flow speed. The graph in figure 3.7 shows the relationship between pressure and sink-in offset (*O*) for a profile thickness of 2 mm and a sink-in depth of 10 mm, according to formula 3.1. The shape of the function is very similar for other commonly used profile thicknesses and sink-in depths. It can be seen that apart from the range of very narrow sink-ins, the influence of the offset on the pressure is very smooth and subtle. That means that a small correction to the flow speed can be made using a relatively large change in the geometry, e.g. milling away a part of the sink-in. Note what geometric change corresponds to a 40 MPa pressure difference in figures 3.3 and 3.7 (indicated by the grey areas). In the case of a bearing angle change this can be as little as 0.02°, whereas in the case of a variable sink-in it can correspond to as much as 8 mm. As the sink-in offset becomes far greater than the sink-in depth, its influence on the flow resistance (pressure) starts to diminish to the point where no flow control is possible anymore.

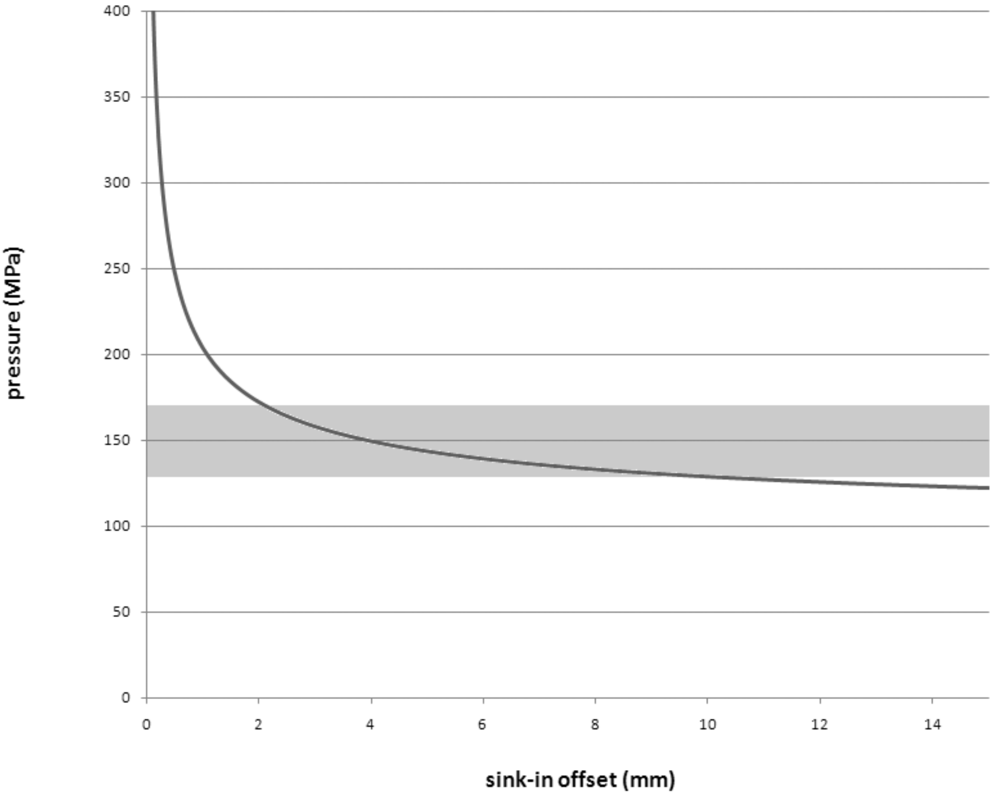


Figure 3.7 Relationship between pressure and sink-in offset for a profile thickness of 2 mm and a sink-in depth of 10 mm.

The reduced sensitivity at large offsets and the increased sensitivity at small offsets can be easily understood. At relatively large offsets, the sink-in pocket will still influence the pressure required for extrusion, due to the increased friction and deformation [39]. However, the exact location of this step is not very relevant, because the wall friction of the sink-in does not directly affect the flow directed through the bearing opening (see figure 3.8 left). At very small offsets the sink-in pocket starts to closely resemble an extra section of the bearing (see figure 3.8 right). Its behaviour toward the flow will then also resemble that of the bearing. The width of that section will have a great influence on the flow resistance and the addition of the sink-in will be equivalent to a drastic elongation of the bearing channel. This observation and explanation is confirmed by a research report by the Alcan extrusion company [40].

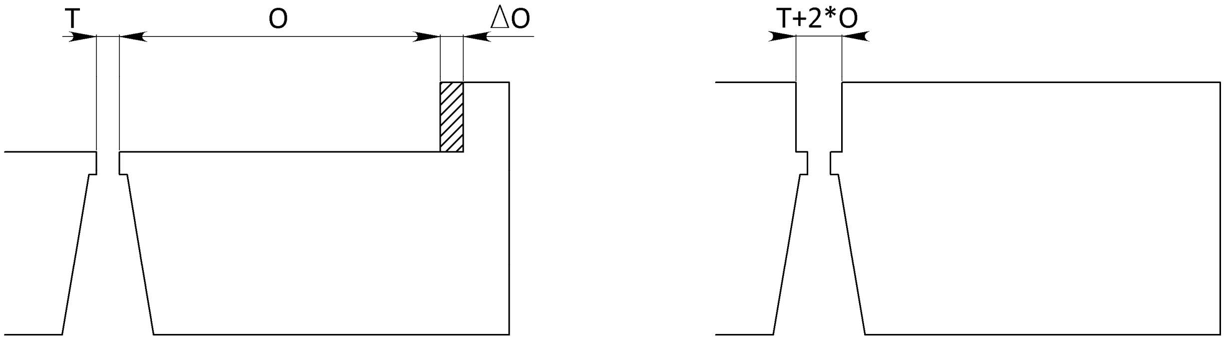


Figure 3.8 Sink-in with a very large offset (left) and a very small offset (right)

Li et al [41] also conducted a FEM study of the effect of sink-ins on the aluminium flow. Instead of expressing the sink-in geometry in terms of depth and offset, they investigated the effect of varying pocket angle and pocket volume. They showed that the flow resistance of the sink-in is strongly related to the sink-in angle (given by the ratio of *S/O*) and almost independent of sink-in volume (the magnitude of *S* and *O*). In other words, the resistance to flow does not change as long as the ratio of *S/O* is constant. This is in very close agreement with the behaviour of Lof's sink-in design rule. Figure 3.7 shows that a sink-in of S = 10 mm and O = 10 mm has a corresponding back pressure of 130 MPa. For the same values of T and R formula 3.1 predicts a pressure of 120 MPa for a 5 by 5 mm sink-in and 110 MPa for a 2.5 by 2.5 mm sink-in.

3.5 Combined flow control with sink-in and bearings

The design rule given by equation 3.1 was used to design a number of flat dies with sink-ins with variable offsets and short relieved bearings. Early production results at Boalgroup were reported to be very good [38], with exit velocities being uniform and extrusion forces low due to the small area of contact in the bearings. This verified that a sink-in with a variable offset, as designed according to formula 3.1, was indeed effective in eliminating exit velocity differences of the aluminium profile. However, there are a number of reasons why it can be beneficial to make use of longer and variable bearings in addition to a variable sink-in. Four reasons will be mentioned here.

- Extrudate surface quality.
- Fine control over metal flow.
- Staying within the sensitivity range of the sink-in.
- Retaining the possibility of die correction using bearings.

3.5.1 Extrudate surface quality

After a using the variable sink-in with short relieved bearings in practice for some time, it was noticed that there were often problems with the surface quality of the extrudate. These problems disappeared when longer parallel bearings were employed, so it was deduced that the relieved bearings were the culprit. Surface quality problems can be caused by imperfections on the bearing surface. These imperfections may already be present on the bearing surface before production and they are very likely to develop during extrusion. Adhesive layers of aluminium form on the bearing surface and are periodically detached from it, leaving a slightly damaged bearing surface behind [7]. This leads to a slow deterioration of the surface over time. The roughness of the bearing surface may further be increased by adhesion of hard particles such as aluminium oxide or foreign objects. These particles cause abrasive damage to the extruded product [7]. The severity of the adhesive and abrasive mechanisms that damage the bearing surface and the extrudate is strongly related to the normal pressure in the bearing [42]. As this normal pressure is particularly small in relieved bearings, the observed deterioration of surface quality can be explained.

3.5.2 Fine control over the aluminium flow

The sink-in contour cannot always follow small details in the profile cavity such as small local bulges or constrictions, because it follows the profile at a certain distance (the offset on either side). This makes it difficult to provide the correct flow resistance to these details using only the sink-in if the profile is complex [39, 51]. This is demonstrated in figure 3.9 where the thick profile section cannot receive the sink-in offset it requires according to the pressure formula.

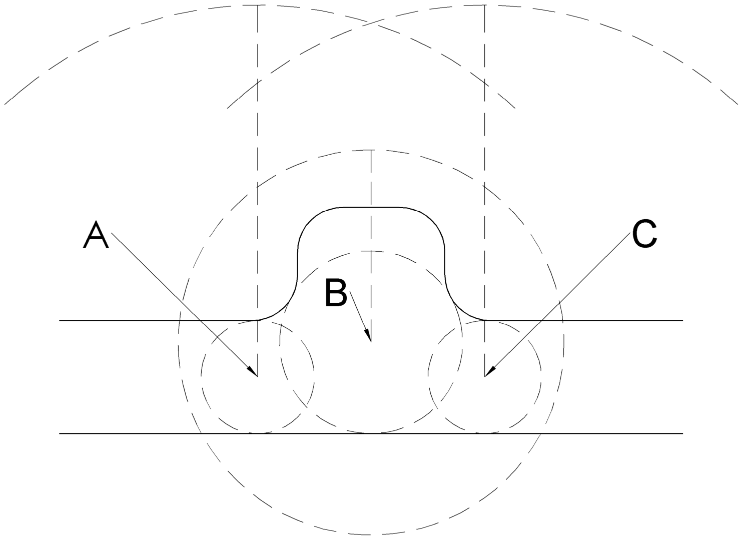


Figure 3.9 Sink-in cannot follow profile detail

The profile is relatively narrow in points A and C (indicated by the inscribed circles), so their required sink-in offsets (indicated by the arcs) are very large compared to the offset required for point B (small circle). Connecting these arcs smoothly whilst still satisfying the required offset for point B is not possible. In general, in sections of the profile where large and sudden thickness transitions are found the demands for sink-in geometry contradict themselves. In these cases the sink-in geometry is constructed in a way that favours the narrower sections. As a result additional measures have to be taken to further decrease the flow speed of the aluminium through the wider sections. The flow speed of the bulbous section can be fully corrected by applying a combination of a slightly narrower sink-in and a longer bearing.

Some die designers make use of multi-stepped sink-ins, where the pocket consists of several depth and offset steps [17, 28, 43]. The deepest step often follows the profile more closely than a single step sink-in would and the separate steps may reduce the interference with surrounding sink-in geometry [43]. It is therefore plausible that this method would offer some more control around the geometric details discussed above. Due to the absence of design rules in literature and FEM simulation data at the University of Twente regarding this type of pocket, it was not investigated further in this thesis.

3.5.3 Staying within the sensitivity range of the sink-in

The shape of the graph in figure 3.7 is similar for realistic values of the profile thickness (0.5 to 5 mm), commonly used die diameters and sink-in depths between 5 and 30 mm. It can be seen that the pressure becomes very sensitive to sink-in offset variation at very small offsets (relative to the sink-in depth) and very insensitive at large offsets. In order to meet space constraints on the die and obtain a level of flow control that is both controllable and effective, these extreme values should be avoided. In other words, there is a certain solution space in which the variable sink-in parameters are a feasible way of controlling the flow. For extreme thickness variations in the profile, additional bearing length variations may be called for.

3.5.4 Die correction using bearings

Although the adjustment of the sink-in offset is a more stable means to correct flow speed differences in the aluminium than the adjustment of bearing geometry, the former method has two disadvantages. Firstly, die correctors are typically unfamiliar with making corrections to the sink-in geometry. If the extrudate quality is below standards, they are used to making small corrections to the bearing length and/or angle and can often quickly achieve the desired result without making any calculations. Secondly, while removing material on the die to increase the sink-in offset can be done quickly, adding material to decrease the offset is much more laborious than adjusting the bearing geometry.

3.5.5 Advantages of combined flow control

Although we have established that the variable sink-in cannot always fully replace bearing geometry variations, there are significant advantages compared to the traditional practice of using only variable bearing geometry. Due to the presence of the variable sink-in, the magnitude of the pressure differences to be overcome by the bearing geometry is much lower. The bearing length differences required will therefore be much smaller. This has the following benefits:

a) The bearing length variation will be much smaller, so less radical length transitions will be required. This greatly improves the manufacturability of the bearing and reduces the risk of die lines.
b) The need for inherently unstable bearing angle variations will be greatly reduced or eliminated, because bearing length variations now are expected to offer sufficient control in combination with the variable sink-in.
c) The average bearing length can be made much smaller due to the reduced need for length variation.

3.5.6 Bearing length formula

In order to combine the use of a sink-in with a bearing length variation, an additional design formula is required. Design rules for bearing length variations can be found in literature, such as those given by Miles [33] and Lee & Im [24] (see also section 3.1). However, these design rules do not take into account the presence of a sink-in that already balances out the flow to a large extent. They also do not use the same average inflow pressure as a measure of flow resistance that the sink-in formula (3.1) does. At the moment of writing this thesis a FEM-based bearing length formula that is compatible with sink-in formula 3.1, or a modified form of such a formula, is not yet available. For the time being, an empirical formula devised by Boalgroup is used.

This formula calculates a bearing length according to a minimum bearing length and an average inflow pressure difference according to formula 3.1.

$$b_i = c_1 \cdot b_{\min} \left(\frac{P_{\max}}{P_i} \right)^{c_2} \tag{3.2}$$

The formula relates the required bearing length for the point under consideration (b_i) with pressure P_i, to the point of maximum pressure P_{max} where the smallest bearing length is chosen (b_{min}). c_1 and c_2 are constants. The pressure difference on which the bearing length variation is based is calculated by the sink-in formula 3.1. This pressure difference may exist when no sink-in is used ($S = O = 0$), the sink-in has a constant offset, or a variable sink-in has a remaining pressure difference.

3.5.7 Bearing angle

It was shown in section 3.1 that the bearing angle, at least in a certain range of values, is also a very important parameter that influences the inflow pressure. In and around the parallel state the contact of the aluminium with the bearing is very unstable and unpredictable. For this reason, this parallel state should be avoided. Relieved bearings offer the lowest flow resistance and hence the greatest production speed. They are suitable in situations when no flow control by the bearings is necessary and surface quality of the extrudate and lifespan of the die are of secondary importance. When (additional) flow control by the bearings is required, however, slightly choked bearings are recommended. The choke angle should be such that full contact with the aluminium is guaranteed, so that the flow resistance is predictable and stable and the influence of bearing imperfections on the surface quality of the extrudate is minimised. However, excessive choke angles, which cause the bearing to take part in the plastic deformation process of the aluminium, should be avoided to minimise the negative impact on production speed [15]. Studies by Lof, Hardouin and Akeret [15, 35, 38] independently show the instability of the flow resistance around a bearing angle of 0°, but do not agree on the precise choke angle at which this behaviour stabilises. This disagreement is most likely due to the different conditions in which these studies were carried out. These were not completely described in the articles. In Akeret's experiment on a real extrusion press the critical choke angle was found to be approximately 0.5°.

3.6 Predicting the consequences of die deflection

When controlling the aluminium flow with a variable sink-in combined with a small length variation of slightly choked bearings, the influence of die deflection is greatly reduced when compared to a situation of flow control using only longer parallel bearings. Angular deflections of the bearing now have a much lower impact on the resistance to flow. However, there are still reasons why the die designer would be interested to know the mode and magnitude of die deflection during the extrusion cycle. Apart from bending of the die as a whole, or 'dishing' [4], there may be areas that are relatively more prone to deflection due to the shape of the profile cavity. An example of this are parts of the die geometry that are referred to as 'tongues' [44]. These are parts with a large surface area relative to their attachment boundary. These tongues have a tendency to bend inwards due to the extrusion pressure. Both of these bending modes contribute to the warping of the profile cavity (see figure 3.10), which may lead to thickness deviations in the finished product and undesired modifications to the bearing angle and the effective bearing length. If the designer can estimate this displacement, corrections to the die cavity can be made beforehand.

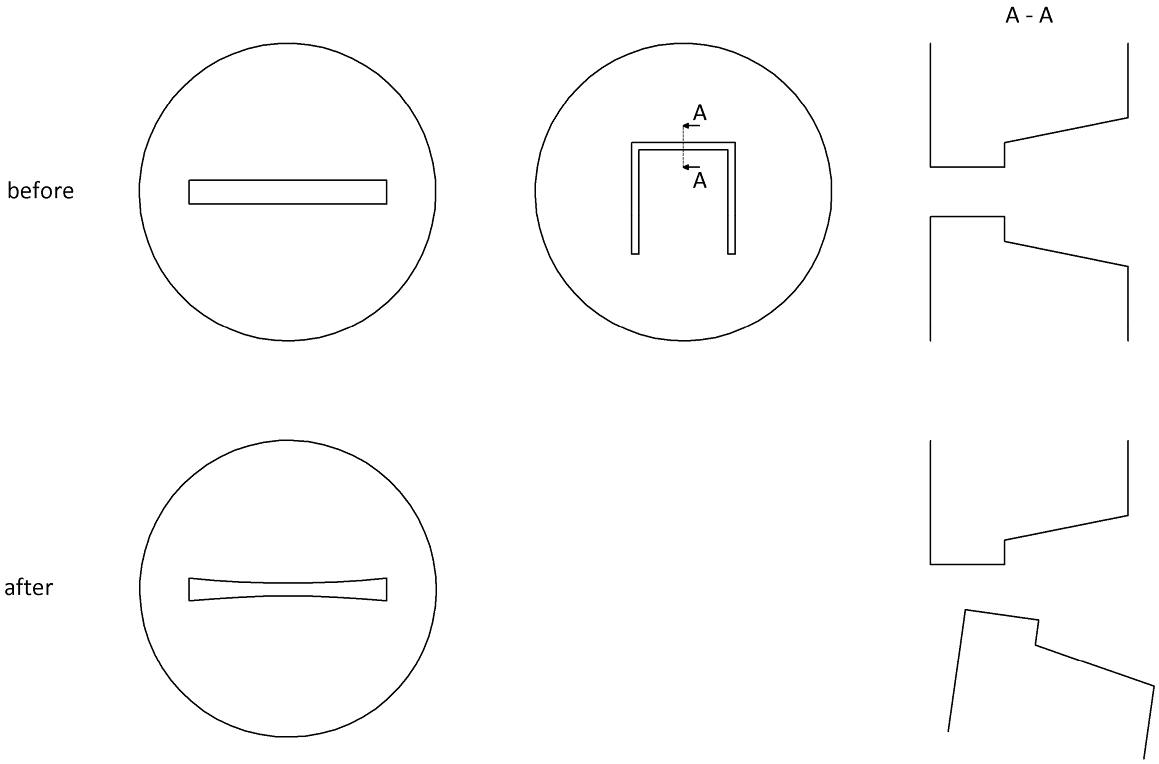


Figure 3.10 Profile warping due to dishing (left) and weak tongues (right)

There are several possible ways to determine the deformation of a die under load. Analytical analysis is not feasible, because it involves complex higher order plate theory where every die design represents a unique problem. Finite element analysis of the aluminium and the die also takes far too long to be a regular part of the die design process. However, in a split approach where the aluminium flow and the deflection of the die are simulated separately [9], it can be noted that the aluminium simulation takes up the majority of the calculation time. Once the forces acting on the die are known and a 3D model of the die exists, a calculation of the die deformation can be done within seconds.

In order to bypass the lengthy aluminium flow simulation, a study was made to derive a formula for the pressure on the die [45]. The stresses that are responsible for the bending of the die can be decomposed into two types; stresses normal to the die surface and those tangential to the die surface. The most important normal stress occurs on the die face as a result of the extrusion force exerted by the ram. The tangential stress that could play a role in die deflection is the friction or shear in the bearing and on the front face of the die. The relative influence of these stresses on the deflection of the die was investigated by running simple 2D FEM simulations of the extrusion of a round bar of 20 mm in diameter, as shown in figure 3.11. Extrusion ratio, bearing length (*L*) and the clearance of a rigid backer (*b*) were varied and the deflection of a point on the bearing (A) for each of these types of stresses was evaluated separately. The die diameter is 200 mm.

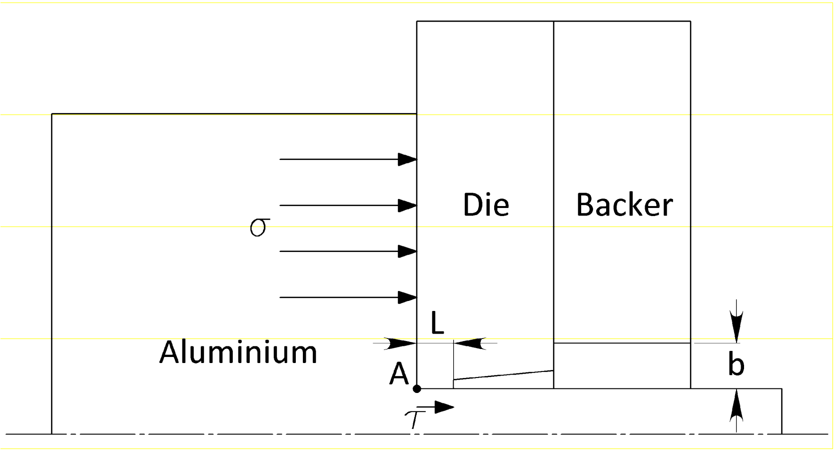


Figure 3.11 Model used for FEM simulations investigating the relative influences of normal and shear pressures on the force on the die

The results of this analysis showed that the influence of the normal pressure exceeds that of the shear force in the bearing, which is also acknowledged by Akeret [15]. Extrusion ratio and bearing length had little influence on the percentage of deflection due to shear, which constituted about 15% of the total deflection for realistic values of backer clearance. For this reason, as a simplification of the model, only the normal pressure on the die face is considered and this pressure is increased by a factor of 1.18 to take into account the shear forces in the bearing [45].

The normal pressure on the die face was investigated further. The distribution of this pressure across the die face is fairly uniform, but pressure dips occur in the vicinity of die cavities. Figure 3.12 shows this behaviour for a die with three circular cavities (one at 0 mm and two at 54 mm from the centre of the die), an extrusion ratio of 25 and a bearing length of 2 mm. The peak pressure was found to be dependent on extrusion ratio and die radius. For commonly used die radii and extrusion ratios at Boalgroup, a formula was derived that mimics this behaviour [45]:

$$P = \frac{c_1\sqrt{ER}}{1+e^{c_2\left(\frac{R_{die}}{ER}-x\right)}} \tag{3.3}$$

where ER = extrusion ratio

R_{die}= radius of the die

x = smallest distance to a point on the profile cavity

c_1, c_2 = constants

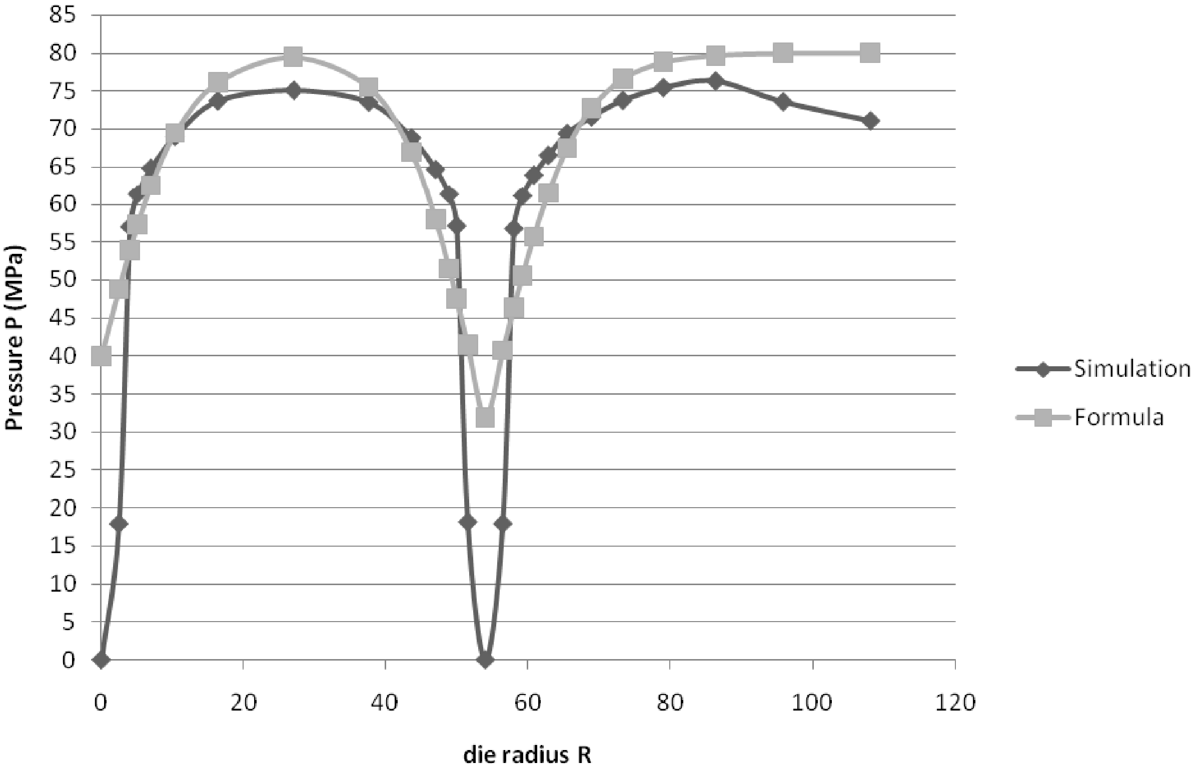


Figure 3.12 Normal pressure on the front face of a die, according to a FEM simulation and the derived formula.

The die and process parameters determine the nominal pressure, whereas distance *x* determines the pressure variation due to the proximity of a cavity. The value of *x* is the shortest distance of the point on the die face for which the pressure is calculated, to the middle of the profile cavity, as illustrated in figure 3.13. Only the distance to the nearest cavity is measured.

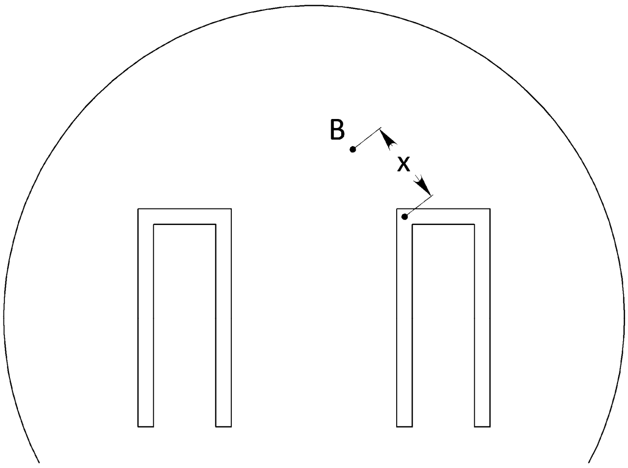


Figure 3.13 The meaning of parameter *x*

In this study only the AA6063 alloy was considered and a ram speed of 9 mm/s was used. The influences of ram speed and bearing length and angle on the nominal pressure require further research.

The formula was validated in a 3D situation by comparing the results of two simulations [45]. In the first simulation the forces on the nodes were determined from a separate simulation of the aluminium flow through the die. The second simulation utilises forces that were calculated by formula 3.3, thus eliminating the separate and time-consuming aluminium simulation. The resulting displacements in the extrusion direction are shown in figure 3.14. It can be seen that the formula slightly overestimates the displacements, which is also visible in figure 3.12. However, right near the edges of the bearing, of which the deflection is of most interest to the die designer, the displacement falls within the same range.

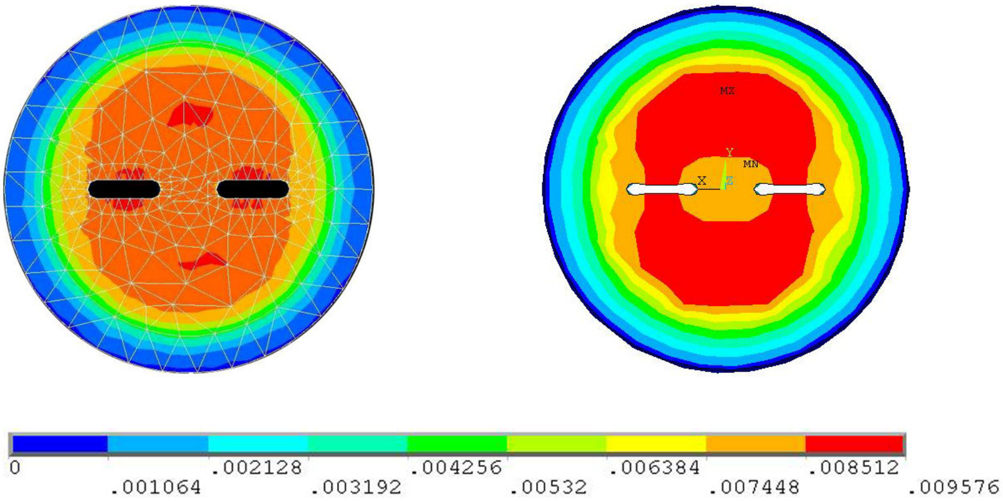


Figure 3.14 Deflection calculations (in the extrusion direction, in mm) with forces calculated by a separate FEM simulation (left) and with formula 3.3 (right).

In a practical application of the method a 3D model of the die must be available before the deformation can be calculated using the formula. This would need to be constructed from a 2D drawing, which is often the format in which the flat die design is represented. The 3D model then needs to be meshed and boundary conditions must be applied. The pressures found using formula 3.3 should be applied to some of the nodes of the finite element model as forces, for which calculations are necessary. Next, the FEM simulation of the die can be carried out. In order to evaluate the displacements in the bearing area, the relevant data needs to be extracted from the results. This will allow the determination of bearing angle variations, changes to the effective bearing length and changes in the profile cavity thickness. These tasks would require a lot of effort from the designer, so this method can only be a feasible part of the design process if a large degree of automation is realised. Chapter 4 will discuss this development.

3.7 Conclusion

This chapter showed that the use of parallel bearings in the die design is an important cause of the unpredictability of the exit velocity of the aluminium extrusion process. The reason is the high sensitivity of the flow speed to deviations in the bearing angle. Manufacturing and correction inaccuracy or deflection of the die can cause changes to this bearing angle that drastically alter the contact between the bearing and the aluminium. A sink-in with variable offset was shown, in theory, to be an effective means of controlling the flow that drastically reduces the need to use bearing geometry for this purpose. For maximum productivity, short relieved bearings may be used. However, this comes at the cost of reduced surface quality and die life. Another problem is that the bearings cannot be used for additional fine tuning of the flow speed in this case. If the bearing length is used for additional flow control, full contact with the aluminium must be ensured. This can be achieved by applying a small choke angle on the bearing, which will make sure that contact is sustained even under slight deflection of the die. A formula was derived that determines the pressure on the die, so that the die deflection and its influence on the shape of the bearing area can be estimated by a relatively quick FEM calculation.

Further development and implementation is necessary before the tools for the creation of sink-in and bearing geometry and for deflection diagnosis can be made operational as part of the die design CAD workflow. The next chapter will discuss this further.

Chapter 4

Implementation of die design support tools

CHAPTER 4: IMPLEMENTATION OF DIE DESIGN SUPPORT TOOLS

In chapter 3 two key results were presented. It was shown that the shape of a sink-in that controls the exit velocity of the aluminium can be calculated. Furthermore a formula was presented that predicts the pressure acting on the die. These formulae and design rules can only become useful to the die designer if they can be integrated into the design workflow as quick and easy-to-use tools. This chapter will discuss the transformation of the models presented in the previous chapter to integrated design tools.

The application of the sink-in formula (formula 3.1) requires the profile to be analysed for thicknesses and distances to the centre of the die. The calculated sink-in parameters then need to be translated to a fluent and manufacturable sink-in contour. The development and implementation of this process is covered in sections 4.2 to 4.12. The formula estimating the pressure on the die also requires many supporting operations before it can effectively be used to visualise the effects of die deflection on the bearing area. This development and implementation is discussed in section 4.13.

4.1 The benefit of automation

The application of the design rules and formulae described in chapter 3 to the design of flat extrusion dies can be very time-consuming. Formula 3.1 can be used to balance the exit speed of the aluminium by compensating variations in profile cavity thickness (T) and distance to the centre of the die (R) by variations in sink-in offsets (O) at a sink-in depth S. In everyday extrusion profiles, values of T and R can vary strongly, so they need to be determined at numerous locations on the profile in order to be able to calculate an appropriate variable sink-in. Furthermore, there may be multiple profile cavities in the die for which the values of R are not the same. Unique sink-in offsets need to be calculated for all of these locations. As explained in section 3.5, additional bearing length variations may be required to be calculated using formula 3.2. Much valuable time can be saved by providing computer support for a large part of this process. It is also expected that automation can improve the consistency of the decisions made during the design process. The implementation of the automated generation of sink-in and bearing geometry for flat extrusion dies will be covered in sections 4.2 to 4.12. The acceleration of the die design process enables the designer to make use of additional tools that enhance the die design, such as the die deflection diagnosis tool introduced in section 3.6.

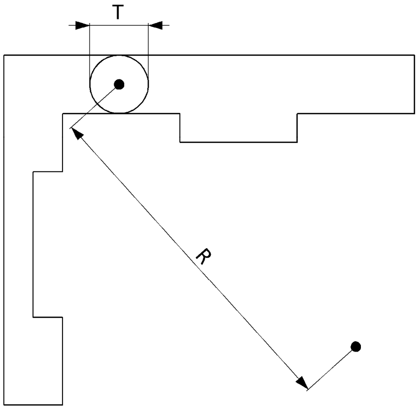
In order to take advantage of the die deflection diagnosis method, a long list of actions is required. Even though the normal pressure on the die can be calculated without a time-consuming aluminium flow simulation, the model of the die to which this pressure is applied needs to be constructed. In many cases, the bending of the die will not be symmetrical, so it cannot be represented as a 2D problem. A 3D computer model of the die must be made. This model needs to be represented as a mesh of finite elements in various densities.

Boundary conditions must be applied to the nodes of this mesh. For example, each node on the front face of the die receives an appropriate force that is representative of the normal pressure at that location (calculated using formula 3.3). After the FEM simulation is completed, the results in the bearing area of the die have to be interpreted. Compared to the current situation at Boalgroup and other die designers, this deflection analysis is an extra activity in the design process. In order for this method to be considered valuable and find extensive use, it must come at a minimum delay to the design process. This is achieved by automating a large number of the abovementioned activities. The implementation that allows this process to be completed in mere minutes is discussed in section 4.13.

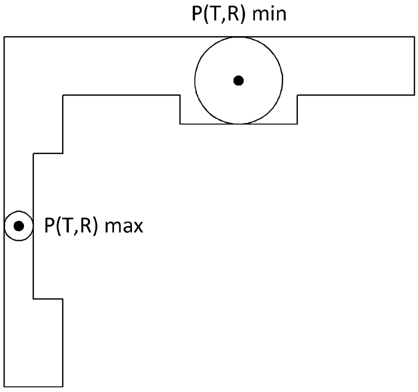
4.2 Creation of variable sink-in geometry

A sink-in can be used to balance the exit speed of the extrudate by using a variable offset (O) at a certain depth (S) to compensate for variations in profile cavity thickness (*T*) and distance to the centre of the die (*R*) according to formula 3.1. The sequence of operations to determine the sink-in geometry on the basis of a 2D boundary representation of the profile is given below. The upscaling of the profile geometry and its positioning on the die are not covered, as these are already standard operations of the die designer.

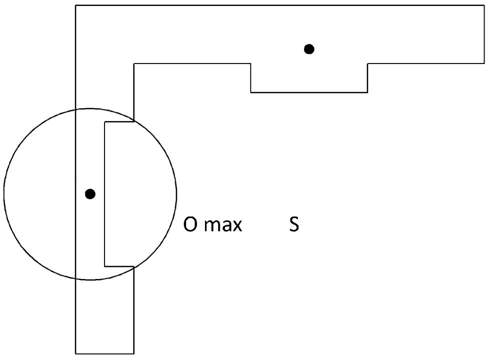
1. Determination of the values of *T* and *R* for all points on the profile. These variables are the input parameters of the sink-in formula 3.1.



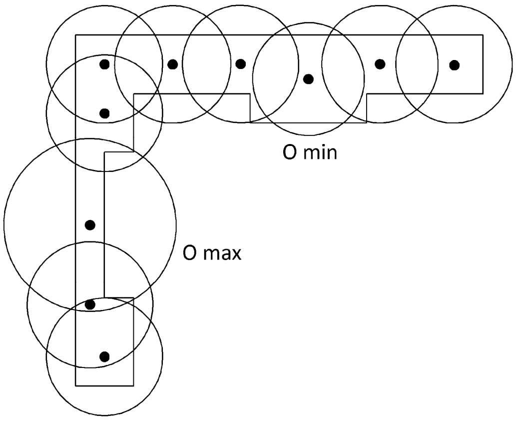
2. Determination of the points with the highest and lowest pressures *P*(*T,R*) if no sink-in is present ($S = O = 0$). At these locations the sink-in will have the largest and smallest offset, O_{max} and O_{min}, respectively.



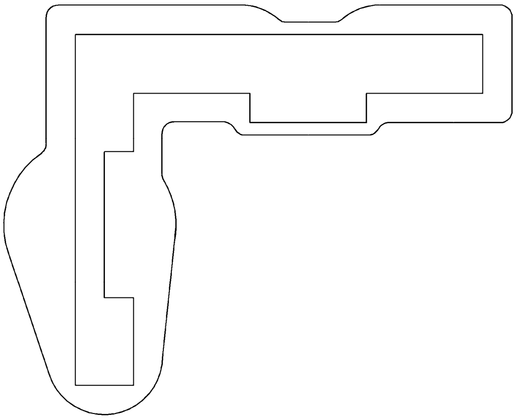
3. Specification of two of the three unknowns (O_{max}, O_{min} and S) by the designer. Given the requirement that the pressure needs to be equal at both extreme points found under *2.*, the pressure $P(T,R,O,S)$ can now be calculated. If O_{max} and O_{min} are both specified, it may occur that pressure equalisation is not possible for any value of S. In this case the designer must provide alternative values for O.



4. The offsets are calculated for all other points on the profile. They will have values in between those of O_{max} and O_{min}.



5. A sink-in contour is drawn in such a way that the offsets for all points are satisfied.



It will be made clear in the following sections that this procedure needs to be expanded in a few areas or situations. These include the use of additional flow control using variable bearing lengths and the issue of manufacturability of the sink-in contour. The complete process will then be presented in section 4.11.

4.3 The medial axis transform

The procedure of obtaining values of *T* and *R* for many different points on the profile cavity, represented as a boundary shape in 2D CAD, can be automated. Both in 2D and 3D CAD programs several methods for representing geometry are available, such as the boundary representation and constructive solid geometry (CSG). The boundary representation describes geometry by defining the boundaries of geometrical entities (such as points, edges, planes and surfaces) and the relationships between them. For development purposes the boundary representation is very well suited for the extraction of data. However, the boundary representation does not include all the information that is needed for the calculation of the variable sink-in. For example, the definition of the local thickness of the profile cavity is missing. A suitable method for the (automated) extraction of thickness information from a boundary representation of a shape is the medial axis transform [13, 46, 47]. This skeletal line through the middle of the profile uniquely defines the local thickness at each point by a radius function. The radii correspond to the maximum circles that can be drawn on the points of the medial axis. Figure 4.1 clarifies this for a simple shape.

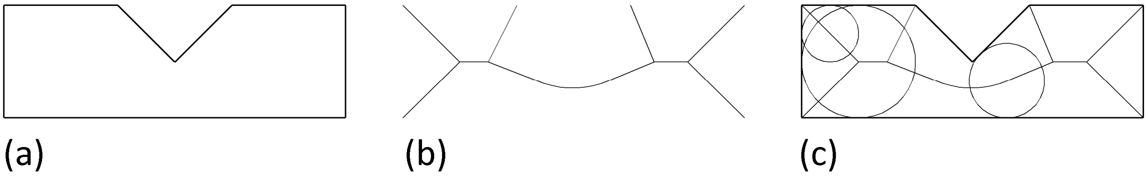


Figure 4.1 (a) Boundary representation, (b) the medial axis and (c) the medial axis with some maximum circles. Reproduced from [1].

The medial axis transform of a boundary shape can be found by traversing the boundary, drawing an imaginary perpendicular line into the shape and finding the maximum circle on that line that touches the point of departure and at least one other point on the boundary [1]. Figure 4.2 shows the medial axis as determined for a typical extrusion profile.

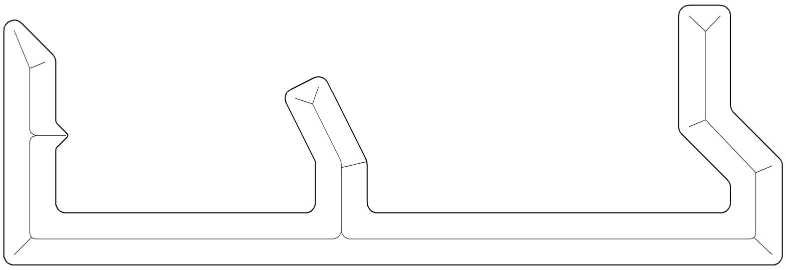


Figure 4.2 An example of a profile with its medial axis

At end points the medial axis either touches a sharp corner or a complete circular arc on the boundary. Branch points are formed where the maximum circle has more than two touch points on the boundary. Other points have maximum circles that touch exactly two points on the boundary.

4.4 Drawing the sink-in contour

A discrete version of the medial axis transform was chosen to be implemented. This means that the axis consists of a series of separate points instead of being a continuous curve. The reason is that it is not always possible to calculate a continuous sink-in offset function by substituting continuous functions of *T* and *R* into formula 3.1. The discrete form of the medial axis representation ensures the validity of the geometry and with that the robustness of the method [1].

The sink-in offset is defined as half the sink-in width minus half the profile cavity thickness, as was illustrated in figure 3.5. From the offsets that are calculated from the set of medial axis points a sink-in contour must be constructed. Just as the medial axis points are the origins of the maximum discs that can be drawn inside the profile cavity, they are the origins of circles representing the offsets of the sink-in. If such a circle is drawn for every medial axis point, a rough outline of the sink-in contour becomes visible, as shown in figure 4.3.

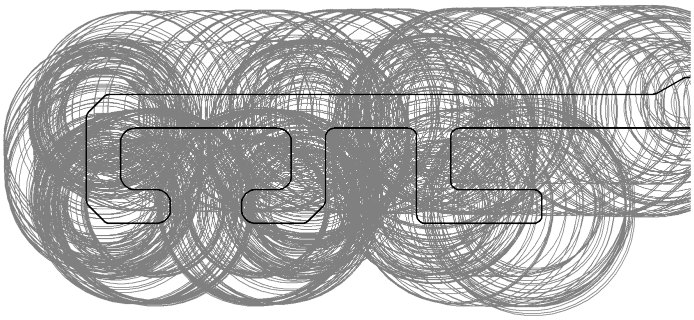


Figure 4.3 Offset circles forming an outer contour

If the outer boundary of these circles would simply be connected, scallops will result on the contour, no matter how fine the resolution of medial axis points is chosen. Scallops complicate the geometry while providing no benefit to the flow control function of the sink-in, thus they unnecessarily hinder the manufacturing process. To minimise this scallop formation a slightly different approach is chosen. Instead of connecting circles, offset points are constructed and connected by lines and/or arcs. These offset points are found as shown in figure 4.4. If the circle belonging to an offset point is swallowed by another circle on the outer boundary, as is the case for point C, the offset point is projected onto this outer circle. This provides extra resolution for connecting the contour smoothly.

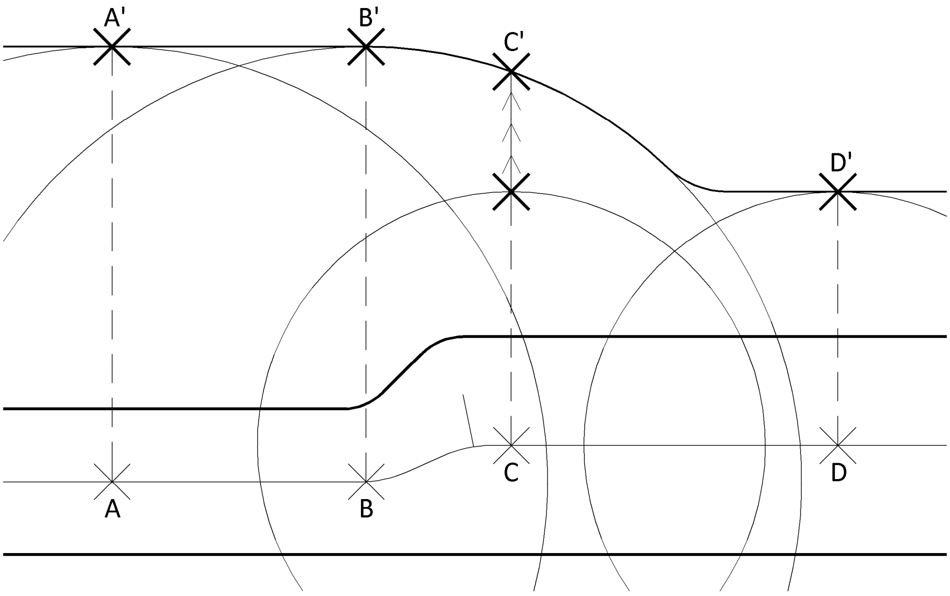


Figure 4.4 Drawing the sink-in contour. For clarity only a few medial axis points and circles are depicted

The offset points (A’, B’, C’ and D’ in figure 4.4) are connected by lines and arcs to form the sink-in contour. The choice for lines or arcs as connectors is made by looking at the relationships between the offset circles that belong to the points considered. If, for example, the offset points share an offset circle (such as B’ and C’), an arc is chosen for a connector. If they lie on separate circles and the radii of these circles are parallel (such as A’ and B’) the connection will be made using a line. Some more complex situations are also handled by the software. For example, it covers instances where an offset circle is swallowed by another circle belonging to a different profile section. Mechanisms to prevent the sink-in contour from intersecting itself and the profile boundary are also included.

4.5 *Filtering to include only relevant circles*

The medial axis transform defines the local thickness of the profile unambiguously. However, its definition of thickness can differ from that which is intended by formula 3.1. The medial axis transform includes maximum discs (‘thicknesses’) that are located on side branches. These maximum discs are therefore not always representative of the local profile cavity thickness [51]. Figure 4.5 shows two of these cases. At sharp corners, when no fillet is present, the maximum disc will even be zero.

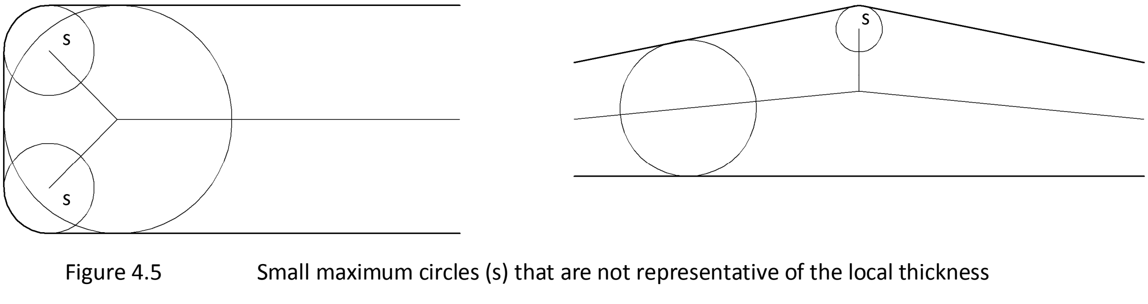


Figure 4.5 Small maximum circles (s) that are not representative of the local thickness

If these (infinitely) small circles were to be included in the variable sink-in calculation process, they would be interpreted as very narrow profile sections with a high resistance to the aluminium flow. As a consequence the formula would prescribe very large (or infinite) sink-in offsets at these locations. This would result in huge bulges in the sink-in geometry, as demonstrated in figure 4.6. Unless corrective measures are taken, small and insignificant details have very large consequences for the resulting sink-in geometry.

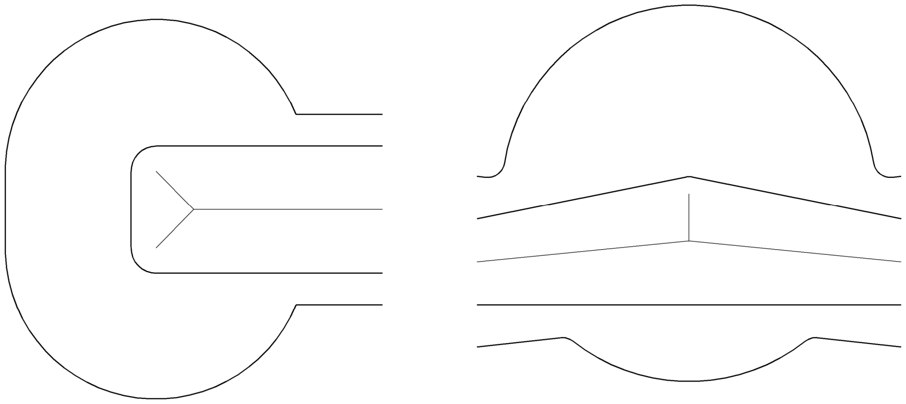


Figure 4.6 Bulges in sink-in geometry that result from the inclusion of small radii

Only the circles that define the local thickness of the profile should be included in the calculation and the rest should be ignored. Identification of the branches of the medial axis whose maximum circles should be ignored is a fairly easy task for a human designer. However, this manual identification is time-consuming and open to individual interpretation. For the sake of the repeatability of die design, identification criteria are needed that are as unambiguous as possible. These have the additional benefit that they can be handled by algorithms for the creation of geometry. The following identification criteria of circles to be ignored were found to cover the vast majority of cases.

a) The circle lies on an end point branch of the medial axis. An end point branch is defined as a branch that contains an end point. An end point has a maximum circle that touches the boundary in only one contiguous set of points [1, 46, 47]. In figure 4.5 the end point branches are the small branches that end in a point (s) whose circle is coincident with a single arc on the boundary. The maximum circles on the medial axis branch in figure 4.7a are fully representative of the local thickness and therefore should not be excluded from the calculation, even though the branch contains an end point.

AND

b) The end point branch does not represent a nearly parallel profile section. For nearly parallel sections the rate of change in maximum circle diameter is small as the end point branch is traversed. This often means that these circles are relevant to the sink-in calculation and must not be ignored. End points can be associated with points (for sharp angles in the boundary geometry) or arcs (for fillets). Nearly parallel sections will be defined as sections for which the angle on the boundary is smaller than 25°.[2] Figure 4.7 illustrates.

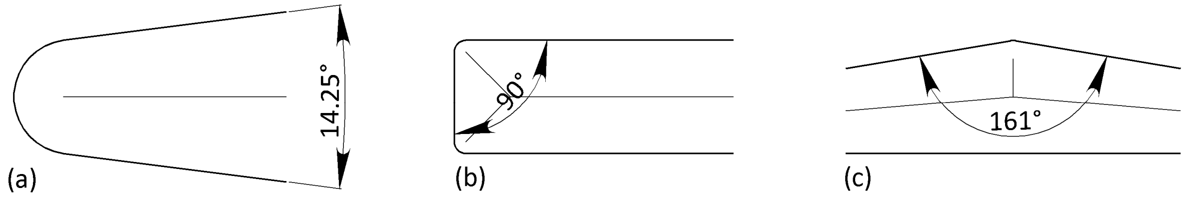


Figure 4.7 End point branches of nearly parallel sections that must be included (a) and branches that will be ignored (b and c)

AND

c) The end point branch is small compared to the overall dimensions of the profile. This criterion makes sure that very small nearly parallel sections that were not ignored based on the previous criterion are ignored still. An example of this is the semi-circular protrusion on the profile shown in figure 4.8. Due to its small scale this branch is only a small detail with little impact on the flow speed. It should not be identified as a profile branch.

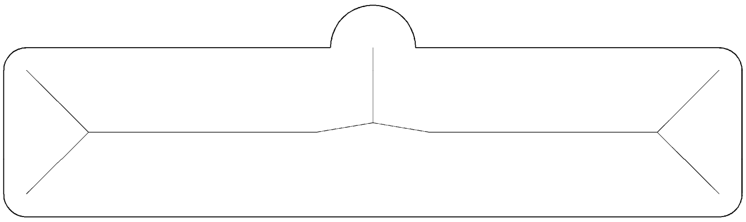


Figure 4.8 An end point branch that is not ignored based on its angle, but on its scale

Although the small maximum circles associated with some end point branches are ignored based on the above criteria, the branches themselves have to remain part of the sink-in calculation. The sink-in contour is constructed on the basis of offset points that originate from the medial axis. If the end point branches were neglected completely, then important offset points would be missing. This would e.g. result in the sink-in shown in figure 4.9a, which is much too narrow around the corners. The solution is to assign the offset of the branch point B to the circles of the points E (and to all the points that lie in between). This results in a sink-in that does not 'cut the corners', as shown in figure 4.9b.

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[2] This number is an arbitrarily chosen system constant that can be tuned by the designer for optimal results. A filtering criterion of 25° worked well for the extrusion profiles on which the software was tested. A company producing a different kind of profiles may want to choose a different value to make the filter match the designer's intent.

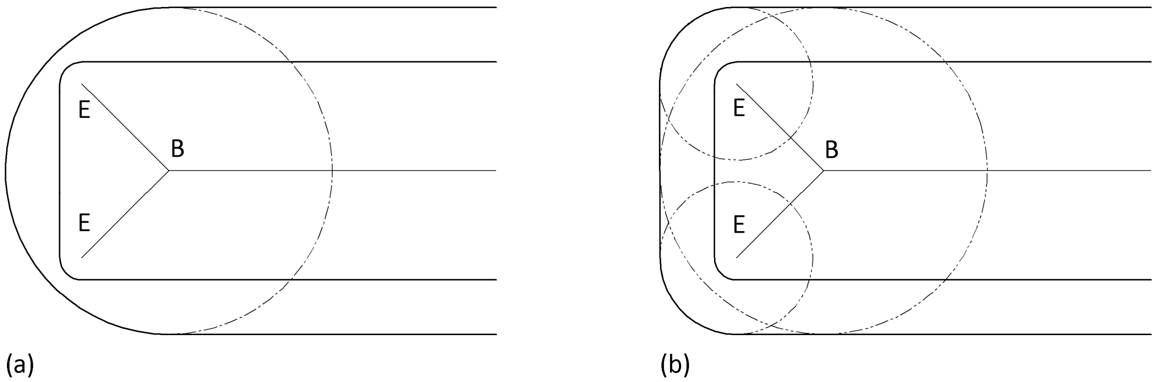

Figure 4.9 End point branches are assigned the offsets of the branch point B to obtain a sink-in contour (b) that does not cut corners as in (a).

One of the most pronounced cases of small details that add many branches and small circles to the medial axis are so called ID tags. These small features on the profile boundary are intended to identify the extruder that made the profile. They usually take the shape of a small series of saw teeth on the boundary (see figure 4.10). Their influence on the flow (if any) is very localised, but their impact on the shape of the medial axis is enormous. Instead of filtering for the end point branches that result from the ID tags, it was therefore decided to ignore this geometry altogether. When traversing the boundary to construct the medial axis a feature recognition algorithm is used to detect ID tags. These ID tags are then replaced by a straight boundary.

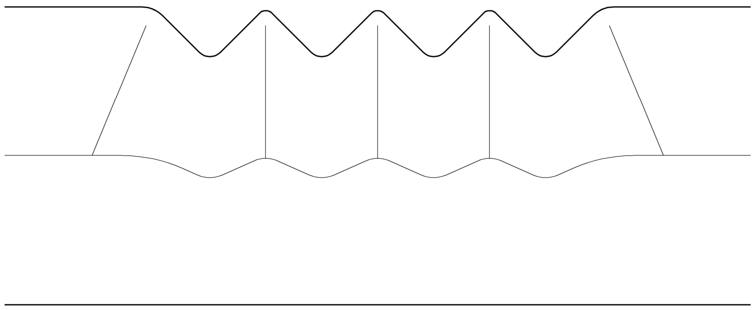

Figure 4.10 An ID tag and its impact on the medial axis

The impact of the above described measures on the operation of the die design software tool is illustrated by figure 4.11 below. The radii of the small circles in the corners are ignored, but the circles are used for the construction of a sink-in contour that does not cut the corner. The notch in the profile shape is successfully identified as an ID tag and the medial axis (and consequently the sink-in) is drawn as if it was not there.

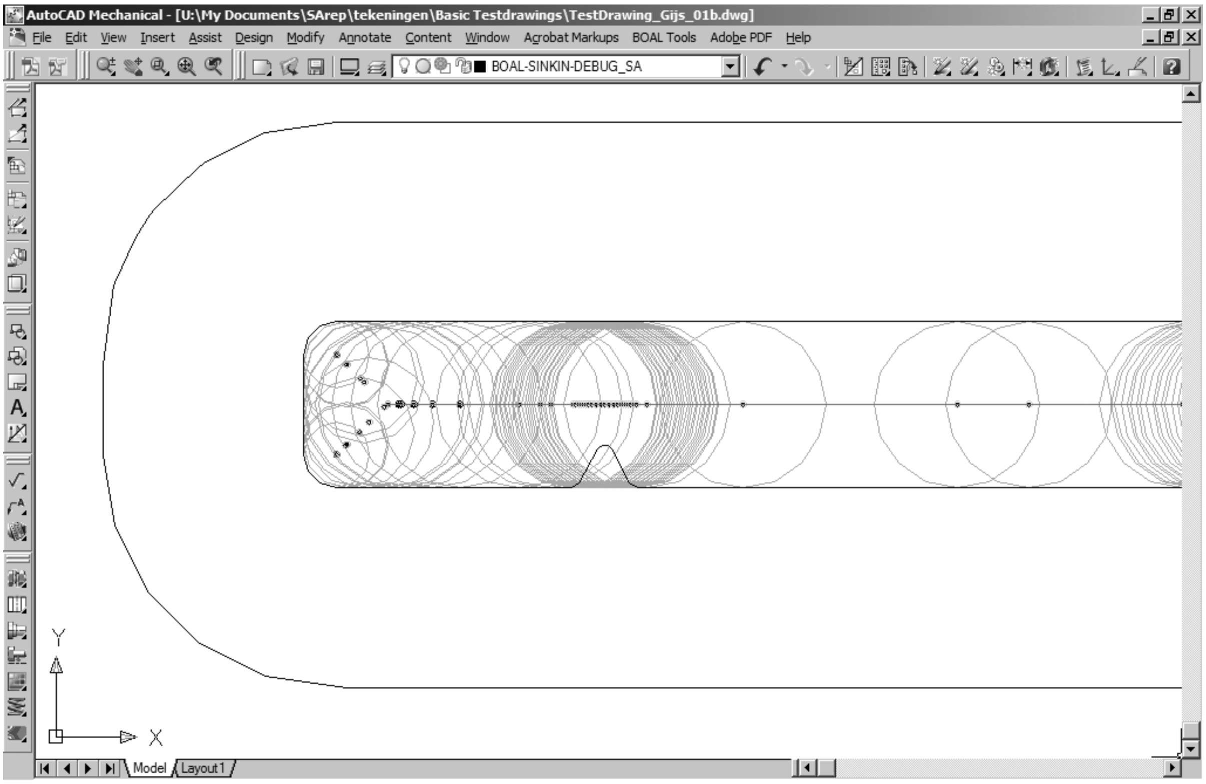

Figure 4.11 Dealing with small circles and ID tags

4.6 Special treatment for leg tips

At the tips of legs of the profile cavity shape the aluminium flow meets more bearing surface than in a straight section. The resulting extra friction is not modelled in the sink-in formula (3.1), which expresses flow resistance (without a sink-in) only as a function of the thickness *T* and the distance to the centre *R*. To compensate for this the formula needs to be overridden. Lee and Im, when faced with the same problem in their design rule for calculation of bearing lengths, added a factor to their formula that shortens the bearing length near leg tips [24]. Boalgroup adapts the same practice, but in some cases they also locally elongate the sink-in to enhance the feed of leg tip sections. Whichever method is chosen, leg tips must be identifiable by the computer support tool so that the desired measures can be taken automatically.

Leg tips are not entirely the same as the end points discussed in the previous section. Not all end points occur at leg tips. Leg tips can occur at branch points, or at end points that do not require filtering for irrelevant circles. Figure 4.12 shows some examples of end points and leg tip points.

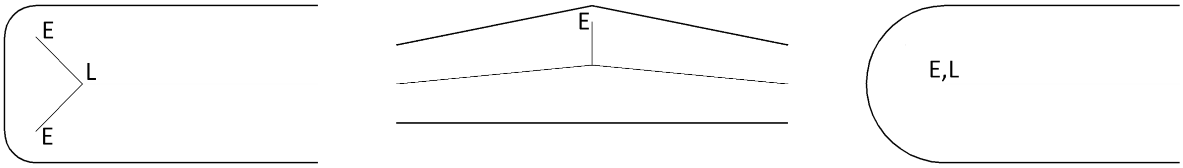

Figure 4.12 End points (E) and leg tip points (L)

For extrusion profiles occurring in practice, leg tip points can be uniquely identified by the following logical statement.

IF **[** { *point is an end point* } OR {*one or more end point branches are connected to the point*} **]**
AND **[** *no more than one non-end point branch is connected to the point* **]**
THEN **[** *point is a leg tip point* **]**

If compensation for the extra friction associated with a leg tip is desired, one method is to locally elongate the sink-in. To do this, a copy of the leg tip point and its offset circle is made and it is moved in the direction of the tip. The sink-in contour will thus be extended, as shown in figure 4.13a. Compensation by locally decreasing the bearing length requires the determination of the length of the profile over which the shortening is to be carried out. Good results were obtained in practice by shortening the bearing along a length equal to the width of the leg tip, as indicated by the dashed lines in figure 4.13b. Formally, in a procedure suitable for implementation, this boundary is found as follows. On the medial axis branch on which the leg tip point is located, the medial axis points enclosed by the leg tip point's maximum circle are found. The required boundary is then found as the geometry that is touched by the maximum circles of these medial axis points, plus the geometry in between.

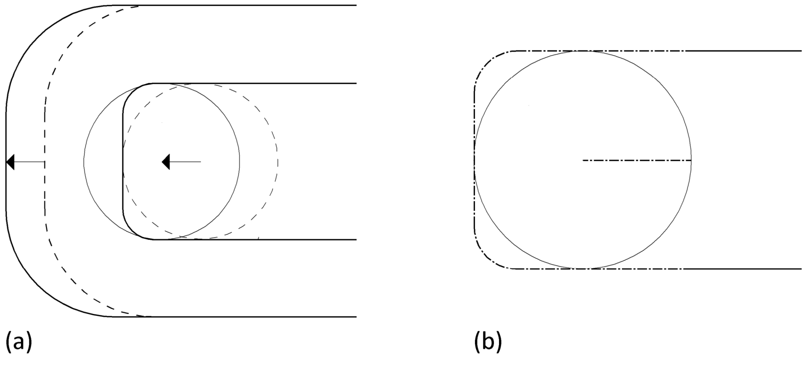
(a) (b)

Figure 4.13 Measures to deal with extra friction at leg tips: (a) extension of sink-in, (b) local shortening of bearing.

Insufficient practical results were obtained to determine which of the two methods of compensation is the most effective. The local shortening of the bearing was implemented due to its successful application in die design practice. Further research is needed to determine whether there are situations where one method is better than the other or that a combination of methods is to be preferred.

4.7 Special treatment for junctions

Another special case exists in which the size of the maximum discs in the profile cavity is not proportional to the exit velocity of the aluminium. In junctions in the profile cavity, as shown in figure 4.14, the presence of fillets will make it possible to draw a larger circle (B) than in the adjacent sections (A). Due to this locally larger opening, the design approach discussed here would predict a higher exit velocity at B. However, in extrusion practice it is found that in many such cases no flow correction is necessary and the exit speed of the profile is equal for sections A and B. Two possible explanations for this phenomenon can be given. The aluminium flowing through circle B has a mechanical connection to the aluminium flowing through the adjacent sections. In combination with the action of the puller that guides the extrudate along a straight line at the same speed, this localised non-uniformity may be equalised [15]. Another possibility is that the extra wall friction at the junction cancels out the reduced resistance to flow due to the greater opening.

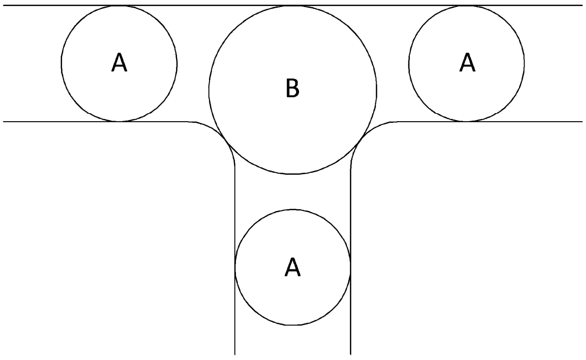

Figure 4.14 A larger maximum disc (B) at a filleted junction in the profile cavity

The phenomenon described here calls for a filtering action similar to the ones discussed in sections 4.5 and 4.6. This filter would make sure that the greater circles at junctions would not yield smaller sink-in offsets or longer bearing lengths than their neighbouring sections. This functionality has not been implemented in the software yet. The created sink-in and/or bearing geometry around junctions can be edited manually. However, to accommodate the introduction of the die design software into Boalgroup’s daily operation, a function was implemented that automates manual edits to the bearing geometry in these areas. By picking the appropriate menu option and dragging a box around the junction in the profile cavity with the mouse, the bearing lengths at the junction are made equal to those of the straight sections around it. This sequence is shown in figures 4.15 through 4.17. The numbers indicate the bearing lengths assigned to the corresponding profile sections.

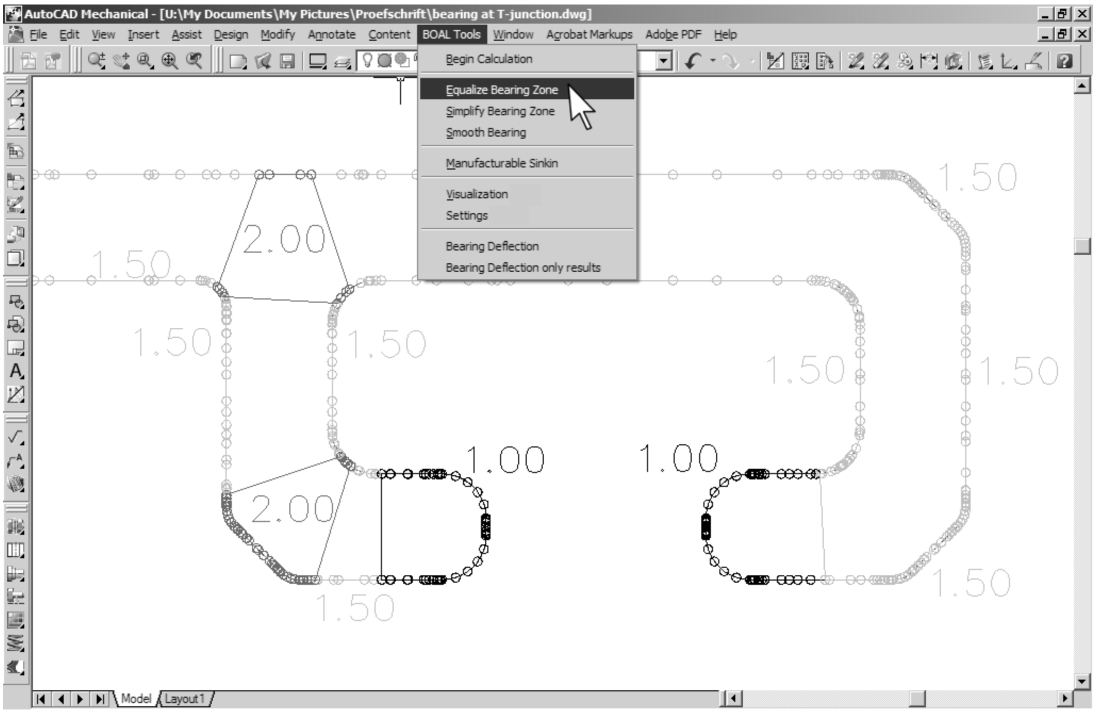

Figure 4.15 Picking the *Equalise Bearing Zone* menu option

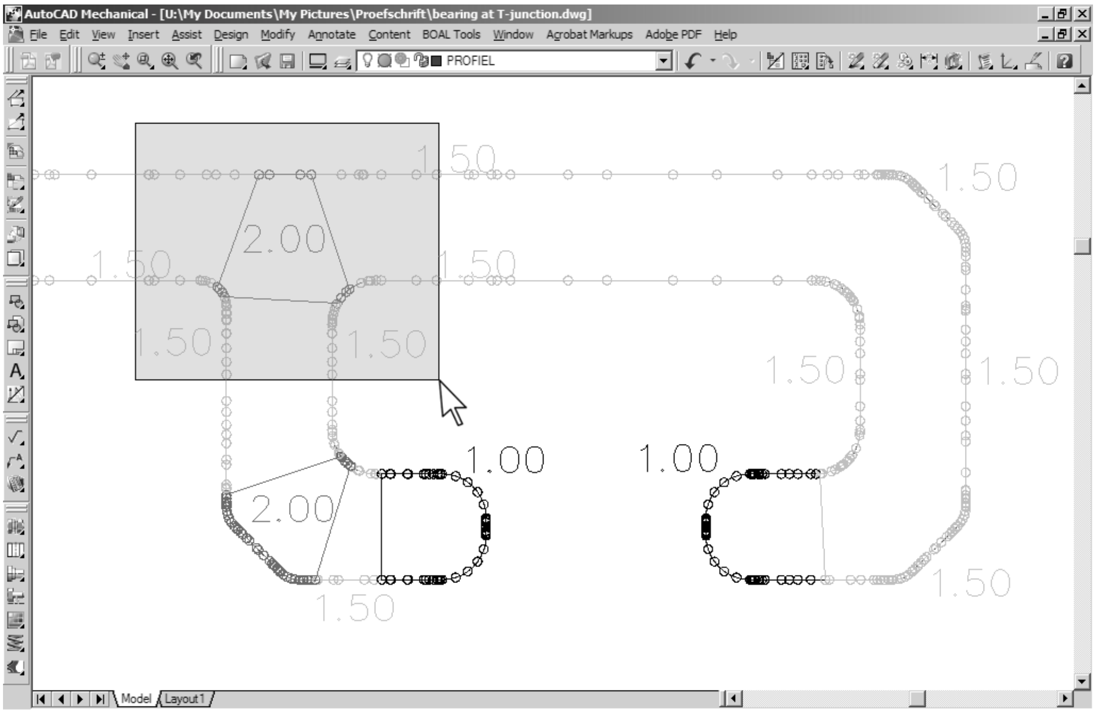

Figure 4.16 Dragging a box around the junction for which bearing lengths are to be levelled

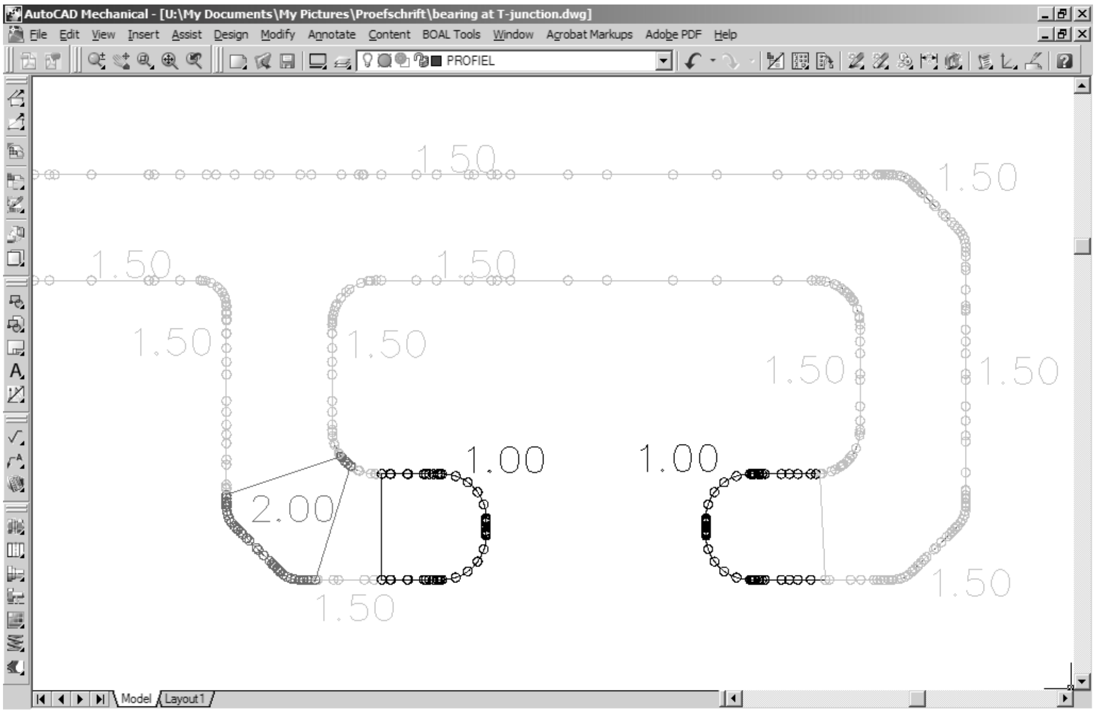

Figure 4.17 Result of the *Equalise Bearing Zone* function

4.8 Bearing length variation

A bearing length variation is beneficial as an additional means of flow control in the following situations:

- When the profile exhibits small and sudden thickness transitions and the sink-in provides insufficient flow control due to enclosed circles (see section 3.5.2).
- Where the sink-in parameters would be considered extreme and the sink-in behaviour is expected to be too sensitive or too insensitive to the flow (see section 3.5.3).
- To compensate for the extra friction of leg tips, if this is not done by locally extending the sink-in (see section 4.6).
- If the designer chooses to use a sink-in that is only partially variable, of constant offset or entirely absent.

Many modern extrusion profiles are of such complexity that the first situation almost always occurs somewhere on the profile. Some offset circles are completely enclosed by others and the outer circles are used for the construction of the sink-in contour. The points on the medial axis whose circles are enclosed are thus fed more aluminium than they require. This pressure difference is determined by noting how much the offset has to be extended in order for it to touch the sink-in contour (and match the offset of the neighbouring enclosing circle). This offset difference can be translated to a pressure difference using formula 3.1. To express the pressure difference as a bearing length difference the bearing length formula 3.2 is used (see section 3.5).

The developed die design application has an option to constrain the sink-in offsets between two extreme values specified by the user. For instance, this may be used to create a variable sink-in that is no wider than 7 mm and no narrower than 2 mm. This can be desirable if the available space for a sink-in is limited or to avoid areas of excessive (in)sensitivity of the sink-in contour. The use of this option could mean that the sink-in cannot balance the pressures completely and that some areas may need a longer bearing. This can be calculated using formula 3.2.

The final situation in which the bearing length may be changed is when dealing with leg tips, as discussed in section 4.6. The bearing is shortened slightly at these locations to compensate for the added friction. The distance over which this is done is the same as the local profile cavity width (see figure 4.13). The bearing length of these sections is obtained by multiplying their nominal bearing length with a factor of 0.7, an empirically determined value which has given good results at Boalgroup.

Bearing length variations are traditionally applied in a step-like manner. That is, instead of calculating and specifying a different bearing length for every point on the profile, according to the point's parameters, the profile is divided into zones of constant bearing length. In the transition between these zones, the bearing length makes a jump, typically no smaller than 0.5 mm (figure 4.18).

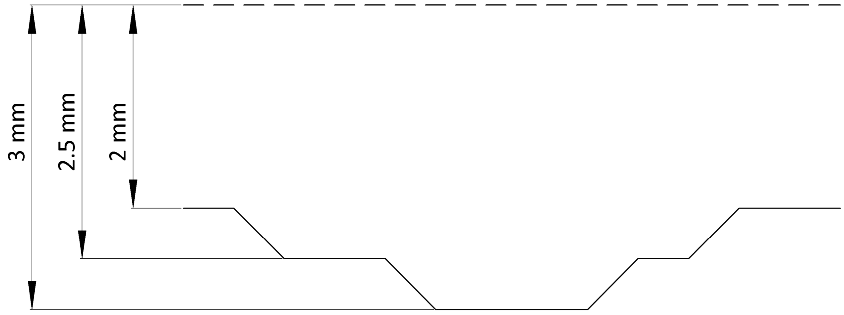

Figure 4.18 Bearing lengths implemented in steps of 0.5 mm

The reason for this practice is that in the traditional setting with no computer support available to the die designer, there was only time to manually calculate bearing lengths at a limited number of locations. In addition, numerically controlled machines that are used to produce bearing length transitions are still often programmed by hand, making it too labour-intensive to utilise a smooth function. If software is available at die manufacturers to automate the programming of NC machines, it is often tailored to working with discrete bearing length steps. These programs are commonly locally developed extensions of commercially available CAD software that support the drawing of 2.5D transitions between bearing length steps. With the bearing length calculation method presented in this thesis there is no need to work with bearing length steps to save time. The bearing length variation can be calculated and drawn as a smooth function. However, if such a design would be sent to a die manufacturer they would need significant changes to their software and workflow to accommodate to this new way of working. These changes are not easily imposed upon a die manufacturer by a single customer. Therefore, in order to ensure the immediate applicability of the software into design practice, the length steps are supported. This is done by rounding the calculated bearing length values to the nearest 0.5 mm (or another value, depending on the step size specified). The resulting visualisation of the various bearing length steps in a 2D drawing is shown in figure 4.19. The asymmetry in the results is due to the decentralised location of the profile on the die face. Figure 4.20 demonstrates that the drawing is no longer flat like the original profile drawing. The bearing length transitions are visualised in 3D.

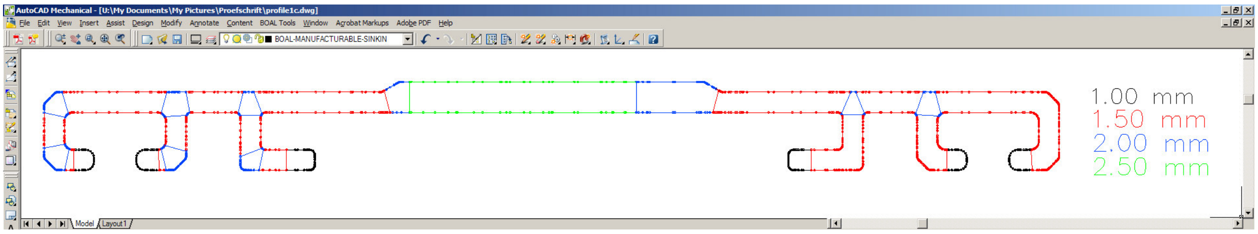

Figure 4.19 Bearing length representation of the die design software

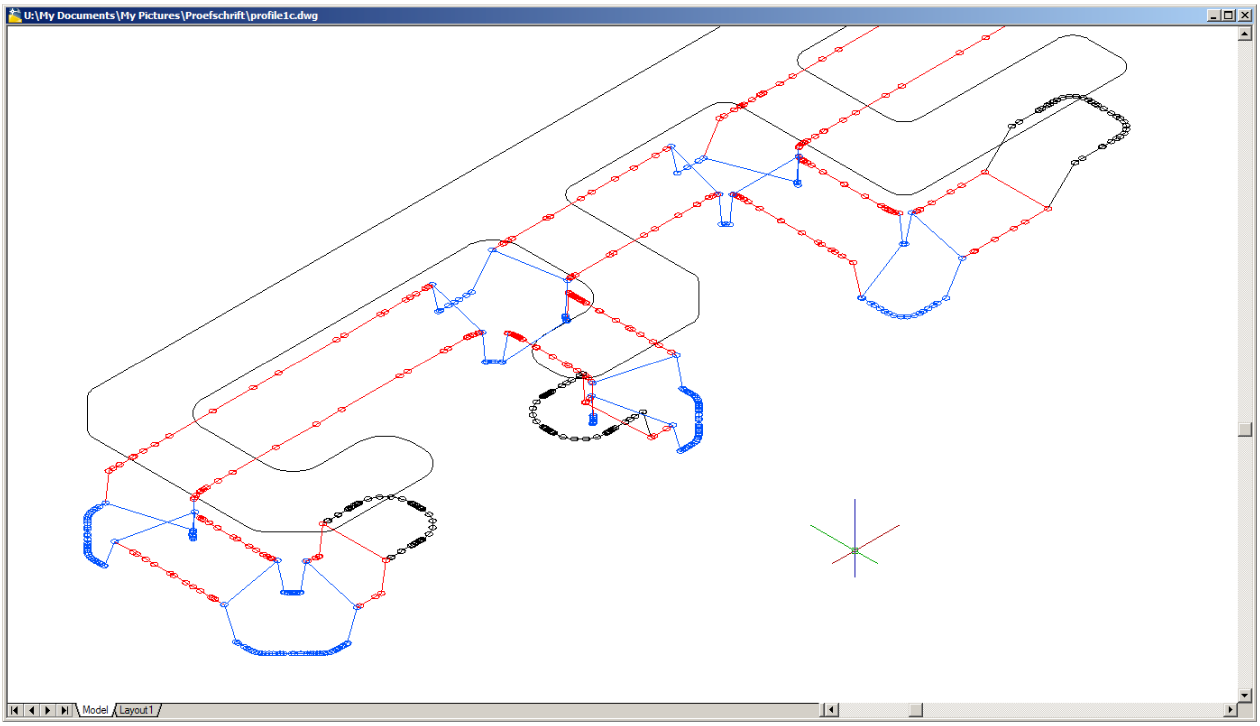

Figure 4.20 3D representation of bearing lengths

4.9 Manufacturability of the sink-in contour

Sink-in pockets in extrusion dies are made by end milling. This production process is capable of producing very complex sink-in shapes, but the more intricate the shape becomes, the higher the production time and cost will be. Small radii or narrow sections in the contour call for the use of small diameter mills with a low material removal rate. The die manufacturer will quite likely make alterations to the sink-in contour to enhance manufacturability if this is not sufficiently taken into account during the design process. These modifications may compromise the functionality of the calculated sink-in. To avoid this, manufacturability should be already considered during the design process.

When constructing a sink-in contour using the medial axis and formula 3.1, manufacturability is not automatically taken into account. The required parameters are calculated for every individual point of the medial axis, without looking at neighbouring geometry. The contour is formed by connecting the outer boundary formed by the sink-in offsets, as described in section 4.4. The offset points are connected by lines and arcs where small radii are avoided, but it is not known at that point what mill diameter can cut the contour exactly. Another relevant tool diameter that needs to be determined is the one that fits inside the minimum width of passage in the contour. These two critical diameters are illustrated by figure 4.21.

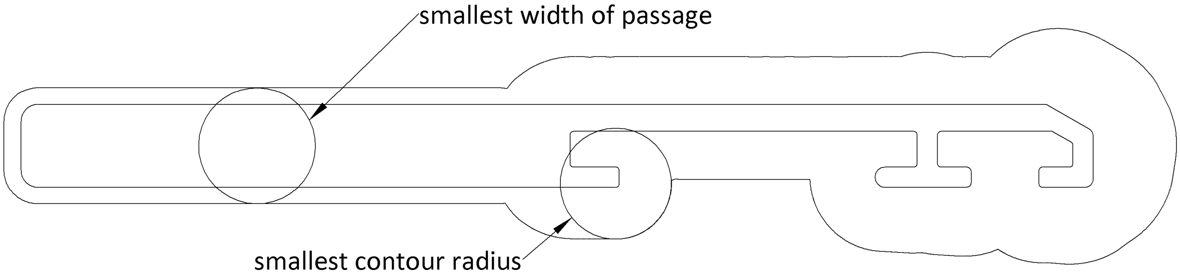

Figure 4.21 Minimum width of passage and smallest radius in a sink-in contour

For practical values of the sink-in geometry, where extremely small offsets are shunned, it will be possible to make the exact shape of the sink-in by milling. However, in order to make the milling process as quick and cheap as possible, large tool diameters are preferred as these provide the highest material removal rate. For relatively small pockets such as sink-ins tool changes are usually very inefficient. It is therefore desirable to find the largest possible mill diameter that can make the entire contour. Small modifications to the sink-in contour may drastically improve manufacturability, but changing the sink-in geometry may impact its function; the balancing of the flow pressure. It is known from section 3.4 that, if used in the proper range of offset and depth combinations (e.g. in figure 3.7 this is true for offsets greater than 2 mm), a relatively large offset change of the sink-in has a relatively limited impact on the flow resistance. It is therefore plausible that under these conditions some manufacturability related adjustments of the contour are permitted without disturbing the balance of flow speed. It must therefore be agreed on how much the sink-in geometry may safely be changed, if the consistency and repeatability of the design process is to be sustained. Looking at figure 3.7 again, it makes little sense to express the allowed deviation from the original sink-in contour in units of length, because one millimetre of offset deviation may correspond to different amounts of pressure deviation at different locations.

It is the pressure deviation itself that must be guarded. In accordance with experienced die designers it is established that a 5% pressure difference does not negatively affect the flow balance in a significant way[3]. Using this assumption, two new sink-in contours can be constructed that represent the upper and lower pressure limit. Within the zone that is thus created, modifications that enhance manufacturability may be made [48, 49, 52]. This means that in figure 4.22 the middle contour may be changed at will, as long as the new contour stays within the other two. It can be seen in this example that the tolerance for changes is much smaller in the central part of the profile where the sink-in is narrower, even though the pressure difference between the inner and outer contours is the same. This is due to the increased sensitivity to changes in the sink-in offset at small offsets (see figure 3.7).

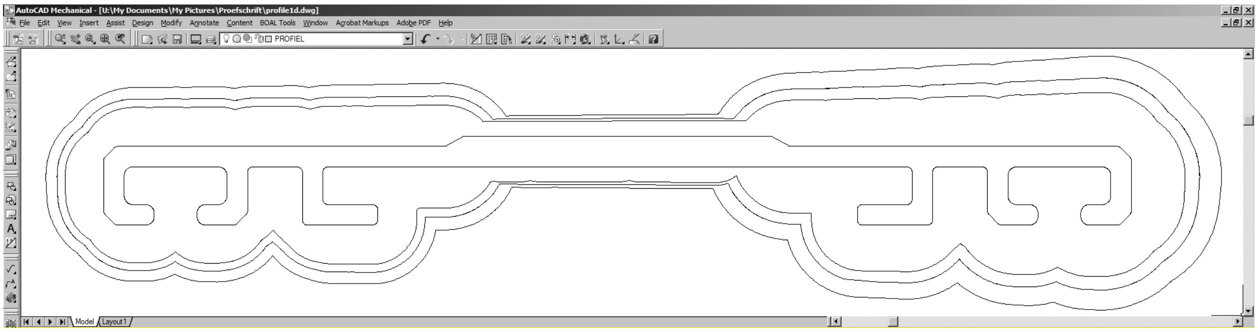

Figure 4.22 The original sink-in contour and the inner and outer pressure tolerance margins

Apart from indicating the zone of allowed modification, the program can also find the maximum tool diameter that can be used to machine the whole pocket whilst adhering to this constraint. It then draws this optimised new contour, highlighting the parts of the sink-in where modifications were made (figure 4.23).

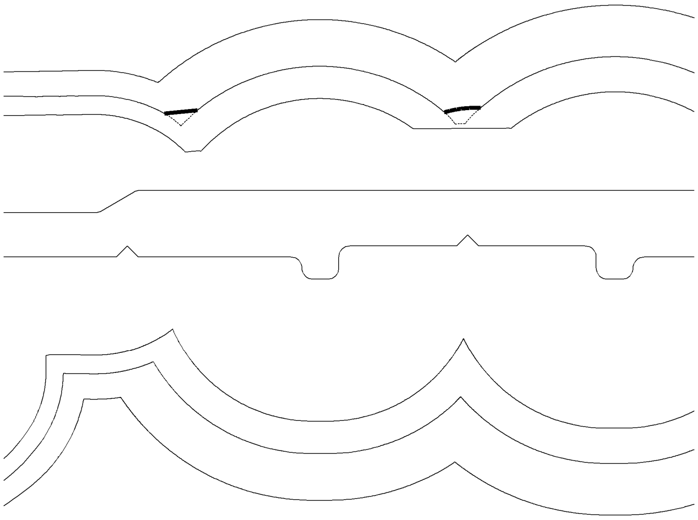

Figure 4.23 Modifications applied to the sink-in contour (bold)

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[3] This percentage is a constant parameter in the software that can be changed if practical results offer new insights.

To find this maximum tool diameter the original sink-in contour is traversed with tangent circles that represent the mills. The program has a list of the available mill diameters in the tool set at its disposal, so it can analyse and modify the contour according to the actual tools that can be used. The first mill with which the traversal is executed is the one of which the diameter is equal to or slightly smaller than the largest offset circle in the contour. It is checked if this circle can be kept tangent to the original contour without having the resulting path intersect either the inner or the outer contour of the tolerance of deviation. To check for the smallest width of passage the medial axis is traversed also. It is checked if the diameter that is investigated does not violate the outer contour on either side of the passage. Moving down the toolset with decreasing mill diameters, the tool is found for which no illegal intersections occur. The final sink-in contour is then formed for this tool diameter. If no acceptable solution can be found with the available tools, the program offers the possibility to automatically draw a new (wider) sink-in contour that satisfies both the pressure balance formula (3.1) and the manufacturability constraints, based on the acquired data of the analysis.

4.10 Manufacturability of the bearing length variation

When designing the bearing length variation, manufacturability is also an important factor. As mentioned in section 3.1 too strong variations can cause problems in two ways. Firstly, steep transitions may degrade the surface quality of the extrusion, showing up in the form of so called 'die lines'. Secondly, they can cause difficulties in the manufacturing of the bearing contour. The bearing length transition shown in figure 4.20, calculated by the algorithm of the application, exhibits both of these problems. If sent to a die manufacturer in this form, the transitions will be changed beyond the die designer's control and with unknown consequences for the flow balancing function of the bearing geometry. To avoid this, the manufacturability of the bearing geometry can be enhanced as part of the design process.

The most common way to manufacture the area behind the bearing opening that forms the bearing lengths and relief angles is to first make a cavity in the back of the die that extends to the longest bearing length. Next, the bearing length difference and final relief angles are machined into this pocket. This can be done by direct milling or by using electro- discharge machining (EDM). In the latter process an electrode of the desired shape is lowered into the cavity. This electrode is made by milling, so in either case the bearing contour shape is milled. With regard to the bearing length variation, two manufacturing issues are most important.

1. Space is very limited in the die relief cavity. Therefore, if direct milling is used to cut the bearing length variation, bearings on either side of the narrow profile cavity usually cannot have different lengths as they are cut in one pass. The bearing lengths should therefore be symmetrical about the central line of the medial axis.

2. The shapes of the peaks and troughs in the bearing variation dictate which mill diameters will fit to reach the entire contour. If direct milling is chosen over EDM the contour it is important to note that the contour will be milled from the opposite direction.

The first issue concerns the 'symmetry' of bearing lengths for manufacturing with one pass in direct milling. The fact that the pressure is evaluated on the medial axis is a great advantage when constructing bearing length variations. If the bearing length variation is milled in one pass, the tool path would follow the medial axis. The points on the boundary that lie opposite to each other are connected through the medial axis, so the required symmetry is obtained by default. Adjacent points can always maintain their relationship, even if the bearing function is altered. Figure 4.24 shows the symmetrical and the asymmetrical situation. The latter (figure 4.24b) would require very small tool diameters to mill directly.

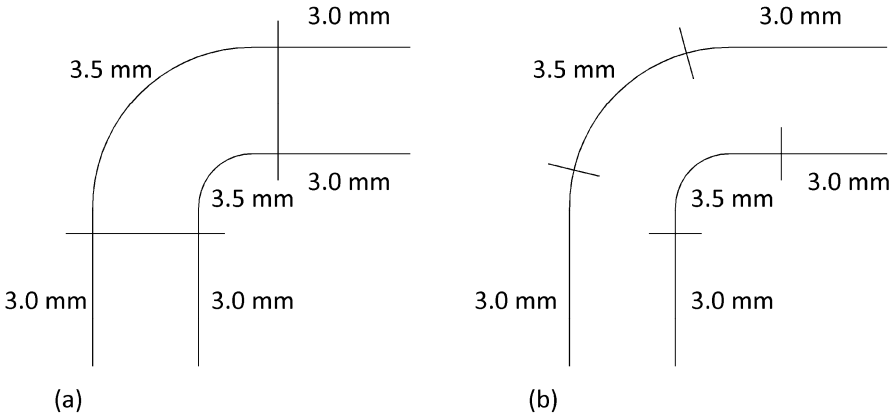


Figure 4.24 Symmetrical (a) and asymmetrical (b) bearing length variations

The second issue, in combination with the avoidance of die lines on the extrusion, has the implication that both the steepness of the bearing length changes and the distances over which the bearings have a certain length need to be investigated. In the current implementation only the steepness of transitions is controlled. Using feature recognition and filtering similar to that used in the detection and removal of ID tags (see section 4.5) the size of the peaks and troughs could be analysed and compared to the size of the available mills. Currently the bearing function is edited in such a way that no angles greater than 45° remain (see figure 4.25). The result of a bearing smoothing operation as carried out by the flat die design software application is shown in figure 4.26. Steeps transitions have been eliminated and the symmetry of the bearing length variation is upheld. A clear difference with the unsmoothed and unmanufacturable situation of figure 4.20 can be seen.

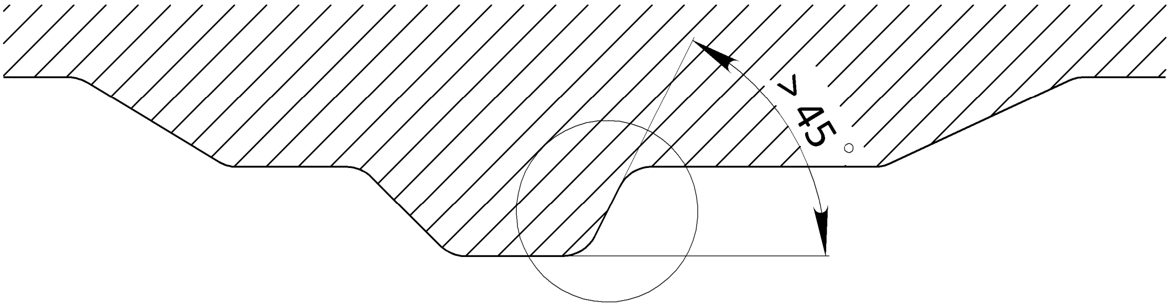


Figure 4.25 An angle over 45° is not used, because it can cause die lines

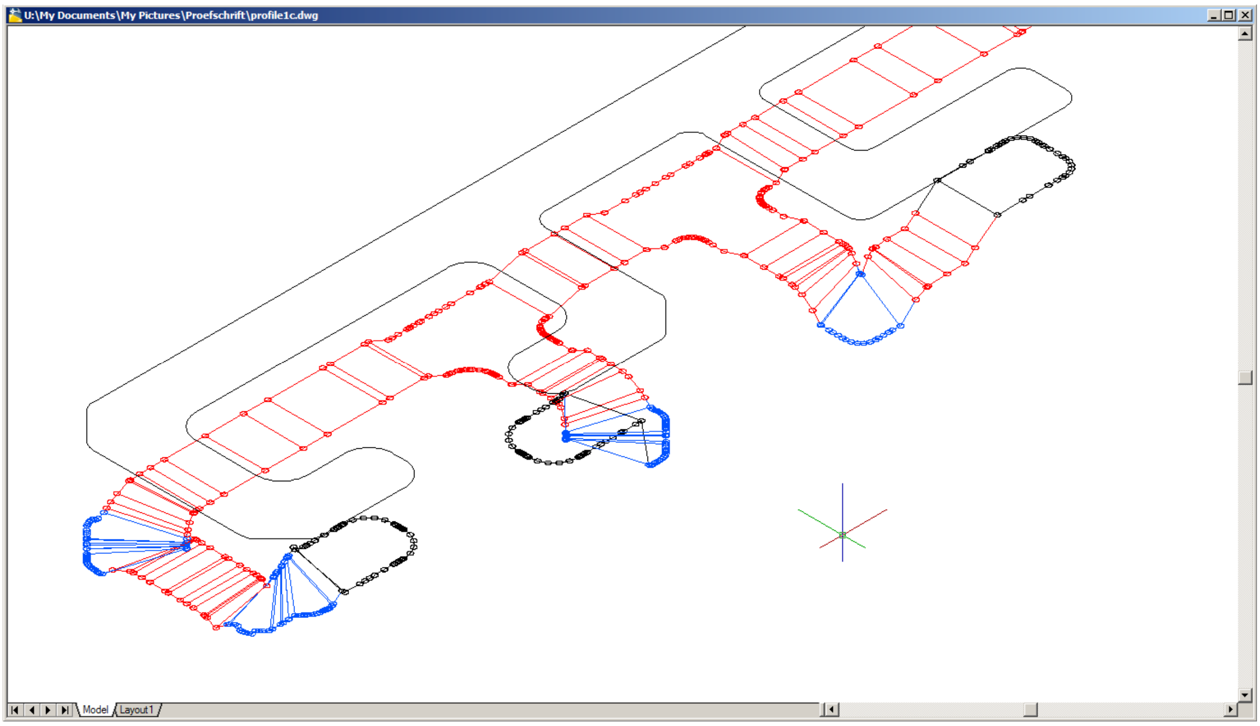


Figure 4.26 The length function after smoothing for manufacturability

The shorter bearing sections at leg tips are protected by the algorithm, so that the smoothing of the function is done outside those areas.

When milling the bearing length variation into the EDM electrode, the machining direction is opposite of that when the contour is milled directly into the die. When tool diameter specific smoothing is implemented in the future, the machining direction can be specified in order to minimise the required modifications to the contour. Figure 4.27 shows that a detail in the bearing function may be manufacturable for one machining direction, but not for the other.

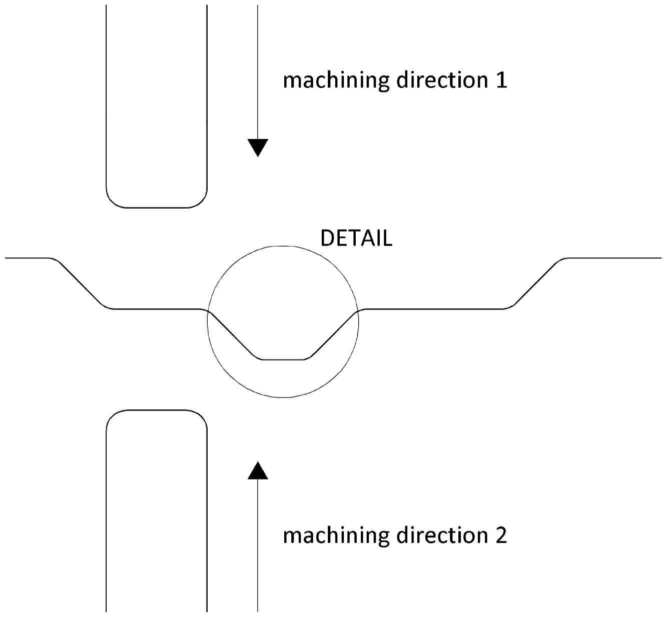


Figure 4.27 Detail that is only manufacturable for machining direction 2

As with manufacturability related modifications to the sink-in contour, changes to the bearing length function also influence the pressure and with that the exit velocity of the aluminium. For manufacturing related modifications to the sink-in contour a maximum pressure difference of 5% was tolerated. If the same constraint is placed upon bearing length modifications then a 2.5% pressure deviation is allowed in either direction (to make peaks lower and troughs less deep). For typical values of the bearing length and total pressure, this amounts to a maximum deviation of around 0.4 mm. With a typical bearing length step size of 0.5 mm, this means that the pressure difference due to smoothing of peaks and troughs can often be greater than 5%. Reducing the amount of smoothing is not an option, because the steep transitions in the bearing function can mean that it is not just difficult to manufacture, but even impossible.

Instead, the pressure difference introduced by the manufacturability operation to the bearing function can be compensated by the sink-in geometry. The pressure difference can be calculated from the bearing length change using equation 3.2. Using formula 3.1 this pressure difference can be translated to a change in sink-in offset. This means that the sink-in, which was already checked and corrected for manufacturability, now may need a second correction step. For this reason this sink-in offset compensation is not currently implemented.

4.11 Summary of sink-in and bearing creation process

The creation process of the sink-in and bearing geometry described in detail in the above sections is summarised in the flow chart in figure 4.28. This clarifies the relations between the various sub-processes. Also depicted is the relationship with the bearing deflection diagnosis tool, which is covered in the section 4.13. For reasons of clarity not all processes are pictured. For example, the user input mode where the minimum and maximum bearing length are specified and the sink-in is calculated based on the remaining pressure difference is omitted. Also not shown are some feedback loops that handle invalid user input. Complex processes that can be further subdivided are pictured as grey boxes. The contents of these boxes are shown in appendix C.1. The ‘construct sink-in contour’ process is too comprehensive to be displayed as a flow chart. Instead, its most relevant features are described in section 4.4.

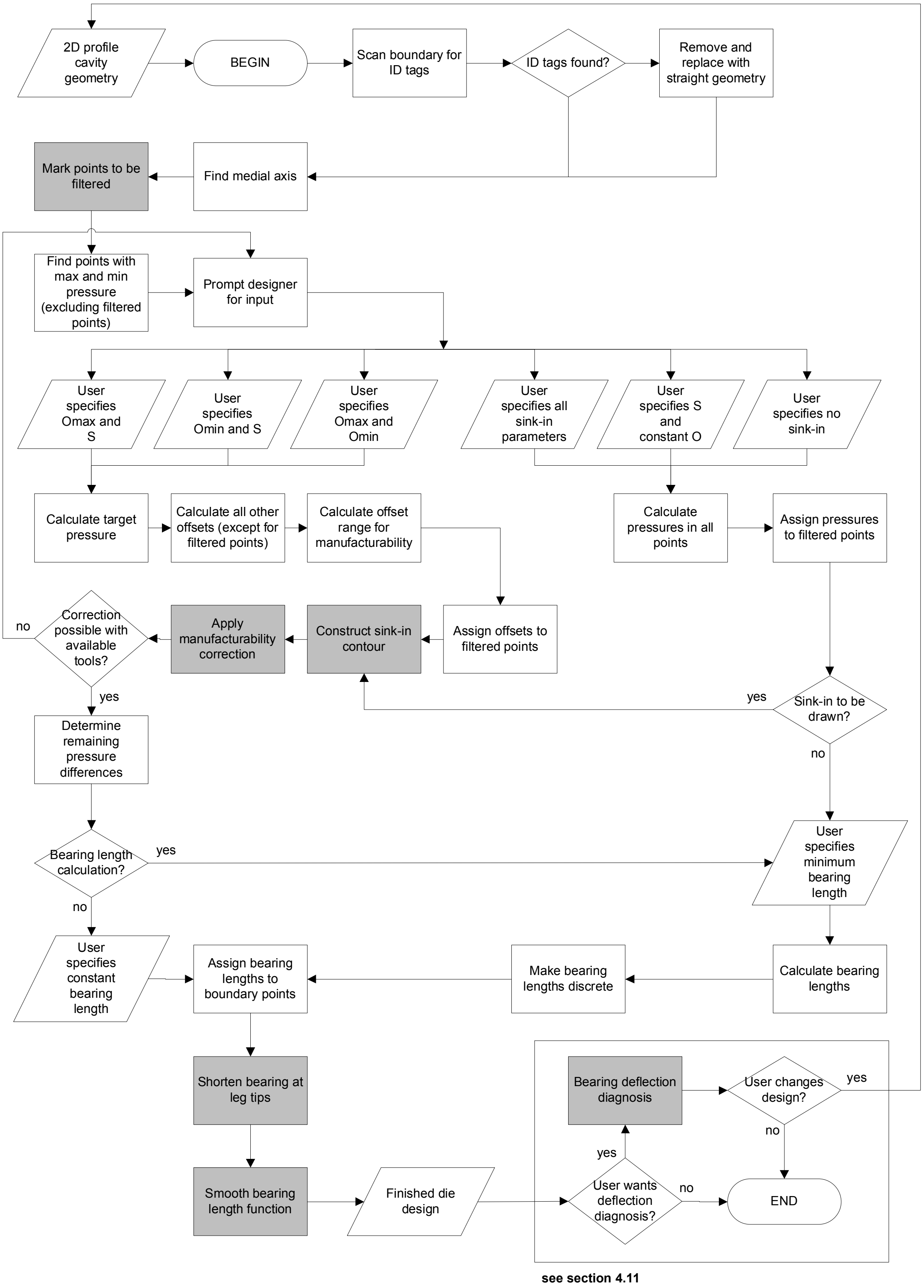


Figure 4.28 Flow chart of sink-in and bearing geometry creation process

4.12 The application's user interface

The flat die design software tool is an extension to AutoCAD. This was a logical choice, because Boalgroup was already using AutoCAD to draw their profiles. The functions of the add-in application appear in an extra menu that is added to the AutoCAD interface, as shown in figure 4.29.

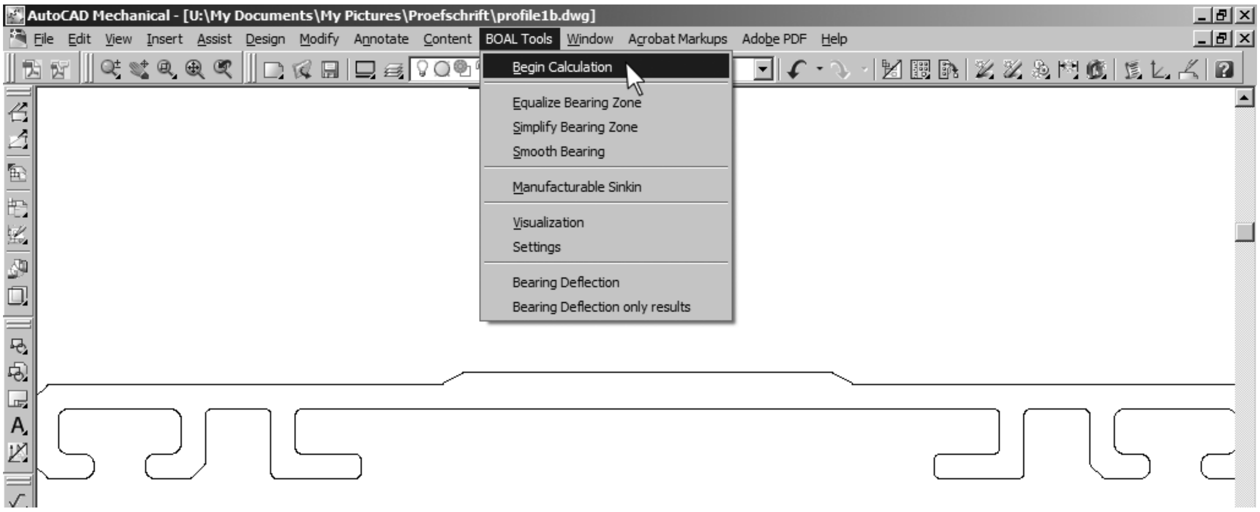
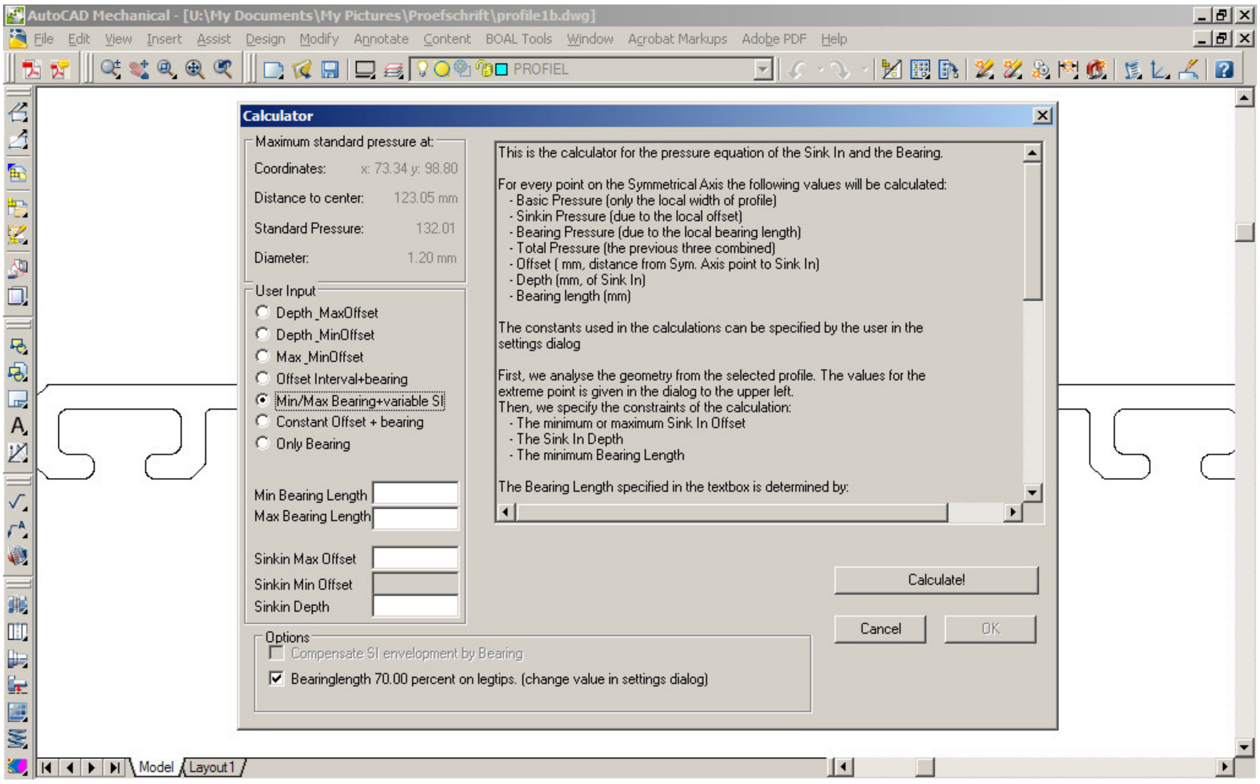


Figure 4.29 The 'BOAL Tools' menu that is added to AutoCAD

The backbone of the application is the *Begin Calculation* option. This initiates the calculation and drawing of sink-in and bearing geometry in a combination specified by the user. The dialog box brought up by selecting the *Begin Calculation* menu item is shown in figure 4.30. The required user input fields on the lower left are activated according to the input mode chosen through the radio buttons. After the required values specified by the designer are entered and the *Calculate!* and *OK* buttons are clicked, the resulting geometry is visualised in the profile drawing. Figure 4.31 shows an example of this possible output.



Maximum standard pressure at:

Coordinates:	x: 73.34 y: 98.80
Distance to center:	123.05 mm
Standard Pressure:	132.01
Diameter:	1.20 mm

User Input

○ Depth _MaxOffset
○ Depth _MinOffset
○ Max _MinOffset
○ Offset Interval+bearing
● Min/Max Bearing+variable SI
○ Constant Offset + bearing
○ Only Bearing

Min Bearing Length
Max Bearing Length

Sinkin Max Offset
Sinkin Min Offset
Sinkin Depth

This is the calculator for the pressure equation of the Sink In and the Bearing.

For every point on the Symmetrical Axis the following values will be calculated:
- Basic Pressure (only the local width of profile)
- Sinkin Pressure (due to the local offset)
- Bearing Pressure (due to the local bearing length)
- Total Pressure (the previous three combined)
- Offset (mm, distance from Sym. Axis point to Sink In)
- Depth (mm, of Sink In)
- Bearing length (mm)

The constants used in the calculations can be specified by the user in the settings dialog

First, we analyse the geometry from the selected profile. The values for the extreme point is given in the dialog to the upper left.
Then, we specify the constraints of the calculation:
- The minimum or maximum Sink In Offset
- The Sink In Depth
- The minimum Bearing Length

The Bearing Length specified in the textbox is determined by:

Options

☐ Compensate SI envelopment by Bearing
☑ Bearinglength 70.00 percent on legtips. (change value in settings dialog)

Figure 4.30 The *Begin Calculation* dialog window

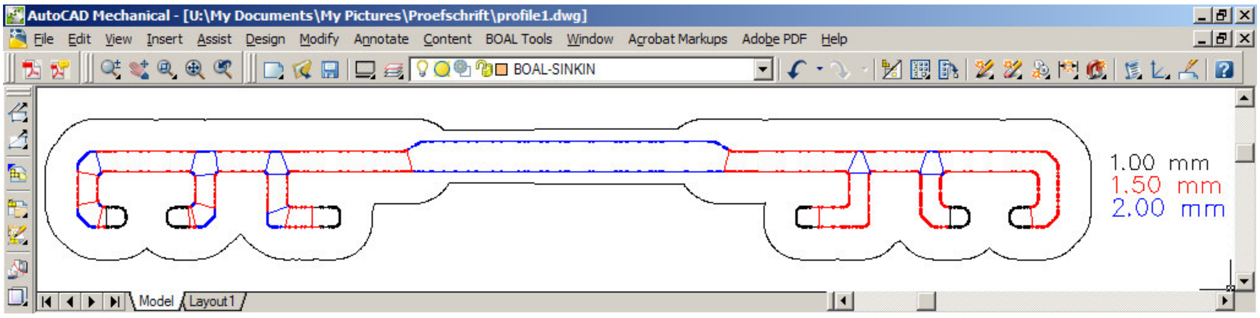


Figure 4.31 Visualised result of the sink-in and bearing calculation

Visualisation and *Settings* are menu options (shown in figure 4.29) that affect how the results are displayed and how the algorithms operate. Using *Visualisation* the user can, for example, choose to display the medial axis of the profile or turn the bearing length legend on or off. *Settings* brings up a window in which the application's constants can be managed. These are the constant coefficients in formulas 3.1 and 3.2, options to turn filters (such as those for end points and ID tags) on or off and parameters that affect the operation of those filters. These settings not need be changed on a regular basis.

The remaining menu options are operations or analysis that can be carried out based on the proposed geometry. The *Equalise Bearing Zone* option was discussed and demonstrated in section 4.7. *Simplify Bearing Zone* reduces the number of entities on the bearing length contour by joining collinear lines together. This option makes the bearing geometry more manageable if it is to be exported to e.g. CAM applications. *Manufacturable Sink-in* and

Smooth Bearing are the functions to ensure the manufacturability of the sink-in and bearing geometry, as described by sections 4.9 and 4.10. The *Smooth Bearing* function currently has no required user input. The user dialog window that appears when the *Manufacturable Sink-in* option is clicked is discussed in appendix D. Finally, *Bearing Deflection* starts the bearing area deflection diagnosis tool. Its operation and user interactions are covered in the next section.

4.13 Die deflection diagnosis

The necessity to predict the deflection of the die during the design process was discussed in chapter 3. Due to dishing and tongue deflection, the bearing angles may change and the cavity opening may become wider or narrower. In situations where this kind of deflection is expected, the designer will want to check if the bearing angles are sufficiently choked to prevent large flow speed changes and if the profile thickness will still be within specifications [52].

From FEM simulations a formula (formula 3.3) was derived that specifies the pressure that the bearing area around each medial axis point is subjected to as a result of the aluminium flow. In order to investigate the deflection that results from the application of this pressure, the following steps need to be taken. It is assumed that a 2D CAD model of the die is available.

1. A 3D model of the die should be made.
2. This model should be meshed with finite elements.
3. Boundary conditions and forces corresponding to the pressure of the aluminium should be applied to the appropriate nodes of this finite element model.
4. The simulation should be run.
5. The deflection of the bearing area should be distilled from the results and clearly visualised to the designer.

These steps need to be carried out within a short time and with limited user interaction. Otherwise the design process would be delayed beyond an acceptable level and usefulness of this tool would be lost. This requires a high level of automation and integration within the CAD tool that is used to design the die. A prototype of the deflection diagnosis tool was created that starts with a 2D model of the die in AutoCAD and runs Ansys below the surface to create the 3D meshed model of the die and carry out the simulations. The results are then visualised in AutoCAD. This section will discuss the way this is done step by step. A flow chart of the procedure is shown in figure 4.32. Like in figure 4.28 the grey boxes contain more detailed processes, shown in flow charts in appendix C.2.

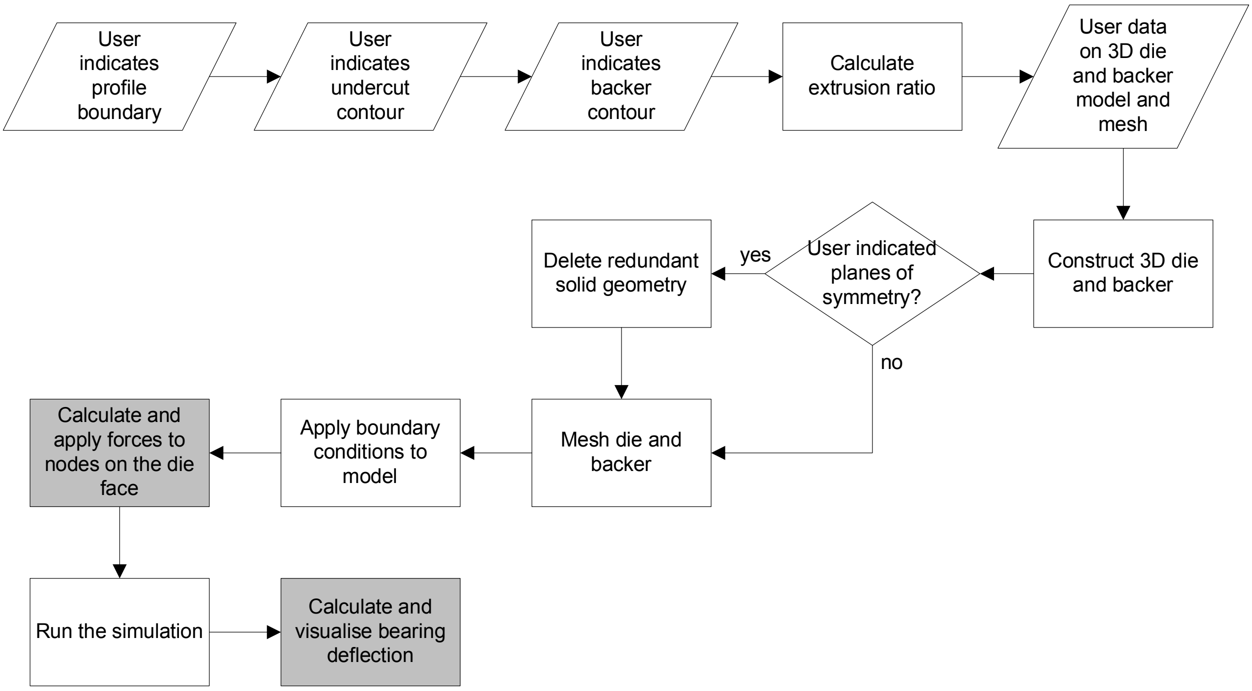


Figure 4.32 Flow chart of the die deflection diagnosis process

4.13.1 Construction of the 3D CAD model

A die design starts from a 2D drawing of the profile boundary and the calculated sink-in and bearing geometry was represented in 2D and 3D respectively. In order to construct a full 3D model suitable for deflection analysis it is necessary to model the die plate with its relief cavity and the support tooling. The model needs to be created based on as few parameters as possible and it needs to be simple enough for easy meshing and fast simulation. For these reasons the following simplifications are applied.

1. The die backer is modelled, but the bolster and the stiffness of the press are not. That is, the backside of the backer is clamped and contact elements are used to simulate some friction between the die and the backer.
2. The bearing length is modelled to be constant.
3. Only the offset of the relief, the bearing undercut, is modelled, not the relief angle.

These simplifications are illustrated in figure 4.33.

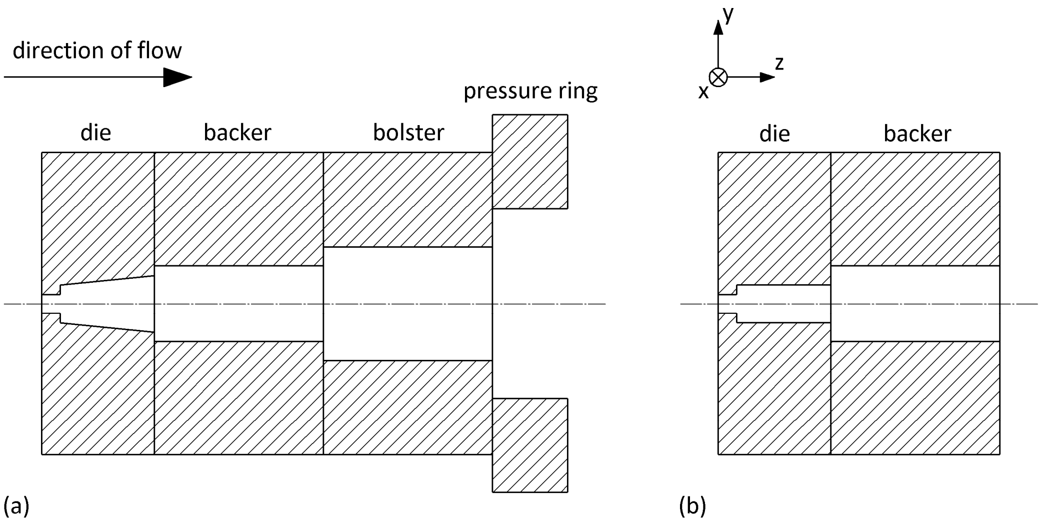


Figure 4.33 Cross-section of the 3D die stack model before meshing; (a) original and (b) simplified.

The possible impact of the simplifications on the results of the die deflection simulations were investigated by running some test simulations. The situation shown in figure 4.33a was modelled in 3D for a U-shaped profile, which is typically prone to severe deflection. The die and its support tools used in this example are actually used in production. A constant distributed load was applied to the entire die face. The relative displacement in the extrusion direction of the adjacent bearing edges at the bottom of the U-shape was taken as the measure of deflection (see figure 4.34).

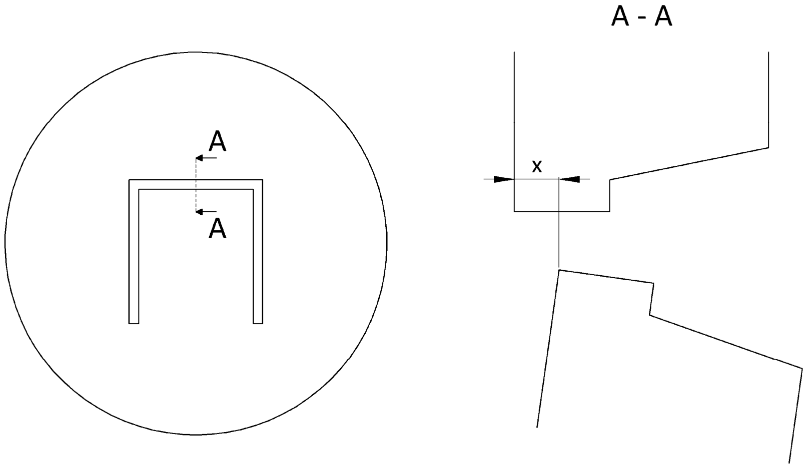


Figure 4.34 Distance x, the measure of deflection in simulations of a U-profile die

The effects of the three simplifications were investigated separately. First the bolster was removed from the model and the back face of the backer was restrained at its area of contact with the bolster (the hatched area in figure 4.35a). The fact that the die stack is made thinner in this simplification reduced the rigid translation in the extrusion direction of the die face as a whole, as expected. However, the error in the relative movement of the bearing edges remained within 1% compared to the full die stack.

The current prototype implementation of the deflection tool only supports the restraining of the backer on its entire back face (the hatched area in figure 4.35c), as opposed to just the area of contact with the bolster (figure 4.35a). The reason for this choice is that for many tool stacks, the bolster closely follows the shape of the backer, as shown in figure 4.35b. In these cases the effect of a simplification to the situation in figure 4.35c is much smaller. In this example, however, the added support reduced the deflection by a factor of 4.5. This clearly shows that the software tool should provide the application of constraints to the backer based on the actual geometry of the bolster. It also illustrates to the die designer the importance of using a matching bolster for the reduction of bearing area deflection.

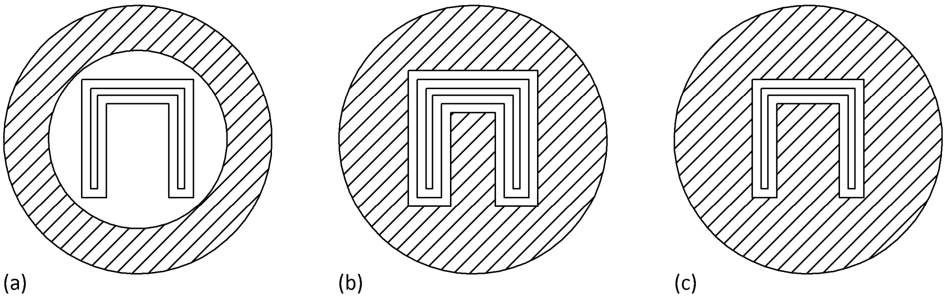

(a) (b) (c)

Figure 4.35 Areas of restraint on the back face of the backer

Next, the effects of two simplifications made to the bearing are considered; the die relief being modelled as a straight line and the bearing length being constant. These measures influence the amount of material that is present behind the bearing edge for support, as illustrated in figure 4.36. Since the straightening of the die relief reduced the deflection by only 2%, the influence of bearing length was assumed to be negligible too.

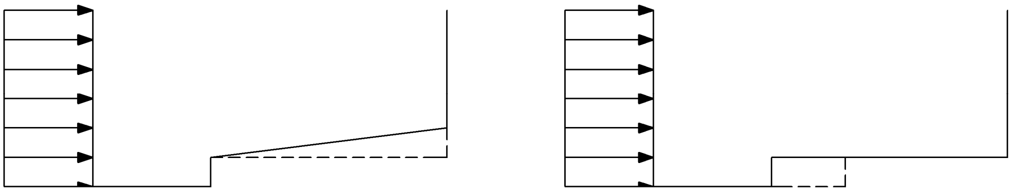
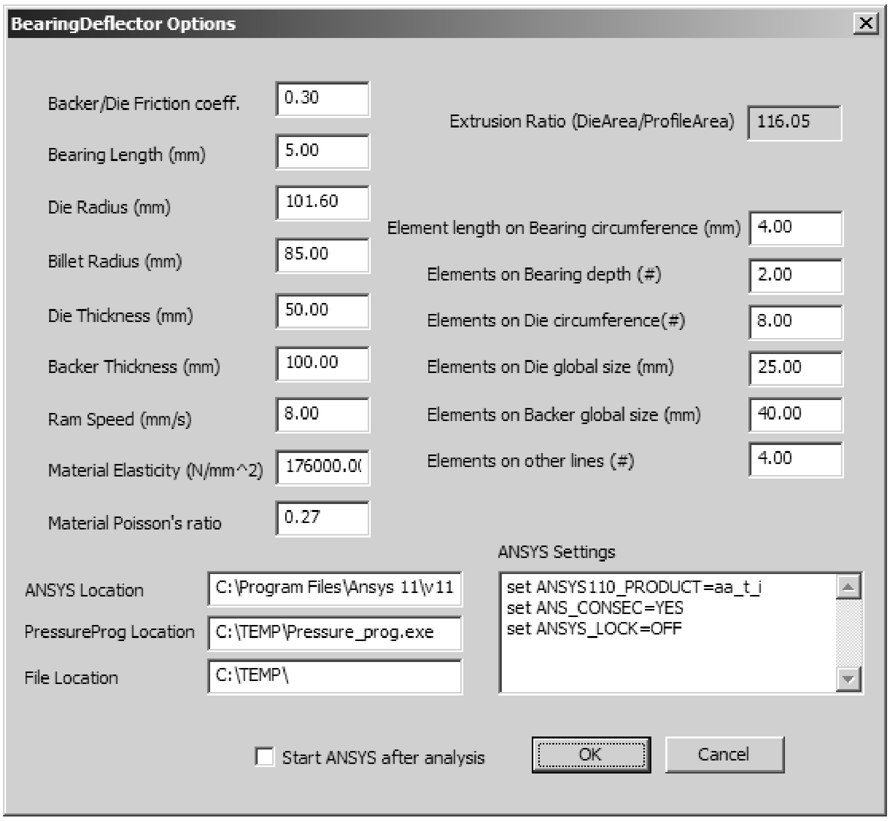


Figure 4.36 Effect of bearing area modifications on bearing edge support

The simplified 3D geometry is constructed based on only a few geometrical entities and parameters. The program needs to know the contours of the backer openings that are located behind the profile cavities. These are usually available as CAD drawings, because the designer needs them to position the profile cavities on the die surface. These contours can be indicated by a mouse click. Another contour that needs to be known is the bearing undercut. If the undercut is constant, this is just an offset contour from the profile boundary. It can be automatically drawn with a standard CAD function. Should the offset be variable, the contour needs to be drawn by hand and indicated with a mouse click.

With the guide geometry specified, only a number of parameters need to be entered in order to be able to construct the 3D model and apply the finite element mesh. Specifying the bearing length, die radius, die thickness and backer thickness is necessary for the construction of the 3D model. Other parameters, shown in figure 4.37, are required for the automatic meshing of this model and for applying the material properties and boundary conditions. The modulus of elasticity of the tooling is taken as 176 GPa, which is a typical value for tool steel at the extrusion temperature.



Backer/Die Friction coeff. 0.30
Bearing Length (mm) 5.00
Die Radius (mm) 101.60
Billet Radius (mm) 85.00
Die Thickness (mm) 50.00
Backer Thickness (mm) 100.00
Ram Speed (mm/s) 8.00
Material Elasticity (N/mm^2) 176000.0(
Material Poisson's ratio 0.27

Extrusion Ratio (DieArea/ProfileArea) 116.05

Element length on Bearing circumference (mm) 4.00
Elements on Bearing depth (#) 2.00
Elements on Die circumference(#) 8.00
Elements on Die global size (mm) 25.00
Elements on Backer global size (mm) 40.00
Elements on other lines (#) 4.00

ANSYS Location C:\Program Files\Ansys 11\v11
PressureProg Location C:\TEMP\Pressure_prog.exe
File Location C:\TEMP\

ANSYS Settings

```
set ANSYS110_PRODUCT=aa_t_i
set ANS_CONSEC=YES
set ANSYS_LOCK=OFF
```

☐ Start ANSYS after analysis

Figure 4.37 Input parameters for the creation, meshing and simulation of the 3D die model

4.13.2 Finite element meshing

The finite element that is used for this deflection analysis is a ten node tetrahedral structural solid element with quadratic displacement behaviour. Its name in Ansys is Solid92. Tetrahedral elements are well-suited for irregular meshes and the ten nodes are required for sufficient accuracy. Figure 4.38 shows the shape and node distribution of the Solid92 element.

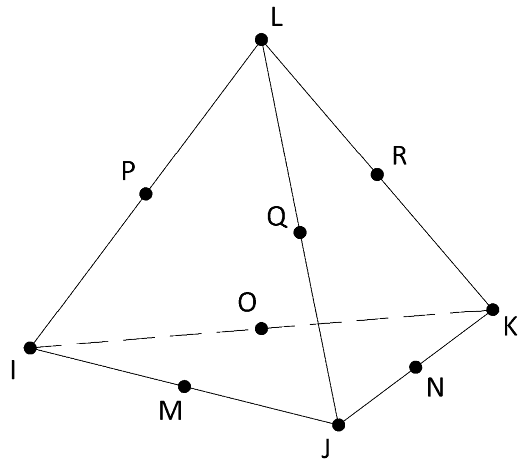


Figure 4.38 Solid92 ten node tetrahedral element

Contact elements are defined on the surface between the die and the backer. The mesh is automatically made denser in the die than in the backer and the element size becomes smaller nearer to the bearing area. This way sufficient accuracy can be obtained with a relatively small number of elements and therefore a short calculation time. Adjustments to the element sizes can be made in the dialog window shown in figure 4.37.

4.13.3 Application of forces and boundary conditions

With the elements in place, the boundary conditions can be applied. The cylindrical outer surface of the die and backer are constrained in the x and y directions, which lie in the plane of the face of the die (see figure 4.33), and the back of the backer is fixed in the direction of extrusion (the z coordinate). The user has the possibility of indicating an axis of symmetry on the die face, should one exist. In this case only a portion of the cylinder needs to be modelled and movement perpendicular to the plane of symmetry is constrained.

Next, the forces of the aluminium are applied. According to equation 3.3 the pressure is given by the extrusion ratio, the die radius and the shortest distance of the particular point to the medial axis. The extrusion ratio is determined from the billet radius entered in the dialog window of figure 4.37 and the cross-sectional area of the profile calculated by the die design tool. The distances to the medial axis are computed by the program from coordinate information stored in temporary files. This allows a pressure to be calculated per element on the die face touched by the billet. However, the pressure needs to be expressed as forces on the nodes. Due to the shape functions of the chosen element, a pressure is represented as forces on the midside nodes of the exposed face of the element. The magnitude of these forces is calculated from the area of these exposed surfaces and the pressure. Because an element face has three midside nodes, the force is distributed evenly over each node as:

$$F = \frac{1}{3} \cdot p \cdot A \tag{4.1}$$

This process is summarised by a flow chart in appendix C.2.

4.13.4 Simulation and the interpretation and visualisation of the results

With the finite element model fully defined in Ansys, the simulation can be completed in mere seconds. However, interpretation of the results in their raw form takes much longer than that, if the user has to manually search the nodal solution of the entire model for the relevant information and then apply calculations to it. Therefore, this interpretation process is automated. Macros carry out the following tasks.

- construction of nodal lines
- forming of pairs of nodal lines in the plane perpendicular to the medial axis
- noting the deformed state of these line pairs
- projecting these deformed lines onto the plane perpendicular to the medial axis
- calculating the angles and distances
- show the results on screen

For every medial axis point lines are constructed on the bearing surface in the direction of flow connecting the nodes at the top and at the bottom of the bearing channel. Nodal lines on either side of the channel form pairs and construct a plane perpendicular to the medial axis. Their relative movement in the deformed state will determine the change in angle and thickness in that part of the bearing. However, in this deformed state the nodal line pairs often move out of alignment. This makes it difficult to measure the resulting angle and thickness changes. Therefore, using vector operations, the deformed lines are first projected back onto the plane that they constructed in their undeformed state. In this plane the total angle and thickness change is calculated. Every medial axis point has a number of nodal line pairs of which the deflections are averaged.

The results of the simulation are displayed to the user as numbers throughout the profile cavity, as shown in figure 4.39. One set of numbers corresponds to the relief angle of the bearing in the deformed state (so for a choked bearing the value is negative) in various places. The other set of values are percentages of the original profile width that remain in the deformed state. A number of 94.7 therefore means that the cavity thickness is only 94.7% of the original value.

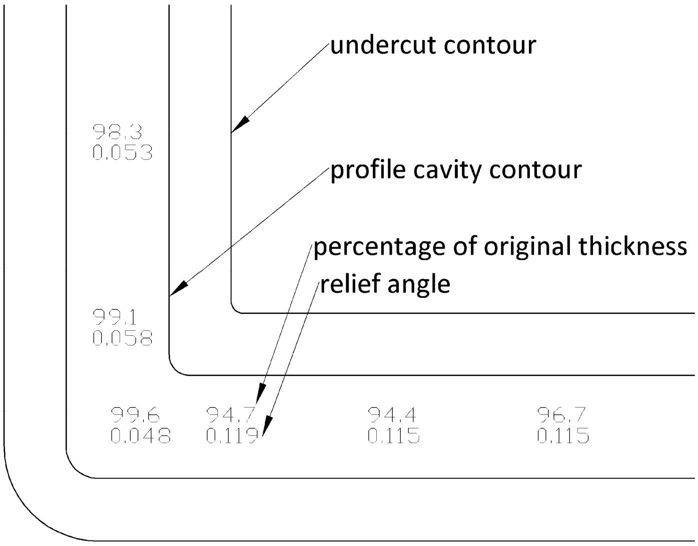


Figure 4.39 Information about bearing deflection displayed to the user

In this example the bearings started out being parallel. The introduced relief angle will cause a significant pressure drop. Knowing this, the designer may choose to choke the bearings a few degrees, so the deflection has no longer a great influence on the exit velocity. Extreme profile thickness changes discovered using this tool can be a reason to make compensations to the profile cavity outline in the die design. This early insight and compensation can eliminate multiple trial and correction cycles before production.

As an additional means of visualisation the user can view the deformed shape in Ansys (figure 4.40).

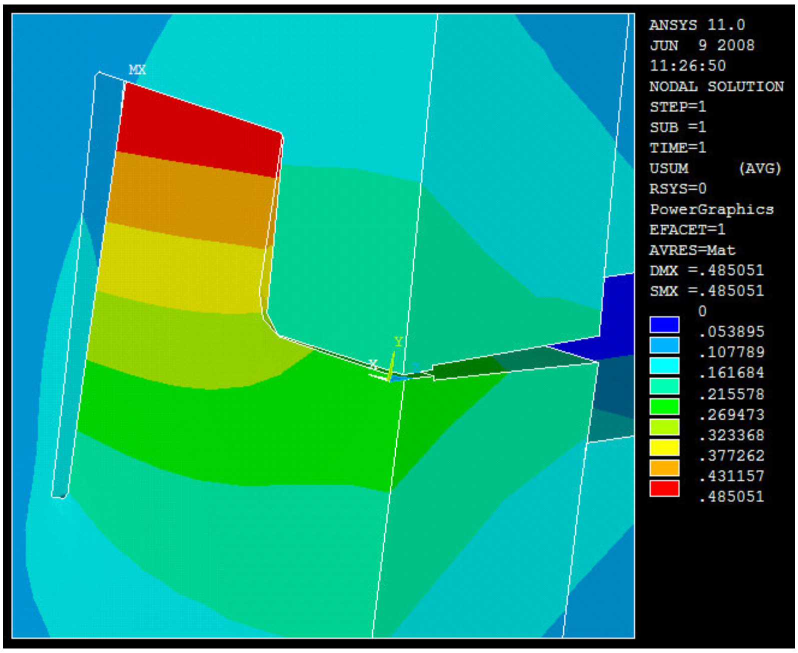


Figure 4.40 Deflection of a die (in cross-section and with displacement scaling) as viewed in Ansys after running the deflection diagnosis tool.

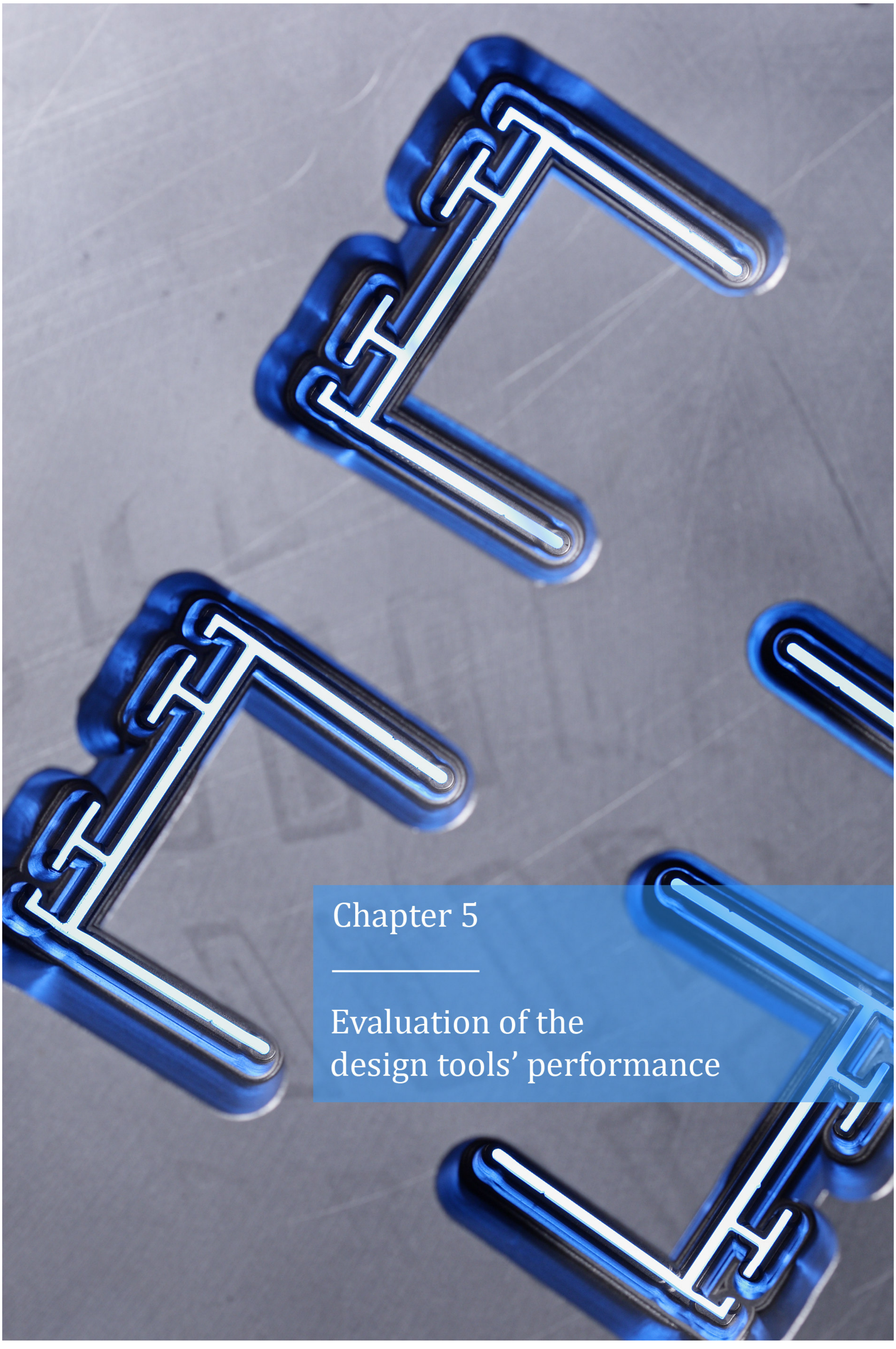
4.14 Conclusion

In this chapter the method for the use of a variable sink-in, optionally in combination with a variable bearing length, was developed further and implemented into a die design tool. The basis of this implementation is the medial axis transform of the profile cavity. This representation defines the critical profile parameters unambiguously and is a suitable starting point for constructing the sink-in and bearing geometry. In order to make the implementation match the method's intent, some filtering actions are necessary. These are,

- The dismissal of maximum circles on the medial axis that do not represent the local profile thickness in the way that was intended.
- Compensation for extra friction at leg tips.
- Representing the bearing length variations in discrete steps.
- Making the calculated sink-in and bearing geometry manufacturable.

This die design tool not only significantly speeds up the die design process for complex extrusion profiles, but it also produces designs that provide a more stable means of flow control than traditional flat dies that use only bearings to control exit velocity.

While the performance of the flat dies designed using the abovementioned tool is already much less vulnerable to the effects of die deflection, a tool that enables a quick estimation of this deflection was also presented. Although finite element analysis is usually very time-consuming, some simplifications and a high degree of automation allow this diagnosis to take place in a matter of minutes. This makes it possible to carry out this deflection diagnosis of the bearing area as part of the die design process. If problems are detected, changes can be made to the die design before it is manufactured.



Chapter 5

Evaluation of the design tools' performance

CHAPTER 5: EVALUATION OF THE DESIGN TOOLS' PERFORMANCE

This chapter will discuss the results of the work covered in chapters 3 and 4 and will determine if the goals set for this research have been achieved. Some design rules derived from finite element simulations were implemented into design tools. These design tools will now be evaluated based on their accuracy and effectiveness and the amount of time that is gained by their use. It will also be established if the development and use of the design tools has led to increased insight into the extrusion process. Section 5.1 will discuss some general developments in Boalgroup's operation. Section 5.2 will evaluate the effectiveness of the design rules and approaches that are at the basis of the design tools. The success of the implementation will be evaluated in section 5.3. Section 5.4 will describe the cumulative benefits that Boalgroup has received from this research.

5.1 General developments

Before the results regarding the development and application of the die design tools are discussed in detail, it is useful to note the changes in Boalgroup's overall approach to die design. The insights and design tools developed in this project have had quite an impact on the way Boalgroup approaches die design. The developments have given Boalgroup the confidence to begin designing their dies in-house. This is remarkable, because in the industry as a whole the trend is the opposite. Even extruders that had their own die manufacturing facility before are now starting to outsource the design and manufacturing of their dies to die makers. Boalgroup recently expanded their die design department, because they believe that they can design better dies for their company than die makers can. The next sections will show that this strategy of using their own die designs, according to design rules and their implementation developed in this project, has proven to be very beneficial to Boalgroup's net product output.

5.2 Effectiveness of the design rules and approaches

This section will discuss the success of the design rules and approaches that are the basis of the implemented die design software. The relevant criteria for this are the practical effectiveness of the methods of flow control and the process of deflection analysis that were proposed in chapter 3.

5.2.1 Effectiveness of the flow control approach

An extrusion company aims to make optimal use of their press capacity to maximise production. Downtime of a press is extremely costly. For this reason it was not possible to conduct controlled extrusion experiments at Boalgroup to evaluate the effectiveness of the design rules and approaches and the die designs derived from it. Instead, the results must be based on data recorded from real production. Boalgroup keeps track of their production results very thoroughly and the performance of dies is logged. Die performance is expressed as a performance index. This index is a measure of the contribution of the die to the profit of the company, relative to other dies. Important variables that influence the index are percentage of scrap produced, die life and production speed (in kg/hr).

Unfortunately, the influence of die design on the performance index is not always clear. Radically different performance indices were observed for repeat dies that were identical in design to their predecessors. This phenomenon can have several causes. Scrap production during die trials, the necessary corrections and even premature die failure can often be attributed to die manufacturing errors (see section 3.2) and/or production errors. If a die is not heated to a high enough temperature, it will cool down the aluminium, resulting in higher resistance to flow, higher die wear and sometimes instant die failure. An insufficiently preheated billet will cause similar problems. A die is often not made exactly as it was designed. Particularly the length, angle, surface quality and relief of the bearing have been shown to be subject to manufacturing inaccuracies that can vary substantially from one repeat die to another [36]. Corrections may or may not be incorporated in the repeat die. Whatever the case, it is very difficult for a die corrector to make identical corrections to repeat dies. When different people are involved, the variations become even larger. These corrections influence the performance of a die in a way that is difficult to relate back to its initial design. Therefore, to assess the effectiveness of a new die design strategy, trends in die performance indices over longer periods of time should be studied, not individual cases. Even then it is hard to prove with absolute certainty that the long term improvements were due to better die designs, rather than a higher competence of press or correction personnel or improvements in the production process at die makers.

Despite the uncertainties Boalgroup is benefitting significantly from the practice of in-house die designs incorporating their own design strategy. The die design software and the design rules incorporated in it are used to design flat dies for extrusion production in The Netherlands and the UK. In 2007 approximately 1500 dies were designed in-house and in the year 2008 around 2000. Due to the reuse of older dies that were designed by die manufacturers, the percentage of Boalgroup’s own designs used in production in The Netherlands and the UK was just 25% in 2007 and is estimated to have been 50% in 2008. 60% of these own designs, which include porthole dies not covered by this research, showed an improved performance index of at least 5%. The percentage of scrap produced by the dies designed in-house was, on average, between 4% (The Netherlands) and 7% (UK) lower than that produced by other dies used in production in 2008. Although the FEM investigations used as the basis of this research were tailored to the circumstances and process conditions occurring in the Dutch plant, transferability of the design rules to the UK plant is very good. The most important distinguishing element of the two factories is the 9’’ press in the UK. It is bigger than the 7’’ and 8’’ presses in The Netherlands and has a lower container temperature due to differences in press hardware. Die designers find that a slightly larger minimum bearing length must be utilised for dies intended for this press. Besides this, similarly good results as on the Dutch presses are obtained on this press.

All the bearing length variations of the in-house designs are determined by calculating the pressure differences due to variations in profile thickness and distance to the centre of the die (formula 3.1) and the relation of pressure to bearing length (formula 3.2). The application is currently used mostly to generate flat die designs with constant offset sink-ins and variable bearing lengths. The profile geometry in combination with the constant sink-in leaves a remaining pressure difference, in accordance with formula 3.1. This pressure difference is then expressed as a bearing length difference by using formula 3.2, a design rule developed empirically by Boalgroup. The increased performance index of the in-house die designs proves that these formulas are an effective way to balance the exit speed of the aluminium. Some concern exists about the validity of the empirically derived bearing length formula 3.2 in situations where the profile cavity has large thickness variations. In some of these cases the performance index of the die was lower than earlier designs made by die manufacturers. As discussed in section 3.3 the sink-in pressure formula (3.1) was derived for a short relieved bearing where bearing length has a negligible influence on the resistance to flow. The temporary empirical bearing length formula (3.2) is based on the assumption that a constant bearing length does not result in a pressure difference, regardless of the variation in profile cavity thickness. This assumption is false, because both the length and the width of the bearing channel determine its resistance to flow. For a profile cavity with a thickness variation, increasing the bearing length by a constant amount affects the pressure difference and this is not reflected in formula 3.2. It is recommended that this empirical formula be replaced with a FEM-based design rule.

It was mentioned in section 3.5 that early production runs at Boalgroup that employed a variable sink-in as a means of flow control gave very good results [38]. Problems with the extrudate surface quality arose due to the short relieved bearings that were used in these dies. Even though the principle of flow control using a variable sink-in offset was proven in practice, the company partly reverted back to older die design methods by using a constant offset sink-in in combination with longer bearings in most cases. As a result, no further production results of variable sink-ins in flat dies could be obtained. In porthole dies a variable sink-in is used successfully to overcome the local slowing effects of the presence of legs (see figure 1.4). In these cases the width of the sink-in is varied to constrain the flow to areas of the profile that are directly underneath a feeder hole and enhance the feed to sections that are obscured by the legs. In the sink-in formula (3.1) the presence of a mandrel is not yet modelled, so in its current form it is not suitable for calculating this offset variation.

5.2.2 Effectiveness of the die deflection diagnosis

The die deflection diagnosis tool described in sections 3.6 and 4.13 enables deflection analysis of extrusion dies to be performed as part of the design process. To make this possible, simplifications to the FEM analysis process of an extrusion die under load are made in two key areas. Firstly, the pressure acting on the die is estimated by a formula (3.3) instead of a time-consuming aluminium flow simulation. In addition, the 3D model of the die under analysis is constructed automatically and in a simplified form from a 2D drawing.

As discussed in section 3.6, formula 3.3 gives a very similar estimation of the pressure acting on the die as an aluminium simulation run in DiekA. This is formula is not yet complete, however. If the ram speed or the alloy composition differs from those values used in the simulations that derived the formula, the error is expected to increase. The effects of the simplifications made to the 3D model of the die were investigated in section 4.13. It was shown that the thinner tool stack and the simplifications made to the bearing area have very little impact on the calculated deflection compared to a very detailed FEM model. Deviations stay within a few percent. The only case in which a significant error is introduced is when the area of contact between the bolster and the backer is much smaller than the back face of the backer. This can happen if a bolster is used that was not made for the specific die. In its current implementation, the deflection tool constrains the entire back face of the backer and this will make the model much too stiff in these cases. A general aspect of FEM simulations that affect the accuracy of the results is mesh density. The prototype of the application currently only supports 30,000 nodes and this means that sometimes only three elements can be used over the thickness of the bearing. It also limits the complexity of the profiles that can be investigated, as intricate profile shapes with a low degree of symmetry require more elements than simply symmetrical ones.

No direct comparison between the performance of the deflection tool and measurements on a real press can be made yet. For this reason the tool will only be used for qualitative analysis of die deflection for the time being. Despite the lack of certainty about the quantitative accuracy of its results, the tool is a very useful instrument to determine the nature of the deflection. The results show the designer which profile cavity parts are likely to become narrower under deflection, which parts become wider, and how the bearing angle is likely to change. Bearing angle changes of choked bearings only introduce small pressure changes (see section 3.2). Using qualitative analysis to make changes to the profile cavity width to correct for deflection is always better than making changes based on guess work or making no changes at all. Not only does this analysis help the design of that particular die; it also gives the designer general insights into modes of deflection of dies under load. Even in the prototype phase the first analyses of deflecting dies made with this module have been hailed with much enthusiasm by Boalgroup.

5.3 Effectiveness of the implementation

The success of the implementation of the design rules and approaches will be evaluated according to three different criteria. An aspect that is relevant to the creation of the sink-in and bearing geometry is the extent to which the geometry generated by the software is equal to that calculated and drawn by a human designer based on the same design rules. The second important criterion is the amount of time that is gained by using the software compared to calculating and drawing geometry by hand. Finally, the level of acceptance of the software by die designers at Boalgroup is evaluated.

5.3.1 Analysis of the accuracy of computer generated geometry

In this section an evaluation will be given of the differences between the sink-in and bearing geometry generated by the die design software and that drawn by a human designer based on the same design rules. In both cases the medial axis is used to find the local profile cavity thicknesses and distances to the centre of the die. Based on these parameters the pressures are calculated and balanced using sink-in and/or bearing geometry. The geometry proposed by the die design software is largely equal to that calculated and drawn by a human designer using the same design rules. The situations in which differences were encountered and the explanations for that are covered in this section.

The number of points for which the calculations are made differs between the human designer and the computer program. The human designer will try to identify points on the profile cavity where e.g. a thickness transition occurs or a long section begins or ends. He will make the measurements and calculations only on these points and interpolate the results for the points in between. The computer program works with a much higher resolution, incorporating hundreds of points on the profile cavity. It therefore only has to interpolate over short distances when drawing the sink-in contour. Lacking the insight of the human designer, the computer program is vulnerable to error if it has to interpolate over large distances. For example, it could intersect itself or the profile boundary. The added detail of the high resolution has a tendency to produce small jagged details in both the sink-in and bearing geometry that need to be smoothed in a manufacturability check. The human designer is likely to produce geometry with smoother transitions, although this does not guarantee manufacturability.

The lack of resolution in the human calculation is particularly a source of error in the bearing length calculation. The exact locations of transitions from one bearing length to another (see section 4.8) are hard to determine with just a few calculation points. For flat dies with more than one cavity, the instances of the profile are not always positioned symmetrically on the die face. This may call for different bearing lengths from profile to profile or for different locations of their transitions. These subtleties are easily overlooked by a human designer, especially when combined with a low resolution of the calculations. The computer generated geometry is much more consistent, repeatable and less inclined to take things the easy way.

As first described in section 3.5.2 the sink-in contour cannot always follow the required offsets precisely, particularly near strong variations of thickness in the die cavity. The computer program has a very well-defined way of dealing with this; favouring the biggest offsets and compensating the bearing lengths at the medial axis points that receive too big an offset. For a human designer this procedure is very difficult to carry out consistently and repeatably. Results will vary between designers and between designs.

An area where the human designer has an advantage is the handling of certain leg tips (see section 4.5 and 4.6). Automated detection of leg tips is not entirely foolproof, because the criteria or their parameters were chosen arbitrarily. Even if a leg tip has been correctly identified, it is sometimes difficult to determine over what distance on the profile section the medial axis points need to be included in the filtering. This issue is elaborated in appendix E. Further development of these algorithms can reduce the number of times that unwanted results are produced, but in the end the software developer will find that 90% of the programming effort is lost in covering for situations that occur in less than 10% of the designs. One has to accept that for complicated products like extrusion dies a computer program cannot foresee all possible situations. In the majority of cases the software will quickly and consistently construct geometry that successfully balances the exit velocity of the die. If the program produces unexpected results, the human designer is needed to analyse the situation and make the necessary changes to the geometry.

Finally, small differences in the geometry generated by the software and the human designer may be observed in profiles that exhibit symmetry. If two or more sections of a profile (or multiple profile sections between cavities on the die) are perfectly symmetrical about an axis (i.e. in terms of shape, thickness and distance to the centre of the die) they should ideally receive identical sink-in and bearing geometry. The computer program cannot always accomplish this, because the sink-in and bearing variations are not continuous functions and their exact shape depends slightly on the locations of the discrete set of medial axis points. The deviations of pressure (and exit speed) due to this limitation are, however, negligible. The human designer may identify symmetrical sections easily and assign identical die geometry to them. Contrary to the computer program, however, the designer may be fooled into seeing symmetry where it’s actually not there. Sections may have slightly different thicknesses or distances to the centre of the die. The error that is thus introduced may be much bigger than the slight asymmetry in the computer generated geometry.

5.3.2 Decreased design time

One of the objectives of the development and implementation of computer support for the design of flat dies was the acceleration of the design process. The application of both variable sink-in and variable bearing geometry means that measurements and calculations need to be made in a large number of points on the profile cavity.

An average flat die takes 30 minutes to design. The balancing of the flow typically takes about a third of that time. The rest of the time is spent on activities such as upscaling the profile geometry to allow for shrinkage, deciding on the number of cavities and positioning them on the die surface. Using the die design software on a modern desktop computer, the 10 minute design time of sink-in and bearings can be reduced to less than one minute. For complex dies with many thickness variations, the manual design time is much longer, whereas the increased calculation time of the computer generated design is much less noticeable. Similarly, for very simple profile configurations (e.g. uniform cavity thickness and a high degree of symmetry) the advantage of computer support diminishes.

The time gained by using the die design software can optionally be used to compare several design alternatives. The link between the design rules for the sink-in offset variation and the bearing length variation makes many flow control combinations possible. It could be that the designer is unhappy with the degree of sink-in offset variations of the design and wants to increase the bearing length variation. This could have many reasons. The sink-in may be too wide and/or too narrow for the intended level of flow control, there may be space constraints on the die or there may be a manufacturability related problem. This means redoing the flow control calculation. The speed advantage of the computer program pays off every time the calculation is repeated.

Another possible use for the extra design time gained by using the die design software is to run a deflection analysis. Deflection analysis using the finite element method is not feasible as part of the design process when not using the automated deflection diagnosis module. Without making use of the formula to estimate the pressures on the die, one has to do a separate aluminium flow simulation that typically takes about four hours. This does not include the time it takes to make a 3D model, mesh it, define boundary conditions and interpret the results. Replacing the aluminium simulation with the formula that estimates the pressure on the die significantly reduces the time required, but this method benefits greatly from automation. To reiterate, the tasks carried out automatically by the deflection diagnosis module are,

1. Construction of a 3D model based on the 2D design and some parameters entered by the user.
2. Meshing of this 3D model with a higher mesh density in critical areas.
3. Application of boundary conditions and forces corresponding to the pressure of the aluminium. This pressure distribution is calculated according to extrusion and profile parameters.
4. The running of the simulation.
5. Interpretation of the results in the bearing area and visualisation to the user.

Even a very experienced user of 3D FEM analysis software, who will be able to do the modelling and meshing fairly quickly, will need hours to calculate all the forces on the nodes and make a proper interpretation of the results. Considering that the average design time for a flat die, even without computer support, is half an hour, this added time is unacceptable. Using the program module the deflection diagnosis can be performed in about two minutes. This makes this tool a practicable part of the die design process.

5.3.3 Acceptance of the software tools by die designers

The die design software developed in this thesis is used by all employees of Boalgroup that design flat dies for The Netherlands and UK. The design department estimates that in 9 out of 10 cases the die geometry proposed by the software tool is usable. This includes cases in which minor edits to the geometry need to be made. A common modification performed by Boalgroup's designers is the equalisation of the bearing length around junctions in the profile, but a menu option is provided that allows this task to be performed with simple click and drag actions (see section 4.7).

The die deflection diagnosis tool was completed only recently and requires an installation of Ansys, for which Boalgroup does not have a licence yet. The deflection of a small number of dies was analysed at the University of Twente following a request from Boalgroup's designers. Without the availability of deflection data from real extrusion tests as a comparison, the quantitative part of the results from the tool was not currently regarded as very valuable. However, the qualitative results, showing the designers the modes of deflection that occurred in the bearing zone of dies prone to tongue and/or dishing deflection were considered as an eye opener. The value and acceptance of this tool can only truly be evaluated once it has been incorporated into Boalgroup's design process.

5.4 Overall results

As mentioned in sections 5.1 and 5.2 Boalgroup has undergone a development that is unusual for an extrusion company by today's norm. Rather than deciding to outsource the design of their dies, they have expanded their die design department and have increased the percentage of in-house die designs used in production to about 50% in 2008. This has a number of implications. Firstly, the supply of ready-made designs to die manufacturers often results in a reduced delivery time of the die of at least half a day, allowing Boalgroup to supply their customers with extrusion profiles quicker. This gives Boalgroup a strong competitive advantage. Furthermore, the in-house design of dies according to design rules that are applied consistently by software removes a part of the variation in the performance of dies that is experienced when they are designed by different designers at different die manufacturers. As already stated in section 5.2, 60% of the in-house die designs showed an increased performance index of at least 5%. On average, scrap production was significantly lower for the in-house die designs. This led to an increased overall productivity of about 1%

in 2007 (measured for The Netherlands and UK plants) and is expected to be even higher in 2008. This may not seem significant, but it makes a substantial contribution to the compensation of the increasing labour and energy costs. This greatly encourages Boalgroup to continue to make use of their own die designs. It is to be expected that their productivity will continue to increase with the increasing percentage of own die designs used in production.

Chapter 6

Conclusions and recommendations

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This thesis reported on part of the research done within the Simalex project, a continuation of two previous projects that were conducted by the University of Twente in cooperation with Boalgroup. In this chapter the most important conclusions are presented. Recommendations for further research will also be given.

6.1 Conclusions

The main objective of this thesis is the structural improvement and acceleration of die design for aluminium extrusion in order to reduce scrap and increase net production output. This goal has been achieved. The insights in the extrusion process gained in this project and the design tools that put these insights into practice have given Boalgroup the belief that they are better at designing their dies than specialised die manufacturers are. With a newly established die design department around 3500 dies were designed in the last two years. The die design tool developed in this thesis is used for nearly all flat die designs intended for production in The Netherlands and the UK. The majority of the in-house die designs show an increased production performance index of at least 5% and their average scrap production is reduced significantly. As the contribution to the production of older dies not designed by Boalgroup decreases, the net overall productivity was found to increase. This greatly helps Boalgroup in dealing with the ever increasing labour and energy costs. Furthermore, the acceleration of the die design process realised by the software tools and the ability to order extrusion dies from die manufacturers with ready-made designs in many cases reduces the time-to-market of their profiles with at least half a day.

The strategy of working with in-house die designs ensures that the same design methodology is applied to all dies. This promotes the fine-tuning and further development of the design rules according to long term production results. It was found to be difficult to evaluate the performance of individual dies based on short term productions results. Particularly, influences of and variations in manufacturing accuracy, process control at the press and the actions of correctors pollute the short term performance index data of the dies. In order to be able to better optimise the effectiveness of design rules over time, these factors need to be more carefully controlled by the extruder.

It was shown through various finite element simulations that the most robust and effective way to balance the exit velocity of the aluminium is to utilise a sink-in pocket with a variable offset in combination with a short slightly choked bearing, which can have a variable length if required. As much flow control as is possible with regard to space constraints on the die should be applied by the variable sink-in. The subtle influence of the pocket geometry to the flow speed reduces the criticalness of manufacturing accuracy and allows for easy correction of the die. The slightly choked bearing significantly reduces the unpredictable consequences of die deflection on the exit velocity by ensuring permanent full contact. The overall resistance to flow is made relatively small by keeping the bearing short. A bearing length variation can be used to make fine adjustments to the flow in cases where the sink-in cannot provide it.

The above guidelines are currently not yet completely followed by Boalgroup’s designers. The traditional practice of using relatively long bearings for flow control has evolved to using a sink-in and shorter bearings, but the sink-in still usually has a constant offset. Nevertheless, this more robust method of flow control has already contributed to an increase in performance index of the majority of dies, as mentioned above.

In order to greatly reduce the need for unforeseen manufacturability related modifications to the die design, manufacturability is taken into account at design time. The sink-in contour and bearing length function that are designed to balance the exit velocity can be made manufacturable by modifying the geometry according to the available mills. The deviation from the required flow resistance that this introduces is either kept within a controlled tolerance margin or compensated for with other geometry.

A software tool was implemented that automates flat die design according to these principles. The central component of this implementation is a discrete form of the medial axis transform. This skeletal representation of the profile geometry provides a central framework upon which the flow resistance that the aluminium experiences due to the die geometry is expressed as a pressure. After this transform is executed the software has immediate access to important parameters such as local thickness of the profile cavity and distance to the centre of the die. These parameters are very hard to identify unambiguously, by a computer program or otherwise, if the geometry is represented as a boundary only. The medial axis was also used effectively in the manufacturability analysis and the die deflection diagnosis. In the manufacturability analysis of the sink-in contour the medial axis provided the most effective way to find the minimum width of passage for an end mill to make the contour. The medial axis was also used to maintain the relationship between points on the boundary on either side of the profile cavity. This allows bearing length variations that are “symmetrical” and therefore suitable for one-pass milling.

The medial axis transform generates some data that is not valuable input to the algorithm that calculates the flat die geometry. An example of this are the small maximum circles associated with side branches of the medial axis, which are not representative for the local profile cavity thickness. The software requires some filtering algorithms in order to exclude or ignore such unwanted data. These filters are tailored to deal with input that is expected from extrusion profiles. A flawless performance was not realised, nor is it expected to be possible. Skilled personnel, which remain indispensable to an extrusion company regardless of the performance of design automation, are required to scrutinise and if necessary correct the geometry proposed by the design software. Nevertheless, in approximately 9 out of 10 cases the results proposed by the flat die design software tool that was developed as part of this study are found to be usable by Boalgroup's designers. The tool offers a significant increase in design speed and consistency compared to manual application of design rules and drawing of geometry in CAD.

A software tool for the prediction of the effects of die deflection on individual die designs was also developed. The forces on the die for the specific profile shape and extrusion ratio are calculated using a formula that replaces a time-consuming finite element simulation of the aluminium flow. These forces are applied to a simplified 3D finite element model of the die. The simulation of the die under load takes less than a minute and the deflections in the bearing area are quantified and visualised to the user. This provides a useful and time efficient diagnostic tool to check the influence of deflection on the bearing angle and displacement as part of the die design process. The implemented prototype of this tool does not support a sufficient number of elements to analyse complex profiles. More validation of the tool's quantitative results is required by comparing its results to actual extrusion tests. However, the results calculated by the tool come very close to those calculated by much more detailed and time-consuming FEM simulations. Furthermore, the mode of deflection that can be observed from the results of using this tool is expected to be accurate. This tells the designer where the bearing of the particular die will be deflected and also helps to build his general insight into the effects of die deflection.

6.2 Recommendations

So far the design rules and geometry generation tools offered by the flat die design software were predominantly used to create designs with a constant sink-in and short variable bearing lengths. Insufficient practical results are available to conclusively prove or disprove the benefits of the use of a sink-in with variable offsets. Many die designs still feature parallel bearings, which could explain the remaining minority of die designs that have not shown improved performance indices. The author recommends that more designs with variable sink-ins and slightly choked bearings are taken into production. Slight changes to the (coefficients in the) design formulas may be needed to fine-tune the performance.

Apart from changes to the values of coefficients to more accurately model the effects of, for example, profile cavity thickness or distance to the centre of the die, some further changes may be called for in the design formulas.
For the bearing length formula to be a more accurate representation of the resistance to flow, the influence of the thickness of the channel should be included. Further FEM investigations are needed to accurately describe the resistance to flow of a non-relieved bearing of some length. This research could amend the existing formula 3.2, or could result in an extra term in formula 3.1. The latter is preferred, because it would describe the average inflow pressures due to the sink-in and bearing in the same formula. This would, for example, make it easy to calculate the flow balancing geometry in such a way that the total resistance to flow is minimised and higher extrusion speeds could be realised. In FEM

simulations that investigate the influence of a longer bearing in the presence of sink-in geometry, it could also be determined if the sink-in and bearing geometries can indeed be viewed as additive sources of flow resistance, as they are now, or that they influence each other's behaviour in some way.
In the sink-in formula 3.1 it can be seen that the presence of a sink-in reduces the effect of the profile cavity thickness on the pressure. This is plausible, because the sink-in changes the flow pattern of the aluminium towards the bearing channel. For the same reason, however, the presence of a sink-in will also have an effect on the container effect (the influence of the distance of the point to the centre of the die) [39]. This is not currently modelled as such and may be the object of further study.
Further research into the formula that estimates the pressure acting on the face of the die (formula 3.3) is also recommended. It is expected that the bearing length and angle will affect the pressure acting on the die, because they influence the pressures in the bearing area and consequently the extrusion force as a whole [10].

The design rules implemented in the software were derived for typical production conditions at Boalgroup's extrusion plants. Ram speed, temperatures and alloy composition were not varied. Good transferability of the design rules was achieved with Boalgroup's UK plant. However, if any of these conditions change, it may be necessary to fine-tune coefficients in the formulas or include extra parameters that describe these new variations. Particularly the influence of the ram speed, which has been shown to have a significant impact on exit speed uniformity [19] and the load on the die face, will likely call for an update to the design rules in the near future. The same applies if other aluminium alloys are to be extruded. The relationship between alloy composition and exit velocity uniformity was shown by Nagao [18].

Before the fine-tuning of the design rules will have any noticeable effect, great progress should be made by gaining more control over process variations. It was noticed that variations in the performance of repeat dies, measured in terms of a die performance index, were often due to other factors than die design. Examples of such factors could be the manufacturing accuracy of the die, variations in billet and die preheat temperatures or press parameters and actions of different correctors. If manufacturing accuracy can be reliably measured by the extruder then it is much easier to check whether the manufactured die matches the die that was designed. It was shown that the manufacturing accuracy of die makers can be significantly increased if their mistakes are pointed out to them [36]. If external factors like this cannot be controlled and it remains difficult to relate die performance to die design, then the advancement of design knowledge is hindered. Boalgroup has made an important step towards addressing these issues by recently investing in a 3D scanner for their dies.

Even though the die design application for the creation of sink-in and bearing geometry is already a part of the daily operation at Boalgroup, some improvements can be made to it. An algorithm to ignore small thickness variations at junctions in the profile cavity may be added. Currently sink-in and/or bearing geometry is created in those areas that requires manual edits from the designer. For the bearing geometry these edits were automated, however.

A modification is also recommended for the die deflection software tool. It was shown in section 4.13 that much more accurate results can be obtained by restraining the back face of the backer only in the area of contact with the bolster. This is easily achieved by prompting the designer to indicate the contour of the bolster cavity with a mouse click, in the same sequence in which he indicates the contours of the die relief and the backer in the current implementation. The series of automatically generated commands that apply the constraints to the backer is easily modified to accommodate this small change. This would greatly improve the accuracy of the results of the die deflection diagnosis in cases where the bolster contour differs greatly from the backer contour. The extra effort required from the designer executing the analysis is minimal.

The die design application discussed in this thesis does not cover the entire design process of flat dies. For example, the decision of the number of profile cavities and their positioning on the die can also be automated to a large extent. This is currently covered by separate software developed by Boalgroup. A design feature that is not yet covered is the back relief of the die. The designer specifies the desired clearance and relief angle to the die manufacturer. The manufacturer then has to check what the back face of the die looks like if these parameters are adhered to. It could be that in certain places the relief does not actually fit on the die or too little material remains to provide adequate support. The contour of this relief on the back face of the die is easily modelled automatically in 2D CAD based on the die thickness and the relief angle. The designer can then visually evaluate if the support is adequate.

The angle, depth and minimum width of the back relief together with the available tools determine the manufacturer’s choice for the production process; milling or electro-discharge machining. Knowing beforehand which production process will be chosen by the die manufacturer makes the manufacturability optimisation of the bearing geometry easier, because it determines the machining direction of the bearing length function (see section 4.10). If the back relief can be modelled in sufficient detail and the mill diameters and maximum working depths of the manufacturers are known then the choice of production method can be made at design time. Milling is by far the most time efficient process of the two and could decrease the delivery time of the die.

This thesis showed that the design of flat dies can benefit greatly from automation. The same is expected to be true for porthole dies. The sizes and shapes of feeder holes and legs could be quickly calculated and modelled on the basis of design rules. To incorporate the changes in the flow distribution toward the die plate compared to flat dies the sink-in design rule should be updated. To a large extent the design of porthole dies can be kept in 2D and this is still the common practice in the die making industry. A disadvantage is that due to the complex nature of porthole dies the geometry definition will often be incomplete or ambiguous. Parts that are not fully defined are often completed according to machine operators' own judgement. This introduces variety between repeat dies and puts a greater demand on the level of expertise of machine operators. A way to overcome the ambiguities is to model porthole dies in 3D. There are two main obstacles, however. Firstly, it is difficult to construct a full 3D model of a porthole die with all its curved surfaces in a CAD program. The development of a (partly) automated module for drawing 3D dies based on design rules imbedded in the software will be a time-consuming project. A second problem is that most die manufacturers do not have the machinery to make such a 3D model with only numerically controlled machines. Many curved surfaces can still only be finished by hand tools. These are important considerations if the road to 3D modelling is to be taken.

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Appendices

APPENDIX A: MATERIAL PROPERTIES OF AA6060 AND AA6063

Source: Granta Design CES.

A.1 Properties of AA6060, T6

Typical Composition	Aluminium (Al)	99%
	Iron (Fe)	0.1%
	Magnesium (Mg)	0.5%
	Silicon (Si)	0.5%
Properties	Density	$2.67 \cdot 10^3 – 2.73 \cdot 10^3$ kg/m^3
	Modulus of elasticity	69.5 – 73 GPa
	Shear modulus	25 – 27 GPa
	Poisson’s ratio	0.325 – 0.335
	0.2% Proof stress	204 – 226 MPa
	Tensile strength	233 – 257 MPa
	Compressive strength	204 – 226 MPa
	Hardness (Vickers)	85.5 – 94.5 HV
	Melting point	610 – 655 °C
	Thermal conductivity	205 – 213 W/m·K
	Specific heat capacity	878 – 914 J/kg·K
	Thermal expansion coefficient	22.8 – 24.0 µstrain/°C

A.2 Properties of AA6063, T6

Differences with AA6060 are printed in bold

Typical Composition	Aluminium (Al)	99%
	Iron (Fe)	0.1%
	Magnesium (Mg)	**0.7%**
	Silicon (Si)	**0.4%**
Properties	**Density**	**$2.66\cdot10^{3}$ – $2.72\cdot10^{3}$ kg/m^{3}**
	Modulus of elasticity	69.5 – 73 GPa
	Shear modulus	25 – 27 GPa
	Poisson’s ratio	0.325 – 0.335
	0.2% Proof stress	**200 – 221 MPa**
	Tensile strength	233 – 257 MPa
	Compressive strength	**200 – 221 MPa**
	Hardness (Vickers)	**76 – 84 HV**
	Melting point	**615 – 655 °C**
	Thermal conductivity	**197 – 205 W/m·K**
	Specific heat capacity	**882 – 918 J/kg·K**
	Thermal expansion coefficient	**22.9 – 24.1 μstrain/°C**

APPENDIX B: THE USE OF FEM IN THE SIMALEX PROJECT

There are many ways in which the finite element method (FEM) can be applied to gain insights into the extrusion process. The configuration of the FEM models depends largely on the aspect of the extrusion process that is researched; the aluminium flow, the deflection of the die, or both. For every aspect there are many options. It is up to the FEM researcher to find the configuration that successfully balances the model's realism with the modelling effort and calculation time it requires. This appendix covers some of the available options and explains the choices that have been made in the FEM simulations that were done as part of the Simalex project and its predecessors.

B.1 Applications of FEM to die design

Figure B.1 shows some of the options for various kinds of simulations of the extrusion process. It is separate in columns representing the aspects of the process that can be simulated and lists considerations for each.

		simulation of AL flow	**simulation of die deflection**	**simulation of both**
WHAT		exit velocity, temperature, extrusion force, dead metal zone formation	deflection and/or zones of plastic deformation	both
HOW				coupled / decoupled approach
	thermal aspects	isothermal / heat transfer		
	FEM formulation	updated Lagrangian / Eulerian / ALE	updated Langrangian	both
	material model	viscoplastic / elasto-viscoplastic	elastic / elastic and plastic	combination of both
	friction model	areas of stick and slip		
		Coulomb or shear model		
	geometric complexity	2D/3D, number/type of elements, symmetry, geometric details		
WHY		simulate existing dies with poor performance		
		simulate future die designs		
		conduct experiments		

Figure B.1 Possible applications FEM when applied to the die design

Unlike simulations of the aluminium flow through a rigid die, investigations into die deflection require the die to be modelled and meshed. Especially the combination of the simulation of the flow and the die deflection is very time-consuming. The die deflects under influence of the forces exerted by the aluminium. This deflection may change the flow characteristics of the aluminium, which in turn may again influence the forces exerted on the die, etc. The heat generated by the large deformation of the aluminium (a temperature increase of up to 100°C [9]) is also transferred partly to the tooling, influencing the die's mechanical properties. In order to take this heat transfer into account, the supporting geometry, such as a part of the container, should be included in the finite element model [9]. This finite element model, with all the dependencies mentioned above, would be huge and calculation times would become very impractical. For this reason it is common to simplify the model in a number of ways. The following sections will discuss these further.

B.2 Decoupled approach

For simulations investigating the aluminium flow through the die, it may be decided to assume a rigid die if the deflections are not expected to be significant [19]. If the focus is on the deflection of the die, the aluminium simulation may be skipped and the pressure on the die estimated (see section 3.6). The calculation of these two aspects can also be decoupled, as suggested by Mooi [9]. Using this technique the forces on the die are determined from an aluminium simulation with a rigid die. In a separate simulation the deflection of the die is determined. If desired the flow of the aluminium through the deformed die can then be simulated. Apart from greatly reducing the problem's complexity and calculation time, this splitting technique has the additional benefit that further simplifications can be applied to individual simulations instead of to the whole model. For example, the simulation of die deflection can be made isothermal whereas thermal effects are included in the aluminium flow calculation (see section B.3). In some cases one of the two simulations may also be simplified by a 2D representation. These further simplifications can drastically reduce calculation time at the expense of only little accuracy [9].

B.3 Thermal aspects

In order to fully include thermal effects into a FEM calculation of extrusion the problem will become very complex. The tool stack (die, backer, bolster, etc.), aluminium and container have different starting temperatures and the heat that is generated during the extrusion cycle is dissipated through the aluminium itself and to the geometry around it. If this temperature fluctuation in the aluminium is to be calculated and not just estimated, then all geometry that can absorb heat during the process needs to be modelled. This drastically increases modelling and calculation time. The less accurate, but also much less time-consuming alternative chosen for many of the Simalex simulations is to run an isothermal simulation with an estimated average temperature.

Temperature is also an important variable in the deformation of the die during the process. The modulus of elasticity of the tool steel is considerably lower at the extrusion temperature than at room temperature. For all but the utmost detailed calculations of the die deflection it will be sufficient to work with a constant reduced modulus of elasticity that is based on an estimate of the average temperature of the bearing area of the die.

B.4 Finite element formulations

Three important types of finite element formulations can be distinguished. The Updated Lagrangian formulation is very suitable for problems of solid mechanics, such as a die undergoing deflection due to the extrusion pressure. The finite element mesh follows the shape of the material as it deforms. History dependent properties such as strain hardening are easy to take into account. When modelling an aluminium billet that is being extruded the deformations are very high. This is where an important disadvantage of the Lagrangian formulation surfaces. Because the mesh moves with the material, the mesh distortion often becomes too great and the calculation cannot be completed. Remeshing or mesh rezoning after each step is a possible remedy, but comes at the cost of greatly increased simulation time.

In the Eulerian formulation the mesh is stationary throughout the calculation and the material flows through the mesh. Because no mesh distortion occurs at all the calculation can continue infinitely. It is often used for fluid dynamics problems. It is also well suited for forming processes such as extrusion, but there are some difficulties. Free surfaces and the interaction between fluid and structures usually cannot be modelled, nor can history dependent properties be taken into account.

The advantages of both formulations are combined by the Arbitrary Lagrangian-Eulerian (ALE) method. In this formulation the allowed movement of the mesh may be chosen arbitrarily by the user. The calculation can follow the material and keep track of free surfaces and history dependent properties while avoiding excessive distortions of the mesh. The latter is accomplished by redefining the mesh for each new step by using remapping techniques [9]. The mesh topology remains the same, unlike in remeshing techniques. History dependent parameters are remapped onto the new mesh. This is very well suited to the modelling of the aluminium flow and is the formulation of choice for Lof’s experiments of the flow resistance of the bearing geometry [10].

B.5 Material models

Apart from controlling the behaviour of the mesh the material model is also a very important aspect of a finite element simulation. The behaviour of aluminium flowing through the die is strongly influenced by temperature and deformation rate. It is often represented by a viscoplastic material model, which neglects elastic deformation. In the overall process elastic deformation constitutes a negligible fraction of the total deformation [9], but in the bearing area elastic behaviour plays a major role and has a strong influence on the simulation results [10]. For simulations investigating the exit velocity of the aluminium an elasto-viscoplastic material model was therefore the model of choice [10]. Rate dependency can be incorporated into both viscous and elasto-viscoplastic models. Hardening of the aluminium is usually neglected, because it is largely counteracted by dynamic recrystallisation in the temperature range occurring during extrusion [9]. For viscous models the relationship between stress and strain rate is described by the Sellars-Tegart law. The parameters in this formula are specific to the aluminium alloy. A temperature dependent strain rate parameter can be added in order to include an elastic region. This modified Sellars-Tegart law is therefore compatible with an elasto-viscoplastic material model [10]. As mentioned in chapter 2 the Simalex simulations were carried out only for one alloy that is commonly used at Boalgroup, AA6063. Other alloys can be modelled by changing the elastic and plastic properties (see appendix A.2) in the modified Sellars-Tegart equation.

Contrary to the aluminium being extruded the deformation of the steel die is mainly elastic and therefore reversible. Some permanent deformation may occur [9], although this applies mostly to porthole dies and not to flat dies. Mooi offers the occurrence of creep and thermal ratcheting as possible explanations for this behaviour and suggests formulae that describe this behaviour. These formulae can be built into an existing material model.

B.6 Modelling friction

No lubrication is used in common aluminium extrusion practice and the stick between the billet and container is exploited to shear off the oxidised and impure outer layer of the billet. Stick also occurs in most other areas of the interface of the aluminium and the tooling. Only in the bearing area the pressure may decrease to an extent that frictional stresses no longer exceed the internal shear strength of the aluminium. In such cases the aluminium will slip along the die surface [10, 19]. For areas in the finite element model where slipping friction is permitted, the Coulomb friction law [10] or a shear friction model [19, 28] can be used. The former is used in the simulations of the flow resistance in the bearing area.

B.7 Mesh and geometry considerations

Another factor that greatly influences calculation time is the mesh density. A fine mesh is necessary at locations in the model where the deformation gradients are expected to be great. In other places a coarser mesh may often suffice. The greater the number of elements in a model, the greater is the calculation time. The bearing area deserves particular attention. Not only are deformations very large (in the case of an aluminium simulation), the behaviour of this part of the model can also greatly influence the results. Particularly in an aluminium flow simulation there is a strong urge to mesh the bearing area very finely. With a coarse mesh and a sharp corner, schematically shown in figure B.2a, the corner node that is fixed due to the boundary conditions has a great effect on the velocity field in the element in the bearing. It causes the bearing to behave as a much narrower channel with a greater resistance to flow. Using the equivalent bearing model in figure B.2b, Lof [10] solved this problem without resorting to a much finer mesh. This bearing model uses a triple node construction in order to prevent the locking effect and simulate the resistance to flow of a much more finely meshed bearing area.

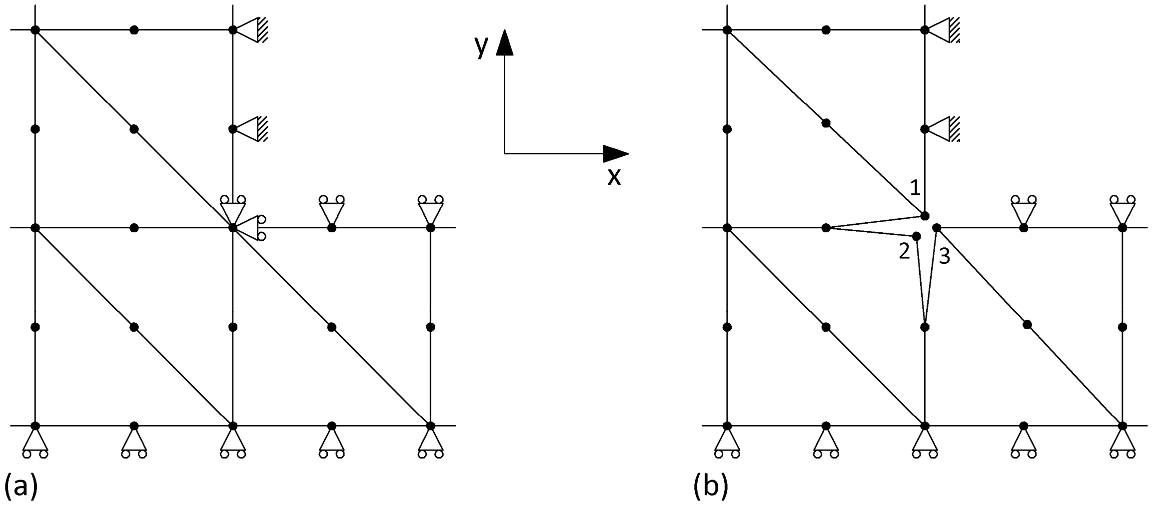


Figure B.2 Triple node construction (b) to avoid locking effects (a), reproduced from [10]. The aluminium movement is in the positive x-direction (from left to right).

In the triple node construction points 1 and 2 are allowed to move together in the y-direction and points 2 and 3 in the x-direction. It should be noted that although this equivalent model accurately describes the resistance to flow in the bearing, it is not suitable for an accurate determination of stresses and strains in this area [10].

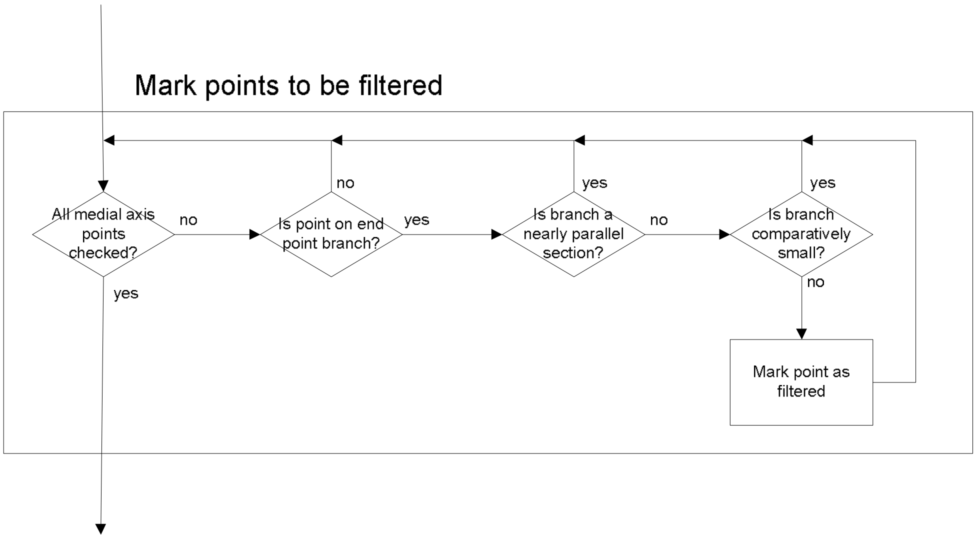
Any planes of symmetry that exist in the die that is being simulated can be exploited to make the finite element model smaller. Symmetry can also open up the possibility of representing the problem in 2D, as is the case in figure B.2. This reduces the degrees of freedom in the problem and therefore the size of the stiffness matrix and the calculation time.

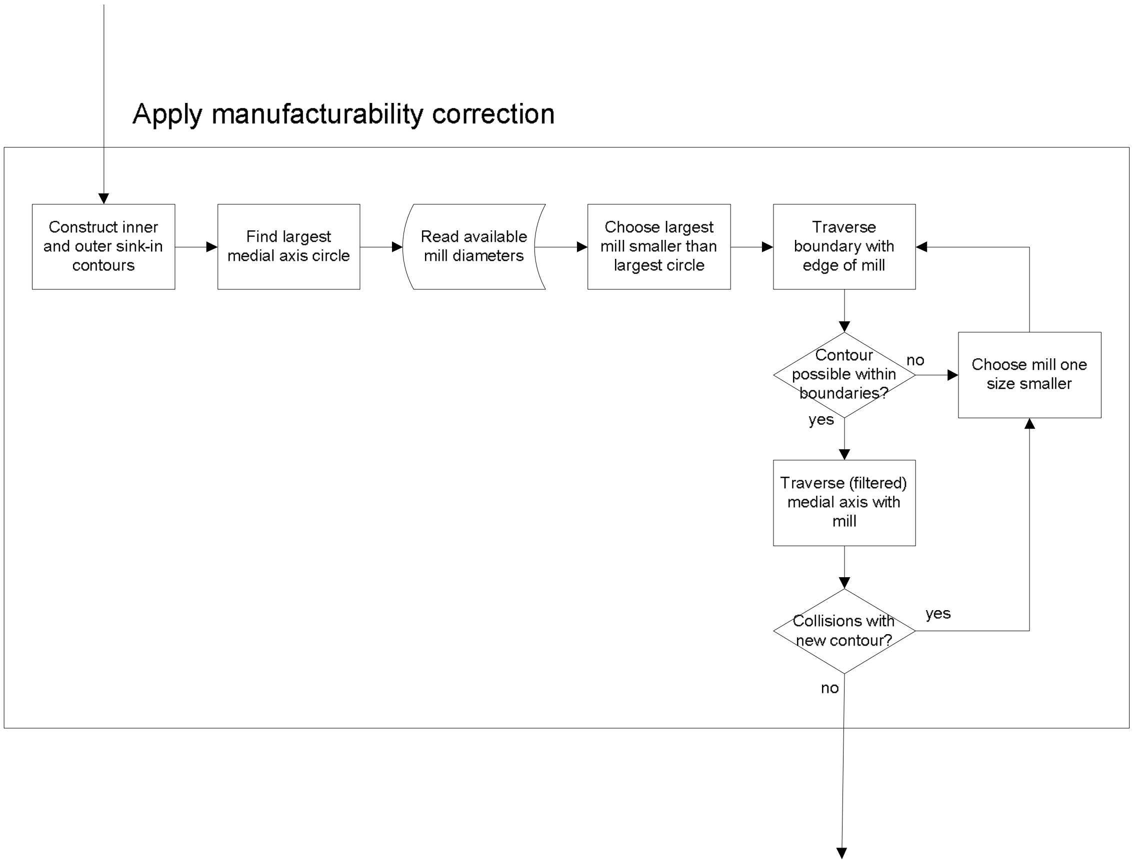
B.8 Finite element software

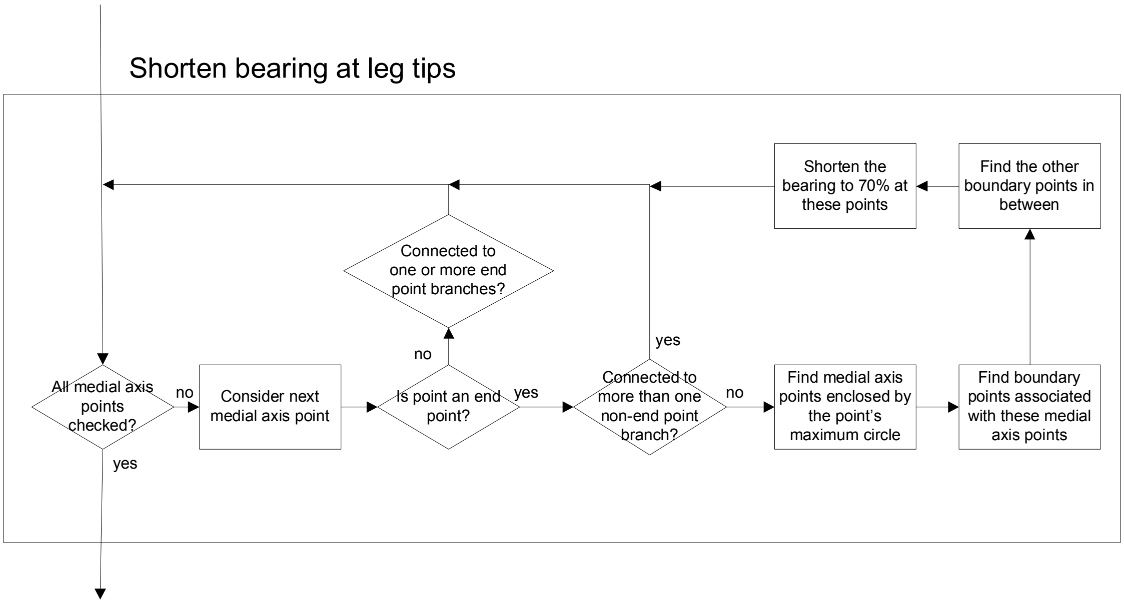
Several commercial and academic FEM packages that are suitable for simulations of extrusion are available. DiekA is an academic FEM code developed at the University of Twente over the last twenty years [50]. It is specifically tailored to simulations of processes with large deformations, such as deep drawing, rolling and extrusion. It is therefore based on the ALE approach (see section B.4). Because the updated Lagrangian and Eulerian descriptions are essentially special cases of the ALE method, they can be used also. As a locally developed academic code, DiekA can be customised exactly to the needs of experienced FEM researchers. It was therefore the code of choice for the simulations of which the results will be used in this thesis. As a commercial package DiekA is less suitable, because little is offered in the areas of a user interface and pre- and post processing functionality.

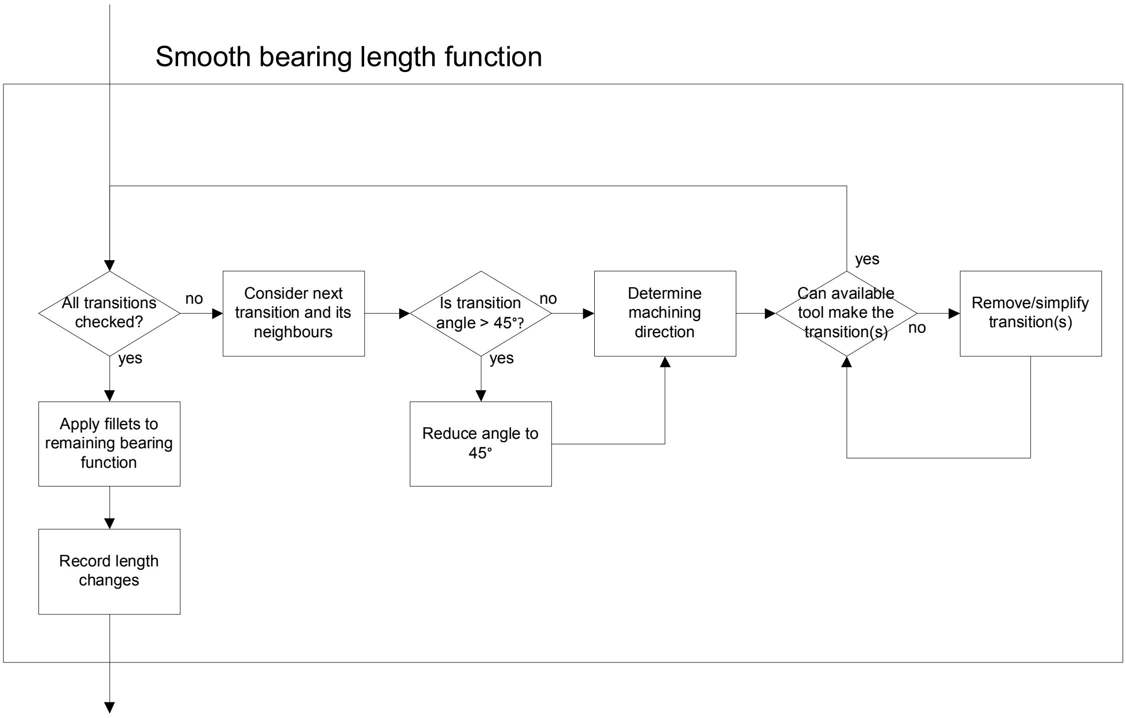
APPENDIX C: FLOW CHARTS OF THE SOFTWARE PROCESSES

C.1 Sink-in and bearing geometry creation processes

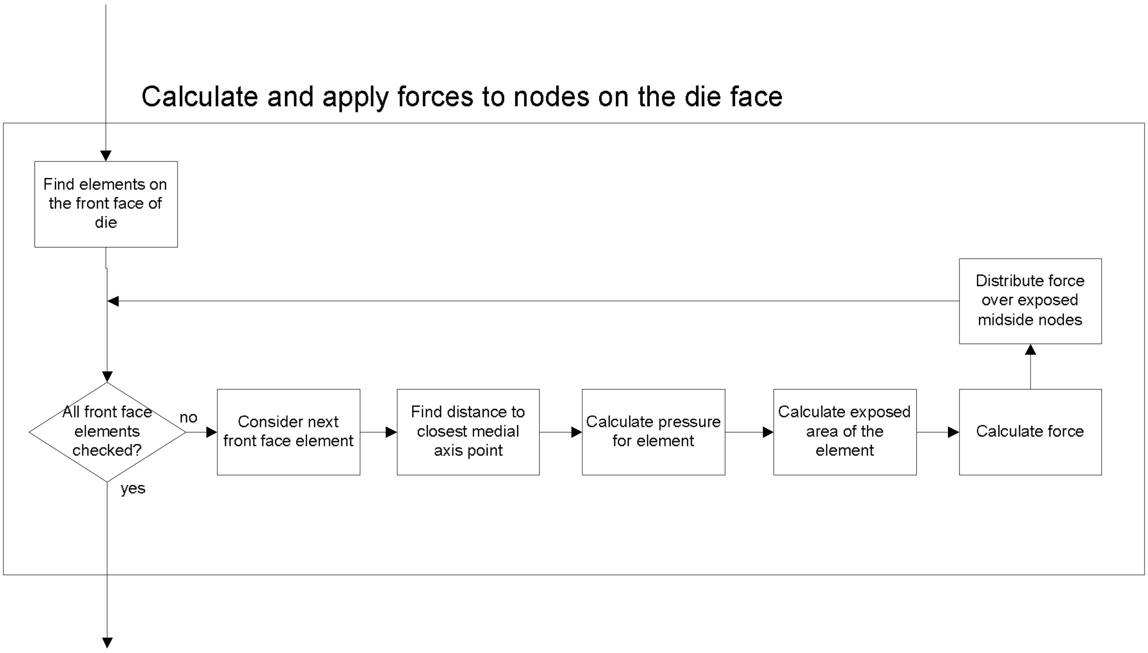


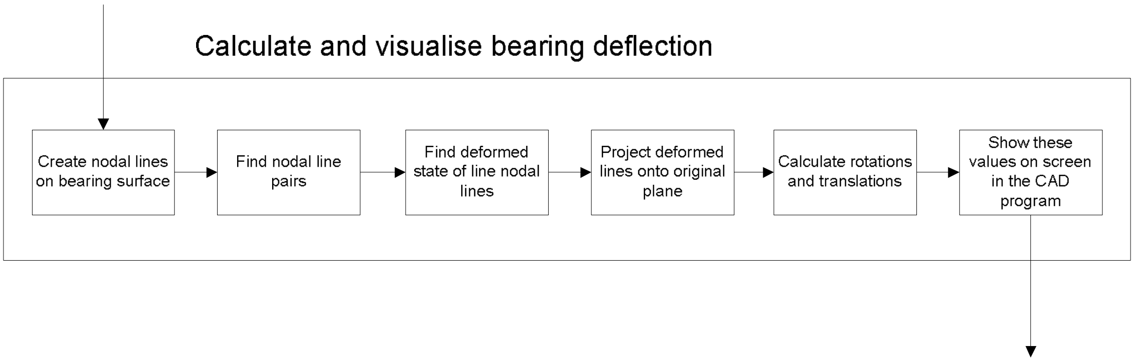



Shorten bearing at leg tips
All medial axis points checked?
no
Consider next medial axis point
Is point an end point?
no
Connected to one or more end point branches?
yes
Connected to more than one non-end point branch?
yes
no
Find medial axis points enclosed by the point's maximum circle
Find boundary points associated with these medial axis points
Find the other boundary points in between
Shorten the bearing to 70% at these points
yes


Smooth bearing length function
All transitions checked?
no
Consider next transition and its neighbours
Is transition angle > 45°?
no
Determine machining direction
Can available tool make the transition(s)
yes
no
Remove/simplify transition(s)
yes
Reduce angle to 45°
yes
Apply fillets to remaining bearing function
Record length changes

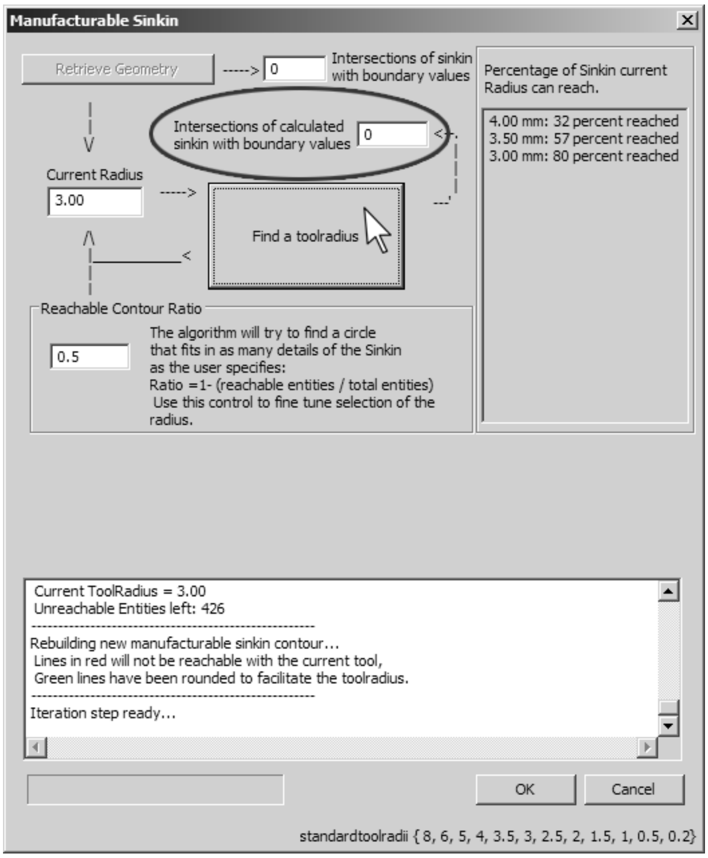
C.2 Die deflection diagnosis processes





APPENDIX D: MANUFACTURABLE SINK-IN USER DIALOG

In section 4.12 the die design application’s user interface was described. This appendix demonstrates the dialog window that appears when the user selects the *Manufacturable Sink-in* option from the drop-down menu. This dialog window is shown in figure D.1.



Intersections of sinkin with boundary values: 0

Intersections of calculated sinkin with boundary values: 0

Current Radius: 3.00

Reachable Contour Ratio: 0.5

The algorithm will try to find a circle that fits in as many details of the Sinkin as the user specifies:
Ratio =1- (reachable entities / total entities)
Use this control to fine tune selection of the radius.

Percentage of Sinkin current Radius can reach.

4.00 mm: 32 percent reached
3.50 mm: 57 percent reached
3.00 mm: 80 percent reached

```
Current ToolRadius = 3.00
Unreachable Entities left: 426
----------------------------------------------------
Rebuilding new manufacturable sinkin contour...
 Lines in red will not be reachable with the current tool,
 Green lines have been rounded to facilitate the toolradius.
----------------------------------------------------
Iteration step ready...
```

standardtoolradii {8, 6, 5, 4, 3.5, 3, 2.5, 2, 1.5, 1, 0.5, 0.2}

Figure D.1 *Manufacturable Sink-in* dialog window

The process starts at the top left corner of this window. By clicking on the ‘Retrieve Geometry’ button the relevant data from the CAD drawing of the die design is read. The presence of a sink-in contour is required for this tool to work. Based on this sink-in, the profile and medial axis data, the inner and outer sink-in contours that represent the pressure tolerance margin (see section 4.9) are calculated. The available tools, which can be customised for a specific die manufacturer, are shown in the bottom right of the window. The algorithm that assesses the manufacturability of the sink-in contour starts by trying the tool that is closest in diameter to the largest circle that can be drawn inside the contour. It is evaluated if the contour can be milled with this tool diameter while staying between the inner and outer contours specified by the pressure tolerance margin. If this is the case the number of intersections, displayed within the ellipse, is found to be zero and the process stops. If there are intersections, the process is repeated for a smaller tool diameter until no intersections remain. In the example shown in figure D.1, a tool diameter of 3 mm can successfully cut a contour within the specified margin. Diameters 4 mm and 3.5 mm were found to have intersections. Using the tool of 3 mm in diameter it is indicated that 80% of the geometrical entities (lines and arcs) of the original sink-in can be reached. If the designer wishes to more closely match the original contour, he can choose to reduce the value of the Reachable Contour Ratio (shown here to be 0.5). This may result in a smaller tool diameter to be chosen.

APPENDIX E: END POINT FILTER OPERATION

This appendix elaborates on the operation of the end point filters that were implemented in the die design software (see sections 4.5, 4.6 and 5.3.1). It describes a case in which small medial axis radii at leg tips are not successfully filtered, despite having been properly identified. Figure E.1 shows the sink-in contour that results if this issue occurs.

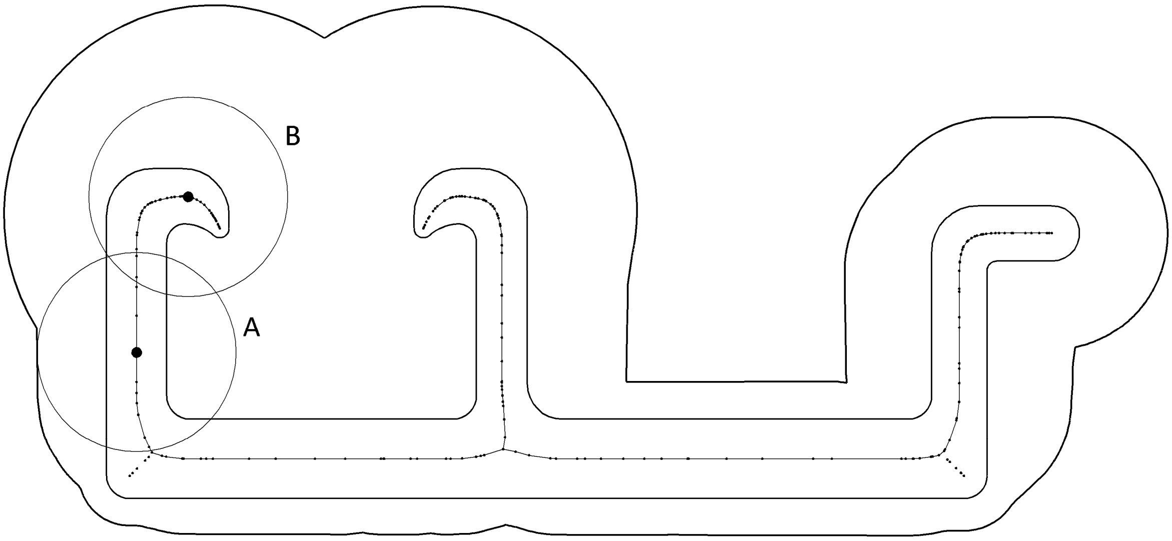


Figure E.1 End point filter not working as intended

Circle B represents the sink-in offset that would be expected near this leg tip based on the local cavity thickness of this section and its distance to the centre of the die (approximately equal to the offset circle A). As can be seen the actual offset drawn by the program is much bigger. The program detected the leg tips, but failed to judge correctly the length on the medial axis over which these leg tips extend. Figure E.2 clarifies this.

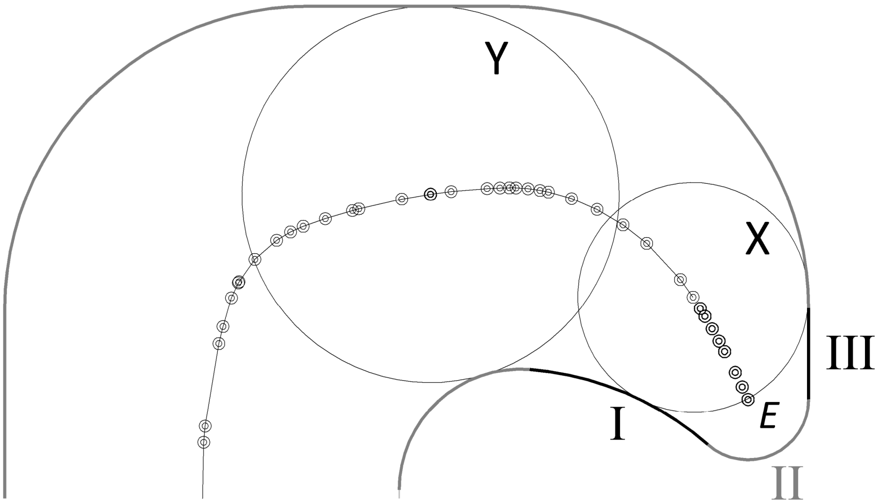


Figure E.2 Detail of the leg tip

Point E was identified as an end point and the angle of the boundary arc entity II is such that this profile detail qualifies as a leg tip (see section 4.6). The algorithm now finds the medial axis points associated with the entities before and after arc II, being arc I and line III. These medial axis points are considered to be part of the leg tip. Their offsets are copied from the point just before them. This point has a local width given by the diameter of circle X. The medial axis points between circle X and circles Y are not classified as leg tip points, so their local thicknesses are evaluated as normal. This explains the large sink-in offsets seen in figure E.1. Although this may be a matter of debate, a human die designer is likely to consider circle Y as the beginning of the leg tip. This would create a sink-in that is much narrower around this profile cavity section and better suited to the local resistance to flow exerted by the profile.

In this case the program would have been more effective if more medial axis points before the end point had been considered to be part of the leg tip. These points can be found by changing the algorithm to include more boundary entities before and after arc II. However, this may be detrimental to the performance of the algorithm in other situations. Any change like this would call for many extra criteria (e.g. related to the scale and curvature of the leg tip) that need to be implemented for satisfactory performance.

The phenomenon where the software judges the length of a leg tip incorrectly has an unfortunate side effect. Small profile thicknesses that should have been ignored in the calculation are now included. The absolute thickness variation is bigger than it should be, so the resulting variation in sink-in offsets will also be bigger. In this case the maximum offset will be assigned to the leg tip section and the other sections will receive offsets that are much too small. In other words, the incorrect handling of a small detail has negative implications for the entire flow balancing geometry; both sink-in and bearing. This requires the geometry to be recalculated and redrawn by hand. A solution to this problem would be to build more interactivity into the application of filters. The user could, for example, indicate to the program how long the leg tip should be and the program could ignore the appropriate medial axis points in the calculation. This functionality has, however, not been implemented yet.