

**High Speed Cutting
and
Electric Discharge Machining
as Complementary Processes
in the Die and Mould Industry.**

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work (unless specified otherwise) and that I have not previously, in its entirety or in part, submitted it at any other university for the purpose of obtaining a degree.

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Synopsis

High Speed Cutting (HSC), specifically milling is a significant contemporary development in machining. The Die and Mould industry is experiencing a difficult business climate. There is competitive pressure for shorter lead times and lower prices. Companies worldwide, are under financial pressure, to meet the challenges of a globalised business environment.

The conventional position of milling and Electric Discharge Machining (EDM / Erosion) is discussed with the proposal to use HSC and EDM as complementary processes. Among new developments the progress in computer infrastructure is prominent. There is also a paradigm shift that should be made from experience based process planning to modern, up to date knowledge based process planning. High Speed Cutting is now a mature process capable of acceptable process security. The examples detailed include crankshaft-forging tooling, injection moulding tooling and powder sintering tooling. A process chain is proposed for the complementary HSC / EDM process with estimated illustrative time saving over the conventional EDM dominated process. HSC will be the first process removing the bulk of the material, finishing as far as possible and with EDM finally machining the features that will be difficult or impossible with HSC.

To facilitate the use of the complementary processes a decision model to determine the crossover point between HSC and EDM is proposed. The decision model is firstly presented as a flow diagram to determine whether the task is a candidate for HSC only, EDM only, or the complementary HSC / EDM process. The key parameters e.g tool ℓ / d ratio are variables. This is in order that the flow diagram may be adapted to a specific machine tool infrastructure and expertise level in a company. The second part is a HSC machining time estimation model. The time is estimated per segment roughed, semi-finished, or finish machined. The model is in an empirical form with constants that can be adapted to the practices of a specific company. It is intended that the constants also be periodically revised to reflect the development in HSC expertise that will occur during the use HSC in the company. The model is practically evaluated with a case study, including the detail steps, not included in the model. Conceptual guidelines are given for software implementation.

It is concluded that HSC and EDM are suitable complementary processes. It is a necessary prerequisite to use pallets to avoid multiple set-ups. Complementary HSC and EDM is especially appropriate for the gradual deployment and skill development for HSC. HSC and complementary HSC / EDM is considered the opportunity for companies to make a major breakthrough in lead time and operating expense if the necessary pallet/fixtures equipment, CAx infrastructure and human capability is available.

Opsomming

Hoë Spoed Masjinerie (HSC), spesifiek frees is 'n betekenisvolle ontwikkeling in masjinerie. Die Gereedskap en Gietvorm bedryf ervaar 'n moeilike besigheidsklimaat. Daar is kompeterende druk vir korter lewertye en laer pryse. Maatskappye wereldwyd is onder finansiële druk om in die geglobaliseerde besigheidsmilieu te presteer.

Die posisie van frees en Elektriese Ontladingsmasjinerie (EDM / Vonkerosie) word bespreek met die voorstel om HSC en EDM as komplementêre prosesse te gebruik. Onder die nuwe ontwikkelings is daar prominente vooruitgang in rekenaarinfrastruktuur. Daar is ook 'n paradigmaterskuiwing nodig van ondervinding gebaseerde na op datum kennis gebaseerde proses beplanning. HSC is nou 'n ontwikkelde proses met voldoende prosesekerheid. Die voorbeelde sluit krukas smee gereedskap, inspuitgiet gereedskap, en poeier-sinter persgereedskap in. 'n Prosesketting word voorgestel vir die komplementêre HSC / EDM prosesse met 'n beraamde illustratiewe tydbesparing oor die konvensionele EDM gedomineerde prosesse. HSC sal die eerste proses wees wat die meerderheid van die materiaal verwyder en oppervlaktes so ver as moontlik afwerk, met EDM wat die finale afwerking doen en ook die masjinerie wat vir moeilik haalbaar of onmoontlik is vir HSC.

Om die gebruik van die komplementêre prosesse te fasiliteer, word 'n beluigningsmodel vir die oorgangspunt tussen HSC en EDM voorgestel. Dit word eerstens as vloeiagram gebruik om die taak te klassifiseer vir HSC alleen, EDM alleen of vir komplementêre HSC en EDM. Die sleutelparameters, bv die beitel l/d verhouding, is veranderlikes. Dit is sodat die vloeiagram aangepas kan word by 'n spesifieke masjienvermoë en 'n kundigheidsvlak in 'n maatskappy. Die tweede deel is 'n HSC masjineriestyd model. Die tyd word beraam per segment uitgerof, afgewerk, of finaal afgewerk. Die model is in empiriese vorm met konstantes wat kan aangepas word by die praktyke van 'n firma. Dit is die bedoeling dat die konstantes periodiek aangepas word om die ontwikkeling te weerspieël wat in die maatskappy plaasvind. Die model word prakties evalueer met 'n gevallestudie, insluitend die detailstappe, wat nie in die modelformulering ingesluit is nie. Konseptuele riglyne word gegee vir programmatuur implementering.

Die gevolgtrekking word gemaak dat HSC en EDM geskikte komplementêre prosesse is. Dit is 'n voorvereiste om pallette te gebruik om veelvuldige opstellings te vermy. Komplementêre HSC / EDM is veral toepaslik om HSC geleidelik in 'n firma te ontplooi en kundigheid te bou. Die HSC / EDM kombinasie word ook die geleentheid geag vir firmas om 'n deurbraak te maak in lewertyd en bedryfsuitgawes as die nodige pallettoerusting, CAx infrastruktuur en menslike vermoë beskikbaar is.

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Glossary

Ø6R1,5 – Toroidal tool specification, diameter 6 radius 1,5

2½D Simultaneous interpolation in two axes with the third incremented stepwise

3D Simultaneous interpolation in three axes

b_r Stepper / “Bahnabstand” or direction of stepwise feed (\perp to feed direction)

CAD Computer Aided Design

CAM Computer Aided Manufacturing

CAP Computer Aided Process Planning

CAX Computer Aided Manufacturing processes, Design, Process Planning etc

CMB Controlled Metal Buildup

CNC Computer Numerical Control

Cu Copper, used for EDM electrode material

d diameter of tool (\varnothing) (mm)

dia diameter of tool (\varnothing) (mm)

DMG Deckel Maho Gildemeister, German Machine Tool Manufacturer

EDM Electric Discharge Machine / Machining

EMO European Machine Tool Exhibition in Hanover

HEM High Effectivity Milling, emphasis on cut cross section and speed, up to $\pm 25\,000$ rpm

HPM High Performance Milling, similar to HPC, HEM

HPC High Productivity Milling, emphasis on cut cross section & speed, up to $\pm 25\,000$ rpm

HSC High Speed Cutting – The cutting can refer to machining, but mostly milling

H²SC High Speed Cutting of hard materials typically HRC > 40 - HSC Hard Milling

- HSM High Speed Machining, HSC Machine Tool category beyond 40 000 rpm
- HSM High Speed Milling – USA terminology equivalent to European HSC
- HSS High Speed Steel, tool material
- HVM High Velocity Machining, HSC Machine Tool category 10 000 – 40 000 rpm spindle
- IDEAS Specific CAD/CAM software

l/d ratio – The ratio of the length to the diameter (\varnothing) of the milling tool

- NC Numerical Control
- R Radius
- TiCN Titanium Carbon Nitrate – Tool coating material
- TiAlN Titanium Aluminium Nitrate – Tool coating material
- V_c Cutting speed (m/min)
- V_f Feed rate (m/min)
- WOP Workshop Oriented Programming

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1 Introduction

1.1 High Speed Cutting in the Die and Mould Industry

High Speed Cutting (HSC) and specifically milling has become, since about 1990, one of the major new technologies in the Die and Mould industry. The industry in the developed world has embraced this technology to reduce lead times, to reduce manual finishing and to lower costs. At present the South African Die and Mould manufacturing industry is not getting the share of the international business, which reflects the level of the craftsman skills or level of investment in the industry. The areas where growth is necessary are perceived to be in lead times, networking with global customer organisations and price competitiveness. The author is convinced that the deployment of HSC in the South African industry could make a significant contribution towards regaining international competitiveness for the local industry. This research aims to illustrate how the industry can retain confidence in their ability to deliver projects on time within the quoted budget while implementing a new technology, namely HSC. In Europe process security or "Prozess Sicherheit", the ability to execute projects exactly as they were planned, is a major focus of the industry. This process security can be retained while implementing HSC though the use of HSC and Electric Discharge Machining (German "Erodieren") as complementary processes.

1.2 Investigation at the Enterprise, Process and Architecture levels

The investigation is done on three levels, the enterprise level, the process level, and the system architecture level. The first objective is to investigate the business (enterprise) level challenges that the Die and Mould Industry is experiencing in a globalised manufacturing environment. It is argued that the industry is under substantial competitive pressure and can greatly benefit by implementing faster processes like the HSC process.

The enterprise level is discussed in Chapter 2. It is noted that labour and investment costs are steadily rising while profits are stagnating. Globalisation is changing the face of the industry's customer. There has been growth of the enterprise type of system supplier and the trend of customers wishing to reduce numbers of suppliers. The changing business environment can be summed up in two major challenges, to reduce the time to market and at the same time to reduce cost.

The process level is discussed in Chapter 3, Process Chains. The new process chains typically include HSC. The more conventional process chains rely heavily on the much slower Electric Discharge Machining (EDM). From the process point of view, the demand for shorter time to market is highly significant. The rapid prototyping industry has developed into a mature industry. This industry is ready to move into new markets. It has the basic advantage of business structures focused on quick project delivery. The rapid tooling technologies have also advanced and can now deliver longer life tooling at competitive costs. Some of the new processes namely conformal cooling and abrasive flow machining are discussed. These processes may enable the rapid prototyping / tooling industry to successfully compete in the growing "shorter time to market" segment of the Die and Mould market. For the Die and Mould industry to successfully defend this growing "shorter time to market" segment of their market, faster processes like HSC will have to be introduced. Part of the second objective is therefore to show that HSC machining, specifically HSC milling is the key technology for a Die and Mould business to meet these new requirements. HSC however has several limitations. If HSC and EDM are used as complementary processes the benefits of HSC can be exploited.

The background investigation also includes an operational perspective, which includes system architecture factors. The industry consists of predominantly smaller companies with experienced craftsmen. It is considered necessary that the industry move away from the business concept of a craftsman centred technological capability. Unfortunately the craftsmen's skill sets become static and lose touch with the market developments. Examples are quoted in the text where craftsmen feel comfortable with the old slow processes and hinder the development into new technologies like HSC. The industry needs to move to a business model where the technology needs are deduced from market demands and embedded in the business processes, manufacturing processes and the system architectures as a whole. The third objective will be to show that complementary HSC / EDM is indeed feasible. Although everything is not in place at the present moment, it will be argued, that with

development towards a creative technologically based industry, enabled by appropriate integrated CAx (CAD, CAM, CAP) systems and fixturing, which minimises skilled but non value adding operations, the business benefits will be within reach with complementary HSC/EDM.

1.3 Overview of HSC Technology

In the cases where HSC milling can be used there is a very large improvement in the completion time of the project. In the chapter on High Speed Machining it is discussed how HSC can respond to the market need by reducing the time to market. The way in which HSC can replace EDM to achieve the same goal is also discussed. HSC is however a rather vaguely defined technology. HSC is mostly defined as using cutting speeds, which are significantly beyond common industrial practice. The problematic nature of this definition is discussed against the background of the technology now having reached the stage of widespread industrial use. The terminologies e.g. H²SC and Hard Milling, of leading German research institutions are presented. The limitations of HSC, for example the problem of long slender tools and small radius features at relatively large depths are discussed. Later in the text these tool length to diameter ratio limitations become part of the decision model.

The concept of complementary use of HSC and EDM is confronted with the issue of double set-ups. The question arises whether setting the work piece up firstly in the HSC machine and then again, in the EDM machine does not eliminate the potential time saving. In paragraph 2.6 the practice is indeed described where the company policy is as follows: If a project is technically feasible with HSC, no other process is considered and HSC is used. If there is any part where however only a small amount of EDM is necessary, the entire project is done with EDM. It is a basic assumption that the time loss of a second set-up and divided (craftsman based) responsibility will eliminate the benefits of a combined process. A relatively new fixturing technology where all the machine tools are equipped with quick couple pallets elegantly solves this problem. Repeatability of 2 – 5 µm is achieved which is well within the accuracy requirements of the Die and Mould industry. In principle, this makes it possible to fix the work material and the electrode material on pallets and load them into a magazine. After loading the CNC and robot programs, the process can be completed without any further human intervention. The process will then typically consist of HSC milling of the electrode, HSC Hard Milling and finally the finishing of deep cavities and deep sharp edges with EDM of the work piece. The quality assurance both in process and for final acceptance will be performed by

transferring the pallet-mounted work piece to a pallet receptacle on a Coordinate Measuring Machine. An industrial robot or a human could perform the work piece and tool handling. Automation (robot handling) is perfectly feasible with the current state of the technologies. It can increase work hours to 24 hours per day. The daytime will be used for the human part of the operation namely programming and set-ups on pallets and the machining could take place 24 hours of the day.

In the light of the financially difficult position in which many smaller Die and Mould Manufacturers find themselves, pallet technology is equally feasible for manual handling. The capital investment in pallets and receptacles alone then becomes small compared to the benefits of complementary HSC and EDM as well as the extended operation hours resulting in shorter lead times.

1.4 HSC and EDM as Complementary Processes

The nucleus of the work lies with the second objective i.e. to show that HSC and EDM used expertly in combination can yield shorter manufacturing times. According to general management theory, a shorter manufacturing time in the key manufacturing activities results in higher throughput, and ultimately has a positive influence on time to market and towards reducing cost. A key issue is the decision when a specific one of the two processes should be used to achieve synergy beyond the sum of the individual processes. The decision model described in the text is presented as two steps. The first is presented as a flow diagram to indicate which process of HSC only, the conventional milling and EDM chain and the complementary HSC / EDM is the best suited process. The second part is intended to be a mathematical model to ultimately predict the HSC machining times and material removal rate per stage of the HSC process. The process planner should then be able to determine when the HSC process becomes slower than the potential rate of progress of EDM. This then becomes the optimum changeover point from HSC to EDM.

1.5 Case Study and Use of the Model

In order to demonstrate how the decision model works and how it can be applied, a case study is presented. For the purpose of clarity, a relatively simple example of the tool of a medical injection ampoule holder was used. The decision model has a number of variables to accommodate varying skill levels and different capability machine tools in industry. The intention is that the model may be set up to suit a situation in industry where the company has just bought a HSC machine tool and there is still very limited HSC expertise. The model will then allocate work to HSC,

which is easy to program guaranteeing process security. As the level of expertise in the company grows, the parameters of the model are adjusted to gradually allocate more complex HSC work and less work to the EDM part of the process. In this way, the model could facilitate gradual growth into HSC technology retaining process security throughout the learning process.

As a final result, it is aimed to illustrate how the use of HSC and EDM as complementary processes will contribute towards enterprise level competitiveness, through increased process effectiveness.

1.6 Research Objectives

The following objectives are set out as the goal of this research:

- 1.6.1 To investigate the demands of the globalised manufacturing business environment of process chains in the Mould and Die industry.**
- 1.6.2 To promote the complementary HSC/EDM process as a strategy with which HSC can be introduced to the Mould and Die Industry in the developing world and specifically South Africa, for increased business competitiveness, with manageable process security.**
- 1.6.3 To prove that the complementary HSC/EDM process is conceptually feasible and that multiple set-ups can be avoided.**
- 1.6.4 To present a decision model conceptually that will enable a user to do complementary HSC/EDM process planning.**
- 1.6.5 To validate the decision model with a case study.**

2 Challenges Facing the Die and Mould Industry

2.1 Introduction

The approach in this chapter is to study the Die and Mould Manufacturing Industry as one of the most prominent “customer” industries and to determine the requirements that are to be met by the emerging machining technology, specifically here High Speed Cutting. Electric Discharge Machining (EDM), the current default key technology in the industry will also be examined in the light of these contemporary requirements.

HSC, which is the central foundation topic of this research project, has the potential to find prominent application in the Die and Mould Making Industry. The objective of this chapter is to discuss the threats and opportunities that exist in the Die and Mould Manufacturing Industry on the enterprise level. These modern day requirements as expressed by Antonana (2000:4), Eversheim (2000:6), include for example reduced delivery time enabling the system supplier a reduced time to market, lower cost, and increased flexibility in a global market. As will be shown later, the complementary use of HSC and EDM is considered one of the key technologies to enable the Die and Mould Industry to use these challenges to improve business competitiveness.

2.2 Profile of the Die and Mould Industry

2.2.1 Introduction

This view of the industry is discussed from the perspective of the International Special Tooling and Machining Association, ISTMA. ISTMA is an international federation type of association of twenty-four tooling and machining associations throughout the world. ISTMA seems to be the largest association of its kind with the bulk of Western Europe, North America and the East represented. Large parts of South America and Eastern Europe are however not represented (Antonana, 2000:3).

2.2.2 Die and Mould Company Profile

The average annual company turnover per employee varies in a narrow band from 60 000 Euros to 120 000 Euros with an average of 85 000 Euros (Antonana, 2000:6).

The average number of employees in Europe is considered a fair indication of the industry at 23 employees per company (Antonana, 2000:6).

The resulting turnover of the average company is therefore approximately 2 million Euros per annum. It can therefore be concluded that the Industry is predominantly a small business operation Industry. This statistic may support the observation at the Braun¹ Die and Mould manufacturing facility that the core expertise in the industry is craftsman and experience based as opposed to technology and innovation based.

2.2.3 Business Trends

A few trends, which may have a bearing on the demand for High Speed Cutting and HSC in combination with EDM, are detailed.

Internationally the total investment in machinery as a percentage of turnover is increasing. This is the case in Europe and in the world as a whole. Total investment at 11% of annual turnover seems to be under control but many firms are spending above 5 % and up to 12% of turnover annually on new equipment alone. Seen against the backdrop of a constant 5% profit before tax since 1995 which Antonana calls profit stagnation, it is deduced that this trend will have to be offset by better utilisation of the machinery. (Antonana, 2000:3-11)

Labour cost is a very significant cost at just above 45% of turnover in Europe and only marginally lower worldwide. This risk factor is singled out by Antonana as one of the most important problems of the industry. The secondary risk factors are a scarcity of skilled workers, pressure on prices and the continuous pressure to reduce the time to market. All these risks, against the backdrop of stagnating profits, really demand drastic attention. It can safely be concluded that the cost of skilled man-hours will have to be extended to more machining hours than currently. Eversheim (2000:12) specifically states that one person should be operating several machines. The industry is already finding it necessary to work considerably more hours than

¹ In September 2000 the author visited the Braun Die and Mould Manufacturing facility in Kronberg im Taunus near Frankfurt in Germany. The Braun factory is part of the International Gillette Group.

normal working hours at a world average of 1977 hours worked per year per employee. It is the opinion of the author that the mastering and large-scale implementation of HSC and EDM as complementary processes and allied technologies like palletisation² can make a significant contribution to this situation. (Antonana, 2000:4-13).

2.3 Globalisation

2.3.1 Globalisation and the Tool and Die making Industry

In order to understand the current era of change, a glimpse into the history of the Tool and Die making Industry is worthwhile. The Tool and Die making industry is considered the somewhat wider concept of which the Die and Mould Industry forms a part.

Since the earliest times when man started using tools, there were craftsmen who manufactured these tools. Around 1750 an era started with the invention of the steam engine and ended around 1850, which can be labelled as the start of the industrialised world we know today. The world has however since 1989 experienced a new period of rapid growth and emerging change. In the absence of superpower competition, the international political arena has been relatively peaceful. Science, technology and information have become converged in an open, free trade dominated environment, which is accelerating development. Modern day historians regard the fall of the Berlin wall in 1989 as the landmark event. The impact is a weakening of governments, the empowerment of international corporations and individuals (Coffey, 2000:1).

2.3.2 Global Business Practices and Opportunities

For the first time in history, it is possible for a company to market its products to the whole world. The key is the Internet and World Wide Web. If this new economy is seen as being 12 years old (since 1989), there have been some developments worth mentioning.

² Palletisation is the practice where a work piece is set up only once on a carrier which can quickly couple with repeatable accuracy into a receptacle. These receptacles are mounted on the beds of all the machine tools in the process chain.

Globalisation is changing supplier customer relationships. The new economy has given birth to an enormously empowered enterprise commonly referred to as the global corporation. These businesses are manufacturing wherever it is the cheapest. They are however also exploiting the inconsistency of the laws and legal systems around the globe. They generally ignore the geographic and political boundaries in order to enhance competitiveness. Economic activity will be moved to that location in the world where the competitive advantage is the greatest. Unfortunately, this unprecedented level of power of the global companies can be related to cases where rather drastic demands were placed on suppliers previously unheard of. The example is of a US global corporation demanding of their supplier to move operations to Mexico.

Possibly an even more far reaching trend is that global corporations are realising that they are in extremely secure positions regarding market dominance. They are certain that they face no threat of suppliers moving downstream to supply directly to the customer. The Mould and Die making industry is in this specific situation, where the system supplier sells a functional system to the customer, and the moulded components or tooling are sourced from the Mould and Die maker. At the end of 1999, these global corporations requested rebates from their suppliers if they were interested in doing business with them in the future. These rebates or kickbacks were based on work that was contracted, correctly carried out, paid and long after the completion thereof a part of the payment had to be paid back to the global corporation. A typical example of this was where an international system supplier asked for a rebate of \$ 1 Million from a supplier. This supplier did \$6 Million of business with the system supplier through the course of the year. In this specific case the Tool and Die maker did not pay the requested amount but only \$ 50 000. There are other companies as well who are so terrified of losing their core business, that they pay these rebates.

Another phenomenon is the global company loading a Tool and Die maker with work until the customer has the majority or even exclusivity of business with the Tool and Die maker. The questionable business practice then is to demand a substantial price reduction with a threat of placing all the business with another supplier.

One of the phenomena accompanying the drive for competitiveness in the new economy is rationalisation and downsizing. The practical impact on Tool and Die companies is that purchasing departments are being slimmed down. The solution for the downsized company lies in larger lot sizes (with staggered delivery). The times

given for quotation is reduced and orders are grouped together. It is becoming increasingly difficult to compete from a company running a craftsman's shop as a business model (Coffey, 2000,2-3).

2.3.3 The System Supplier as an emerging Enterprise type

In the 1990's, the world's automobile companies went to great lengths to become more flexible and agile. Part of this initiative was to limit the supply chain management of upstream parts suppliers. The preferred supplier became a system supplier. The automobile company did not want to do business with individual component suppliers any more. They required the system supplier to supply the complete (sub)system e.g. a braking system, electrical system, and suspension system. Volkswagen took this concept even further by even requiring that the system supplier mount their systems supplied themselves to the vehicles on the assembly line. The assembly workers on Volkswagen's light truck assembly line in Mexico therefore were not employed by Volkswagen but by the various system suppliers (Chase 1998: 465).

The impact this has on the Mould and Die makers is one of isolation from the automobile companies. The Mould and Die maker in many cases had good relationships with their counterparts in the motor companies. After these changes new relationships had to be built with the system suppliers. In many cases, these system suppliers are based overseas. This meant that these markets were suddenly almost impossible for the local Mould and Die industry to access.

2.4 The Internet

2.4.1 Expansion of the marketing horizons of the smaller Tool and Die makers

From the above mentioned scenarios it seems at first as if the Tool and Die makers are powerless to the changes taking place in their business environment. It seems as if the Tool and Die maker has the technical competency and facilities, but the global corporations have the financial resources, the size, the access to the markets and now also the ability to move Mould and Die work all over the world (Coffey, 2000: 4). The Internet however offers the Tool and Die maker access to the same worldwide markets for his products and competencies, that he has to compete with. Previously, Tool and Die makers located themselves close to major markets for them. In many cases, these major markets were either a geographical area or a major (group of) globally active companies. This is probably the reason for the relative concentration of toolmakers in Port Elizabeth, to be close to Volkswagen, Delta and

their network of suppliers. The Internet is now also giving these Tool and Die makers access to medium and small companies across the world. With the average Tool and Die maker becoming isolated from the automobile companies, the smaller companies requiring Mould and Die services become a natural and very important market segment for the Tool and Die maker. The broadening of a smaller Tool and Die maker's market to other small companies is considered a significant development. Although the constraint of geographical location or remoteness thereof can be largely eliminated or rather softened by the Internet, this development may take some time. Smaller companies as potential customers may not be on the forefront of technology, which may make this small company to small company business via the web a relatively slow starter. It is however, a potentially very rewarding prospect for the smaller Mould and Die maker to pursue.

In the USA, the National Tooling and Machining Association (NTMA Precision) launched a buyers guide on the web where its members' capabilities are detailed. The web now has information directly of use by a customer looking for a Tool and Die maker. The number of hits increased from 10 000 a month when it was a general information web site to 231 000 for the site with actual Tool and Die maker information as potential supplier information (Coffey, 2000: 4).

2.4.2 The Internet as a Business Intelligence Source

The Internet is also a source of business intelligence, in the sense of obtaining information about competitors but especially about business prospects. There are reams of information on the company to be targeted, their strategy, their focus, where they are heading. Even a small company can, with the help of the Web, now make a professional, informed marketing approach to a potential customer (Coffey, 2000: 4).

2.4.3 Internet Auctions

The Internet is drastically changing the buying /selling relationship. It is becoming increasingly common for the classical customer of the Tool and Die maker to use an Internet business to run an auction on his behalf to procure the components. Freemarket.com is one of these Internet business entities. They operate by building up a group or database of Tool and Die makers. They will continually screen "Request for Proposals" and then circulate the Request for Proposals to say 10 to 20 Tool and Die makers selected from their group. The customer then chooses the bidders for the auction. The auction is conducted on the Internet. The bidders go to their computers prepared and knowing exactly where their limits are. These auctions

roughly last for 30 minutes. The concept is spreading in the United States and it seems as if a large proportion of business will be conducted in this way in the future (Coffey, 2000: 5). Antonana (2000:10) expresses the opinion that in future most of the tool purchasing will be conducted over the Internet.

In South Africa the contracting is currently predominantly conventional, but the South African firms wishing to compete in the global market will be exposed to these predicted trends. At a technical level information transfer, especially for quotation purposes, including CAD files, is already taking place on a large scale.

2.4.4 The Internet as a purchasing tool

The Internet is also suited as a tool to empower the relatively small enterprise's purchasing function. In the first place, it puts the information on availability and price of standard components, materials and tools at the Tool and Die maker's disposal. In the second place, a group or society of Tool and Die makers can also utilise Internet auctions to reduce the cost of bought – in components (Coffey, 2000: 5).

2.5 Virtual Global Enterprises – External Networking

2.5.1 Globalisation: Enterprise Collaboration in a new Light

The globalisation of the international markets is leaving especially the mid-size Die and Mould maker in an unprecedented fight for survival, fuelled by an accelerating pace of technological change.

The various commodity markets previously defined by geographical boundaries are developing into a single market, the world market. It is being accompanied by increasing market transparency where transport costs are fading into the background.

There are two distinct market demands emerging from the globalisation trend. The first is that the Die and Mould company should focus on a major customer and build a relationship. This results in the Die and Mould manufacturer having to address a larger spectrum of the customer's requirements than before. On the other hand, customers demand that their suppliers display a technological leading position, which is only possible if suppliers focus on narrow market segments or differentiate themselves from their competition. It is clear that these two demands are in apparent conflict.

Operational excellence, which is defined by competitive costing, delivery times, and quality, are basic necessities to be able to compete. International communication

abilities, international acquisition, and the ability to negotiate international transactions now define competitiveness. The ability to utilise new technologies in service and international collaboration are the new performance areas where companies differentiate themselves from the competition.

With this as background, it becomes evident that new enterprise models for business should be developed. One of these concepts is the concept of virtual enterprises (Bremer 2000:1).

Reflecting the view of the automobile companies, Fallböhmer (2000:1) of BMW states directly that the small and medium enterprises will only be able to survive globalisation if they concentrate their strength in co-operative networks.

2.5.2 Virtual Enterprises

A virtual enterprise is a number of companies bound together in a network or cluster. Each company contributes its core competency to the virtual enterprise. Together this virtual enterprise can undertake projects that are totally impossible for individual members of the network.

An expertise exchange (in the sense of a stock exchange) is created which is based on individual enterprises but covers a wide spectrum of abilities and products. Free capacities can be offered and be bought in. Through this co-operation, the companies can ensure survival and efficient marketing of their capacities to the outside world.

A virtual company is seen by others as a network of relationships, which amounts to a loose alliance of independent partners. It is seen as a long-term partnership within the alliance in which the partners co-operate on specific projects with specific time frames. Specifically complementary areas of core expertise are supplemented in projects. This approach of working with long standing alliances as the foundation for virtual enterprises is common in the developed world. There is a significant challenge for Mould and Die makers to develop partnerships beyond long standing partnerships and national borders. This specifically applies to the South African firms.

New markets can be conquered through such (unique or new) grouping of competencies. The collaboration network is used to explore new business ventures and to strengthen existing ones.

Inside networks, individual partner enterprises build core competencies in a structured way and with the entire network in mind.

The so-called broker assumes the role of identifying the market opportunity and to configure the virtual enterprise. After the market opportunity was transformed into a business venture and completed by the participants, the virtual enterprise dissolves. In this way a continuous cycle of the bringing together of competencies and the dissolving of co-operative efforts is created. This structuring of business is not visible to the customer who sees a consolidated image of the enterprise.

Collaborative projects can be divided into 4 stages:

1. Marketing and negotiation of the contract.
2. Preparation, internal negotiation and structuring
3. Project execution
4. Dissolving of collaboration.

For the effective functioning of the virtual enterprise an inter-partner information technology and communication infrastructure should be in place and well managed.

For the growth and development of the virtual enterprise, strategic planning, knowledge expansion planning, innovation capacity development and all partner friendly project management should be executed at the virtual enterprise level and cascaded down to the partners.

In the past, these virtual networks were limited to regional networks. The challenge is now to make these virtual enterprises work in the global context.

The developments in the Die and Mould industry can be summarised as follows: Up to now single processes were optimised. The flow of the product through the CAx chain, process simulation, optimisation of the manufacturing technologies, facility modernisation and the introduction of new technologies (e.g. rapid prototyping, rapid tooling) received the attention up to now. In the future, the emphasis will be on integration into the process chain of the customer and the development of competitive core competencies (Bremer 2000:1-3).

2.5.3 A Virtual Enterprise in Action

Prof. Carlos Bremer of the University of Sao Paulo in Brazil is taking the initiative to develop such consortiums of Latin American and European companies. Having done research in Aachen, he has a good network of ex fellow researchers with German mould makers for a pool of potential advanced capability partners and contacts with systems contractors as a marketing network. He is therefore in a good position to be the broker between the German systems contractors as the customer, the German toolmakers as partners and the mainly Brazilian mould makers performing the nucleus of the Tool and Die projects. These virtual enterprises are in a good competitive position compared to fully European contenders due to the lower labour costs in South America. The technological capability of these enterprises compares favourably with the European contenders.

Prof Bremer cites the advantages as an enlarged product palette and diversification for his pool of collaborators. The virtual enterprise concept furthermore enables companies to enter new markets, which they could otherwise not have done. Industry flexibility is enhanced and customers are served with an exact fit to their requirements. The end effect is enhanced competitiveness in the market place and less sensitivity for demand fluctuations.

The implementation of virtual enterprises presents a formidable challenge for the Mould and Die industry. It also presents them with the possibility of competing in a market with an intensifying global character (Bremer 2000:1-3).

2.6 Profiles of Leading Die and Mould Makers

2.6.1 Introduction

In a world where technology is driving change at a rapidly increasing pace, the Tool and Die making industry was one of the last strongholds of craftsmanship. Craftsmanship is actually out of pace with the seemingly invincible paradigms such as economy of scale, mass production, division of labour and narrow specialisation, and even robotic assembly and automated manufacture. It is ironic that an impersonal technology namely information technology (the computer) with its derivatives CAD, CAM and lately also rapid prototyping and rapid tooling is effecting the most far-reaching change to this craftsman character of the Die and Mould Industry. This industry is now increasingly moving towards technology enabled minimal human operational intervention manufacture of products.

The following paragraphs aims to give an insight into the way two Mould and Die companies operate. The first is the Mould and Die division of the Braun factory specialising in personal care (e.g. hair dryers, shavers) and domestic consumer goods. The second is **pgam** who has grown from a typical Mould and Die company to a system supplier in the automotive sector.

2.6.2 Impressions of the Die and Mould Function at Braun GmbH

Braun GmbH is a company in the International Gillette group. The Kronberg im Taunus facility includes an advanced capability Mould and Die making function.

Braun manufactures shavers, electric toothbrushes and a range of kitchen appliances. The company is experiencing competitive pressure from companies in developing countries placing products on the market at significantly lower prices. Braun's market share in bedside alarm clocks, once a profitable product line, is down to a level where the contribution to business volume is almost insignificant. The next product line that is perceived to be on a downward trend nearing the end of the business life cycle for Braun, is the kitchen appliance line. The reason for the erosion of Braun's competitive position in these product lines is cost pressure, which Braun has decided not to try and meet. Enterprises in the East and other developing regions such as South America place products on the market at considerably lower prices. The initial quality inferiority disqualifying these contenders with the quality conscious majority of European consumers is gradually being eradicated.

Braun's business strategy is to sacrifice the severely cost pressurised market segments and to move into new markets where the consumer is prepared to pay for superior technology, quality, innovation and aesthetic design. It is very clear from brochures and discussions with Braun engineers that Braun strives to be a market leader in the aesthetic appearance of their products. This approach has led to market demand to change a product's appearance while the functionality of the current product still fully satisfies the needs of the market. It will lead to frequent product changes of the parts determining the product's appearance, notably the external polymer parts of the product. The shaver line is a good example of the trend where aesthetic preferences of the consumer are proactively predicted and drives product economic life span. This new policy of frequent design changes and technically complex designs has a major impact on the Tool and Die Making facility.

Braun is also moving into products where the technology places them in a protected market niche. An example of this type of product is the infrared radiation

thermometer to measure eardrum temperature and hence diagnose ear infection. This range of personal medical accessories also includes a user-friendly blood pressure measurement device.

The strategy to lead the market with aesthetic appearance will lead to frequent changes and pressure to shorten the time from concept to market. Because aesthetics come first with almost no compromise to function, ease of manufacture is hardly a factor. It is expected that good design and advanced processes will make the nearly uncompromised appearance feasible.

Over the years, the demand at Braun was for a range of well-controlled surface finishes, and designs making the ultimate use of space and weight. This meant moulds with small wall thickness and long thin walled ribs. EDM developed into a preferred technology. The expertise in the mould making facility is heavily focused on EDM. In order to respond to cost challenges, the facility's management is promoting a change to HSC wherever possible. The policy is currently that if a mould part can be made with HSC at all, EDM is not considered, because of the cost and lead-time saving. In practice, however 85% of mould components are still manufactured with the conventional process chain with EDM the key process. The technical management cite the reason as process security. Due to time pressure, the possibility of reaching a "dead end" with a process where the process has to be abandoned and the part is to be remanufactured from the start with another process is not even considered. Given the fact that shop floor expertise is so heavily EDM biased, this explains the high percentage of EDM usage. It is also a dangerous situation, which amounts to a sophisticated resistance to change limiting the growth into new technology for example HSC. Together with a possibly low preference level for uncertainty and failure among the German population, the result is sub optimal growth into new technologies.

Braun depends on the mould shop toolmakers' goodwill. They are sensitive not to create feelings of insecurity among the toolmakers by forcing the use of relatively new technologies (e.g. HSC).

There are signs at Braun that the need is there to extend the limits of currently used processes. Braun has invested in a Controlled Metal Build up Machine in order to overcome the limitation of HSC machining deep cavities. The mould shop is also currently introducing a pallet system to utilise the non-working hours of the 24 hours of the day more fully. (Ziebeil 2000:3)

2.6.3 Mould and Die Making at **pgam**

In the past, before 1989, the original equipment manufacturers (OEM's) managed their own Die and Mould making procurement function. Typically, the small and medium enterprises fitted into these shallow but extremely diversified supply chains. These companies, notably the automotive companies, are increasingly contracting their dies and moulds as complete sub-systems to a chain of suppliers. The Tier 1 supplier or supplier immediately upstream of the OEM is expected now to take (sub) system responsibility. The opportunity to do business with the OEM as a limited involvement Mould and Die manufacturer is something of the past.

The solution for the bigger companies is to grow into or consolidate their position as system suppliers. **pgam** advanced technologies is a good example of this strategy. The company started off as a design bureau for the automotive industry in 1979, added Die and Mould making to their business activities in 1990 and are currently a system supplier to some of the major automotive companies including VW, DaimlerChrysler, Opel and Porsche. Apart from operating from five locations in Germany, they also run a facility in Coventry, UK and have recently opened a new plant in Michigan, USA. The company's turnover exceeded the 40 million dollar mark in 2000. Their vision is one of opportunity underlined by the slogan, Grow or go (Gnass 2000:2)

pgam's vision for the Tool and Die making industry can be summarised in the following points:

- Cost pressure, selling price pressure, company will have to increase productivity
- Perhaps only do what the company does really well
- Collaborate with others to access markets (system suppliers)
- Collaborate to access internet auctions
- Collaborate to form virtual enterprises

2.6.4 Strategic factors in Common Between the two Die and Mould Companies

Although the two companies that were taken as examples differ substantially, some common factors can be distinguished.

Both companies experience pressure on selling price. Both companies react by moving into differentiated or niche market segments. Braun achieves this through an emphasis on aesthetics and innovative application of technology, for example with the medical self care equipment. **pgam** achieves the same goal by "doing only what the company does really well". **pgam**'s niche was to become a system supplier.

At the detail level Braun is using HSC wherever possible. The paradigm that Die and Mould making centres around empowered craftsmen creates an environment of dedicated people. It however has a down side as well. Experience, a backward looking knowledge base, rather than an emphasis on new technology, becomes the norm. These craftsmen are unfortunately biased towards the technologies of the past, EDM in their case. HSC is not used to its full potential.

2.7 Die and Mould Business – A Look Towards the Horizon

The future scenario could be aptly described by quoting a McKinsey study (Gnass 2000:1); "Profitable Strategies of Growth in the Automobile Industry". The trends from the suppliers' perspective are:

- Increasing price and cost pressure
- Globalisation of production
- Increasing outsourcing of development and assembly
- Reduction of the number of direct suppliers
- OEM's driving assets and investment to tier 1 and tier 2 suppliers
- Tier 1 suppliers are now the global integrators and responsible for supply chain management

Requirements:

- Tier 1's require the full service support from Tier 2 's
- ISO 9001 and related specifications are becoming mandatory
- E-business interfacing is becoming essential

2.8 Summary of Enterprise Level Challenges

The threats and opportunities will be grouped into five groups and discussed. Because the industry is totally free market driven, every threat is at the same time an opportunity to gain a competitive advantage on other players in the industry. These groups include cost pressures, globalisation, virtual enterprises, the human factor and open flexible process chains.

It is generally accepted in the industry that the HSC Milling machining time is considerably lower than for EDM for the same component. This is demonstrated in the case study in paragraph 5.6.2 (Daniel, 1999). The average Mould and Die Company cannot exploit the potentially shorter lead times because of the lack of HSC expertise and related process security. HSC and EDM are proposed as complementary processes to maintain high process security and to exploit the shorter process time when some EDM is substituted by HSC.

2.8.1 Cost Pressure

Probably the factor that will attract the most agreement is that the industry is experiencing substantial cost pressure. Amid pressure to keep technology up to date, investment costs are substantial. Skilled labour cost is at 45% of total cost a serious concern in Industry circles. This high labour cost is against a background of companies commenting that it is difficult to find suitably skilled staff. Overtime is also common practice. Above all profits have stagnated at approximately 5% since 1995.

It seems imperative that the capital infrastructure as well as the rather expensive labour component of the industry should be utilised better. This can be achieved in a variety of ways:

- The machining time can be reduced.
- A larger part of the 24 hours can be utilised.

Considering the high cost of overtime this strategy will only make a contribution if the machines can run after normal work hours with minimal supervision.

One of the objectives of this research is to prove that the proposed complementary use of HSC and EDM will reduce the machining time (reduced manufacturing or lead time). Together with the necessary accompanying fixturing technology namely

palletisation, the machining itself will require minimal supervision making after hours machining feasible.

To conclude, the first enterprise level challenge requires a reduction of machining time per project. This can be achieved with HSC but with risk and not with success in all applications. The use of HSC and EDM as complementary processes yields the time saving of HSC and eliminates the risks because the problematic parts of the projects can be assigned to EDM. The second challenge requires a larger part of a 24-hour day to be utilised. With the complementary use of HSC and EDM, together with the accompanying palletisation technology exactly this can be achieved. Tasks can be machined through the night and be transferred from machine tool to machine tool by a low cost operator or even a robot. This can be achieved because the complementary use of HSC and EDM can perform all the necessary machining steps. It therefore appears as if the use of HSC and EDM as complementary processes may contribute to reducing cost pressure.

2.8.2 Globalisation

Since the last decade of the previous millennium, globalisation took on a new meaning. The automotive companies started drastically reducing numbers of suppliers, giving birth to the global system suppliers. Together with the Internet enabled e-commerce developments, the Die and Mould industry has seen its traditional market transformed. In the past, the customer would define the requirements precisely requiring a craftsman's service supported by a personal relationship between customer and mould maker. Globalisation and e-commerce have drastically transformed the personal relationship driven business to an impersonal type of business dominantly based on impersonal business criteria. Lead-time and cost have become the major parameters. The secondary parameters are now whether the Mould and Die maker can support the value chain with expertise outside of the mould maker's contribution sphere.

Because HSC yields quicker lead times and indirectly lower cost and the complementary approach enables the use of HSC, complementary use of HSC and EDM is believed to reduce lead time and cost. The complementary use of HSC and EDM will therefore help die and mould firms to meet the challenge of globalisation.

2.8.3 Virtual Enterprises

For the mid size Tool and Die company, which is the predominant company profile in the industry, competitive cost and lead time capabilities are essential basic pre-requisites to be in the market at all. The current sphere for differentiation from the competition lies in the ability to integrate into the process chain of the customer. State of the art technological expertise must be offered, which necessarily leads to specialisation for the smaller enterprise. For the smaller enterprises to offer all the technologies required, co-operation among one another and integration into the client's process chain is a key ability. The vehicle for this co-operation is becoming the virtual enterprise.

For a virtual enterprise to function, firstly advanced, flexible CAx infrastructures are necessary. Design, product and process information exchange needs to be rapid and seamless. In the extreme cases the CAx standardisation and (intelligent) fixture standardisation could facilitate HSC and EDM being utilised in a complementary manner with the HSC and EDM machines even at different locations.

The proposed complementary HSC / EDM process will not make a direct contribution towards the Mould and Die company's ability to participate in virtual enterprises. The supporting technologies and infrastructure, namely state of the art CAx chains, transportable fixturing and the development of specialist process expertise will however enable both the complementary HSC / EDM process and participation in virtual enterprises alike.

2.8.4 The Human Factor

The dominant business paradigm in the Die and Mould industry is that of a craftsman's workshop. Both the employees and the management see the Mould Maker as a master craftsman who has considerably more claim to "artistic" freedom than his counterpart in the other segments of manufacturing.

These employees think in terms of their experience. A new project is very often seen as an adaptation of a past project. This leads to rigidity in conceptual thinking, which is not successful in meeting the contemporary demands of the very competitive globalised Mould and Die industry.

The result is a process biased (either EDM or Milling) toolmaker. Such cases were observed at Braun GmbH. A toolmaker with experience in and enthusiasm for EDM, did not consider it his role to conceptually think which existing process chain could be

used most efficiently. If the toolmaker with experience in EDM would be allocated a project, he would have a strong preference to do the project with the process chain with EDM as the key technology. With empowerment having the advantages of a motivated and committed work force, this strategy (empowerment) leads to organisations wanting to give the toolmakers freedom of their own decisions. This is a rather dangerous situation in this industry. The process decisions are left in the hands of rigid decision makers focused on their expertise comfort zones. The growth towards new process technology is limited and the firm's competitive situation may very easily erode.

The industry needs objective engineering and innovatively thinking process designers without bias to a specific process to use. The HSC / EDM processes as complementary processes, where appropriate, should be considered as a standard procedure. To simplify this matter, a decision tool, which can be implemented as standard practice in a company, could contribute towards solving this problem.

2.8.5 Open Flexible Process Chains

The era of the toolmaker standing next to his machine programming coordinates into the machine with the machine at standstill is still a practice in even the developed countries. A survey at the WZL in Aachen, points out that the percentage of CNC programming in Germany still done this way has remained more or less constant at 50% (Eversheim 2000:9). Another more progressive way of programming, at least from the process technology point of view, was to have the programming done in the planning department. This practice has decreased from 40%(1993) to 20%(1999) presumably because of the workshop floor employee becoming an operator and no longer a craftsman. The next development namely workshop oriented programming where the toolmaker at the machine programs the next job with the help of CAM software while the machine is running on another job, is gaining in popularity (7% in 1993 and 25% in 1999). Therefore, the data is no longer manually entered on the shop floor but received and used in CAD model format.

It is definitely a requirement for the future that Die and Mould firms should have flexible CAx chains, which can interface to customers both upstream and downstream in the supply chain. This then includes customers as well as potential collaborators. This would even include artists who would like to interface through hand crafted clay models. The mould maker should have a scanning or reverse engineering facility among potential collaborators, for example.

Fixturing systems hold the key to facilitate hardware networking. It could specifically enable one company who has specialist expertise in one process to form an alliance with another where specialist expertise exists in another process. For example, firms who plan to collaborate could decide to standardise on a certain palletising system. Firm A with a machine with good rough milling capability will mount the work piece on a pallet. The pallet mounts onto the bed of the milling machine into the pallet receptacle or chuck. The whole work piece with the pallet is then sent to the next Mould Maker in the process chain (in or outside the firm – Firm B). The pallet simply clicks into its receptacle (chuck) eliminating re – set up. These fixturing systems will eliminate repeated set ups and facilitate CMM quality control in process.

These pallet systems are precision tools and require capital investment. For 2 μm accuracy a pallet chuck (mounting on the bed of a machine tool) able to carry a 500 mm x 500 x 500 mm work piece, costs R 63 300. The matching pallet on which the workpiece is fixed, costs R5 300. The smaller pallet chuck, also capable of 2 μm accuracy, able to carry a 140 x 140 x 140 mm workpiece costs R 42 350. The matching pallet costs R6 100. If the required accuracy can be lower, namely 5 μm , the pallet chuck for the smaller dimensions reduces to R 11 600 and the matching pallet to R5 300. The above pallet chucks can withstand the forces of milling.

In EDM machines the lower machining forces allow lower cost chucks to be used. For the 140 x 140 x 140 mm chuck the price for the EDM version is R 19 200 for the 2 μm version.

Therefore, the investment required to equip machine tools with a pallet system should be $\pm 5\%$ of the capital invested in the machine tools themselves.

2.8.6 Conclusion on Enterprise Level Challenges

It was stated in this chapter that the five enterprise level challenges are cost pressure, globalisation, virtual enterprises, the human factor and the open flexible process chains. They can either be turned into a competitive advantage or will function synergistically with the complementary use of HSC and EDM. The next challenge is to investigate how the complementary process can be incorporated into current process design or into the industry's typical process chain.

3 Process Chains in the Die and Mould Industry

3.1 Introduction

The processes with which plastic injection moulds are manufactured will be discussed. Other types of tooling for example sheet metal forming and forging tooling use similar processes.

Process chains can be studied on different levels of abstraction. The classical process chain is concerned with the processes the tool or work piece physically goes through. Another process perspective is that of the transformation process of the information from concept to physical tool. The CAx chain is the key component of this process and is therefore also covered.

In the previous chapter the suggestion is made that the industry should make a paradigm shift from a craftsman (process and experience centred) to a technology centred paradigm. Development and exploitation of the CAx chain then becomes of paramount importance.

3.2 Tooling Value Chains

As mentioned earlier most of the Tool and Die maker's value added activities lie in the manufacture of the tool itself. Usually the market research, product conceptualisation, series manufacture and marketing lie outside of the traditional Tool and Die company's business domain. It seems as if the trend is for the large companies, notably the automobile manufacturers, to prefer not to do tool design and procurement any more. They prefer a system supplier to take the full responsibility for designing and supplying a sub-system. This responsibility includes ensuring that the sub-system integrates seamlessly into the main product, which is supplied to the customer. This philosophy of expecting downstream participants in the value chain to become committed and partners expected to share the responsibility is cascading

down in the value chain. Antonana (2000:4) sees this as a contemporary market requirement for the mould maker to offer added value contributing to the optimisation of the product life cycle both upstream and downstream of their specific contribution. Klocke (2000:1) stresses that all the processes in the process chain should be optimised because of the large influence on quality and lead-time. It seems as if the total optimum solution which could span wider than the Tool and Die maker's direct value added contribution, should be sought.

Practically this means that a few Mould and Die makers will become (sub) system suppliers. The example of **pgam** is discussed in paragraph 2.6.3. Most Tool and Die makers will however remain specialist Tool and Die makers but will have to become an active partner with the (sub) system supplier. Their upstream contribution will be towards design of the tool and downstream towards performance of the tool, (e.g. modifications) in moulded part manufacturing.

3.3 Conventional Process Chains

The traditional process for mould making is to machine the material in the soft state, followed by hardening and tempering. Finish machining techniques are subsequently used. These processes include grinding, but also include Electric Discharge Machining (EDM). As stated previously, one of the most demanding requirements placed on the Mould and Die maker is to limit the process-related lead-time. In the case of heat treatment a sub-contractor usually provides this supplementary service. Being an external operation or an additional link in the process chain, it becomes difficult to control the lead-time. Geometrical distortion possibilities during heat treatment add to lead time uncertainty. The modern trend is for a process chain as short as possible. There has therefore been substantial growth in hard milling which eliminates the external heat treatment process.

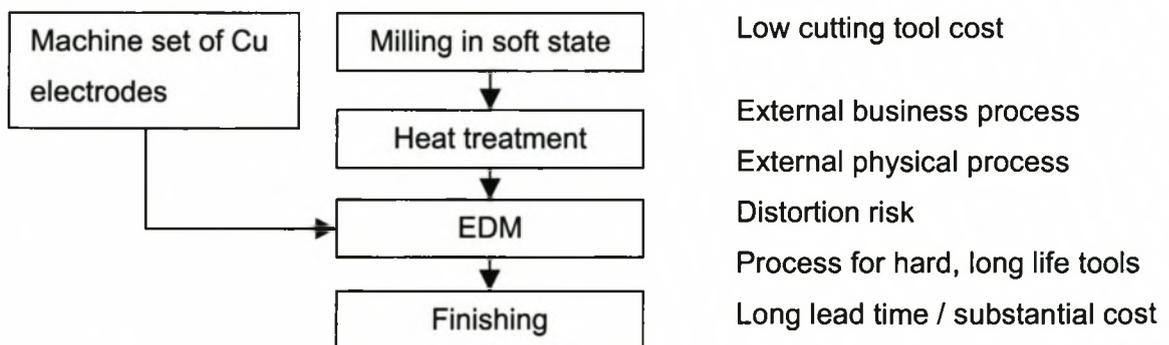


Figure 3.3.1 Overview of a Conventional Process Chain

3.4 An Example of a Contemporary Process Chain

3.4.1 A Generic Process Chain applied to a specific Product

The end product determines the selection of processes in the process chain. Considerable variation is possible in the chain. The process chain to manufacture the mould for a computer mouse described by Klocke (2000:11) is used here as an example. It seems as if the Aachen Fraunhofer Institute considers this a worthwhile benchmark for tooling process chains, because the same mouse is used as the example for a discussion on production tooling (Bergs 2000:8). This publication is somewhat earlier and does not include the rapid prototyping, rapid tooling and laser surface treatment steps.

There are however numerous case studies in the literature including innovative work done also in South Africa. Vincent and Taylor (2001:103) describe chains that include 3D printing and CNC machining for prototypes as well as bridge tooling for complex automotive inlet manifolds. De Beer (2001:128) cites examples in the medical and consumer products fields using Selective Laser Sintering for limited volume production. Booysen (2001:179) also describes SLS for medium volume rapid tooling against the backdrop of the limitations of soft tooling. He adds that in 2001 this technology was still in its infancy in the South African Mould and Die industry.

Mettke (2001:113) describes process chain developments in Germany, up to the rapid tooling stage, including Direct Metal Laser Sintering and Stereolithography.

Therefore, although process chains are rather diverse and tailored to the product and the process components available, it is worthwhile to study the general trend. Klocke's "benchmark" computer mouse is considered representative of the trend and its process chain is described here.

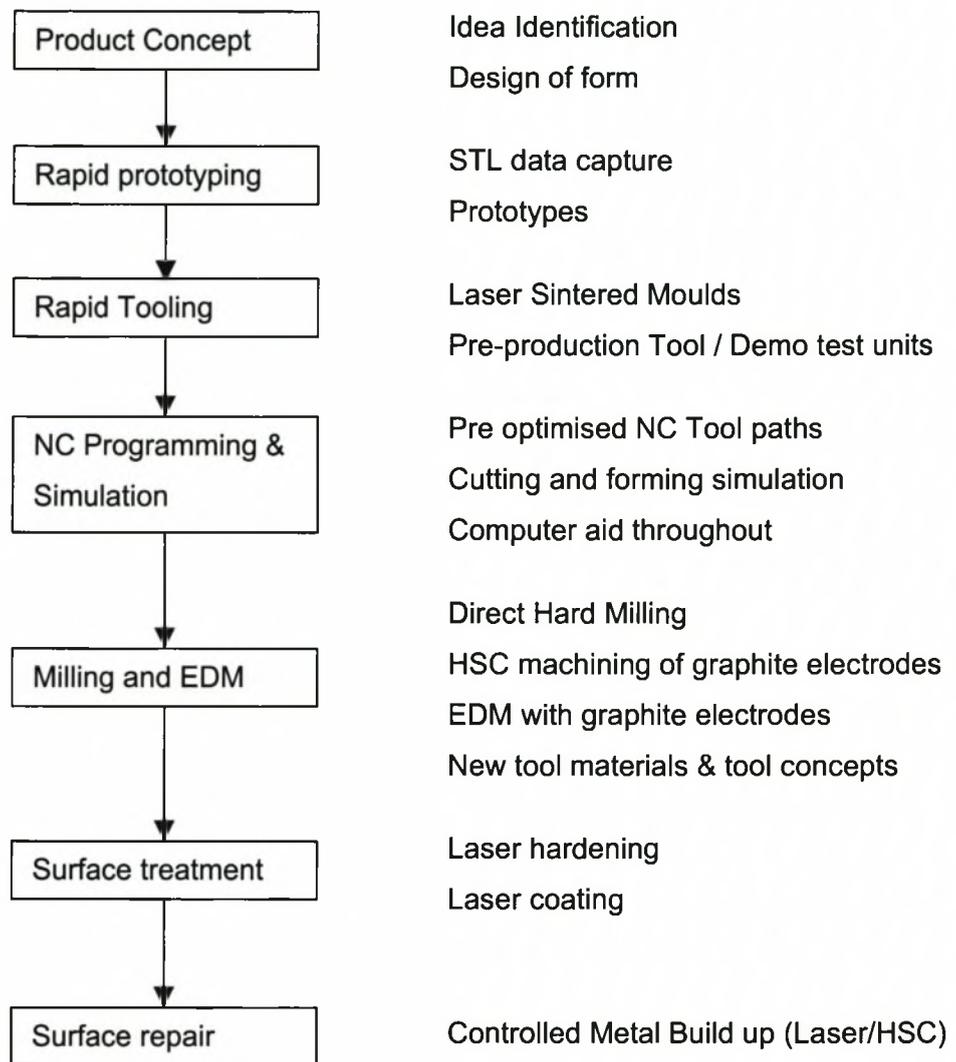


Figure 3.4.1: Overview of a Contemporary Process Chain

3.4.2 Product Concept Design

In essence an idea is transformed into a real world three-dimensional object during the design stage. From an engineering point of reference it is assumed that the required shape will be defined in some CAD format which leads to a structured entry into the project. It should be considered however that just as the engineering environment is becoming more competitive, the design environment, or the customer's demand for a product with a pleasing aesthetic appearance, is also becoming more competitive. Appearance design and the emotional identification of the customer with the product are gaining in importance. Previously the appearance of the product could have been regarded as secondary to functional design and with function dictating form, the appearance design was incorporated into the functional design done by the technical designer. The trend in the global market is to use

specialist industrial designers for the product design placing strong emphasis on the aesthetic aspects of the design. These individuals distinguish themselves as artists rather than technologists. They often work with other mediums than CAx format for example with hand shaped clay models. It is then expected of the Mould and Die process chain to capture this data in this basic geometric shape form. Various 3D scanning technologies are available to scan the object and ultimately to generate data in CAx format. Usually the primitive scanned data is a point cloud, which is converted to surface data by STL or NURBS techniques.

In the developing world, the initiator of a project is often an entrepreneur who sees a business opportunity. These individuals often define a product in terms of another existing product. The requirement then typically is for a product similar to product x for which more often than not only a sample is submitted. There are usually accompanying requirements for modifications, e.g. that the dimensions should be altered or that additional features should be added.

The conclusion is that die and mould process chains are no longer limited to bona fide manufacturing operations. The die and mould maker should therefore recognise the changes taking place in the "idea phase" of the product and incorporate these processes or capabilities in his process chain. The most practical avenue for the smaller Tool and Die enterprise is probably through networking or virtual organisations.

3.4.3 Rapid prototyping

Along with the requirement of shorter project lead-time, rapid prototyping has established itself as a technology to supply low quantities of parts for visualisation, design verification and market acceptance probing.

Recent developments reported by Klocke (2000:12) include new materials, which increasingly meet the requirements of the final product in certain applications. The process speed is increasing and smaller and more economically priced systems are becoming available.

Klocke (2000:12) expects the increased usage of rapid prototyping but also states the possibility of virtual prototyping substituting material prototyping.

As with the concept phase, rapid prototyping is an element of the process chain well suited for a network partner.

3.4.4 Rapid Tooling

In this specific process chain to realise the computer mouse the rapid tooling element could also be described as the bridge tooling step. The entrepreneur at this stage of the process, is on the threshold of committing large sums of money for production volume tooling without being able to estimate the commercial success of his product. Bridge tooling is defined as intermediate tooling to be replaced by large volume production tooling for series production. Rapid tooling is also increasingly used to manufacture the final tooling for limited volume production.

Booyesen (2001:170) classifies rapid prototyping as the process for a small number of parts, soft tooling for larger numbers (± 50) and rapid tooling for the 100 to 10 000 category of volumes. These are only broad guidelines and differ substantially between the rapid technologies and the post processing used. 3D Printing could for example print a large number (e.g. 20) of small parts in a single build, which can be used as cores for investment casting. Bridge tooling in the computer mouse process chain will therefore be used to produce pre-production and the early production batches for field testing, distribution chain samples and even for early market segment penetration.

As stated above the concept of rapid tooling is not limited to bridge tooling. With mass customisation becoming increasingly common business practice product variation requires more diverse tool sets to cover the different user options. This leads to products being broken down into a larger number of (optional) components each requiring its own tool set. These optional components are subsequently manufactured in smaller quantities than the single product of the past. As stated earlier the globalised market also demands a faster time to market for products. Booyesen states that the average (conventional) tool leadtime in South Africa is 10 to 20 weeks for non-intricate parts. The leadtime for rapid tooling could be reduced to 10 to 20 days. The concept is especially applicable to plastic injection moulding and die-casting.

The new generation of additive processes including the laser sintering and 3D printing mainly referred to as the rapid prototyping techniques are also utilised as the pivot processes of the rapid tooling technologies. Some metal removal processes, e.g. HSC, are however also used for rapid tooling.

One of the characteristics of the additive processes (laser sintering and 3D printing) is the flexibility of the processes to accommodate complex geometric shapes. This

leads to the practice that a rapid tooling facility will generally utilise the flexibility of their process to accommodate a wide range of projects. Although Klocke states that Selective Laser Sintering (SLS) is the preferred technology for this application, generally rapid prototyping facilities will use their own process with the necessary post processing to manufacture rapid tooling. Surface finish is currently one the focus areas to improve quality of the additive processes. In experimental work, the surface quality has been improved from 40µm down to 5µm. Another limitation of the process is (injection moulding) tool life. This is being improved by the introduction of new rapid prototyping materials. Material choice is a key issue in the rapid prototyping processes contributing significantly towards cost, surface finish and accuracy (Dimitrov 2001:73).

The trend for the future is that the “rapid technologies” may become increasingly feasible for the manufacture of the moulds for series production. The other trend of production runs becoming shorter supports this possibility. The sintering technique makes it possible to manufacture enclosed channels, which is not machineable at all. The technique to address exact local cooling requirements of the mould with unconventional cooling channels is referred to as conformal cooling. The synergy achieved between conformal cooling and rapid tooling manufacturing techniques is emerging as an area for significant future development. It is discussed separately in par. 3.5.5. (Klocke 2000:12)

New developments on the rapid prototyping technology front include developments in plastic laser sintering, metal laser sintering direct sintering of sand cores for casting and further development of the 3D printing technology. In the field of plastic laser sintering the new EOSINT P equipment uses a double laser system for increased productivity and quality. Direct Metal Laser Sintering is available with bronze and steel based materials for rapid tooling applications. The EOSINT S equipment is capable of sintering sand cores directly, finding application in the reduction of series production lead times. (Rosker 2001:57) Another practical but not so technologically revolutionary approach is to use HSC to machine the short run tools using materials facilitating rapid manufacture. Such materials include aluminium, aluminium in standardised steel structures, polymers and polymer/metal powder composites. As with other rapid tooling technologies the life of the mould is relatively short.

The developments taking place in this field should underline the necessity of a Tool and Die enterprise to offer the rapid tooling option in the process chain. Rapid Tooling technologies are mostly specialised requiring high cost equipment not

commonly found in a small to medium Tool and Die shop. It will have to be offered with a specialised bureau or research institution as partner. It is however considered of the utmost importance that Mould and Die makers should offer the option of HSC, which integrates well into normal workshop processes and expertise. Although rapid tooling is roughly defined as applicable to quantities between 100 and 10 000 there are many practical factors making it impossible to lay down hard and fast rules for the transition point between rapid and series tooling. This a continuum with a substantial middle ground where HSC or complementary HSC / EDM can be used for shorter life short lead-time tools.

3.4.5 Abrasive Flow Machining as a supporting technology for Rapid Tooling

Abrasive Flow Machining (AFM), developed by the Extrude Hone Corporation, is described by Klocke (2000:13). The process polishes the surface by forcing or flowing an abrasive paste through or over a work piece. The process is already commercially available. The application to finish hidden surfaces and complex geometries is rather successful. This makes it a very suitable supplementary process for Selective Laser Sintering.

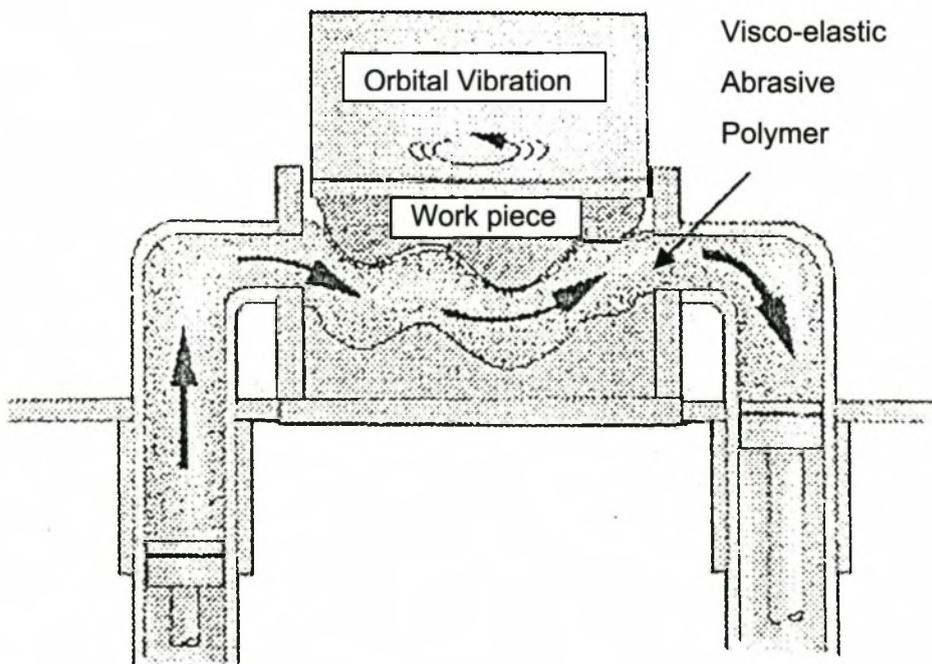


Figure 3.4.5.1 Abrasive Flow Machining Concept (Source Extrude Hone Corp)

Klocke (2000:13) sees this technology developing into a process (orbital polishing) for series Mould and Die application. This process may be well suited to polish the so-

called near mirror surfaces created by HSC. The significant characteristic of a HSC surface compared with EDM is the total absence of surface hardening in the case of HSC, where EDM produces the surface hardening effect referred to as the white layer. This non-hardened surface produced by HSC may prove suitable to be polished with Abrasive Flow Machining.

3.4.6 Conformal Cooling

The laser sintering techniques being used for rapid tooling creates the technical possibilities for cooling channels, which cannot be realised with conventional machining techniques. With conventional machining the tool needs an opening to exit the work piece after cutting. With laser sintering a complex enclosed space can be created. In practical terms complex shape cooling channels with a single exit and an entry can be created. In figure 3.4.6.2 the corner is overcooled with conventionally machined straight cooling channels. The complex cooling channel achievable with laser sintering shown in figure 3.4.6.1 can optimise cooling in the corner. The technique can therefore contribute exact local mould temperature control by the unconstrained placing of cooling channels.

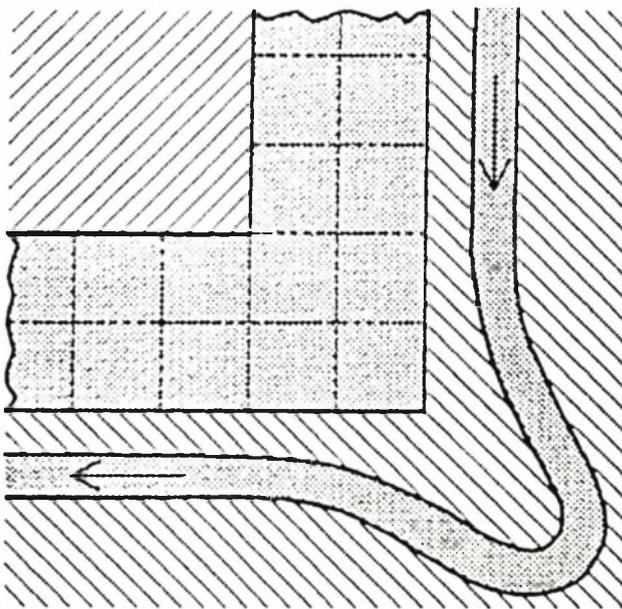


Figure 3.4.6.1: Cooling Channels with Laser Sintering (Klocke 2000)

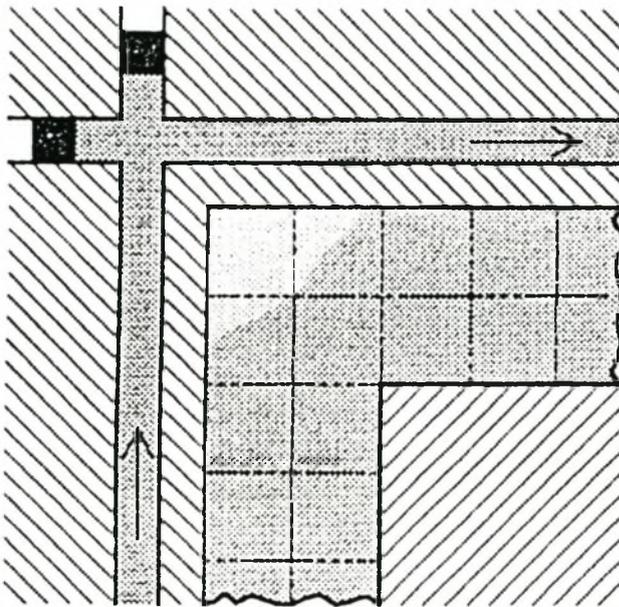


Figure 3.4.6.2: Cooling Channel with Conventional Machining showing overcooled corner (Klocke 2000)

The technology is in the feasibility testing stage. It will find application when laser-sintering techniques are used for series production moulds. Optimum uniform cooling especially with complex geometries will contribute towards the reduction of production cycle time. The quality will be enhanced through reduced distortion and a higher complexity of the final part will be achievable. (Klocke 2000:13)

3.4.7 NC Programming and Simulation

Eversheim (2000:9) reports that in progressive Mould and Die enterprises, the majority of programming has shifted from the shop floor to the planning office. Hahn (2000:1) states that workshop oriented programming is the preferred practice at Thyssen Krupp Nothelfer in Germany. It should be placed in perspective that this is the result of empowerment of the shop floor staff. The shop floor staff is actively contributing in an advanced CAx chain.

Recent developments include the optimisation of NC programs incorporating the analysis of machine tool kinematics and dynamics before machining. Spindle speed and feed rates are continuously adapted to suit the instantaneous cutting conditions optimally. Simulation of the cutting process down to chip formation level is becoming available. The use of the computer-aided chain has now been firmly established from initial modelling through to NC programming.

Although the use of the CA chain is now well established in the industry, further development is still taking place. The availability of CAD / CAM / NC tools via the Internet is becoming a reality. The option is there for the Die and Mould maker to use these Internet based tools, only when he needs them, and is then charged based on the amount of use. It was stated in the beginning of this chapter that the trend is away from person-oriented tasks. The storage and archiving of personal experience expertise in databases is a new development area. Technology selection and process layout as well as virtual reality as support for process technology is a potential for the future (Klocke 2000:14).

3.4.8 Error Avoidance in Milling and EDM

Both Klocke (2000:14) and Eversheim (2000:9) state that the trend for progressive companies is towards process planning in the planning department with full CA support or with CAM trained shop floor personnel on the machine in parallel with operation. In the latter case the shop floor programming is done in an integrated CA system where CAD data is prepared in the planning office and electronically sent to the shop floor for the shop floor personnel to provide the human decisions running a CAM package.

It seems as if the reliable meeting of quoted process lead times is of great concern in Europe. Klocke (2000:14) refers to this factor as error avoidance. It is closely related to the concept of process security discussed elsewhere. It seems as if the European Mould and Die maker is placing significant emphasis and investing considerable time and effort to avoid the possibility of an unforeseen occurrence or mistake which may cause serious time loss. At Braun GmbH, a sub-optimal process will be selected if there is even only a small possibility of a project landing in a process dead end, necessitating restart of the project with another process chain. (Refer to par 2.6.2).

Future trends as stated by Klocke (2000:14) include the introduction of automation in single item and small batch production. This is believed to be a very significant and practically achievable development. Another development Klocke sees is the avoidance of manual activities during set up and positioning. The developments in pallet or fixturing technology including intelligent pallets communicating with the machine where the work piece is placed by a system programmable manipulator supports this view. The avoidance of intuitive process planning and layout will also become a reality when data base storage of process expertise matures.

3.5 Hard machining

HSC Hard machining is probably the development area of HSC that is undergoing the most dramatic and rapid change. The prospect of machining the work in its final hardened state is rather attractive to the industry. The possibility of distortion during heat treatment is a serious process security issue, because a process followed absolutely correctly leading to a failure (distortion) necessitating the restarting of the job, is not attractive to any mould maker.

The other factor is that mass customisation is causing more and more mould clients to require a short lead time for the mould because they need a short time to market. They are prepared to sacrifice mould life in many cases for lower cost and a shorter lead time. In the mass customised market single products with extremely long lives are making way for families of products each addressing a specific market preference. Furthermore these products are updated sooner, therefore requiring a shorter tool life. Hence there is an emerging market for more tools with a medium life expectancy delivered with a short lead time. These medium life tools do generally not need the classic hard materials of 70 HRC and harder but the 40 to 65 HRC hardness range is adequate which is within the capability of HSC hard milling.

In the definition of Schmitt (1996:241) HSC hard machining is part of the HSC field. Aachen considers hard machining (HSC Hard Milling) a related but separate subject. In this work HSC Hard Milling or H²SC is considered as an integral part of HSC. The subject is discussed in more detail in Chapter 5, paragraph 5.3. The decision flow diagrams presented in Chapter 7 also uses the work piece hardness as a primary criterion to determine whether the complementary use of HSC and EDM is the optimum process.

3.6 Other Recent Process Developments

At the Aachen Colloquium in 2000, Casellas discussed the modernisation exercise the tooling division of GKN Sinter Metals went through in Europe. They consider the following technologies the most promising for their operation: High speed Cutting, Hard Turning, High Speed Grinding, High Speed Finishing and Abrasive Flow Machining (Casellas 2000:3). It should be kept in mind that the part sintering process, using metal powder, is probably somewhat more sensitive to the heat-affected layer (white layer) that is characteristic of EDM.

In the Mould and Die manufacturing field, HSC is considered to be an established process but with relatively few industrial companies making use of the technology on a large scale. This could be the reason why such an established company such as GKN Sinter Metals still regards HSC as new technology in 2000. HSC Hard Milling is being used even less in industry but is nevertheless in a rapid development phase.

3.6.1 ED machining with graphite electrodes

EDM is a well-established process in Die and Mould making. Klocke (2000:5) regards it an essential process. It is especially used for fine and small geometrical features. Some of the applications of the technology are however (increasingly) being displaced by HSC and the rapid technologies. Graphite electrodes have made a significant contribution towards maintaining a substantial application niche for EDM. The machining speed has been increased by utilising the low wear rate of graphite. Surface quality has also improved substantially by using the fine-grained graphite. Several other developments in the technology also contributed to sustained competitiveness.

3.6.2 HSC machining of graphite electrodes

The material removal rate advantage of HSC over conventional machining is inversely proportional to material hardness. The MRR benefit of HSC over conventional milling is therefore greatest with softer materials. In spite of the brittle characteristics of graphite it is considered a soft material from a HSC machining perspective. There is therefore an even greater advantage using HSC for graphite machining than for metal milling. Furthermore, special fracture mechanisms, which occur at increased feed and cutting speeds, actually reduce tool wear at the optimum (HSC) cutting conditions.

Application of specific cutting strategies is essential and non-trivial. The same brittle fracture phenomena causing the dramatic improvement in tool wear also (negatively) influences surface quality and edge definition. The combination of HSC and graphite offers the Tool and Die maker a powerful tool to use EDM more productively. (Klocke 2000:5)

3.6.3 Controlled Metal Build up

A significant improvement of HSC over conventional milling is lower cutting forces permitting longer tools. Compared to rival technologies for example EDM, fine detail at significant depths is still a serious limitation of further expansion of the application

of HSC. To overcome this limitation the Controlled Metal Build-up (CMB) process was conceptualised.

CMB combines laser deposition welding and HSC in a single machine. The laser deposits a layer of material (steel) on the work piece. It is then HSC machined to the exact dimensions. The part is built up of successive layers. The immediate advantage is that due to the short tool length, very small diameter cutters are feasible and hence fine detail can be achieved. The benefits of the other “rapid technologies” to create enclosed cavities and other difficult geometries is also applicable to CMB. Cavities with a very large depth to width ratio, which is normally undisputed EDM domain, can also be machined (Klocke 2000:5).

Although a number of machines have been sold commercially in Germany, the process should be regarded as still in the development phase. A promising application of the process is mould repair. Klocke (2000:5) is of the opinion that the process will be integrated fully into the series tool manufacture process chain. If research can yield answers to a few outstanding problems, this process may be the key link in a process chain for a fully automated tool repair cell.

3.7 Overview of Process Chain Developments and the Contributions of HSC/EDM

There have been numerous process chain developments recently.

Clients generally do not want to break projects down into the constituent parts. They increasingly expect the supply chain partners to interface among themselves on their own initiative. It therefore follows that these partners in the Mould and Die value chain should have software interfacing tools in place (CAx chains), hardware interfacing (Fixturing, pallets) and utilize opportunities for process sharing like HSC at one facility and EDM at another.

The classical process of “sending the parts away” for heat treatment does not support the contemporary demands for lower throughput times and increased process security. This is adding impetus to the development of H²SC or HSC hard milling. If HSC hard milling and EDM is used as contemporary processes, EDM can support HSC hard milling initially. It then becomes possible for companies to phase in the new and rather difficult technologies (HSC and Hard Milling) by placing the handover point between HSC and EDM initially far upstream in the HSC process.

In this way the complementary use of HSC and EDM holds the key to maintaining process security and the company's name as a reputable supplier.

The management of information is developing towards a technological IT based process rather than a person based intuitive process. In such an IT managed environment where CAx interfacing is standardised, the complementary use to two diverse processes like HSC and EDM should pose no logistic difficulties.

Where Mould and Die manufacturing operations previously could limit themselves to manufacturing operations only, they are now expected to be active partners in the entire value chain interfacing with contributors as diverse as the artist, giving aesthetic input and the reverse engineering function.

Once tool making as a discipline has developed to the point of becoming the key player in a multi-enterprise value chain, and networking becomes everyday practice, the idea of planning for complementary processing e.g. with HSC at one firm and EDM at another, will become part of the individuals' process planning paradigms.

Rapid Prototyping has been developing into a strong industry during the past decade. This industry has an extremely well development CAx infrastructure. Responding to their customers' needs for tools for intermediate quantities, the rapid prototyping industry is developing its technology base towards manufacturing tooling with increasing production life. This development is at the same time addressing a need for shorter lead times in the Mould and Die industry. This has developed into the rapid tooling industry. At the same time the rapid prototyping industry has also implemented HSC for the manufacture of some categories of prototypes and tooling. If the rapid tooling industry can forge links to the series tool industry, they could be instrumental in facilitating this migration of the Tool and Die manufacturing function to a technology based (CAx) multi-process industry of which complementary HSC and EDM could be among the key processes.

Various new technologies like abrasive flow machining, conformal cooling and Internet based process-planning tools could all contribute to this new way of manufacturing tooling.

4 New Developments in the Die and Mould Industry

4.1 Introduction

After studying machining practices, it is evident that in the Die and Mould Industry the default operational practices are still based on the perception that the Mould and Die maker is a craftsman using machine tools as and when necessary. In the next decade the industry will significantly move towards a structured and scheduled manufacturing environment with information technology being the key interface between man and machine. (Friedrich, 2000:1).

4.2 Die and Mould Industry Operational Success Factors

According to Eversheim the two most important operational success factors are; firstly the effectiveness of engineering together with the level of technical advancement of the machines used and secondly the degree of the synergy between the NC machines and the CAx chain (Eversheim 2000).

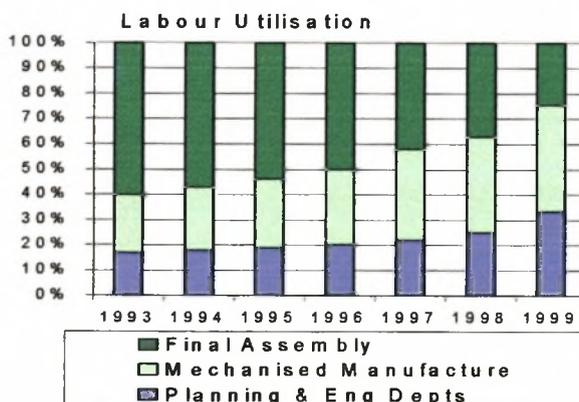


Figure 4.2.1: Allocation of man-hours showing effectiveness of engineering and NC machine technology (Eversheim 2000).

The bar chart shows that there is a trend towards an increased proportion of man-hours spent in the engineering department, planning department and mechanised manufacturing. There is a corresponding decrease in the man-hours spent in final assembly. The conclusion is that manufacturing effectiveness is increasing through efficient CAD-CAM integration and increased precision and efficiency in the mechanised manufacture.

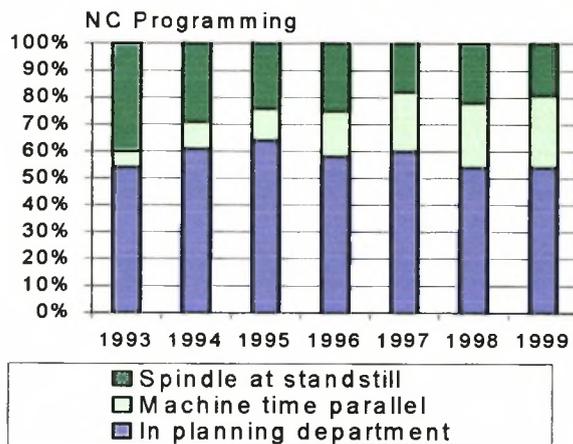


Figure 4.2.2: NC Programming execution as an indicator of NC Machine and CAx chain synergy (Eversheim 2000:4)

The explanation that Eversheim gives, is that with increasing implementation of CAD systems, a decreasing proportion of programming is carried out with the spindle at standstill and an increasing proportion of programming is performed in parallel with the operation of the machine.

Eversheim's conclusion is that the success factor is an efficient CAx chain and making efficient use of the capacity of the machinery.

These two factors are considered of significant importance. They are examined in some detail in the following paragraph.

At first it seems as if Eversheim identifies labour and programming efficiency at the CNC machining workstation to be the major success factors. It however becomes clear that he uses these measurable parameters as indicators of overall engineering and process chain effectiveness. It is the opinion of the author that the industry especially locally, but also in Europe places a large emphasis on efficiency at machine level but are not concerned enough about overall process effectiveness.

The large influence the individual toolmaker as a craftsman has on the process chain selection, often resulting sub optimal process selection is given as an example (Refer par 2.6).

This view is shared by Bremer (2000). His summary of current success factors is an optimisation of Standalone Processes incorporating:

- Ease of CAx chain operation
- Simulation
- Optimisation of manufacturing technologies
- Modernisation of tool shops
- Incorporation of new technologies (rapid prototyping, rapid tooling)

This clearly shows that he is also of the opinion that the industry currently focuses on relatively isolated efforts on different parts of the overall Mould and Die manufacturing operation. Bremer's view of the success factors for the future is the focus on a systems perspective overall optimum. It can be summarised in three points namely:

- a) Tool and Die companies becoming component manufacturing systems suppliers.
- b) Integration into the supply chain of the client.
- c) Concentration on core competencies.

He holds the opinion that modern manufacturing is organised in systems. The system supplier (car manufacturer) is at the highest level supplying the end user. The system supplier is supplied by the subsystem suppliers (e.g. Robert Bosch, electrical systems). It is however critical that this lower level (sub) system supplier should see his system as a system in its own right. By way of an example Robert Bosch carries the responsibility that the electrical system functions as a fully functional system. At the next level the Mould and Die manufacturer supplies tools to the subsystem suppliers (Robert Bosch type of suppliers). It is here that Bremer sees the need that the Mould and Die suppliers should make the transition from manufacturing objects to seeing themselves as the suppliers of component manufacturing systems. The Mould and Die manufacturers become system suppliers in their own right committed to the system goals of quality, production rate

and development. They take the responsibility for the manufacturing system (mould and die set, e.g. for an electrical connector) at their level to be fully functional.

For the system to function optimally as a whole the various subsystems should integrate seamlessly. Bremer holds the opinion that it should be approached from the bottom up. The responsibility lies with the Die and Mould manufacturer to integrate his manufacturing system into the process chain of the client at the next higher system level.

Concurrently with this increase in system responsibility the technology is developing on a wide front. It is not considered feasible for the relatively small Die and Mould companies to keep to date with all the developments in the Mould and Die manufacturing field. Bremer sees a prominent trend in future that companies will at the same time concentrate on core competencies.

4.3 Workshop Oriented Programming (WOP)

4.3.1 Introduction

The new European practice to empower the shop floor employee with CAM knowledge is discussed. CAD data is sent to the shop floor electronically where the Mould and Die craftsman provides the human (cutting strategy and decision) input. This CAM operation is run on the machine parallel with other projects running.

4.3.2 The position of WOP in the CAx chain

Hahn (2000:1) is of the opinion that there has been up to the latter part of the 1990-decade a lack of satisfactory software to do 3D CAM programming concurrently with machining time on the shop floor. It is interesting to observe his comment that 2D NC programming is predominantly done in the office area implying that it is a less desirable practice than (advanced) workshop oriented programming. This comment is in contrast to the comment of Eversheim (2000:9) highlighting CAM programming in the office environment as a desirable practice but seen against the backdrop of the larger industry where roughly 50% of CAM programming is done during machine tool standstill.

4.3.3 WOP Operation

The machine tools in the operation at Thyssen Krupp Nothelfer GmbH run 24 hours per day with three operators, one per shift. Each machine tool has a “free standing” WOP workstation where the programming is done while the machine is in operation. To ensure concurrency, only certain types of programming are done at the WOP workstations. Programming is selected where use can be made of cycles and parametric sub-routines. The categories, which are preferably done in the office, include the following:

1. Parts where the programs are used in more than one department e.g. programs for core manufacturing used a second time for finish machining of the casting.
2. 5 - Axis programming
3. Complex contour machining where different cutting strategies are used on one part – The program segments for different geometrical areas interface at tangents to yield invisible transition areas. This is performed by special software.

Extensive programming is done on the shop floor including 3D work. The following benefits can be listed:

- Reduced throughput time – No machine time is allocated to programming
- Reduced costs – The machine operator is at the same time the programmer (in his idle time while the machine is running)
- Flexibility – The manufacturing data can be changed up to just before machining, facilitating concurrent engineering and flexibility towards the client
- Processing modifications – In machining over welded areas the operator/programmer can adapt the program to the exact geometry – The program won't be cutting air just because the office based programmer had to play safe not knowing how much welding was put on.
- Machining concurrence – It is important to each operator that he executes his own programs. Operators now interrupt and change their own programs if it is not running at an optimum.

- Employee motivation has improved to a large extent. The employee carries more responsibility and is proud of his own work from process planning through to execution.

4.3.4 Milling Strategy

The process planning is done in four steps. The first is to select the cutter. The next step is to divide the area to be milled into areas where the same milling strategy can be used. Next is the selection of the milling direction, which has a marked influence on both tool life and surface finish. The last step is to select the milling parameters namely cutting material, cutting speed and feed rate. CBN tools are a popular choice for finishing (in 2000) (Hahn 2000:4).

At the time of writing this document it could be commented that the Fraunhofer Institute in Chemnitz in 2001 have changed from CBN for finishing to TiAlN. The comment was that the new generation of multi-layer TiAlN coatings give better finishing results.

4.3.5 WOP Summary

It is clear that workshop oriented programming is an extremely valuable development from a time reduction, cost saving and people motivation point of view. There will however be some areas of process planning and CAM programming to be performed in the design office.

Considering the apparent success of WOP at Nothelfer (Hahn 2000) it should be considered to do the process planning including running the proposed HSC / EDM process planning decision tool in the design office. The process planner can specify the changeover point from HSC to EDM in the global process plan. It is practical to specify HSC machining up to e.g. a $\varnothing 6R2$ toroidal tool, with due consideration of ℓ/d ratios and material removal rates. The shop floor programmer knows that he should then program only up to the point where the $\varnothing 6R2$ tool can get in and to leave the rest to the EDM programmer. A simple utility program can update the CAD file that went to the HSC programmer / machinist to remove the material that the HSC program will remove and send the CAD data on to the EDM programmer / machinist to do his programming before the part actually arrives there.

4.4 The CAx chain

Although the CAx chain is closely related to the process chain, the term specifically refers to the processing of information excluding physical material removal or addition processes. The enablers are the software, the architecture and the knowledge supported people skills. Because such a vast number of software packages are used, it is considered adequate to report on one contemporary CAx application.

The following CAD/CAM chain is used at the Vorwerk Tool Company. Most of their work is done for production facilities in the Vorwerk group, but there is also approximately 20% of their capacity, which is sold to outside customers.

The company consists of 35 people of which 3.5 are in management. The rest of the staff is made up of 6 tool designers, 6 in mould manufacturing and 19.5 in the machine shop. There are a further 12 people involved in assembly, backup service and general manufacturing. There is also a group of seven responsible for metrology. Significant support work is done at the manufacturing sites. This enterprise is financially separate of the rest of the group.

The CAD / CAM system which is used at Vorwerk is IDEAS. The Vorwerk tool shop manufactures tools for the Vorwerk production facilities and is mostly fully automated. It is therefore necessary to build robust tools and test them well. Their CAx process chain is as follows:

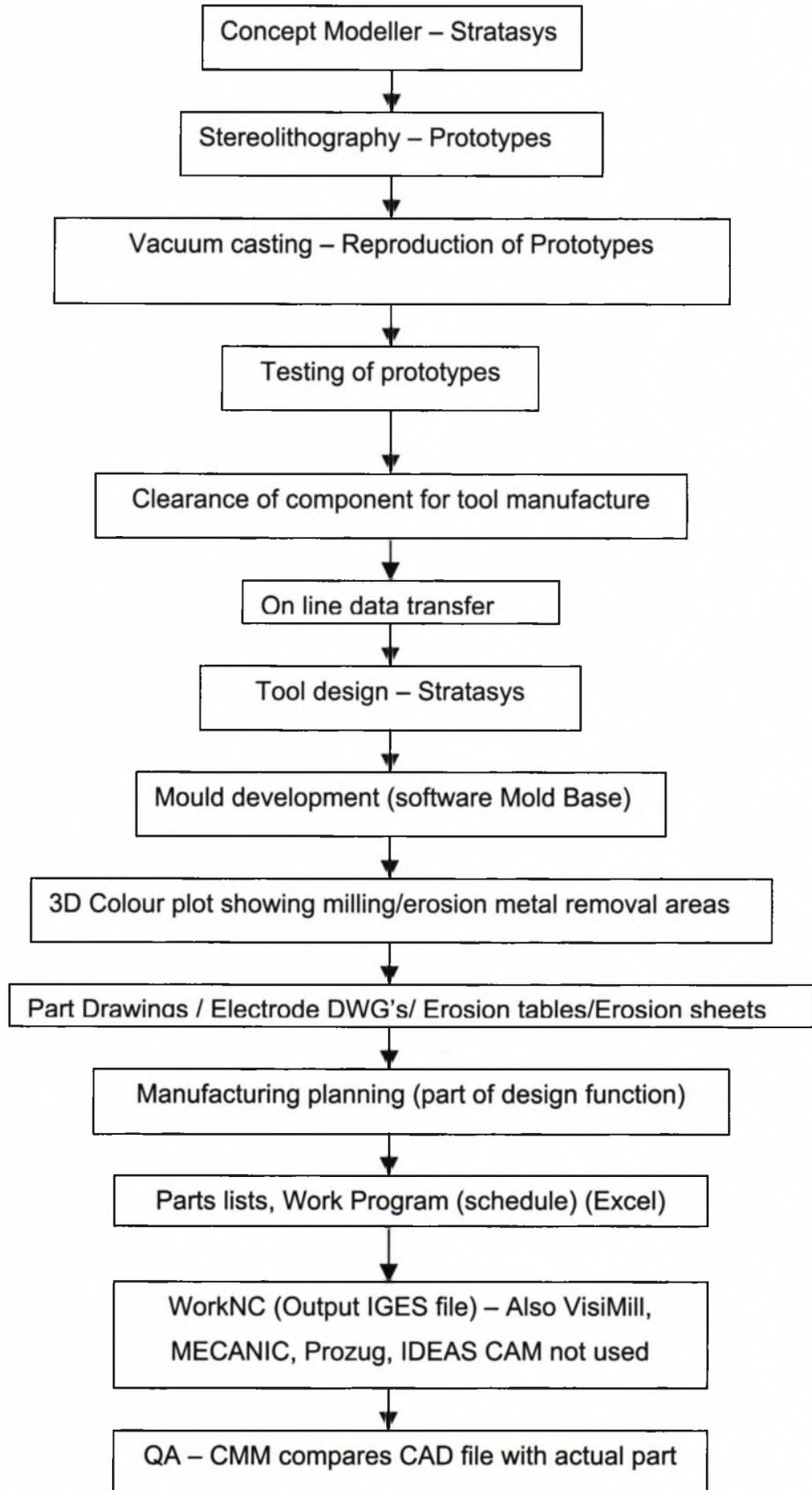


Figure 4.4.1 An example of a CAx chain in a Mould and Die manufacturing facility (Vorwerk) (Uibel 2000:2)

The experience of this company can be summarized as follows:

- a. Updates (software, hardware) are not implemented on the entire facility at once. These are implemented on single workstations and tested first.
- b. Turnover has increased by 20% pa since changeover to CAD/CAM supported by modern machines.
- c. Meeting of deadlines was a problem just after the major change. Deadlines are now met within a week on project duration of between 2 and 16 weeks.
- d. Demands from customers are rising; more freeform surfaces and higher accuracy are required. This change of requirements is reflected in the more comprehensive data required with the tool and more exact quality assurance.
- e. Dependability and integration of the CAx system is an important success factor. CAx networks do suffer breakdowns, therefore alternative (manual disc transfer of data) avenues are recommended.
- f. Networked production is successfully built on a careful selection of interfaces, software and hardware.

4.5 Manufacturing Information and Human Roles

It seems as if the industry is moving from a manufacturing process where a person, the craftsman, is the central point of the process to a technology-paced process. People still make the critical inputs or decisions but the tool or job is becoming less of a certain craftsman's job (property) depending exclusively on this person's skill and drive for progress.

During the process planning of a work piece a file is generated containing all relevant data. This file accompanies the part in the process. It is updated with each manual setting procedure and more significantly with each measurement operation. Klocke (2000:4) stresses that this information gathering process should be strictly controlled to avoid "paper jungles" being created around a facility or a job. Klocke (2000:4) further regards it as vital to move away from a person centred intuitive process design input, which cannot be reconstructed or learned from in a future project.

4.6 Summary of Operational Developments in the Die and Mould Industry

A few very significant developments are taking place, which can be classified neither as machine technology nor strictly process technology. These include the use of operators for programming or not, whether machine tool time is used for programming, the increasing role of simulation and the CAx chains.

It could be said with confidence that the practice of using the entire machine tool to program its controller, while not cutting, is an outdated practice (Refer fig 4.2.2 and par 4.3.3). Machining time should not be interrupted for programming. It should either be done in the design office or concurrently with another operation. Furthermore the practice to enter the data manually from paper drawings is unnecessarily time wasting.

Doing selected categories of programming on the shop floor based on CAD data sent through from the planning office, opens a very practical solution towards implementing the complementary HSC / EDM chain. Process selection and process changeover point planning for HSC / EDM can be done in the planning office by a person with knowledge spanning several processes aided by a computer decision tool to be proposed in the final chapters of this study. After the process chain has been specified, the CAD information can be passed on to the shop floor. There the programmer / operator who will either be a HSC specialist or an EDM specialist will program their own processes.

It is also evident from the information of the successful advanced operation of a CAx chain at Vorwerk that the CAD / CAM architecture is a necessary pre-requisite for a competitive Mould and Die facility. The requirement that the HSC / EDM complementary process chain will need a state of the art CAx architecture to function effortlessly is therefore not a disqualifying requirement.

5 High Speed Cutting (HSC)

5.1 Introduction

HSC offers significant advantages over conventional milling and EDM where it is feasible. In paragraph 5.6 an application is reported where the machining time is reduced by more than 50%. The author is of the opinion that HSC will become the mainstream process in the companies in the Die and Mould Industry adopting the technology in the near future. The technology however requires a substantial investment in machine tools, the CAx infrastructure and most of all in a knowledge base. Many firms however need a gradual phasing in of the new technology and a framework of how HSC can be used with other processes. The use of HSC and EDM is proposed as complementary processes for this purpose. This work is part of a larger task to develop a process planning software tool to show the optimum changeover point between HSC and EDM.

In this chapter the focus is on the unique characteristics of HSC and how the process performs relative to the benchmark processes namely conventional milling and EDM.

5.2 Rapid Tooling as an emerging Market for HSC

The last two decades of the 20th century was the time of intense development of the rapid technologies. Rapid prototyping progressed from the research environment to a technology capable to sustain business in a reliable way. The 1990's have been an era of rapid growth in the industry. Towards the end of the decade this growth has been slowing. The strategy proposed by Wohlers (1999:3) is that the industry should move towards the established series manufacture tool market for sustained business growth. Wohlers quotes Kuroda stating that the worldwide tooling market is

a \$65 billion industry. There are needs in this market that will respond well to new applications of the RP technologies and shorter time scales.

Initially the expectations of the 3D printing techniques were high. Towards the end of the 1990's the direct machining of prototypes gained popularity. Schuett (1999) reports that in their rapid prototyping operation, rapid milling has gained a specific application. The cost of rapid milled prototypes is 10% higher and requires 10% longer lead-time than Stereolithography (SLA) prototypes. The milled prototypes offer a virtually unlimited choice of materials. He reports that their milling capacity is to be expanded with a machine specially suited for electrode milling.

5.3 HSC as a replacement technology for EDM

There are reports of EDM being profitably replaced by HSC hard milling (Vollrath, 2001:32)(Meier, 2001:14). Vollrath reports that the implementation of HSC to replace EDM as the process to manufacture forging tools for crankshafts was a dedicated development process. In this case the tool manufacture is specialised to focus on crankshaft forging tools. It is reported that it took 6 months to optimise machining parameters before the cutting process could be left unattended even for a short period of time. Meier reports a similar experience at Thyssen Krupp and is detailed in paragraph 5.7. This tooling facility also specialises in automotive engine crankshafts. In this case the available tools on the market were not considered adequate. In collaboration with a tooling company special HSC cutting tools were developed.

The majority of mould makers in the industry would not consider this situation where development of the application took 6 months, requiring specially developed tools, as adequate process security.

5.4 Definition of High Speed Cutting

HSC is to many in the industry a new development belonging to the last decade of the twentieth century. In actual fact the process was already patented in 1931 by Salomon in Germany but more than fifty years had to pass before supporting technologies could enable the technology to become a practically applied practice (Schulz, 1996:19).

Since the middle of the 1980's, intensive HSC research and development was done at the Darmstadt Technical University (PTW) in Germany led by Prof Schulz. Their definition of HSC includes all applications of milling, drilling and turning where the cutting speed ("Schnittgeschwindigkeit") is higher than current or normal practice. HSC however mostly focuses on high cutting speed milling.

According to the Darmstadt research group's definition, the milling of aluminium at lower than 1000 m/min or practically speaking cutting at 20 000 spindle rpm and a 5 mm diameter cutter, is not HSC (cutting speed approx 300 m/min). This is seen as conventional milling practice. On the other hand, cutting hardened tool steel at 4000 rpm with a 16 mm cutter is considered to be High Speed Cutting (HSC) (cutting speed 200 m/min in hardened tool steel). This definition is detailed by the diagram from Schulz (1996:24) presented here in Fig 5.4.1. Schulz himself recognises the problematic nature of the definition by stating that the definition will continuously have to be redefined, as the new frontiers of cutting technology become common industry practice. He implies that established industry practice is per definition not HSC.

According to this author's opinion, a definition of this nature is suitable for a research group but not ideal for an established industry practice.

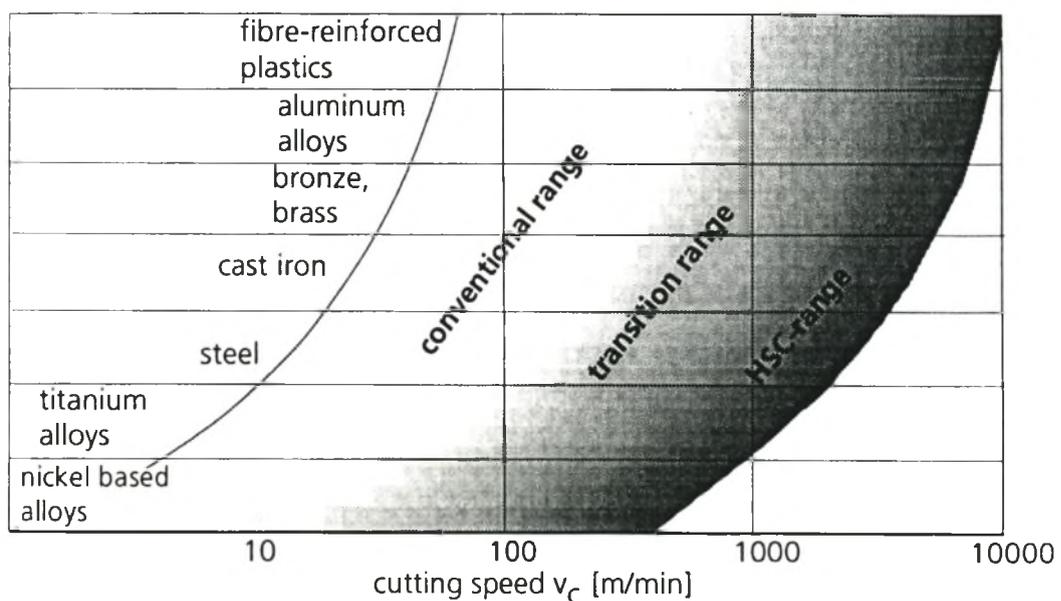


Figure 5.4.1 The Definition of HSC as the new Frontier in Milling (Darmstadt Research Group) – Diagram from Schulz (1996: 6)

Significant work is done in Aachen by the local Fraunhofer Institute and the University's WZL ("Werkzeug Labor" – Machine Tool Laboratory) on HSC. Klocke

and Eversheim are prominent research figures from these institutions. Their definition seems to be High Speed Cutting (HSC) for the softer or brittle easy cutting materials (e.g. aluminium, graphite, composites and polymers) where the cutting speed is relatively high in absolute terms. The term HSC Hard Milling is used for applications where the material, e.g. tool steel, dictates a relatively low cutting speed but where this speed is significantly higher than conventional practice. Although this definition has a more logical foundation than the Darmstadt definition, there are still illogical areas, for example the HSC of certain copper alloys, which are neither absolute high-speed cutting, nor "hard" milling. The unique material characteristics (of copper) dictate cutting conditions, which cannot be incorporated in a simple logical definition (lower HSC cutting speed than for other materials of similar hardness). It also seems as if the Aachen group steers away from using the HSC term for other types of machining than milling. Turning, drilling and grinding is therefore specifically described and the general term HSC is only used for milling.

The universities in Dortmund and in Dresden are also doing significant work in the field. In their proceedings of the 1999 conference the term HSC is used for the cases where the speed is high (softer materials) and the term H²SC is used for the HSC cutting of Hard Materials for example tool steels. This term is seen as the equivalent of the Aachen HSC Hard Milling.

The technology is being developed in the USA, France and Japan as well. In the USA the term High Speed Milling is used extensively with the speed also referring to the cutting speed and not the spindle speed. In France the accent is also on the cutting speed. The standard of research work in Japan is unknown. The standard of the Japanese Machine tools (e.g. Mazak) however indicate that the HSC expertise in Japan is in a position among the world leaders in this field.

In this thesis the term HSC will be used in the general sense referring to higher cutting speed but still dependent on material properties. The reference to speed is therefore not in absolute terms but will vary for different materials. The High Speed Cutting of Tool steel, which is the focus, will be referred to as H²SC.

5.5 Comparison of HSC with Conventional Milling

The author visited the EMO machine tool exhibition in Germany in 2001. The large emphasis machine tool manufacturers placed on HSC capability in machine tools

created a very strong impression that HSC is becoming an established industry practice. It should be added that the most popular machine tool category on the exhibition was the lower end of the HSC spectrum but significantly higher than conventional milling.

The current definitions of the technology is somewhat problematic for an industry comprising of not only academically skilled but also practically developed skilled people. These definitions are being centred around a secondary or calculated parameter (cutting speed). A primary machine parameter such as spindle speed that is set or read from a display would have been a more suitable industry parameter. This has created interpretation problems in industry and to a lesser extent in the research community. Industry has tried to interpret the difference between conventional or high (spindle) torque milling as the conventional practice and high (spindle) speed milling or HSC as the new technology. This definition also does not hold in the light of new developments with tip carriers where there is a requirement for relatively high cutting speed and simultaneously high(er) torque. The relatively large diameter of the modern tip carriers results in high cutting speeds even at relatively low spindle rotational speeds. The popular industry belief that HSC is defined by a high spindle speed is therefore strictly speaking incorrect. According to the definition, a machine tool machining aluminium at 10 000 or even 20 000 rpm may be conventional practice while the same machine machining tool steel at 4000 rpm may be classified as HSC. This example intends to show the inadequacy of this definition of HSC based on cutting speed alone, because machining aluminium at 20 000 rpm requires a machine tool equipped with a high frequency spindle, matching feed rate, high speed axis drives and the appropriate cutting tool holding equipment. This non-correspondence of the technology with machine tool capabilities and parameters will have to be addressed in future terminologies.

It is the author's opinion that in the post 2000 era the definition of HSC is becoming wider. In the strict pre-2000 definition HSC was only well suited for finishing and not for roughing. With the introduction of categories of machining practice within HSC this situation has changed. A prominent factor is the role of the cutting tool technology. This was a pull situation when HSC research identified cutting tool development as a major limiting factor. This industry has made significant progress with full carbide tools (high E value and low deflection) and the multi layer coating technology showing large improvements in the last five years. There has also been a major development of preference for tip carriers with disposable tips wherever possible. It is generally not feasible to sharpen coated tools. It is the author's

opinion that this new tool technology is now “pushing” HSC to within the reach of the broader industry. This has led to the development of so-called High Performance Milling (“Hochleistungsfräsen”). This somewhat lower spindle speed machine tool strategy yields good results with roughing especially in the harder material applications. Most of the machines exhibited at the EMO Machine Exhibition held in Hanover, Germany in September 2001 were of the universal type with the option of high-speed spindles, which could also be termed as a High Performance Milling Machine. These machines can exploit the new generation of cutting tools but are generally speaking either high speed machines in absolute terms capable of high speed cutting of soft materials or sturdier machines suited for high torque / lower speed cutting of harder materials for which the description of a modern universal machine is appropriate. There is however a small group of machines capable of true H²SC (HSC Hard Milling). These three categories of machines that are all marketed as HSC machines are three distinct categories with minimal overlap.

The terms High Performance Milling (HPM) and High Effectivity Milling (HEM) are the terms that developed in the English speaking commercial world. A similar trend is seen in Germany. Thyssen Krupp has successfully pioneered the direct milling of crankshaft forging tooling. This application is referred to as “Hochleistungsfräsen” or high performance milling. The term high-speed cutting (HSC) is well known in Germany and this author is of the opinion that the introduction of the term “Hochleistungsfräsen” was the deliberate use of a different term to HSC. According to the article the machine tool is capable of 12 000 rpm and up to 250 m/min cutting speed was used. Meier (2001:15) reports the use of tools from 3 to 16 mm diameter. With a 3 mm tool rotating at 12 000 rpm the cutting speed is 18 m/s. Only with a 12 and 16 mm diameter tool the 200 m/s cutting speed can be reached. This means that this application is on the lower end of the scale of the strict (academic) definition of HSC (especially with the smaller diameter tools). It is however rather productive use of high performance milling or “Hochleistungsfräsen”.

In a company publication by Deckel Maho Gildemeister (DMG), one of the largest manufacturers of milling machines in the world, the term HSC is used. It is however stated that the article focuses on that part of HSC which is achievable with a 15 000 rpm spindle speed. This information is clearly not based on misconception but rather with the goal of simplifying the technology to the user. DMG is at the same time addressing the bulk of the market. The term High Effectiveness Milling / High Performance Cutting or “Hochleistungsfräsen” is the category of HSC which is addressed by DMG in this case.

It is further noted that many authors state or imply that HSC holds considerable advantage for semi-finishing and finishing but not specifically for roughing. (Aksoy, 1996:245), Schulz(1996:23) and Schmitt(1996:125) agree that the HSC benefits are in the field of finishing.

Schmitt (1996:123) proposes a categorisation of HSC Machine tools in three categories as shown in Fig 5.5.1. He defines the term HSC as the broad overall term for the technology. Conventional Machining, High Velocity Machining and High Speed Machining are the terms that he uses for his proposed categories. The industry or commercial term High Effectiveness Milling (HEM / HPM) or "Hochleistungsfräsen" corresponds to the lower speed part of High Velocity Machining.

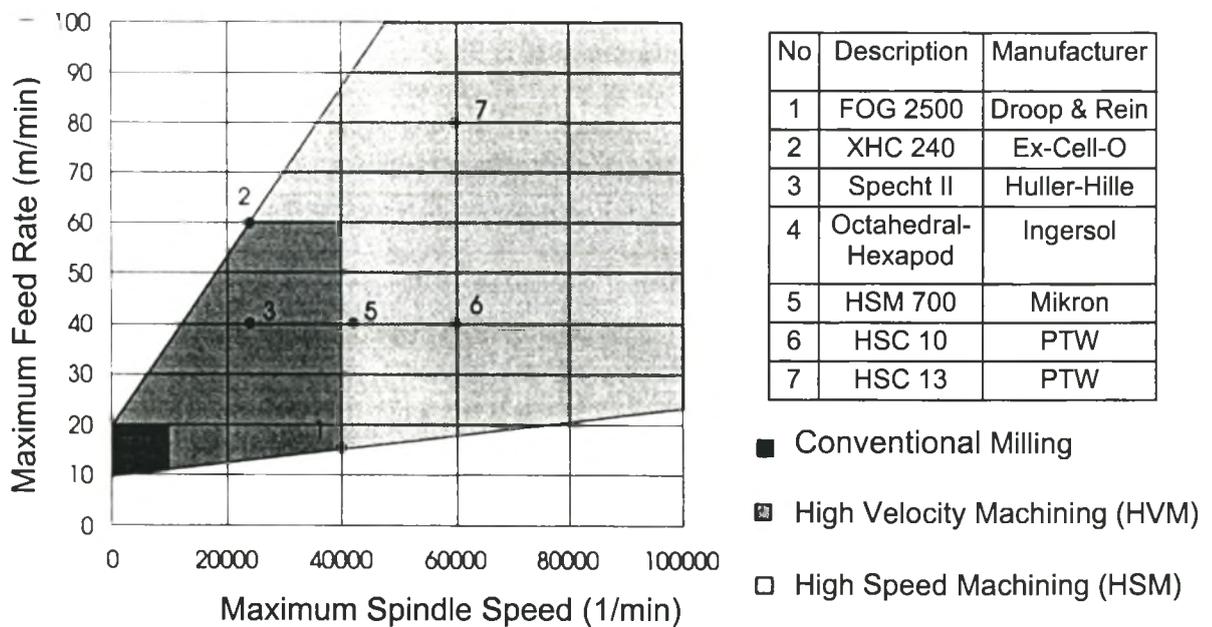


Figure 5.5.1 Classification of Milling Machines according to Spindle Rotation Speed and maximum Feed Rate (Schmitt, 1996:123)

Schmitt states that the majority of machines sold in industry are of the HVM type or "Hochleistungsfräsmaschinen". It can also be seen from the cross section of spindle characteristics available in the market as shown in Fig 5.5.2 that a substantial number of the available spindles are in the 10 000 to 25 000 rpm range. This corresponds to the High Velocity Machining / High Performance Milling / "Hochleistungsfräsen" category.

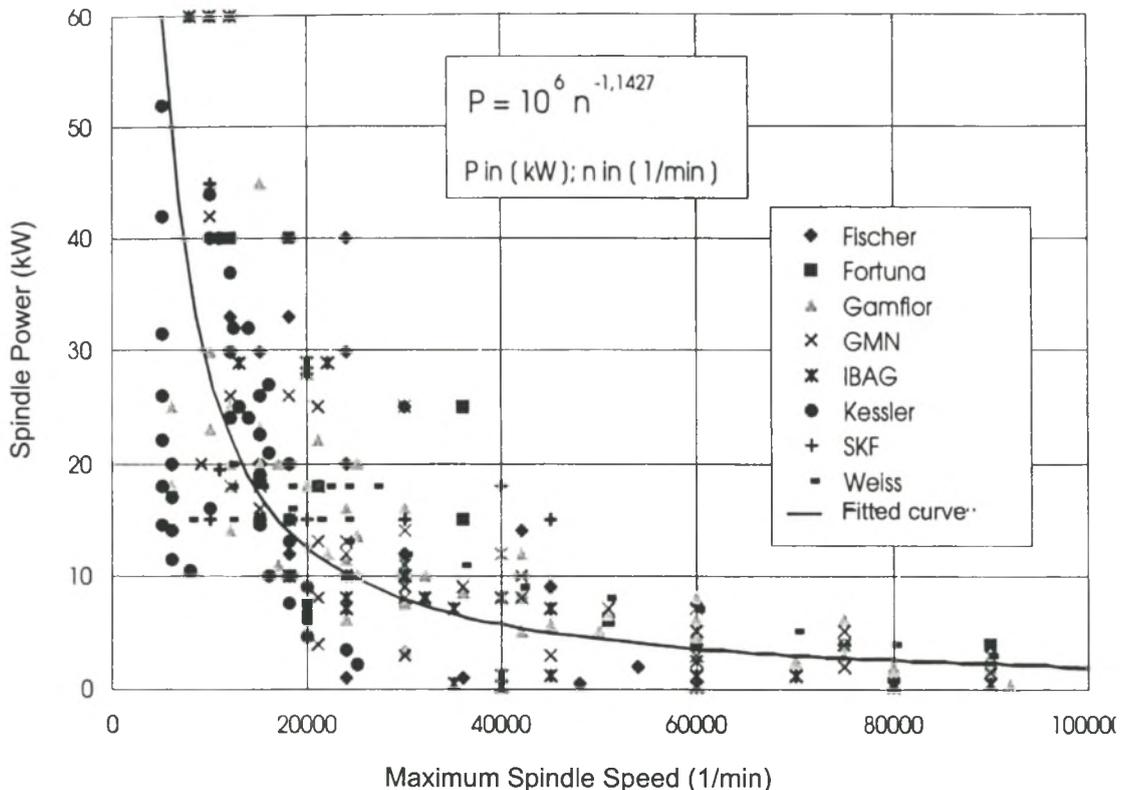


Figure 5.5.2 Spindle Power vs. Maximum Speed of available Spindles (Schmitt, 1996:126)

It is significant to note that Schmitt (1996:134) quoting Schulz reporting on trends in the USA distinguishes between the HVM (“Hochleistung”) machines capable of high metal removal rates (“Zeitspanvolumen”) at cutting speeds in the lower HSC range and HSM machines capable of medium metal removal rates at very high cutting speeds. The user who does not do roughing and finishing on separate machines will have to consider the higher metal removal rate (“Zeitspanvolumen”) of the High Velocity / Effectivity / Productivity / “Hochleistungs” – Machines against the better finishing capability of the HSM (pure HSC) machines. In the USA the term HSM (High Speed Milling) is used for the pure HSC process.

Müller-Hummel et al from Daimler Chrysler Aerospace, Germany, express the same view. They state that High Performance Cutting (HPC) or “Hochleistungsfräsen” is an established practice in the Die and Mould Industry (“Formenbau”) and a distinctly different practice from High Speed Cutting (HSC). They define HSC being the technology where the emphasis is on achieving the highest practical cutting speed. The cutting cross section (“Spanungsquerschnitt”) is of secondary importance. In contrast HPC or “Hochleistungsfräsen” optimises between high cutting speed and cutting cross section to achieve a high material removal rate (“Zeitspanvolumen”). It

then makes logical sense that the aerospace industry is refocusing on HPC ("Hochleistungsfräsen") and not High Speed Cutting (HSC). The author considers this differentiation between HSC and HPC ("Hochleistungsfräsen") as significant for this study. HSC with the emphasis on cutting speed yields high feed rates that in turn yield high rates of area coverage. On the other hand HPC ("Hochleistungsfräsen") places the emphasis on both speed and cutting cross section to achieve optimum material removal rate ("Zeitspanvolumen") (Müller-Hummel 2000: 231).

HSC is then the preferred technology for finishing and semi-finishing and HPC ("Hochleistungsfräsen") is the preferred technology for roughing.

At the EMO machine tool exhibition (2001) in Hanover this trend was strongly observed among the machine tool manufacturers. The author observed a strong inclination among the majority of manufacturers to offer the most of their high speed machines in the High Velocity / Effectivity / Productivity / "Hochleistungs" range with maximum spindle speed 12 000 to 25 000 rpm. Some manufacturers like Hermle state that their focus is on this category of machine and that pure HSC is of secondary importance to them. It seems as if a similar situation exists at Deckel Maho Gildemeister (DMG).

The conclusion is made that since around 1995 the perception was that HSC is the new technology that will eventually be used for all tasks in Die and Mould Making. This view has changed. A new generation of fast Universal, or High Effectiveness, High Velocity or "Hochleistungs" – machines find the widest application in industry. There is however still the specialist pure HSC category of machines described by Schmitt (1996:123) as the HSM machine tool category. For the purposes of this study HSC in the wider sense of the word including HPC ("Hochleistungsfräsen") is investigated as a complementary process to EDM.

For roughing the high performance cutting category of HSC machines ("Hochleistungsfräsen") will be appropriate, for finishing the lower end of the HSM range of machines and for electrode and soft material machining the very high speed HSM category of HSC machines will be most appropriate.

It will be shown further in the thesis that the use of milling is already an established practice in conventional process chains. The differences between conventional milling and H²SC in the proposed process chain as the process preceding EDM will be discussed in the following paragraphs.

5.5.1 H²SC and near net Free Form Surfaces

Conventional pre-EDM machining is usually 2^{1/2}D programmed, machined with relatively large tools leaving an uneven starting surface for EDM.

H²SC is capable of finish machining many of the surfaces and only selected surfaces are left for EDM finishing. Where surfaces are left for EDM finishing, the surfaces can closely resemble the final surface. The required EDM material removal can therefore be uniform resulting in uniform electrode wear. In some cases this may make the difference between using a single electrode and two electrodes to machine a mould insert.

5.5.2 H²SC and Small Radius features

Due to lower cutting forces H²SC can be used to machine small radii. Features with a radius of less than 1 mm can be milled if the depth and the surrounding geometry are favourable.

Conventional milling is impractically slow when using small diameter cutters. In conventional thinking small features requiring small diameter milling cutters, typically below Ø2, are regarded as EDM process terrain with conventional milling as the roughing step in the process chain.

One of the most recent developments in HSC is to use toroidal cutters. The cutter has a small corner radius compared to the tool diameter. This development has improved considerably HSC's ability to machine small radii in corners.

5.5.3 Set-up Time

Using complementary supporting technologies like pallet fixturing the need for repeated set-ups is eliminated in the case of modern H²SC and EDM in combination.

Companies like Erowa and 3R have these systems on the commercial market. This technology was pioneered for automating the EDM industry.

5.5.4 Hand Polishing Minimisation

In some cases the application requires that the machined surface be polished. In the conventional process chain the full final surface is eroded resulting in the full surface to be polished by hand to remove the heat affected zone or white layer.

In the case of the H²SC / EDM process all accessible surfaces will be H²SC finished. H²SC finished surfaces require less time to hand finish than EDM surfaces resulting in a throughput ("durchlauf") time saving.

5.5.5 Automation – Pioneer Work for EDM is Applicable to HSC

The field of series manufacturing tooling has up to now been the domain of Electric Discharge Machining (EDM). In order to meet industry requirements of lower cost and reduced delivery time Helle (2001:16) reports that the series tool industry is investigating automation. There are two main trends. The first is to use one operator for more than one machine tool. The second is direct automation using manipulators and suitable fixturing systems such as pallets. The importance with which the EDM industry regards automation and palletisation is reflected in the acquisition of the well established Swedish company 3R by the Leading Agie-Charmilles EDM machine manufacturer (Agie Charmilles, 2001:6).

Palletisation technology is considered to be a prerequisite or essential foundation technology for HSC and EDM to be used as complementary processes. Complementary HSC / EDM will only be marginally feasible or not feasible at all if multiple set-ups is required at each process step. If the palletisation is already available the proposed H²SC / EDM process chain is suitable for partial automation. Companies like Erowa and System 3R offer complete systems including magazines for in process storage, machine tool loading manipulators and coordinating computers. It then becomes employing established technology to program the process chain during normal working hours and using the night hours for automatic operation. The night hours may be utilised to achieve considerable shorter throughput times.

In general practice conventional milling is a manned operation, the re-set-up also manned and EDM is already a 24 hour unmanned operation outside normal work hours. Using the complementary HSC / EDM process where the total Mould and Die manufacturing execution can be automated in a 24 hour operation will yield further throughput time benefits.

5.6 Applications of HSC in the Mould and Die Industry

5.6.1 Application Catagorisation

In table 5.6.1.1 three categories of application of HSC in the Die and Mould industry is discussed. HSC is a rather wide concept. This table of the requirements of different

applications of HSC points out that different machine tools are required for the different applications.

Series production tool manufacture is usually a project requiring few repetitions, demanding an excellent surface finish. Because the materials used in this category are tool steels the cutting speeds are lower and the moderate speed capability of the High Velocity / High Productivity machine category is generally adequate. For productive roughing in tool steel, also with tip carriers the higher torque capability of the HPM category of machine is essential.

In the case of bridge tooling the materials are generally softer to facilitate the required shorter lead times. It is also interesting to note that in the bridge tooling a fair amount of larger tools are encountered. It can be ascribed to the fact that tool cost increases dramatically with size, and the intermediate phase testing of the design and business feasibility with production materials becomes more common practice than with small tools. The machines required need to have a high spindle speed capability and high axis acceleration because with bridge tooling productivity is directly correlated with lead-time. This requirement of high productivity places the optimum machine for bridge tooling in the approx 20 to 30 000 rpm maximum spindle speed category.

In the prototyping category, true high-speed capability can be utilised. The author experienced the use of a HSC machine for the manufacture of prototypes and small volume tooling. This was a 30 000 rpm machine with full 1 g acceleration which was used rather effectively. The HSC machining based process chain proved to be very effective where repeat orders for prototypes with only limited modifications were processed. This machine was used in a rapid prototyping environment where the unique capabilities of the HSC process chain supplemented rapid prototyping in a productive way.

Application Parameter	Series Production Tooling	Bridge Tooling	Prototypes, Cores
Size	Small to Medium	Up to Med Large	Up to Med Large
Complexity	Very High – Free Form surfaces, Severe contours	Medium to High	Very High
Number of units	Small, mostly one	Small, repeating a few times or more than 1 tool	Med, recurring several times in development
Surface quality	Very High, often optical criteria – near mirror finish	High, but cost constrained, hand polishing feasible	Med high, Very time, cost limited hand finish usual
Form tolerancing	Very High, 5 - 15 μ m	High 10 – 50 μ m	Medium 20 – 100 μ m
Productivity of HSC process	Med High, fully subject to quality	High, req'ments not so high qual	Very high, reserve used for speed
Material	Tool Steel	Alum, Tool Comp	Tooling Comp
Cutting speed	200 (up to 300)	500 - 5000	< 1000 m/min
Forces	Medium	Small	Very small
Tools	Bnose / tip carrier	Bnose / tip carrier	End mills / Bnose
Tool diameter	3 to 32	2 to 20	1 to 10
Feed rate	High	Very high	Very High
Axis Acceleration	High	Very high – 1 g +	Very High – 1 g +
Spindle speed	Med (typ 18 000)	High (typ 30 000)	High (typ 30 000)
Spindle torque	Medium	Low	Low (typ 1.5Nm)

**Figure 5.6.1.1 Application of HSC in the Mould and Die Manufacturing Industry
(Based on Schmitt (1996:124))**

5.6.2 Example 1 of a HSC Application: Crankshaft Forge Tooling

Meier reports that in this case these tools were traditionally machined with EDM (Meier, 2001:14). After application development including special finishing cutters of fine grain coated carbide, this type of project is now done with HSC. The machine tool falls in the High Performance Milling (High Velocity Machining according to Fig 2) category with a maximum spindle speed of 12 000 rpm. The material hardness is between HRC 42 and 44, the tool l/d ratios up to 13 and cutting speeds up to 250 m/min were used. Furthermore the finish was of a sufficient quality that hand polishing was unnecessary in the HSC case. A longer tool life is also experienced due to less sub surface heat damage. The process security, time and lead-time saving is such that EDM is not considered for this type of tooling any more.

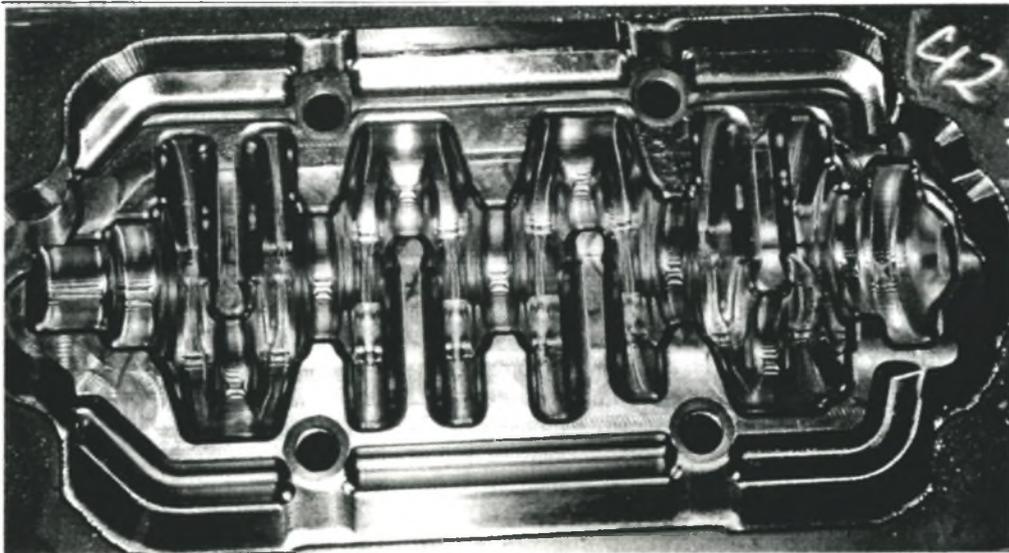


Figure 5.6.1 Crankshaft Forge Tool machined with HSC (Meier, 2001:14).

5.6.3 Example 2 of a HSC Application: Plastic Injection Mould Components

Daniel reports of substantial time saving that was achieved when HSC was used to replace the conventional process chain at the Lego manufacturing facility in Germany. (Daniel, 1999).

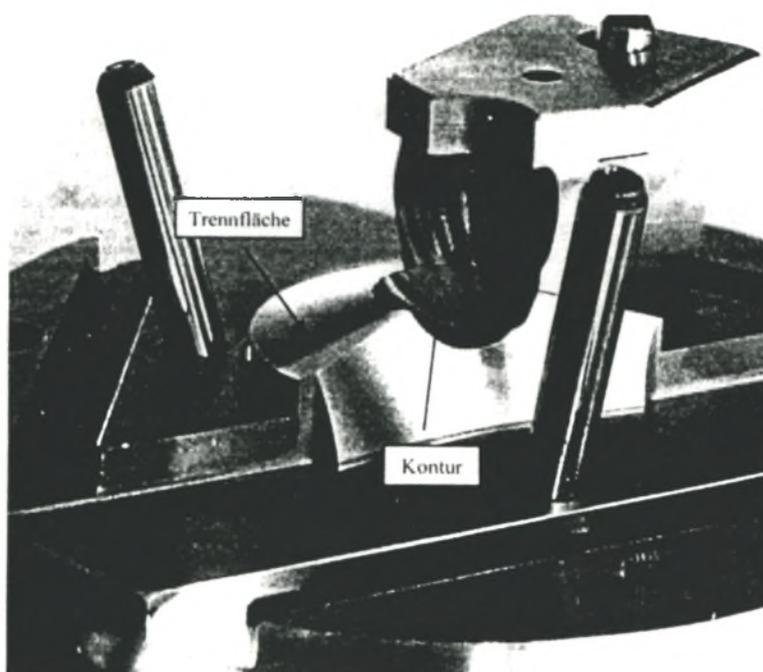


Figure 5.6.2 Example of Injection Moulding tool components manufactured at LEGO (Daniel, 1999).

	Conventional		HSC Milling	
	Electrode Milling -	EDM - Spark Erosion	Roughing Before Heat Treatment	Finishing After Heat Treatment
Programming (h)	60	-	25	35
Machining Part 1 (h)	46	33	6	12
Machining Part 2 (h)	46	33	6	12
Machining Part 3 (h)	50	33	6	12
Machining Contour (h)	132	37	8	16
Total Machining time (h)	274	136	26	52
Total time (h)	470		138	

Table 5.6.3.1 Machining times for the LEGO Injection Moulding tool in Fig 5.6.2

With this time saving of more than 50% it is expected that HSC will become the preferred process in this company wherever technically feasible.

5.6.4 Example 3 of a HSC Application: Powder Metallurgy Punch

Casellas reports a 75% reduction in machining time for a sintering press tool. The conventional process chain was executed as follows:

- EDM Electrode preparation (3 electrodes) 75 min
- Conventional 3D NC Milling of electrodes (3 x 420 min) 1260 min
- EDM Die sinking 600 min
- Finishing 400 min
- **Total time 2335 min**

The identical part was machined with HSC Hard Milling (H²SC) as described in the following process chain:

- Pre-roughing Ø1,5 mm tool 87 min
- Roughing Ø1,5 mm tool 20 min
- Pre-dressing Ø1,0 mm tool 60 min
- Dressing Ø1,0 mm tool 55 min
- Pre-finishing Ø0,6 mm tool 70 min
- Finishing 250min
- **Total time 542 min**

The material was a tool steel of 67 HRC. Apart from the substantial time saving, which will have a similar effect on leadtime and cost, the quality of the HSC machined part is also better. The heat affected zone or white layer is highly undesirable in the powder metallurgy field, limiting the life of the tool. (Casellas 2000:9)

5.7 Concluding Overview

From the discussion on HSC in this chapter the following conclusions are made:

The rapid prototyping industry with a highly developed CAx infrastructure is in a position to expand into the segment of the series tooling market where lead-time is of paramount importance and / or limited tool life is sufficient. This trend, commonly referred to as the development of rapid tooling, is expected to grow. Further differentiation where a demand for short lead-time tooling in tool steel is expected to take place.

The EDM technology is making marked advances in terms of process speed and automation but will not be able to satisfy this new rapid segment of the market on its own.

HSC is currently seen as a total process alternative to EDM only in selected feasible cases. Most of the successful cases required dedicated development. The varied nature of projects in a typical Die and Mould facility does not warrant the dedicated development of a HSC application for every project. Process security with HSC will remain a problem in the near future when complete jobs are to be executed with HSC.

If HSC can be utilised only up to the point where process security is satisfactory, its use is feasible and potentially wider than at present, especially at the smaller non-specialised Mould and Die companies.

Process security is dependent on tool technology, machines, fixturing but most significantly on personnel expertise. The point of complexity up to which HSC is utilised can be a variable based on available expertise.

If the fixturing and automation technology pioneered by / for the EDM industry can be utilised to avoid the cost / loss of throughput time incurred with multiple set-ups, HSC and EDM may be appropriate complementary processes for a single project.

Currently process planning for HSC and EDM in isolation, can be supported with well-developed software tools e.g. tool collision detection, milling time estimation and EDM time estimation. If EDM and HSC are to be utilised as complementary processes planning tools are necessary which consider the higher level of the two processes as an integrated process chain. Examples of decisions at this integrated level are to determine suitability of a project for the combined process and the change-over point between the two processes.

6 Process Chain for Complementary HSC / EDM

6.1 Introduction

For many practitioners in the Die and Mould industry it has become customary to see HSC and EDM as competitive processes. Both Vollrath (2001:32) and Meier (2001:14) describe case studies where EDM was replaced by HSC milling. The object of this thesis is however to promote the complementary use of the two processes.

Daniel (1999:223) reports that the everyday tool manufacture ("Werkzeugbau") at Lego in Germany includes the manufacture of electrodes and tool inserts from aluminium, brass or steel. The combination of the two processes for metal or more specific steel moulds is therefore only a new process chain with existing process and material combinations.

6.2 Limits of proposed complementary use of HSC/EDM

6.2.1 Size of Tool Application

The process chain comprising of HSC and EDM as complementary processes will be focused on small mould manufacturing as defined by Aksoy (1996:245). Small Mould Manufacturing ("Kleinformenbau") finds prominent application in tooling for consumer goods and the electrical industry components. Many of the applications in the automotive industry also fall in this category but major applications however fall outside this category. There are many free form surfaces required in this category of tooling. Concave and convex curved surfaces are mostly machined with 3-axes and ball nose (spherical head) cutting tools. Because of small geometries, five-axis machining is mostly impractical or of minimal benefit. The use of HSC leads to reduction of the manual finishing of the tooling.

Aksoy (1996:245) also reports that in Small Mould Manufacturing the electrodes for EDM ("Senkerodieren") are precision parts. Apart from complex geometries and accurate dimensional requirements a good surface quality is also required. Due to the complexity of the electrodes and relatively large amounts of material to be removed in this category, machining times for the electrodes are substantial. The benefit of using HSC as the electrode preparation process could be significant time and cost savings.

The author considers moulds for a computer front panel (400 x 150 x 50), a computer mouse (80 x 50 x 25), a telephone (200 x 150 x 40) as typical examples of small mould manufacturing. The bulk of the components in this category will however be smaller.

6.3 Process Chain: Overview of the HSC/EDM Process Chain

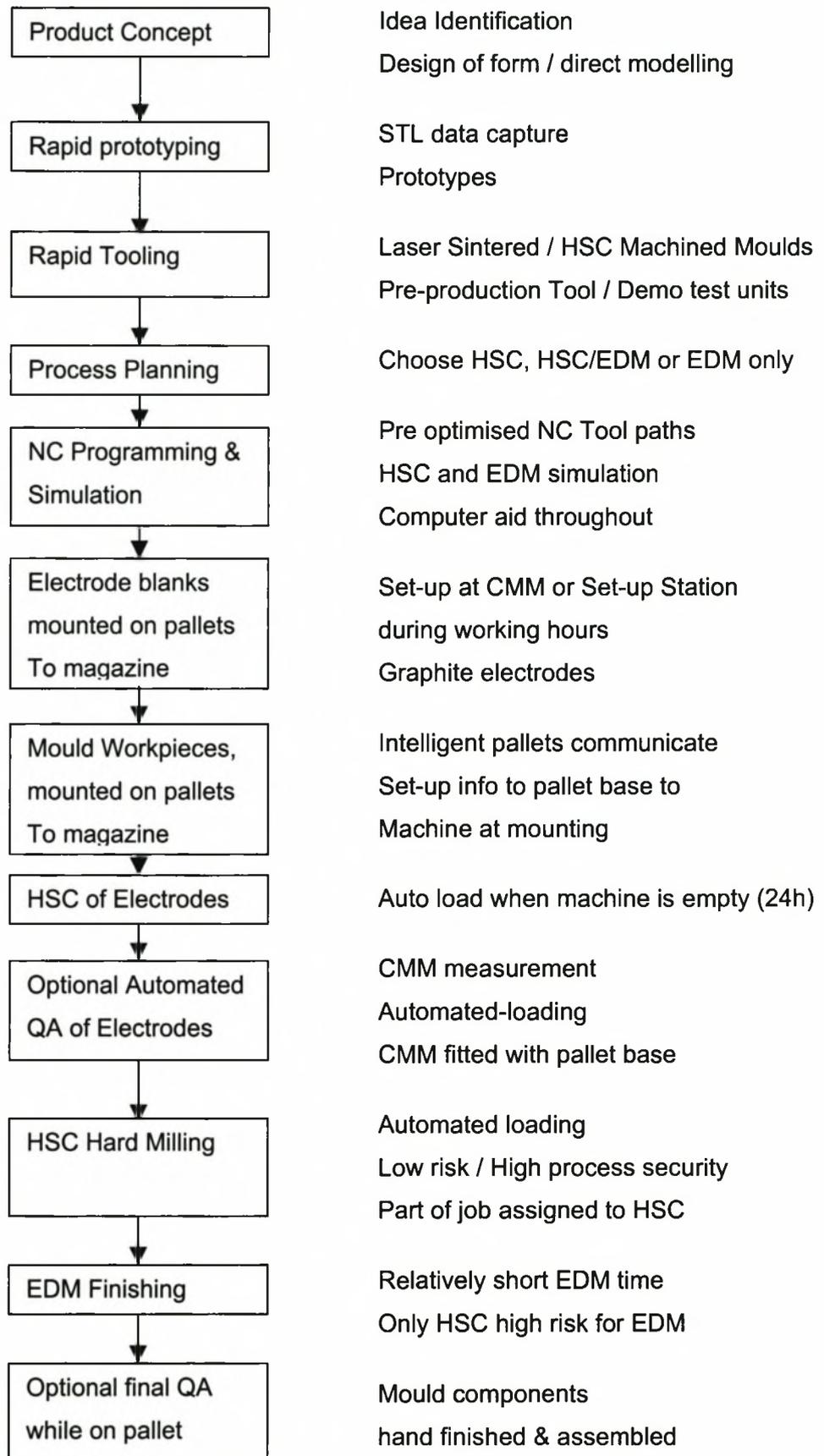


Figure 6.3.1 The process chain for the HSC / EDM complementary process

The process chain in Fig 6.3.1 is discussed in more detail below. The CAD modelling and rapid prototyping phase of the chain will be unaffected by the HSC/EDM complementary process use. The rapid tooling or bridge tooling phase of the chain will have the option of HSC direct machined tools in tooling composite or aluminium or a composite core for cast tooling. In this process chain the available HSC machine can be considered for the other parts of the chain as well. It may however still be more appropriate for the specific case to use a rapid prototyping technique to manufacture the bridge tooling.

When the process planning is done, it is firstly necessary to decide whether the specific project is a candidate for the complementary HSC/EDM process chain. Assuming that HSC is well established in the company the first choice will be for HSC only. There are however many cases where even the most skilled craftsmen and most advanced equipment will not be capable of machining a required cavity with HSC only. If the task is dominated for example by deep narrow cavities the contribution by the HSC part of the combined process may be so minimal that the whole job may be performed with EDM with no substantial loss in leadtime. If the HSC/EDM combination process is used the process planner needs to decide what part of the task is to be allocated to HSC and what is to be left to the EDM part of the process. This will determine the changeover point in the process between HSC and EDM.

The NC programming will use the changeover point as input. The normal roughing, semi-finishing and finishing strategies for HSC are used. Where a surface is finished with EDM, HSC finishing becomes unnecessary. Existing CAM package simulation runs will be used to check for collisions, machining time and tool loading. It should be borne in mind that HSC is rather sensitive for a sudden increase of tool contact angle, which is inevitable when cavities are machined. The large feed rates for optimum tool life in HSC usually results in tool breakages if specific feed rate reduction is not programmed where contact angles are momentarily large. These momentarily large tool contact angles are encountered at corners in a cavity in the xy plane, at the bottom of the cavity in the xz and yz planes. A severe increase in tool contact angle is encountered when the cutting tool radius is similar or equal to the cavity radius. Simulation tools checking for these tool contact conditions decreases the skill requirement of the CAM programmer. Similarly the EDM process can be simulated with the available tools.

It is envisaged that the electrode graphite blanks be mounted on the pallets on a CMM if high accuracy is required or at a workbench if the blanks allow enough material removal so that the initial setup is not critical. The loaded electrode pallets are then placed in the magazine of the machine tool (load and unload) manipulator from where the manipulator will load the pallet into the HSC machine when available for electrode machining. The mounting of the graphite blanks is done independently of the work load on the HSC machine and can therefore be during working hours at the convenience of the mould maker. Similarly the mould maker mounts the work piece material on the pallet and places it in the pallet magazine. A new development that is not yet in common use, is intelligent pallets. The setup information is stored in a memory chip on the pallet. When the pallet is loaded into the machine tool the datum information is communicated to the machine tool.

When the HSC machine becomes available the manipulator (or operator) mounts the pallet with the electrodes onto the pallet chuck on the machine tool's bed. The supervising computer (or operator) will download the relevant program and the electrode is machined. When the electrode is completed the manipulator (or operator) will move the pallet to the CMM for inspection of the electrode. Again the CMM program is downloaded and the inspection performed. The CMM will be equipped with the same pallet chuck as the machine tools. At the Fraunhofer Institute in Aachen the author attended a demonstration of such an automated machining cell with two machine tools and a CMM in September 2000.

Following the electrode machining, the pallet with the work piece is similarly loaded into the HSC machine tool for the HSC part of the machining. In the complementary HSC / EDM process the HSC milling will most probably be H²SC or HSC Hard Milling. In the complementary HSC/EDM process only the part of the machining will be allocated to HSC that can be done with negligible risk to ensure high process security. When the machining is completed the pallet is removed from the HSC machine tool and returned to the magazine.

For the EDM phase the pallet holding the workpiece is mounted on the pallet chuck on the EDM machine's bed. The finished electrode is taken from the magazine and mounted by means of its pallet in the pallet chuck as the EDM die sinking tool. This technology has been established in the EDM industry. The workpieces are generally larger and heavier than the electrodes. Erowa, a pallet system manufacturer, for example has a standard pallet chuck available (UTS) which is used on the machine tools beds (both HSC and EDM) capable of mounting a 500 mm x 500 mm x 500 mm

work piece. This pallet chuck can also accept the smaller (ITS) pallets which has a 140 mm x 140 mm x 140 mm capability and is extensively used for mounting die sinking tools on the EDM machines. The EDM machines are therefore equipped with the large capacity pallet chuck on its bed and the smaller capacity pallet chuck in the tool holder. The HSC machine will be equipped with the dual purpose large capacity pallet chuck on its bed to first accommodate the small pallet carrying the electrode and later accommodate the large pallet with the workpiece. It is however also possible to standardise on the same pallet size.

In a general Mould and Die company a diverse mix of projects is encountered, especially in South Africa. There is limited opportunity for the company to build experience with a certain type of tool. Because there is some amount of uncertainty in the final dimensions of an eroded cavity the finishing stages of the EDM process is often supported by measurement. This measurement can largely be eliminated if sufficient development work could be done on that specific class of tool. As stated above in a general Mould and Die company this opportunity to thoroughly develop an application rarely exists. In these cases the option of effortless in process checking on the CMM will be of value. This will be facilitated by the use of pallets in the process chain.

Finally the mould components can be released for hand finishing and assembly after a quality assurance check on the CMM.

6.4 HSC Chip Volume: A Tool Capability Overview

6.4.1 Introduction

The aim is to formulate a model to guide a user where to use HSC and EDM respectively in a process chain where both processes are used. This aim necessitated this investigation into HSC Milling Chip Volume or Material Removal Rate ("Zeitspanvolumen").

Schulz (1996: 19) describes the HSC process as seen from a holistic point of view. The work-piece material, its fixturing (holding), the tools, the machine tool itself and the CAD/CAM process should be viewed as a whole to be able to study the effective output of the process. The diagram from Schulz is included as Fig 6.4.1.

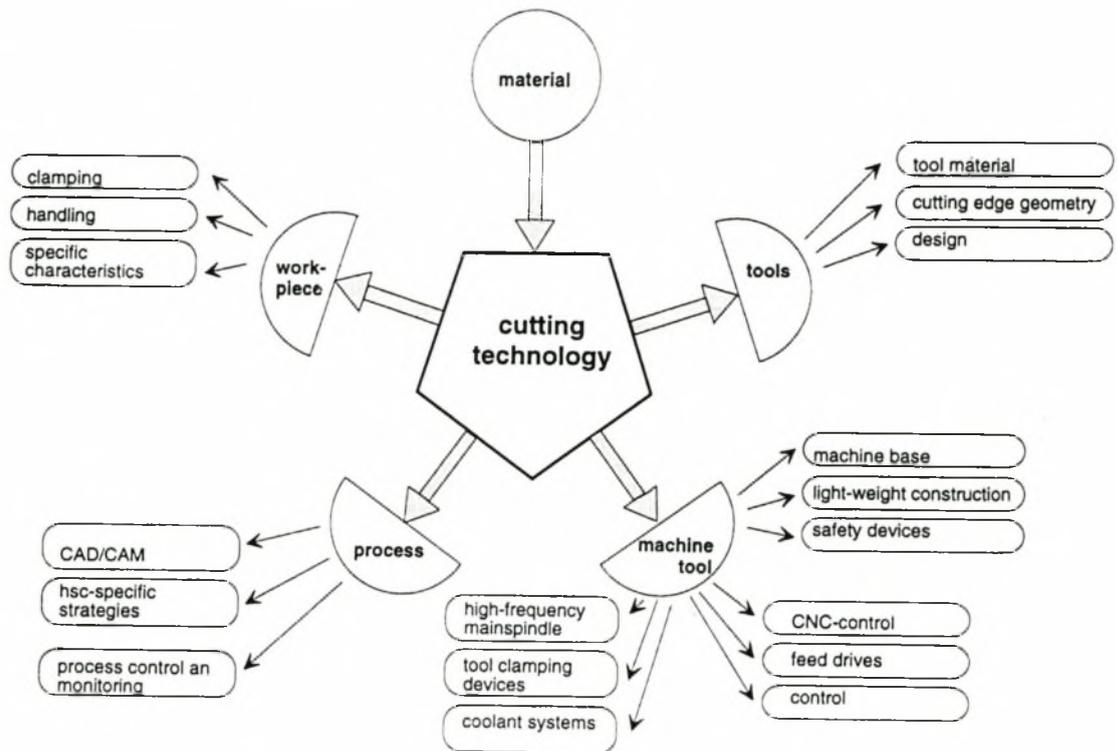


Figure 6.4.1 The HSC process as a Holistic Process (Schulz, 1996:21)

One of the key areas in HSC is cutting tool technology. This thesis therefore considers tool technology as a pace setting technology for HSC. There will be many users with sub-optimal CAD/CAM systems and machine tools that can still exploit the latest developments in cutting tool technology. HSC has several advantages e.g. reduced machining time, shorter project lead-time, better surface finish and reduced manual finishing. There are also disadvantages e.g. generally higher machine hourly rates, more complex, therefore higher skill level and increased time for CNC programming and most prominently larger tool expenses. Seen holistically the nett end result is a substantial improvement in lead time and cost. This prominently higher tool cost should never be seen in isolation.

Practically considered, tool life is shorter at elevated speeds. Smaller diameter tools are generally not sharpened but discarded. For coated tools sharpening destroys the coating. Recoating is now an option but only practical for larger tools. Against this background the statement is made that in HSC tooling, the relatively higher volume (due to shorter tool life), market growth (increasing popularity of HSC) and willingness of the customer to test new technology (progressive firms are those using HSC), has resulted in rapid technological development.

6.4.2 Tool Configuration

Milling for tool manufacture is divided in the roughing phase, the semi-finishing and the finishing phases. In roughing the aim is to remove as much material as soon as possible whereas finishing prepares the final surface. In conventional milling the established practice is to use a relatively large tool at a great depth of cut at a low cutting speed to remove the material. In HSC much less torque is available with the result that smaller diameter tools are used even for roughing. The current practice is to use centre cutting end mills for the roughing phase of free form surfaces and ball nose cutters for the semi-finishing and the finishing phase. The following practice however leads to improvement: For roughing, toroidal tools are used. Cutting with the centre where the cutting speed is zero is avoided like in the case of a ball nose cutter. The rounded shape of the side of the tool approximates the final curved shape better than the stair step surface resulting from the use of an end mill. The material removal rate against tool diameter is shown in Fig 6.4.2.1.

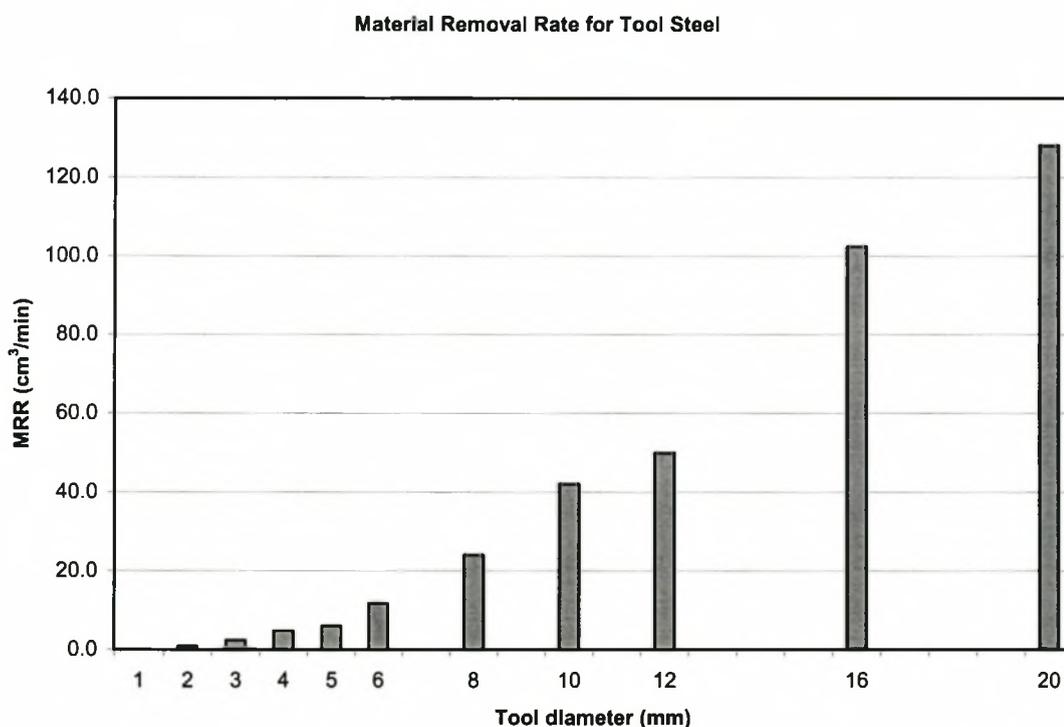


Figure 6.4.2.1 Chip Volume Against Tool diameter for Unhardened Steel

It is clear that the use of the largest possible tool diameter holds great advantage in terms of the MRR ("Zeitspanvolumen"). In HSC the higher speed capability of the spindle compensates to a certain extent for using a smaller diameter tool but the larger tool still results in considerably better material removal rates. With the use of softer work piece materials like tooling composites and aluminium the spindle cannot

rotate fast enough to exploit the maximum cutting speeds achievable with the material. The exception, to a certain extent is the true HSM machines with spindle speeds in the 40 000 to 100 000 rpm range. With the HPM (“Hochleistung”) machines machining softer materials, it is even more important to use larger diameter tools. The larger diameter leads to a higher cutting speed at the available spindle speed. The choice of tool configuration of the Fraunhofer Institute in Chemnitz is given here as recommended practice

Ball Nose	0.8 – 10 mm \varnothing	Solid Carbide, coated
	8 – 25 mm tool \varnothing	Tip carriers
Torus cutters	0.5 – 2 mm radius	Solid carbide, coated
	4 - 12 mm tool \varnothing	
	Larger than 2 mm radius or 12 mm tool \varnothing :	Tip carrier
For tool $\varnothing > 12$ mm	Tip carrier	
	Tip radius	2.5 – 10 mm

When a tip carrier is used the carrier itself has a rotational speed limit. This may be due to balancing but how the method of tip mounting accepts the centrifugal forces under high rotational speeds is the more serious factor. Using these tip carriers a calculation should be made to ensure that the required torque is within the spindle’s capability at the speed required. In spite of these limitations the Fraunhofer Institute has found these tools to be extremely effective and are using them as outlined in the table above.



Fig 6.4.2.2 Examples of some Tip Carriers

6.4.3 Cutting Tool Material used for soft Work-piece Materials

The information is limited to the materials used for die and mould applications. It however includes information on materials like Aluminium and Composite Tooling materials. Rapid tooling is seen as an integral part of the Die and Mould Manufacturing sector.

6.4.3.1 Composite Tooling Materials (e.g. Sika, Vantico)

The densities of these materials vary from 0.7 to 2.5. They are easy cutting and places low demands on the cutting tools. For small one of a kind projects HSS may be considered. The TiCN and multilayer Titanium coatings increase the price of these low cost tools by about 50% that appears to be justified. Full carbide tools are however the recommended option by the manufacturers. Some users use similar coatings to those used for Aluminium. There is however considerable benefit in using an extremely sharp cutting edge. Walter Kienenger in Germany introduced specialist tools for polymers and composite materials at the 2001 EMO Machine tool exhibition in Hanover, Germany. They place emphasis on the cutting edge to such an extent that coating is not used because it essentially rounds the cutting edge. This amounts to uncoated solid carbide being favoured for composite tooling materials.

6.4.3.2 Aluminium

Uncoated full carbide tools are used for Aluminium roughing and polycrystalline diamond coated tools give the best results for finishing.

6.4.4 H²SC / HSC Hard Milling

Many users of HSC become disillusioned with HSC Hard Milling at a first investigation. The process is then regarded as not having reached maturity or the machine tool not being suitable. Bellman (1999: 191) regards the process as a mature, dependable and predictable process (German "sichere Prozess") despite the vast development potential that currently still exists. The limitation that it is for small tools is however added.

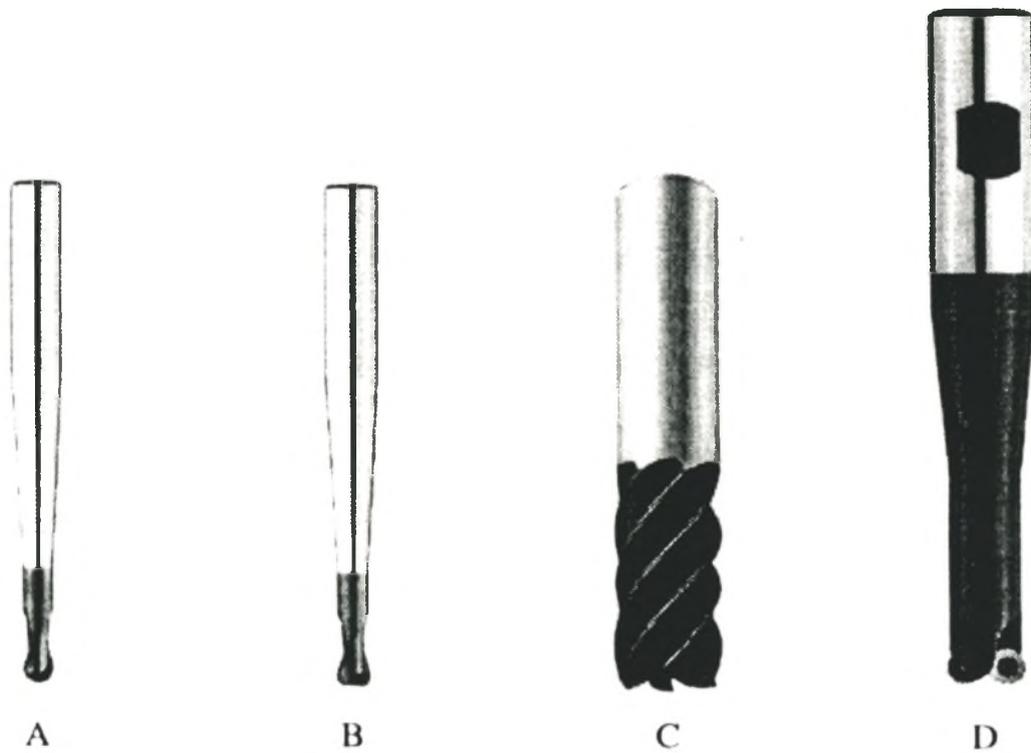


Figure 6.4.4.1 Typical tools used in H²SC / HSC Hard Milling (Bellman, 1999:192) A – Ball nose cutter, B – Toroid tool, 2 flute C: 6 flute end mill, D: Toroid cutter with inserts (tip carrier)

Coating of tools increases tool life considerably. In Fig 6.4.4.2 from Bellman (1999:193) the uncoated tools gave 1/3 of the tool life at 1/5 of the cutting speed.

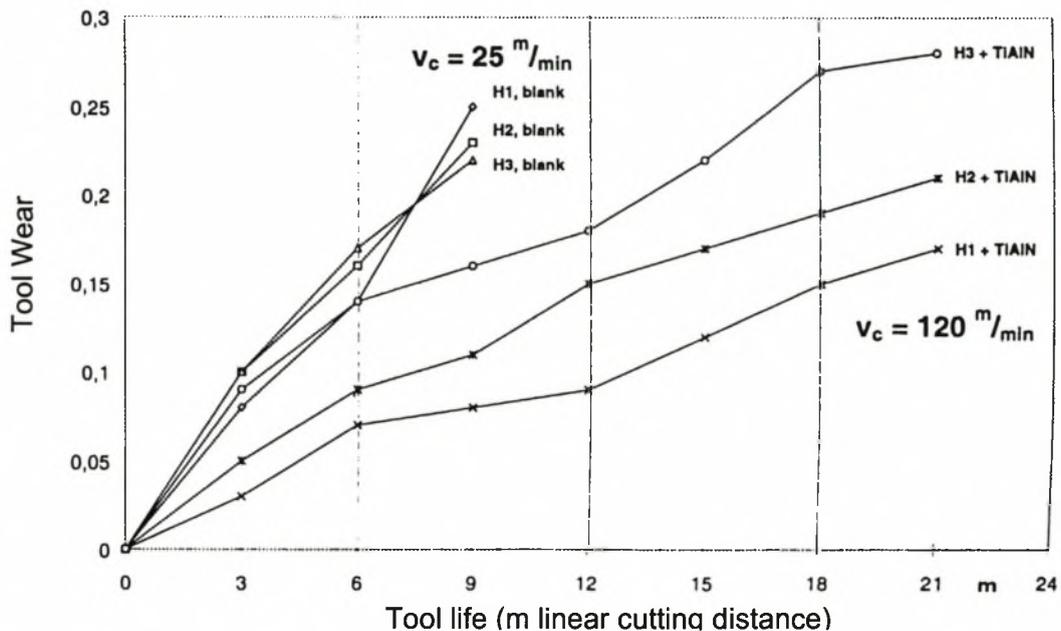


Figure 6.4.4.2 Tool life increase achievable with coated tools. (Bellman)

Tool: Ball nose R5/Z2 60, material: HRC 60 tool steel, Cutting conditions: $f_z = 0.06$ mm, $a_p = 0.5$ mm, $a_e = 1$ mm, air blast cooling. The tool was coated with a single layer of 2 – 3 micron thick with the PVD process. The base material for the tool was a fine grain carbide with a hardness value $> HV_{10} = 1700$.

As reported in Appendix A the Fraunhofer Institute in Chemnitz uses higher cutting speeds namely 200 m/min as general practice. This was with the state of the art tools in August 2001. This was also fine grain full carbide tools coated with a multi – layer coating. These new multi – layers are described as having softer and tougher under layers fulfilling a damping function and a very hard TiAlN outer layer.

Bellmann (1999:197) also states that dry machining with forced air-cooling yields approximately 60% better tool life than conventional wet cutting due to the thermal shock being eliminated. He also states that the manufacturer's specifications for cutting speed being dependent on the material should be adhered to, rather than using general values.

6.4.5 Cutting strategy (Width and depth of cut)

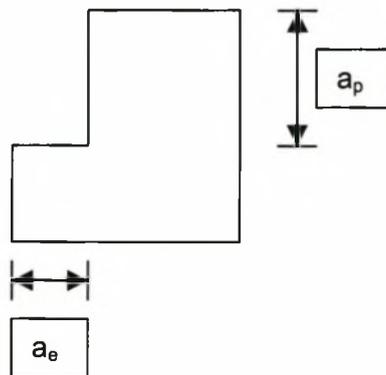


Figure 6.4.5.1 Use of Symbols a_e (cutting width) and a_p (cutting depth)

Normally for HSC a small a_p is used together with the maximum allowable feed rate. The different manufacturers recommend different practices. The Fette company publication (Fette Catalogue 1613) bases the HSC cutting parameters on a maximum a_p of 0.5 times the tool diameter ($0.5d$). For the radius (toroidal cutters) the $a_p = r$ is the logical maximum ($r =$ corner radius of cutter). The value for a_e is not limited which leaves the user the option to choose between the practical maximum of approximately $0.9d$ and the conservative $0.4-0.5d$. Most of the CAM programs indeed only allow a maximum of $0.5d$. The Fraunhofer institute successfully uses $0.8-0.9d$ cutting width.

The Eskenazi company publication (Eskenazi Diaroc Catalogue) favours a large a_p combined with a small a_e . For end mills the following f_z (feed per tooth) correction table is given. The effect of the two different strategies is illustrated in the following table:

Comparison of Cutting Strategies for Roughing								
Tool diameter 10 mm, Material Tool steel, 1100 UTS, 230 HB								
Cut width	Cut depth	Correction Factor	Feed per tooth	Number of Teeth	Cutting Speed	Spindle Revolutions	Feed Rate	Chip Volume
a_e	a_p	f_2	f_z	z	v_c	n	v_f	Q
(mm)	(mm)		(mm)		(m/m in)	(rev/m in)	(mm/m in)	cm ³ /m in
Low a_e / High a_p Strategy (Eskenazi Company Technical Information)								
0.1 d	1.5 d	1	0.053	2	200	6366	675	10.1
0.2 d	1.5 d	0.8	0.053	2	200	6366	540	16.2
0.1 d	1.5 d	1.2	0.053	2	200	6366	810	6.1
0.1 d	1.2 d	1.2	0.053	2	200	6366	810	9.7
Low a_p / High a_e Strategy (Equivalent cut cross section to Eskenazi)								
0.5 d	1 d	1	0.053	2	200	6366	675	33.7
1 d	0.5 d	1	0.053	2	200	6366	675	33.7
High a_e Strategy / Low a_p (Fette Company Technical Information)								
0.5 d	1 d	0.6	0.07	2	200	6366	535	26.7
1 d	0.5 d	0.4	0.07	2	200	6366	357	17.8
Note The Eskenazi Company data recommends a v_c of 400 m/m in for their Diatop Multi-F and Uni-X multilayer coatings.								
The value of $v_c = 200$ m/m in in use at the Fraunhofer Institute is used as a standard for all strategies.								
The Fette Company data recommends a v_c of 200 m/m in for their multilayer TiCN, AlPlus and AlUltra Coatings.								
Tool diameter, $d = 10$								
$n = (v_c * 1000) / (\pi * d)$								
$Q = (a_e * a_p * v_f) / 1000.$								

Figure 6.4.5.2 Comparison of Cutting Strategies for Roughing

If it is considered that the Eskenazi data actually specifies double the cutting speed there will be minimal difference in the chip volume achieved by the two manufacturers' strategies. Bellmann recommends the small a_e / large a_p strategy for the multi-cutting surface tool. For a toroidal cutter used for roughing and near horizontal surfaces the natural conditions are large a_e / small a_p . Under these conditions Bellmann (1999:197) states that the cutting speed should be reduced to half. This has the same effect as the manufacturers' correction factor on the chip volume. There is however a subtle difference reducing the cutting speed as recommended by Bellman or by reducing the feed rate.

The Fraunhofer institute uses the small a_e / large a_p strategy with the multi-cutting edge tools where long tools are used and vibration excitation is to be minimised. With a long vertical cutting edge the next cutting edge spiral engages before the first leaves the material. There is therefore less shock loading on the tool tip. Otherwise when roughing, the institute does not reduce either cutting speed or feed rate for the large a_e / small a_p strategy and thereby achieving the higher chip volume as shown in the middle rows of the table. The following photograph from Bellmann (1999:198)

clearly illustrates the use of the small a_e / large a_p strategy to machine the outer edge. The surface finish achieved was similar to that for grinding. At 22 min for milling and 2.5 hours for grinding the time saving is a factor of 1:6,8.

Outside Edge
Machining Hard
Milling instead of
Grinding. Tool: 8-
flute $\varnothing 18$ cutter
Material 58 – 60 HRC
Roughing – 80 m/min
 $a_p=30$, $a_e=0.4$

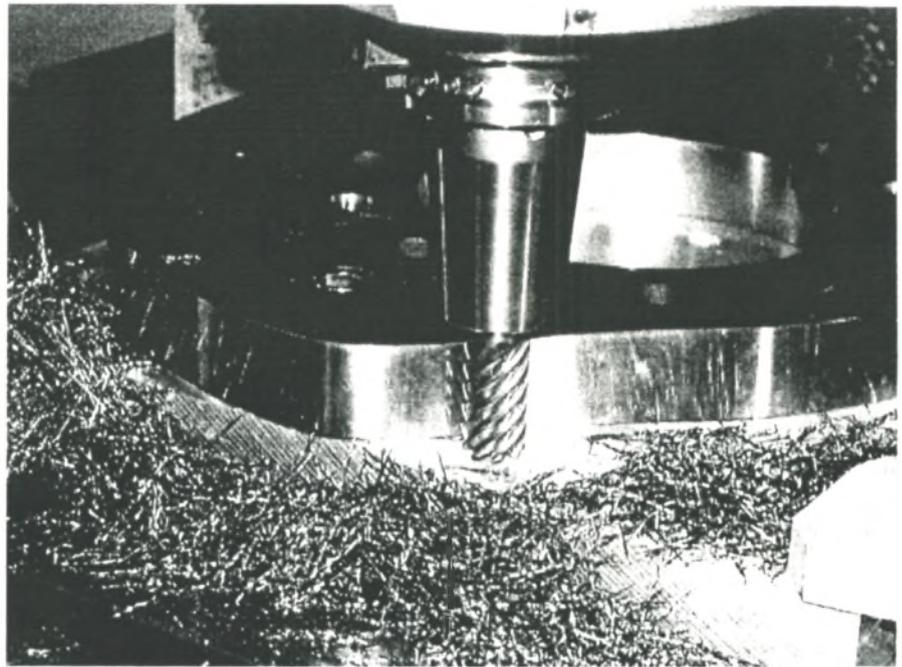


Figure 6.4.5.3 Outside Edge Machining

6.4.6 Cutting Speed

In milling practice the cutting speed is taken as an external parameter prescribed by the cutting tool manufacturer (Bellmann 1999:1997). Mr Schäfer of Paso (Appendix B) is of the opinion that due to competition between tooling manufacturers the manufacturers specify some of these key technical parameters, notably cutting speed, too high. The manufacturers realise that tool users compare factors that has a bearing on productivity e.g. cutting speed and feed per tooth and are therefore tempted to specify these values too high. The result of a tool life that is severely reduced is not of short term (marketing) concern. It should also be considered that the holistic line of thought behind HSC has led to the acceptance of shorter tool life in order to achieve shorter throughput times and savings on machine tool occupation time. The author's experience is that shop floor personnel in many cases have to justify tool purchase as an overhead cost instead of a project related consumable. This practice leads to sub-optimal cutting speeds being used. The recommended cutting speeds that reputable tool manufacturers specify vary widely as can be seen in Fig 6.4.6.2. for hard materials and in Fig 6.4.6.1 for soft materials. Bellmann (1999:193) reported the use of 120 m/min for 60 HRC work-piece materials. The relatively short tool life of 21 m should be noted. The 120 m/min with a 1999 single

layer coated tool places the company guidelines around 100 m/min at 55 HRC with multi-layer coatings in perspective. The Fraunhofer Institute uses 200 m/min as standard practice for hardened tool steel, which is also in the same category. On the softer materials all the values in the table were for full carbide end mills. When tip carriers are used, the WZN Company recommends speeds up to 3000 m/min instead of the 400m/min on aluminium, which again supports the Fraunhofer policy to give preference to the tip carriers for roughing. The Fraunhofer staff considers other factors such as maximum spindle speed to be the limiting factors in the case of aluminium and other soft materials and not permissible cutting speed.

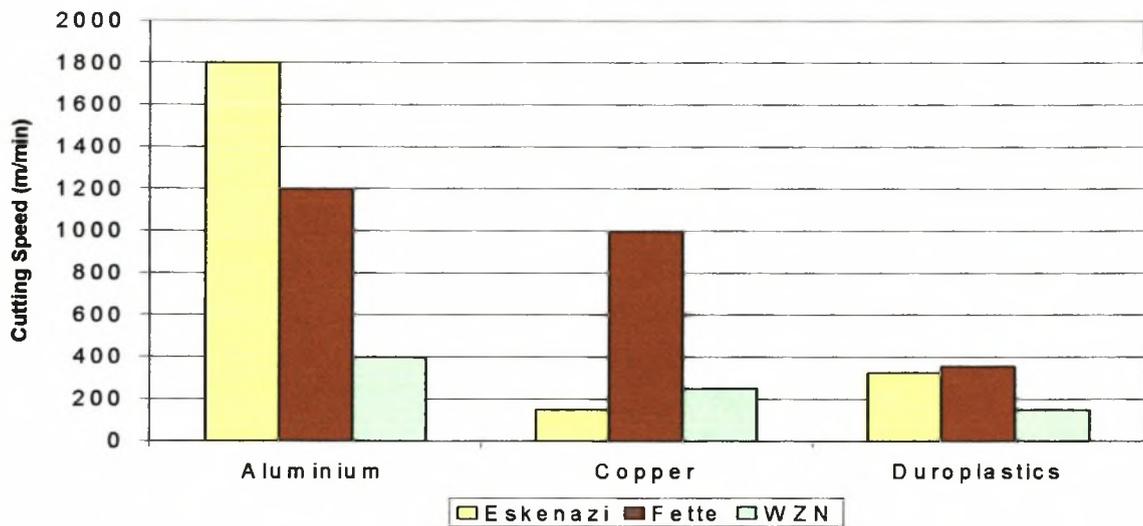


Figure 6.4.6.1 Tool manufacturer data for HSC Soft Material Cutting

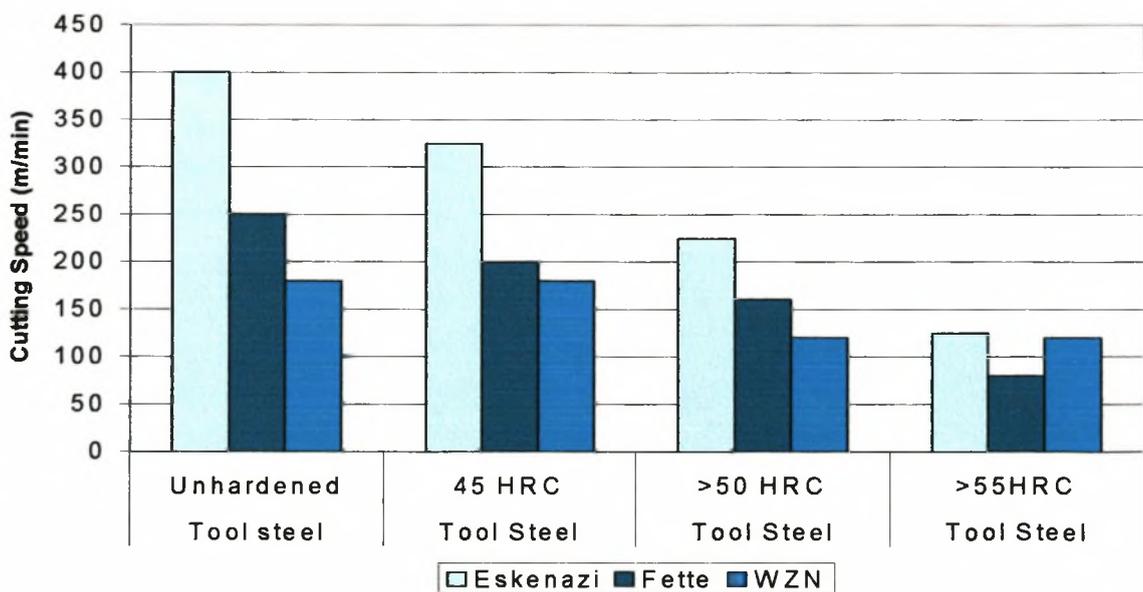


Figure 6.4.6.2 Tool Manufacturer Data for HSC Hard Material Cutting

6.5 Summary of the Process Chain for HSC / EDM

Because the size of the tool to be machined has a considerable influence on the process chain, the boundaries for this application are set with small mould manufacture. This also implies that 3 Axis HSC milling is the most commonly used process.

For the complementary use of the processes, HSC is mainly in the role of material removal process and finishing of the easily accessible surfaces.

EDM has the role of machining the deep small dimension cavities and finishing the small radius features e.g. "sharp corners" and fine detail deep in the cavity.

The tool chosen to be used for the HSC part of the combined process is important. The combined process will be a considerable improvement on the conventional process if the surface formed after the HSC phase is near to the final shape, resulting in uniform EDM tool wear. Toroidal tools have considerable benefits over ball nose tools both on near flat surfaces as well as curves. For the combined process chain, toroidal tools are therefore preferable above end mills especially for roughing and ball nose tools especially for finishing. There will however be some surfaces, because of geometrical constraints where a ball nose tool cannot be replaced with a toroidal tool.

The cutting strategy or the combination of cutting speed, cutting direction, width and depth of cut is of considerable importance. In the case of the combined process chain a holistic approach to the combined process will require that an optimum amount of attention be paid to the surface formed after the HSC phase. Optimum in this case means that it does not make sense to HSC finish the whole surface with the smallest diameter tool required for the smallest diameter feature (that is HSC milled) where there will still be an EDM finishing operation on that surface. On the other hand it makes equally less sense to start the EDM process from a typical stair step surface which is the result of an end mill resulting in a loss of accuracy on the final surface or causing a two EDM tool (electrode) strategy. The two-tool strategy for EDM becomes necessary when one electrode is subjected to such an amount of wear that the final tolerances cannot be met. This requires an electrode for EDM roughing and another for EDM finishing.

7 Decision model for HSC / EDM Complementary Process

7.1 Introduction

The proposed model consists of two parts. The first part is a decision model to make process category selection decisions, which are dictated by geometric constraints, early in the process planning. If the decision flow diagram categorically points towards the combined HSC/EDM process chain, the mathematical part of the model is used to indicate the changeover point, from HSC to EDM. Although not essential to determine the HSC/EDM changeover point the processing time of the HSC part of the process is estimated by the model.

7.2 Decision Flow Chart for Process Chain – Generic version

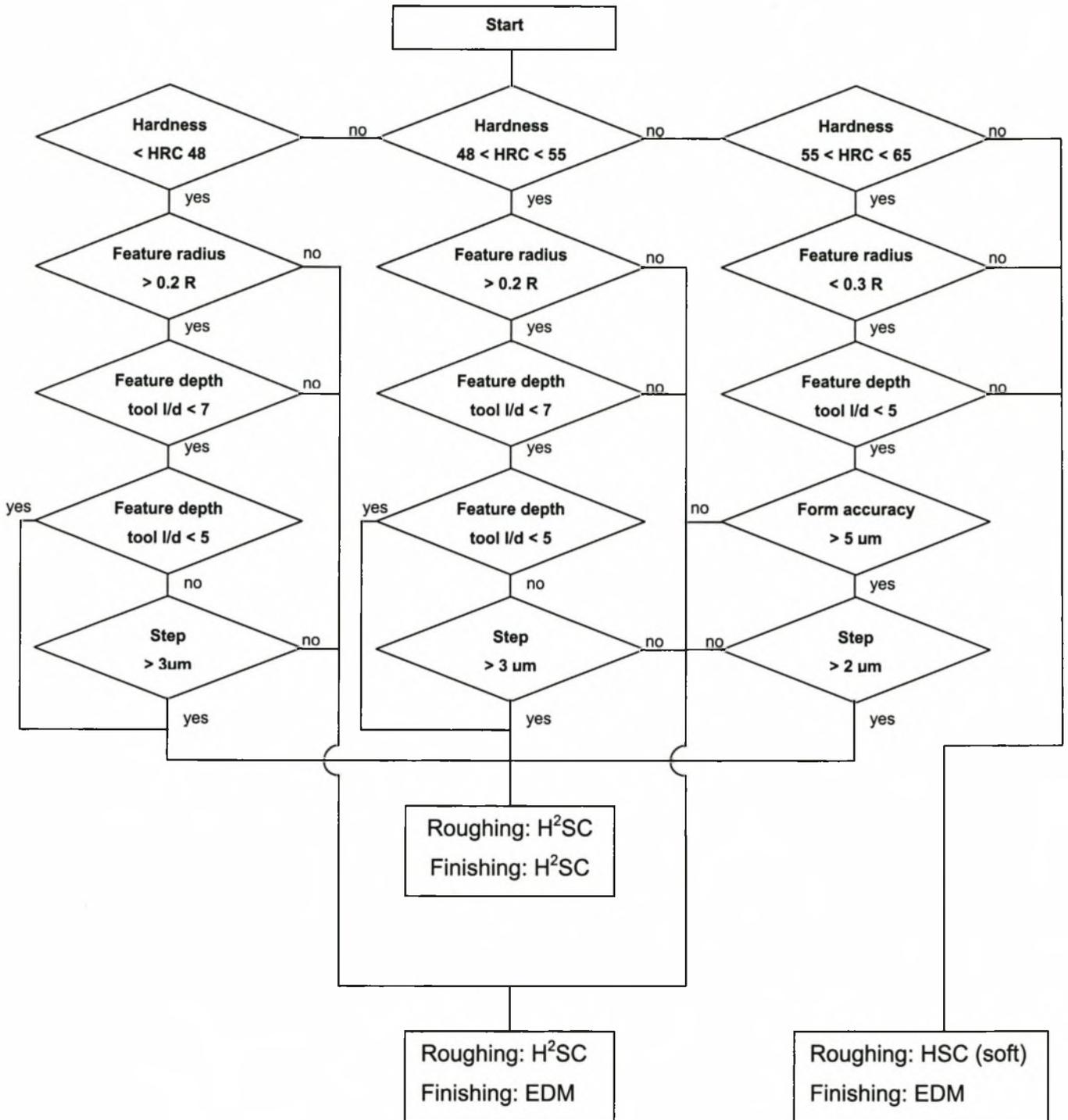


Figure 7.2.1 Selection Flow Diagram for the EDM / HSC Combination Process

This flow chart was adapted from a chart presented by Speetzen (2001: 22). The cut – off point for HSC is at a tool l/d of 7. With dedicated HSC development some companies have already improved upon this ratio. Examples are detailed in the next paragraph. The minimum radius of 0.2 or 0.4 tool \varnothing is however not widely used in

industry. Developments with toroidal tools are giving HSC significantly improved capability with corner radii deep in the mould cavity. There are however cases where the feature requires a small diameter ball nose tool. In these instances the crimp type tool extensions may also extend the limits of HSC. There however remains a class of feature, possibly close to the side that will be problematic. The tools used in the specific company should replace the minimum values in the flow chart.

7.3 Example of Decision Flow Chart for a Specific Company (SFM)

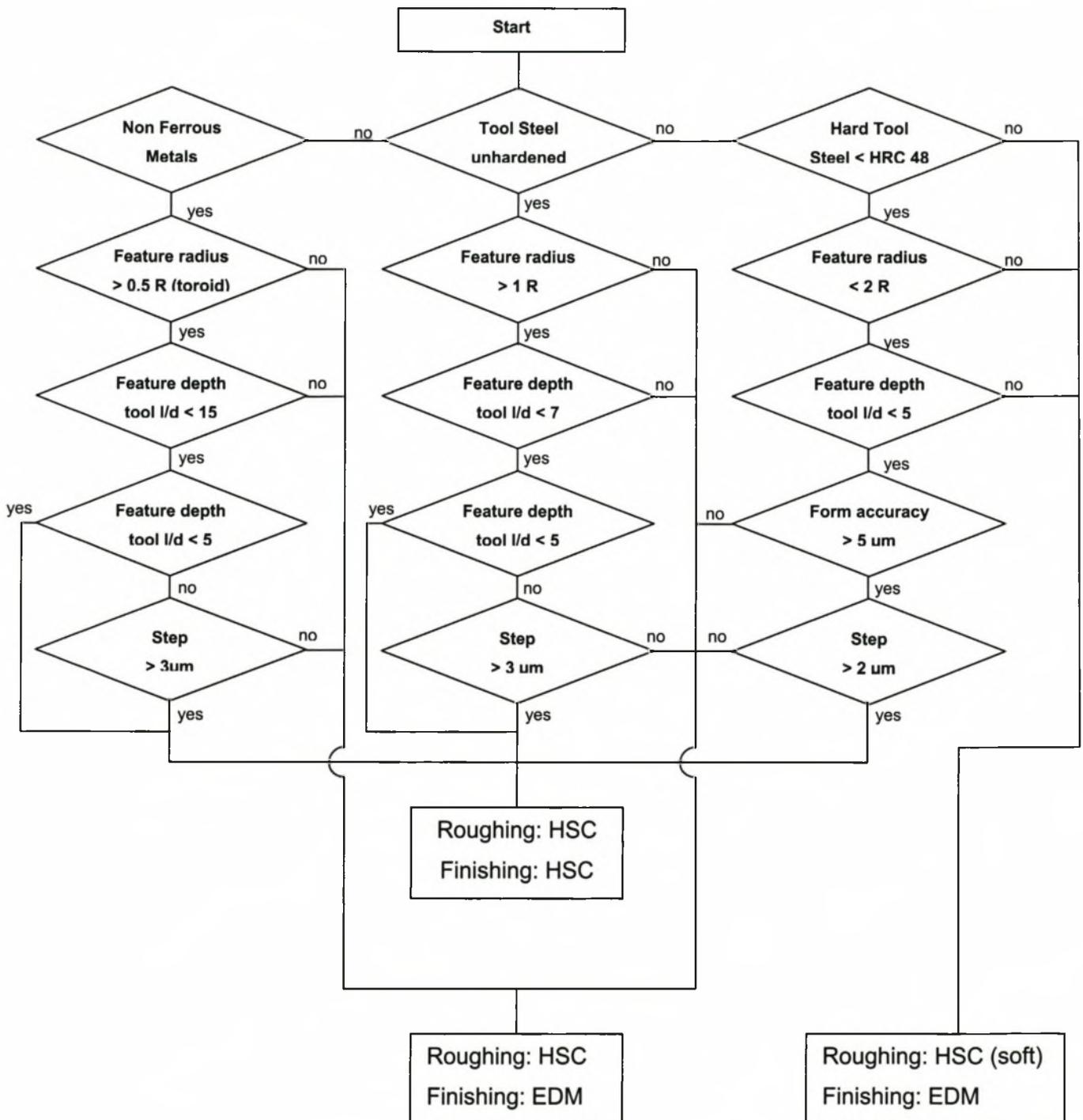


Fig 7.3.1 The HSC Capability at SFM GmbH as an example.

As an example the flowchart above is used to describe the capability at SFM GmbH in Dresden. The materials machined at this company are almost exclusively aluminium and tooling composite. The capability in terms of the machine tool and the personnel expertise is suitable for harder materials as well. Every firm has a unique capability that can be described by this process chain decision flow diagram.

7.4 The influence of the l/d ratio of tools on process boundaries

The flow diagram by Speetzen (2001:22) implies that the boundary for the l/d ratio of tools for HSC and H²SC lies in the region of 7 for a secure operation ("sichere Prozess"). There is substantial evidence that users of HSC are going beyond this figure (Meier 2001:14)(Vollrath 2001:32). In the diagram describing the HSC capability at SFM GmbH, for example, tool l/d ratios up to 15 is being used. This is for relatively soft materials, aluminium and tooling composite.

In paragraph 5.6.5 an application of HSC is included. Meier (2001:14) reports on a newly developed application of HSC for crankshaft forging tooling. At a maximum spindle speed tools with a l/d ratio of up to 13 were used. It should be emphasized that special tools were developed for the application.

Another application of HSC for crankshaft forging tooling is reported by Vollrath (2001:32). The material is of 42 HRC hardness and extraordinarily tough ("aussergewöhnlich zäh"). The l/d ratios in two cases go up to 17 and 20 (6 and 5 mm tools respectively).

The issue of tool length is determined by vibration causing tool breakage in the extreme case and inferior surface finish. There is currently no practical analytical method to predict the vibration potential and hence process stability. The mechanism of vibration as applied to HSC is explained by Hock and Janovsky (1996: 236). Tool diameter, tool length, work piece resonance potential and frequency, machine tool resonance and probably the most important factor, the spindle characteristics, are the factors determining vibration. Hock and Janovsky give extensive guidelines on the contact conditions between the tool and the work piece to minimise vibration potential. A tool / work contact angle between 10 and 20 deg is preferred with the feed in the direction of the tilt angle. This amounts to a drawing cut ("Ziehschnitt, längs") causing the least vibration excitation - Refer Fig 7.4.1. The conventional practice of contour milling on a free form surface amounts to a transverse angled cut with the feed perpendicular to the plane of the angular displacement between the tool and the work piece surface ("Bearbeitung quer zur

Kruemmungsrichtung”). Refer Fig 7.4.1 This is not at all favourable for least vibration excitation. In everyday terminology this amounts to cutting up the contour (drawing cut, lengthwise) being the ideal practice (100% tool life for comparison). This is shown in Fig 7.4.1 in the bottom left diagram, cutting along the curve with interpolation in the x-z plane cutting up the contour. The second best (with 75% tool life) is also shown in the bottom left hand side diagram with the cutter being fed along the curve down the contour (plunge cut, lengthwise). The right hand diagram of fig 7.4.1 shows the conventional practice of cutting across the curve, with a drawing cut the worst with 30 to 50% tool life. It is interesting to note that with transverse cutting (across the curve) a drawing cut (“Ziehschnitt”) yields the worst results of approximately 30% tool life. A plunge cut (“Bohrschnitt”) is slightly better at approximately 50% tool life.

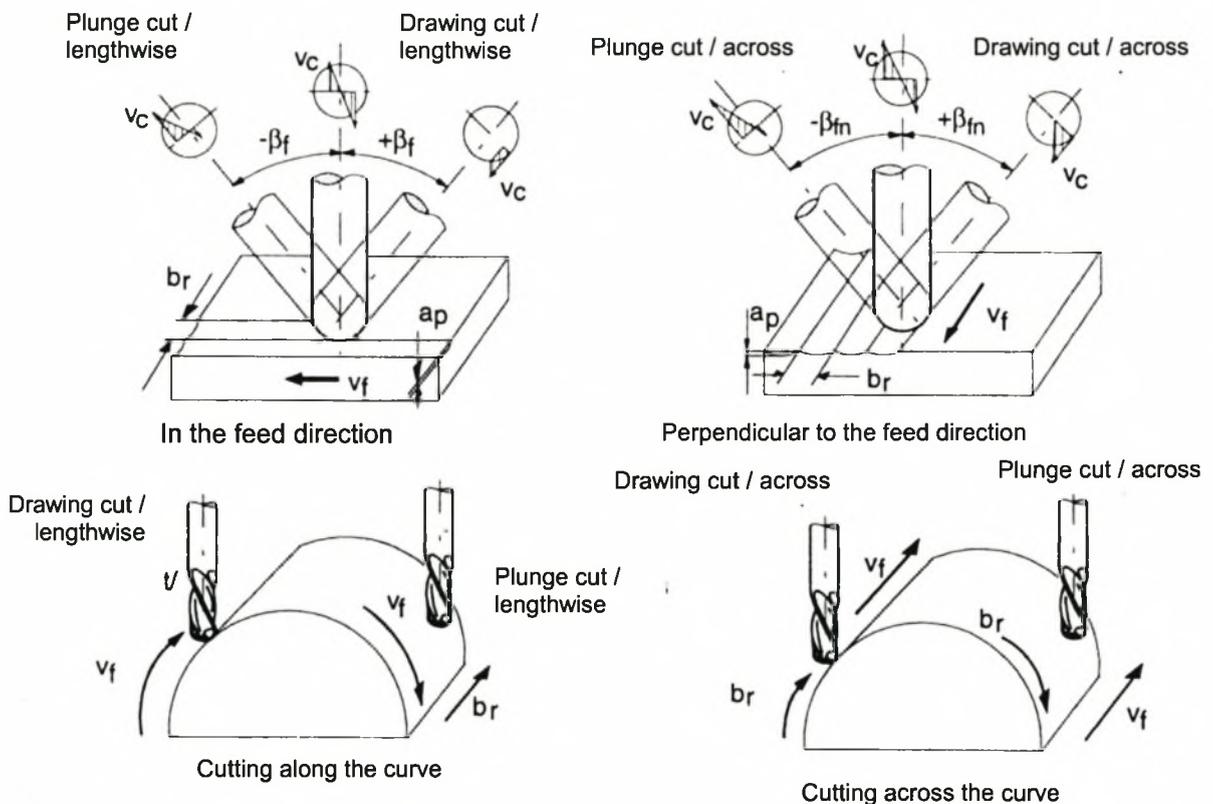


Figure 7.4.1 Cutting configurations and strategies for a Ball nose tool (“Kugelpkopfwerkzeug”) [Hock & Janovsky (1996:230)]

At SFM GmbH a simple but effective method to avoid the resonance frequencies of machine tool / spindle / tool holder / tool combination is used.. The tool is mounted before program operation and the spindle is manually stepped through its entire usable rotation speed range. Especially with long slender tools notable with a l/d

ratio of more than 10 there is already vibration at certain speeds with the tool rotating in air. The speed at which audible vibration can be observed is noted. The operator listens for audible signs of vibration and notes the speeds at which there is vibration. The largest “gap” in the revolution range where no vibration occurs is noted. The middle of this range is then chosen as the selected speed for this tool. The program is then manually edited to enter this speed for this tool. The process of speed selection is repeated for all the tools with a l/d ratio of roughly more than 5.

This rather practical, but effective method is proposed to be improved further as follows. The current method does not integrate the vibration contribution of the work piece and the machine tool table / bed combination. If a program is used to step the cutter through the speed range performing a cut in the work piece where the material has to be removed by roughing, that audible indication of vibration resonance speeds will be even more reliable. If it is not practical to make this vibration trial cut in the work piece itself, a test piece clamped in the bed will also be better, integrating the vibration characteristics of the bed / table.

7.5 The influence of Tool Holding Practice on process boundaries

It was shown previously that the deep cavities, especially features requiring large l/d milling tools, are suited for EDM, where HSC becomes problematic. Because HSC yields a higher rate of material removal (“Zeitspanvolumen”) the HSC process needs to be taken as deep as possible for the shortest throughput time (“Durchlaufzeit”). Taking the HSC process as deep as possible refers to the most common milling operation in Mould machining, namely machining concave mould cavities. Machining as deep as possible will have the largest part of the machining operation being executed by the HSC milling operation.

The l/d ratio of milling tools is limited by vibration. Radial alignment of the milling tool cannot be 100% true. The degree of misalignment will be one of the causes of vibration. Tool holding practice in the HSC operation will therefore strongly influence the changeover point between HSC and EDM in the combined process. The more accurate the milling tool can be held radially, the larger will be the l/d ratio that can be used and the deeper the feature (cavity) will be that can be HSC machined. Because these practices differ from operation to operation, it becomes a requirement in a model to define the changeover point between HSC and EDM to be flexible and

to accommodate various levels of operation capability in the definition of this changeover point.

In industry the most commonly used tool holding method is to use collets. SFM GmbH is no exception and collets are used almost exclusively with a tool diameter ranging from 2 mm to 10 mm. Tool length ranges from the short tools with a ℓ/d of around 4, up to 10 mm tools set up to give a useable length of 150 mm or ℓ/d ratio of 15. Considerable difficulty (vibration) was witnessed with these long slender tools. According to Hochmut (Appendix A) at the Fraunhofer Institute in Chemnitz, collet tool holding is a technology which for HSC has now been superseded by more modern technologies and should not be used any more in an up to date HSC operation. The radial accuracy of a collet is not as accurate as more modern tool holding techniques. The radial tool holding error is a source of imbalance and vibration. HSC operations using collets will limit the ℓ/d ratio achievable as well as the process security ("Prozess Sicherheit"). Collets are not suitable for true HSC applications. They may still be applicable for the lower speeds up to 15 000 rpm and where ℓ/d ratios of less than 5 is used. It could be argued that collets are suitable for HPC ("Hochleistungsfräsen") because speeds are mostly below 15 000 rpm. The author is of the opinion that this is not wise practice because of the nature of HPC the cross section of the cut ("Schnittquerschnitt") is to be maximised together with the speed. Any vibration excitation as in the case of radial alignment error, will limit the depth of cut with a higher ℓ/d ratio tool therefore limiting the cut cross section.

A more modern tool holding technique is the hydraulic clamping chuck ("Hydrospannfutter"). A sleeve surrounds the tool with hydraulic fluid behind it. If the fluid is pressurised the sleeve clamps the tool. The hydraulic fluid is pressurised by a screw displacing the fluid at the back of the tool holder. The radial accuracy is adequate for true HSC applications (up to 40 000 rpm) and the higher ℓ/d ratios. The disadvantage is that the diameter range is extremely limited, practically requiring a hydraulic tool holder for every diameter tool used. These tool holders are also relatively expensive.

The most modern tool holders are the crimp type tool holders. Heating the metal sleeve expands the tool holding sleeve. The tool is then inserted into the sleeve. After cooling the sleeve contracts around the tool shank and holds it with the smallest

radial error currently achievable. The newest generation of these crimp type tool holders are adequately accurate so that the tool can be held in a primary long cylindrical tool holder that is also a tool length extension. This extension then mounts (crimps) into the tool holder that mounts onto the spindle. In this way, tool ℓ/d ratios previously unheard of, is achieved (50). This is not a true ℓ/d ratio however because the tool, tool extension, holder combination requires a conical envelope determined by the extension geometry. Long taper tools fall in the same category. The application itself determines whether these extended tools can be used. Corners of deep cavities can usually not be accessed unless radius tools are used or the withdrawal angle of the cavity is such that the taper tools can be accommodated. It places limitations on the expansion of HSC as an independent process. The HSC/EDM combination process is largely favoured by this new development as even more material from deep cavities can be removed with milling which is generally quicker than EDM. The crimp type tool holders have become much more cost effective in the past year making them the most cost effective tool holding technology for HSC.

7.6 Mathematical Model

7.6.1 Application Goal of Model

If HSC and EDM are to be used as complementary processes there are two main decisions to be made in the process planning. The first decision is to decide between HSC only, EDM only and HSC and EDM combination. This is done with the aid of the flow diagram described in earlier paragraphs (7.2 and 7.3). The second decision is when to change from the one process to the other. This changeover point will in many cases be an uncomplicated decision for a process planner who knows the capabilities of both HSC and EDM. This process planner bases the decision on a very complex and comprehensive knowledge base. The goal of the mathematical model is to serve as an alternative decision tool to make this optimal point of changeover decision. It could make the planning process independent of a process planner with a biased experience profile, who would tend to shift the changeover point towards his experience domain. It could also free the process planner to carry out management or customer contact tasks.

HSC is the process that will be used if both processes are feasible. HSC therefore will be used as the earlier process in the chain. Only when HSC is not feasible any more due to depth of features or in the case of the HSC milling process becoming slower than EDM, the HSC milling option is discarded and the EDM process is chosen. The model should therefore predict where the practical limit of HSC is and when EDM becomes the better alternative. In order to make this decision the focus is on HSC and its capabilities. HSC is also the newer process with less exposure in the mould making industry. It was therefore not considered necessary to detail the EDM process capability.

In the industrial countries the Die and Mould industry HSC capability is not developed to the same level as conventional milling or EDM. In the South African Die and Mould industry the development of HSC is still in the early starting phase. The model should therefore be flexible to accommodate different levels of maturity of the enterprise in the process building blocks especially HSC.

The two elements of maturity is considered to be:

- 1) Personnel expertise levels
- 2) Equipment and technical infrastructure sophistication

7.6.2 Structure of the Mathematical Model

In HSC machining there is firstly a roughing phase, then a semi-finishing phase, finally followed by the finishing phase. The equation consists of a term for each of these three phases.

The equation estimates the machining time spent with HSC expressed as t_{HSC} . The expression is a discrete summation series corresponding to segments being machined with decreasing tool diameter.

The basic form of the equation is therefore:

$$t_{HSC} = K_r \sum_j t_r (Vol_j d_j) + K_{sf} f_{delta1} k^m \sum_k t_{sf} (A_k d_k) + K_f f_{delta2} \ell^p \sum_\ell t_f (A_\ell d_\ell)$$

t_{HSC} - Machining time (min)

K_r - Correction constant for roughing

j - Segment no for roughing

t_r - Time to rough machine the segment

Vol_j - Volume of material to be removed in segment j

d_j - Diameter of the tool used to rough machine segment j (tool \emptyset)

K_{sf} - Correction constant for semi-finishing

f_{delta1} - Correction factor for tool diameter change from rough cut to semi-finish cut

k - Number of segments for semi-finishing with an own cutting strategy

m - Compensation exponent for multi-strategy, multi-segment semi-finishing

t_{sf} - Time to semi-finish machine the segment

A_k - Area to be covered in segment k

d_k - Diameter of the tool used to rough machine segment k (tool \emptyset)

- K_f - Correction constant for finishing
- $f_{\text{delta}2}$ - Correction factor for tool diameter change from semi-finish cut to finish cut
- k - Number of segments for finishing with an own cutting strategy
- p - Compensation exponent for multi-strategy, multi-segment finishing
- t_f - Time to finish machine the segment
- A_ℓ - Area to covered in segment ℓ
- d_ℓ - Diameter of the tool used to rough machine segment ℓ (tool \emptyset)

7.7 Overview of the HSC part of the Mathematical Model

The decision model is presented in two parts. The first is a flow diagram. The process planner will typically examine the model of the tool to be machined. The first criterion is the work material hardness. The other determining criterion is the length / diameter ratio of cutter required by the feature. The flow diagram then determines whether HSC only can be used, whether a conventional process chain with EDM is unavoidable and whether the HSC / EDM complementary process can be used.

The second part or mathematical model consists of three parts namely the roughing, the pre-finishing and the finishing time estimate. In this part of the report it is presented as a general mathematical relationship. Just as in CAM programming the user is expected to use his/her experience to successively identify logical blocks to be machined as a process step. The output of the model is intended to be a bar chart showing tool diameter, material removed and time taken per process step. The process planner can then make an informed decision at which process step he can make the change over between HSC and EDM. This process planning should enhance process security.

It is also important that the decision model is flexible to accommodate different capability levels in a Tool and Die company. It is envisaged that the decision tool might be used to empower people who do not have adequate expertise and self-confidence to use HSC to regard it as a secure process. The boundaries of HSC are simply set high (in the easy application domain of HSC) in the flow diagram. For example the relatively inexperienced HSC programmer / operator will not be expected

to operate tools smaller than $\varnothing 6$ and with an ℓ/d ratio of no larger than 4 – The rest of the process is done with EDM. In such a way a growth phase can be entered. The HSC / EDM process is then obviously initially sub optimal but the fear for failure and lack of process security are reduced to acceptable levels for development in HSC to grow spontaneously.

8 Refinement of the Model through a Case Study

8.1 Choice of test case for the model

A project called the Ampoule Holder executed at SFM GmbH was chosen as the demonstration case for the model. This part was HSC milled out of aluminium in the actual project execution at SFM GmbH. In reality the work pieces which are real candidates for HSC and EDM as complementary processes would be much more complex. These complex geometries are efficiently handled by CAD/CAM workstations with the use of the zoom function. However, the very complexity that makes them candidates for the combined process chain, make them cumbersome for the purpose of demonstration, in a paper-based document. Therefore this relatively low complexity example was chosen for this thesis.

8.1.1 Description of the roughing term of the model

In the model the first summation term corresponds to roughing.

$$K_r \sum_j t_r(\text{Vol}_j d_j)$$

It practically means that the roughing is done in sections ($j = 1, n$) usually starting with a large diameter tool. Each section is therefore milled with a smaller diameter tool and the progress of the roughing phase can be graphically shown as a section taking a certain amount of time using a certain diameter tool. The time spent per section is therefore a function of the tool size and the volume of the material to be removed. The sum of the times is finally multiplied by K_r , which is the correction factor for the roughing phase time. This correction factor can be used to correct for personnel not so experienced with CAM programming. The model is intended to be an approximation aid for process planning, not an exact simulation tool. The CAM

programs available have these simulation tools as part of the CAM programs but they require that the full CAM programming be done before the time simulation can be run. This model, once implemented on a computer, could be run as an aid during process planning which will consume minimal time.

The outside machining ("Aussenkontur") of the work piece is not covered, only the cavity or the matching convex shape. The outside machining usually amounts to an insignificant portion of the machining time. In the test case it was 6 min out of approximately 2 hours or 5%.

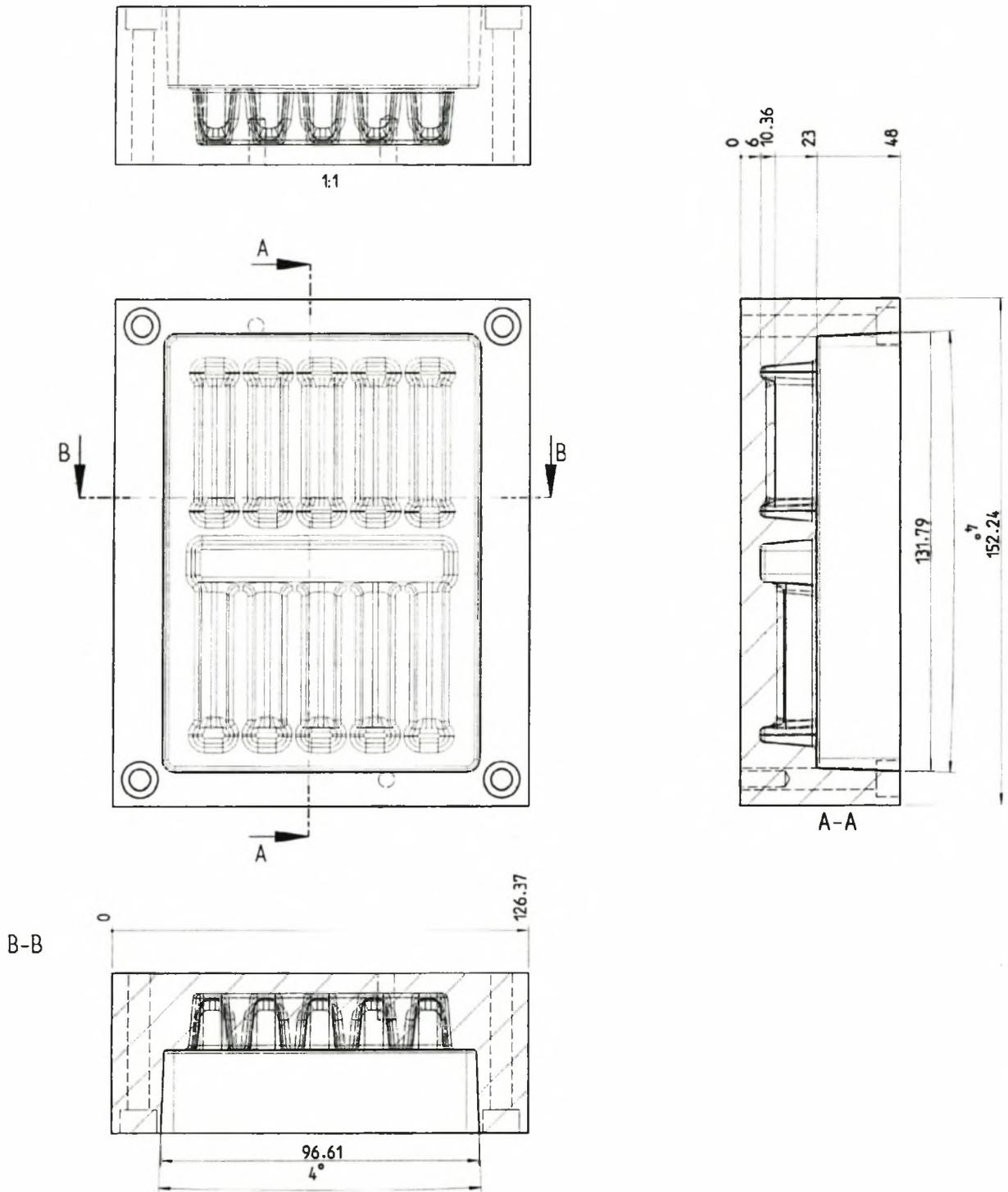


Figure 8.1.1.1 Work piece selected for the case study

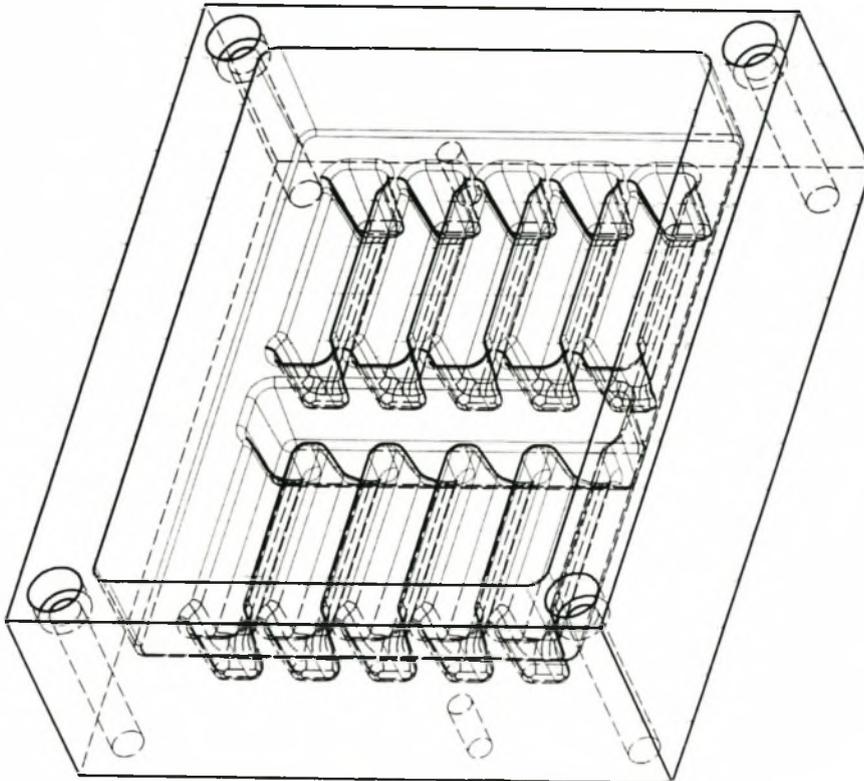


Figure 8.1.1.2 Wire frame model of Work piece selected for the case study

The roughing process planning is carried out as follows:

Given: Work material, in this case aluminium,

aluminium, 7075 (commonly known as aircraft structural aluminium) in the heat treated condition (TF) is becoming a modern alternative for a medium life mould material combining strength with excellent machining properties.

Step 1: Select tool geometry, in the actual case an end mill, centre cutting ("Schafffräser, Zentrumschnitt"), 2 flute ("2 Zähne") was used. Because of the geometry, a horizontal cutting surface or 0° inclination angle ("Kippwinkel") dictates that a ball nose cutter ("Kugelfräser") is not the ideal because of the zero cutting speed in the centre. A modern alternative would be a toroidal tip carrier ("Wendeplattenträger / Rundplattenträger"). For aluminium a cutter should be selected where the possibility for chip clogging is low, probably a 2 flute cutter ("2 Zähne") in the case of the end mill. A tool should be selected with a positive rake angle to facilitate good chip flow, with 0° being workable but sub optimal, 5° better, to 7° being ideal and 12° again sub optimal.

Step 2: Select Tool length. In the actual case the upper rectangular cavity as well as the lower ampoule cavities were machined with one tool. The upper rectangular cavity requires a tool length of 25 mm and the ampoule cavities require a tool length of 44 mm. With a $\varnothing 6$ tool this corresponds to a ℓ/d ratio of 4.2 and 7.3 respectively. A regular length tool $\varnothing 6$ is 57 mm (Pokolm 141247030) or 55 mm (Kobelco 2MA $\varnothing 6$), which leaves 30 mm effective length (using 25 mm for clamping) sufficient for the rectangular cavity. A tool of the extra length type, typical length 95 mm, (Kobelco 2SX $\varnothing 6$) leaving a maximum of 70 mm effective length, had to be used. The machinist at SFM sets up the tool in the collet so that just a sufficient length protrudes. It can be assumed that the effective length was 45 mm or a ℓ/d of 7.5.

Step 3: Select tool material, in the actual case HSS was selected. A modern alternative would be uncoated solid carbide ("unbeschichtete Vollhartmetall"). HSS is the typical low cost all purpose cutter found in most machining facilities, but considerably better machining performance can be achieved with solid carbide, and even better with the tip carriers.

Step 4 Select tool diameter; in the actual case a $\varnothing 6$ tool was used. In general terms the largest tool as possible should be selected. In small mould manufacture the size of the cavity often practically limits the size of the tool. In this case the process planner wanted to avoid a tool change and planned to do the roughing of the top block and 10 ampoule cavities as one operation. The alternative would have been to machine the top rectangular cavity as one CAM operation with the $\varnothing 16$ tool and the deeper ampoule cavities with a $\varnothing 8$ or a $\varnothing 6$ tool. The top rectangular cavity could also very successfully be machined with a toroidal tip carrier (fig 8.1.1.3) or the rhombus shaped tip carrier (fig 8.1.1.4). With a 130 x 96 cavity area a two-tool strategy would have resulted in a lower machining time.

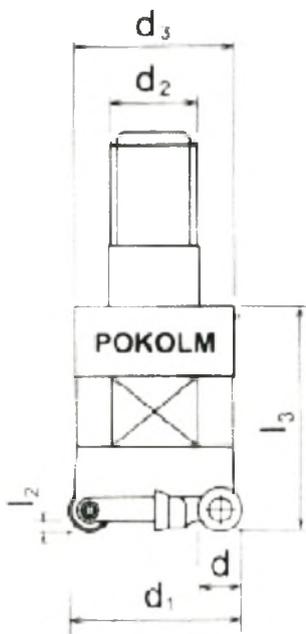


Figure 8.1.1.2 A typical Toroidal Tip Carrier (“Rundplattenfräser”)

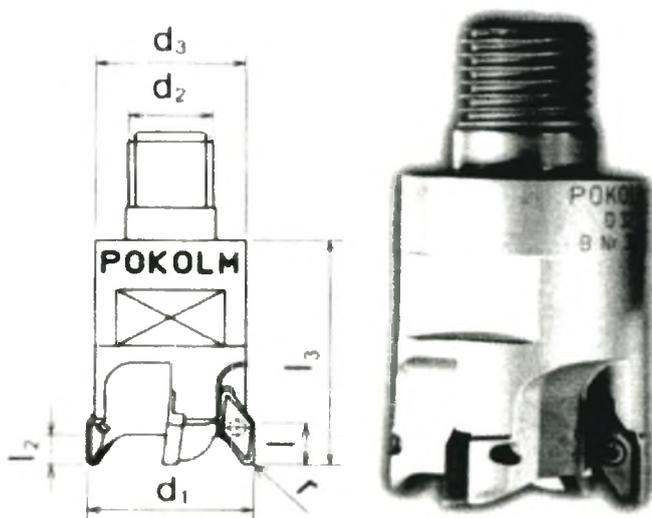


Figure 8.1.1.3 A typical Rhombus shape tip carrier (“Wendeplattenfräser”)

Step 5: Select cutting speed (“Schnittgeschwindigkeit”). In the actual case 400 m/min was used. This is the value recommended by WZN tool manufacturers for solid carbide (“Vollhartmetall”). For solid carbide tools Wilhelm Fette recommends up to 1200m/min and Pokolm 200 to 800 m/min. For the tip tools (“Wendeplattenfräser”) WZN recommends up to 4000 m/min. Hochmut of the Chemnitz Fraunhofer Institute comments that for aluminium the maximum cutting speed of up to 5000 m/min is seldom a limiting parameter. The machine power or the maximum spindle speed is

usually the constraint. Therefore the choice was an appropriate one for the low cost milling tool used, but higher productivity could have been attained with solid carbide.

Step 6: Calculate spindle speed – $n = 1000 \cdot V_c / \pi \cdot \varnothing_c$ – for $V_c = 400$ m/min; $\varnothing_c = 6$

$$n = 20\,000 \text{ rev/min.}$$

Step 7: Select f_z , the feed per tooth (“Zahnvorschub”), in the actual case 0.075 was used. For this parameter the tool manufacturer’s values are usually followed. Pokolm recommends 0.12 to 0.18, Fette 0.12 and Eskenazi 0.25. These feed rates should be examined together with the recommended depths and widths of cut. In isolation they do not necessarily mean that different tools perform differently. The 0.075 is therefore a rather conservative choice. It is ironic that this is probably an attempt to make the tools last longer, but that it has the opposite effect. Optimum feed per tooth gets the volume of material cut away in the least number of cuts, resulting in the longest tool life.

Step 8: Calculate feed rate, V_f (“Vorschubgeschwindigkeit”).

$$V_f = n \cdot z \cdot f_z$$

For: $z = 2$ number of teeth

$f_z = 0.075$ mm/z feed per tooth – “Vorschub pro Zahn”

$$V_f = 3\,000 \text{ mm/min}$$

Step 9: Select width of cut (“Schnittbreite”) (a_e). In the actual case a cut width of $0.5 \times \varnothing_c$ (\varnothing_c diameter of cutter – “Fräser \varnothing ”) was used. The CAM system used at SFM, GIBCAM uses $0.5 \cdot \varnothing_c$ as the maximum width value for the high a_e / low a_p strategy. The modern trend is to make the cutting arc as large as possible for the high a_e / low a_p (depth of cut. “Schnitttiefe”) strategy (Hochmut (2001)). The typical values for a_e then becomes 0.8 to 0.9 \varnothing_c . The other strategy is to limit the a_e to 0.2 \varnothing_c but then work with an a_p of 1.5 \varnothing_c . Eskenazi favours this strategy of a narrow deep cut, with Wilhelm Fette and Pokolm favouring the shallow wide cuts and the Japanese Kobelco data giving data for both. Hochmut (2001) maintains that both strategies have their applications but that the shallow wide cut is the most commonly used in HSC.

Step 10: Select depth of cut (“Schnitttiefe”) (a_p). The actual cut depth used is unknown. The general practice is to use a cut depth of 0.5 $\cdot \varnothing_c$ (\varnothing_c diameter of cutter – “Fräser \varnothing ”).

The length of the tool has a large influence on the depth of cut. In this case the same tool was used to mill the ampoule cavities making it necessary to use a very long tool as described in step 2. The ℓ/d ratio of 7.5 would have limited the cut depth considerably, approximately to 1,2 mm. In the case of H²SC the depth will be considerably less, depending mostly on the rigidity of the machine tool.

Step 11: Calculate the Metal Removal Rate (Q) also referred to as the chipping volume rate ("Zeitspanvolumen")

$$Q = (a_e \cdot a_p \cdot v_f) / 1000$$

$$a_e = 3 \text{ (cut width / "Schnittbreite")}$$

$$a_p = 1,2 \text{ (cut depth / "Schnitttiefe")}$$

$$Q = 10.8 \text{ cm}^3/\text{min}$$

$$v_f = 3000 \text{ mm/min (feed rate)}$$

Step 12: Calculate the required power ("Maschinenleistung"). In HSC the calculation of power is rather inaccurate. The bearings of a HSC machine absorb proportionately more power than in the case of a conventional machine tool. These bearing power losses are not constant at all from one machine tool to the other and therefore cannot be predicted accurately. These calculations are therefore only guidelines. Both Pokolm and Wilhelm Fette have similar approaches dividing the MRR or chipping volume rate ("Zeitspanvolumen") by a constant. Pokolm uses the same constant for all materials (18 cm³/min/kW). Wilhelm Fette publishes a range of constants from 70 for plastics, 50 for aluminium down to 14 cm³/min/kW for tool steel. The Wilhelm Fette range of values recognises density / hardness of the work piece material as a variable influencing the power requirement as a function of the material removed. It is therefore considered more accurate and is preferred by the author. When a long slender tool (ℓ/d ratio > 7.5) is used the limited depth of cut usually causes that the full power of the machine tool cannot be utilised.

$$P = Q / 50 \quad Q = 10.8 \text{ cm}^3/\text{min (Material Removal Rate)}$$

$$P = 0.216 \text{ kW}$$

Step 13: Check the torque required. The HSC machine tools have limited torque.

$$T = 60 \cdot P / (2 \cdot \pi \cdot n) = 0.103 \text{ Nm}$$

$$P = 216 \text{ Watt, } n = 20\,000 \text{ rpm}$$

The 0.1 Nm is well within the maximum of 1.4 Nm available on the Paso Profi 400 HSC machine tool at SFM in Dresden.

Step 14: Calculate the volume of the block of material to be removed in this step (j).

$Vol_j = \text{length} \times \text{width (in top view)} \times \text{height (in side view)}$

$$Vol_1 = [131.79 \times 96.61 \times (48 - 23)]/1000 \text{ cm}^3 \quad (j = 1)$$

$$Vol_1 = 319.5 \text{ cm}^3$$

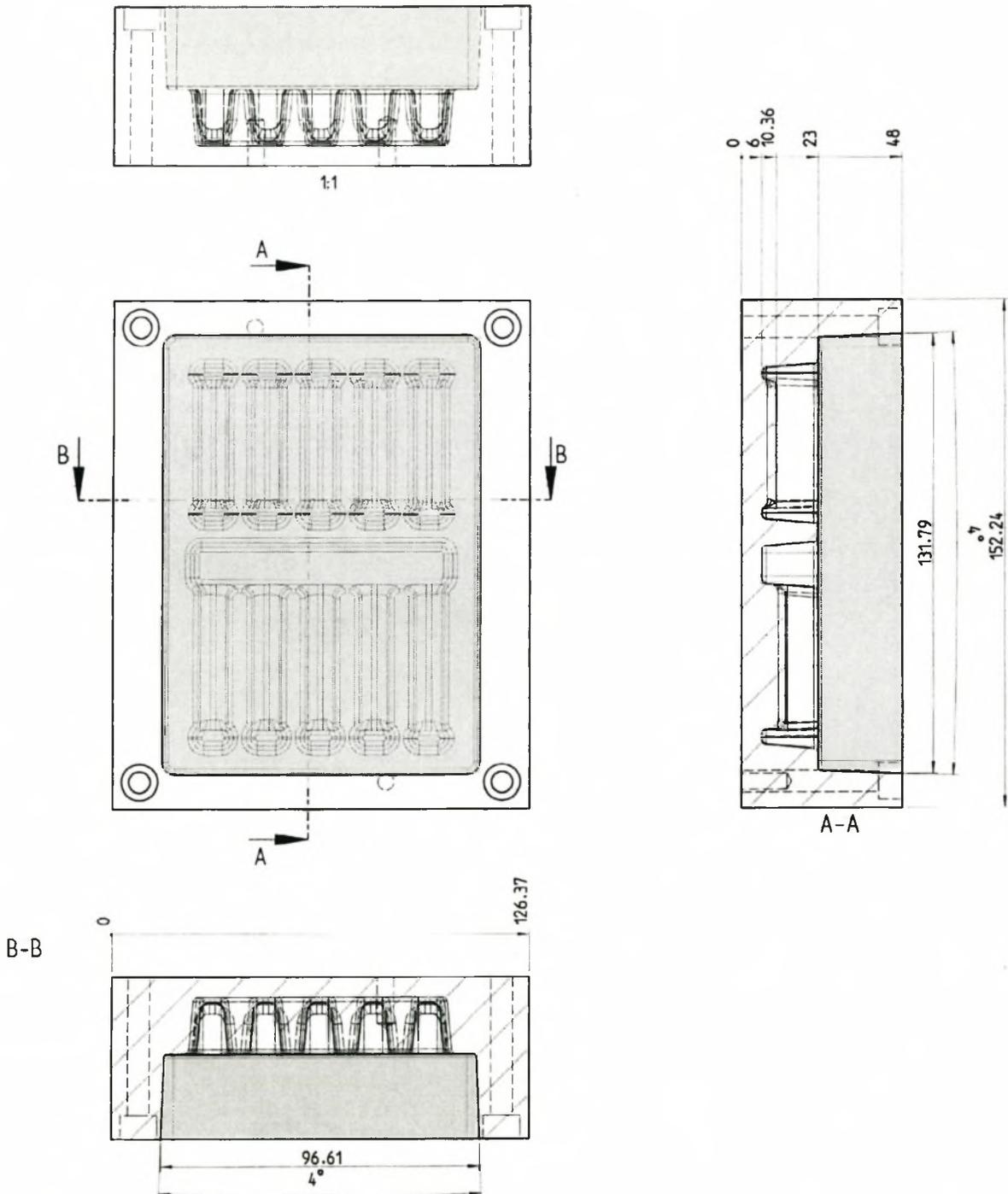


Figure 8.1.1.4 Work piece showing roughing block 1

Step 15: Calculate time for this machining step ($j = 1$).

$$t_j = \text{Vol}_j / Q_j \qquad \text{Vol}_1 = 319.5 \text{ cm}^3$$

$$t_1 = 29.6 \text{ min} \qquad Q_1 = 10.8 \text{ cm}^3/\text{min}$$

Step 16: Record the time as the machining time for that specific tool diameter. The goal is to display the machining times for each diameter tool in a bar chart format to show how much of the total machining time was spent with each diameter tool.

Step 17: Repeat steps 1 to 15 for $j = 2$.

In the actual case the ampoule cavities which is to be machined next ($j=2$) was machined with the same tool and under the same cutting conditions. Steps 1 to 14 is therefore the same.

Step 18 Volume of cavities marked A: 10 cavities \times 45 \times 9 \times 15.5 deep = 62,8 cm³

Volume of cavity marked B: 1 cavity \times 74 \times 11 \times 18 deep = 14,6 cm³

Total volume (for $j = 2$) = 77.4 cm³

Step 19: Calculate time for this machining step ($j = 2$).

$$t_j = \text{Vol}_j / Q_j \qquad \text{Vol}_2 = 77,4 \text{ cm}^3$$

$$t_1 = 7,2 \text{ min} \qquad Q_2 = Q_1 = 10,8 \text{ cm}^3/\text{min} \text{ (same tool)}$$

Total roughing time ("Bearbeitungszeit, Schruppen")

$$t_r = t_1 + t_2$$

$$t_r = 29,6 + 7.2$$

$$= 36,8 \text{ min}$$

Comparing the roughing time estimated by the model (36,8 min) with the actual time (40 min) the correlation is good for a model aimed at only relatively accurate predictions for the purpose of process planning. The remaining 3.2 min or 8% can be accommodated by the correction constant K_r . (K_r is then set as 1.08). It was realised that in small mould manufacture the length of uninterrupted milling is often relatively short. For the model to be reasonably accurate specifically with small

moulds the milling time effect of acceleration and deceleration of the axes will have to be incorporated in the model.

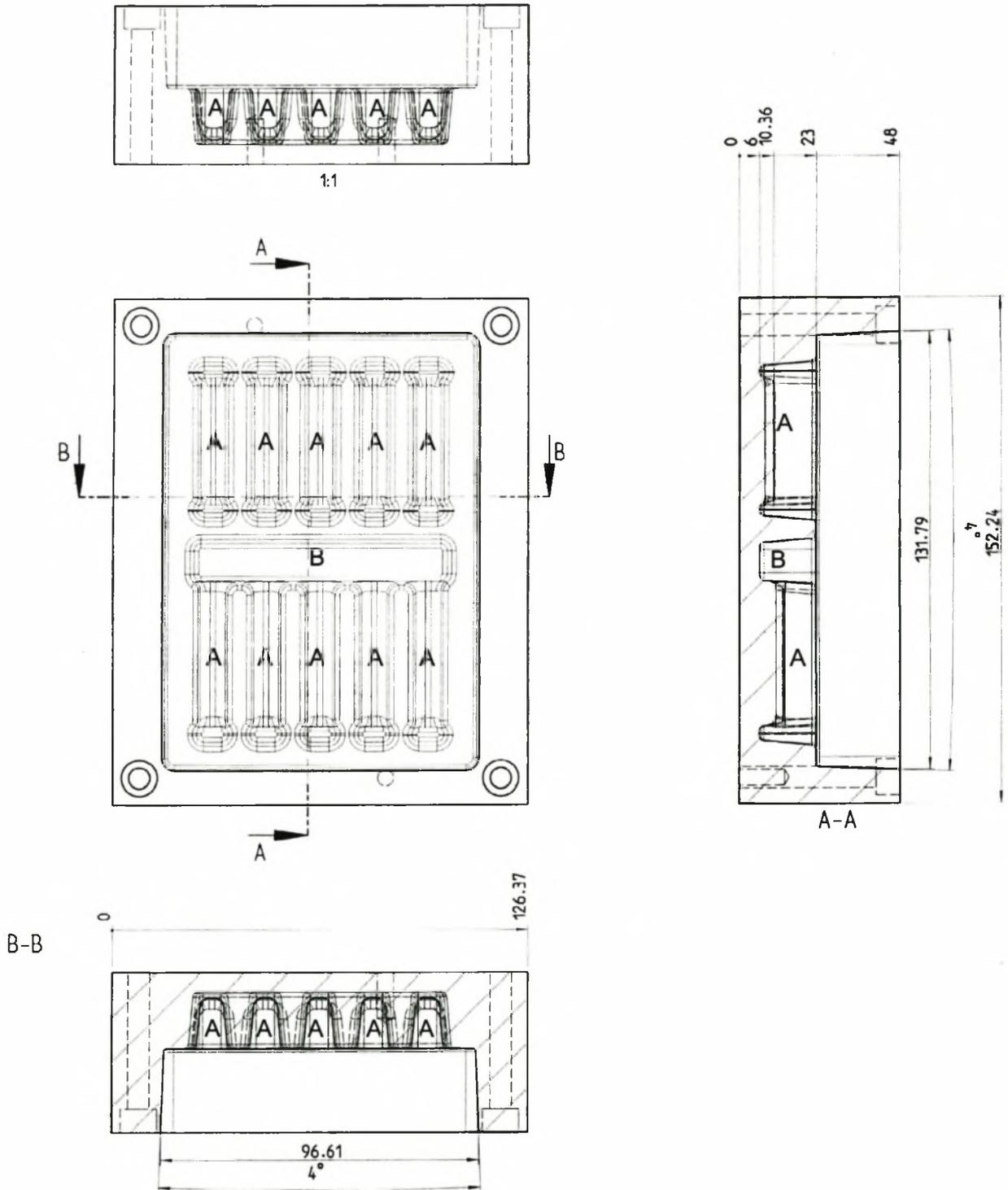


Figure 8.1.1.5 Work piece showing roughing block 2 (marked "A" and "B")

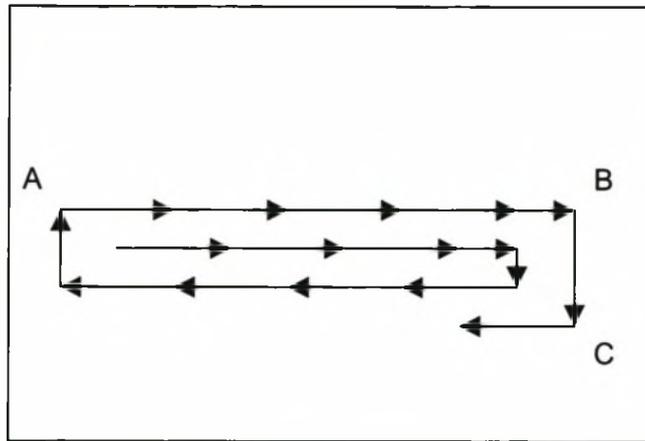


Figure 8.1.1.6 The typical roughing strategy used in HSC Milling

It can be seen that each time there is a change of direction one of the axes has to decelerate to a feed rate of 0 and then accelerate up to the required speed again. The speed / time relationship can be shown as follows:

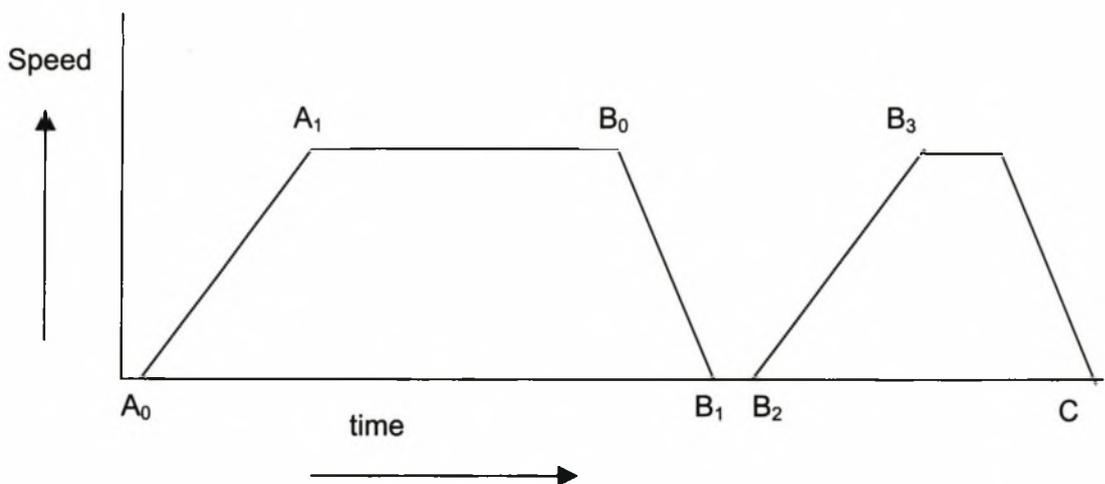


Figure 8.1.1.7 Speed – time relationship of axis displacement

The slope of $A_0 - A_1$ is determined by the acceleration of the machine. This is a crucial performance characteristic available for a machine tool, often expressed as $1g$ for 10 ms^{-2} . $B_0 - B_1$ is the deceleration rate of the machine. Although this can have a different value to the generally published acceleration rate it will be assumed to be the same. On some machines delay $B_1 - B_2$ is a significant time. The CAM software and the machine tool controller jointly determine this. The GIBCAM CAM software in combination with the Andronic controller on the Paso HSC machine at SFM was extremely efficient with no delay observable. This is considerably better than the author's observation of a Leadwell controller in combination with Pro-

Engineer CAM software. The key to this difference could be the look ahead function that is a facility with most HSC machine tools.

The distance necessary for the axis to accelerate to its full speed can be calculated as follows:

Under constant acceleration (a) accelerating from rest for time t:

$$v = at \quad (\text{eq 1})$$

the distance(s) travelled when accelerating at a m/s after time t is given by:

$$s = \frac{1}{2} a t^2 \quad (\text{eq 2})$$

$$t^2 = 2s/a$$

$$v^2 = a^2 t^2 \quad (\text{eq 1})^2, \text{ subs } t^2 = 2s/a \text{ gives:}$$

$$v^2 = 2as$$

$$s = v_f^2 / 2a$$

$$s = 0,13 \text{ mm} \quad \text{For } v_f = 3 \text{ m/min} = 0.05 \text{ m/s}, a = 1g = 9.81 \text{ m/s}^2$$

This means that the axis takes 0,13 mm of displacement before it reaches the programmed feed rate. In this specific case the acceleration times will have a minimal influence on average feed rates. With other machines with axis travel rates of 50 m/min and acceleration of 0,7g (Mazak Super Mould Maker) the acceleration distance becomes 50 mm at maximum feed rate. In the aircraft industry, the other major application of HSC, the Mazak Hypersonic with linear drives has axis speeds up to 120 m/min. Due to the large mass of work pieces but at the same time high power linear drives the acceleration is expected to be in the region of 0.5g. This yields an extreme acceleration distance of 4 m. It means that this machine will for most of the time be on the acceleration /deceleration part of the curve. It therefore becomes clear that a model based on the axis speed only could suffer of significant inaccuracy. This will be the case for the combination of HSC where high axis speeds ("Vorschubgeschwindigkeiten") are common and small mould manufacture ("Kleinformenbau") where path lengths are short as well as for aircraft part machining.

The following discussion of the effect of the acceleration distance will be for the hypothetical case of a Mazak SMM (Super Mould Maker) machine being operated at

24 m/min feed rate and 0,7g acceleration resulting in an acceleration distance of 11,6 mm.

The ampoule cavities are 45 mm long and 9 mm wide. Again for the ease of developing the mathematical expressions the cavity will be assumed to be 29 long ($2 \cdot 11,6 + 6$). The axis travel distance is the cavity dimension minus $\frac{1}{2} \phi_{cutter}$ on either end, therefore:

$$\ell_{travel} = \ell_{cavity} - \phi_{cutter}$$

ℓ_{travel} - axis travel distance

ℓ_{cavity} - length (dimension) of cavity in the direction of the cutting path

ϕ_{cutter} - diameter of cutter

There are therefore 3 possible cases:

Case 1 is where the axis travel is considerably longer than the acceleration displacement (11,6 mm calculated above). The travel will be so long that the average speed will be affected minimally by the time "lost" for the axis to accelerate up to the programmed speed.

Case 2 is where the axis travel is close enough to the acceleration displacement so that the average speed is significantly affected by the acceleration times/distances. In this case each path will be a combination of the acceleration phase, the constant speed travel at the programmed feed rate and the deceleration phase. The movement of the axes could be described by a number of discontinuous mathematical relationships and will practically only be able to be solved numerically. If the model is implemented in computer program this will be quite feasible.

Case 3 is where the axis travel is less than the acceleration distance. The dynamic behaviour of the axes can in this case be described by partially continuous mathematical relationships, which can be solved analytically. These solutions can be used to solve the mixed case (2) numerically as described above with minimal expansion (the expansion is for the constant speed part of the path). In these cases there will be a significant reduction of the average feed rate from the programmed feed rate.

Boundaries:

The case (3 above) described in the following paragraphs is applicable from zero movement to a path length of 2 times the acceleration distance (11,4 mm for this case study) plus the diameter of the tool. Therefore $11,6 * 2$ plus 6 = 29,2 mm for this hypothetical case study. The reason for the 2 times acceleration distance is that the axis must accelerate at the start of the path and decelerate at the end of the path and during both, the speed is lower than the programmed speed. In the aircraft structural component machining this is expected to be a very common phenomenon. The machine tools are large and x and y axis accelerations are lower. (e.g. Mazak Hypersonic 1400L, 4m x 1.25m). Large tool diameters are used requiring large feed rates. The end result is that acceleration times have a large influence on average feed rate.

In the following paragraphs Case 3 is expanded. Roughing in HSC is mostly executed as a series of constant z operations. This refers to the most common configuration where the z-axis is the vertical axis and the x and y axes are the horizontal plane axes. The cavity is milled at the specified z (height) and the full area of the x-y (horizontal) plane is covered with spiral movement or linear line segments approximating a spiral as shown in Fig 8.1.1.6. Next the z value is decremented (cutter moved down and deeper into the material) and the area of the cavity is again covered. If the 2-dimensional ($\bar{x} + \bar{y}$ vector) plane is converted to a 1-dimensional (scalar), which is the speed of the tool (in any direction), Fig 8.1.1.8 describes the cutting process of the ampoule cavities. At the boundary path length (29 mm) the axis accelerates up to the programmed speed when the look ahead control will start decelerating the axis to have it at 0 mm/min when the length of the path is completed. In the case of the width the axis can only travel (accelerate) for a distance of 1.5 mm (or less) before the look ahead deceleration begins. Solving this with the summation of a series of determinate integrals is possible but considered impractical. A semi numerical approach where integration results are obtained calculating the area under the curves will be followed. For the purpose of this discussion the case will be examined where the length of the ampoule cavity is 29 mm or less.

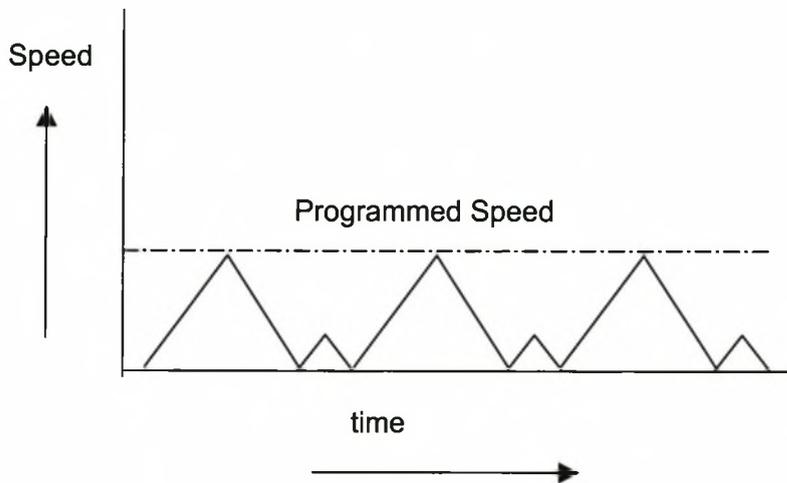


Figure 8.1.1.8 Axis speed time relationship where the longest cavity dimension is equal to the acceleration path length and the other is shorter.

Referring to Fig 8.1.1.9 it can be seen that the average width path length varies linearly from 0 to the cross dimension (width) of the cavity. Actually the tool diameter must also be subtracted but for simplicity this will be corrected later. It can therefore be shown that the average width path length is 0.5 times the width.

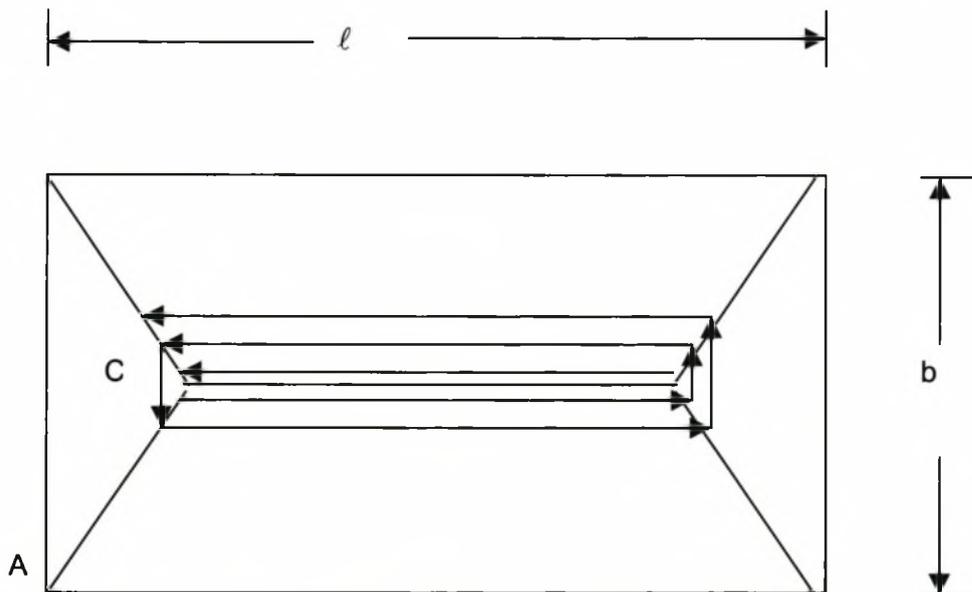


Figure 8.1.1.9 Typical cutter paths for roughing a cavity $\ell \times b$.

It can be seen that the diagonal lines which is the locus of the direction change points, of which AC is a typical example, is at 45° to the main axes of the cavity. The stepover ("Schnittbreite/Bahnabstand"), which becomes the displacement, is the same in the two perpendicular directions (ℓ and b), which causes AC to be at

45°. It then follows that the minimum lengthwise path is $(\ell - 2 \cdot \frac{1}{2}b)$. The average path length is then $\{(\ell - b) + \ell\} / 2 = (\ell - \frac{1}{2}b)$.

The average speed due to the time occupied by acceleration is calculated as follows:

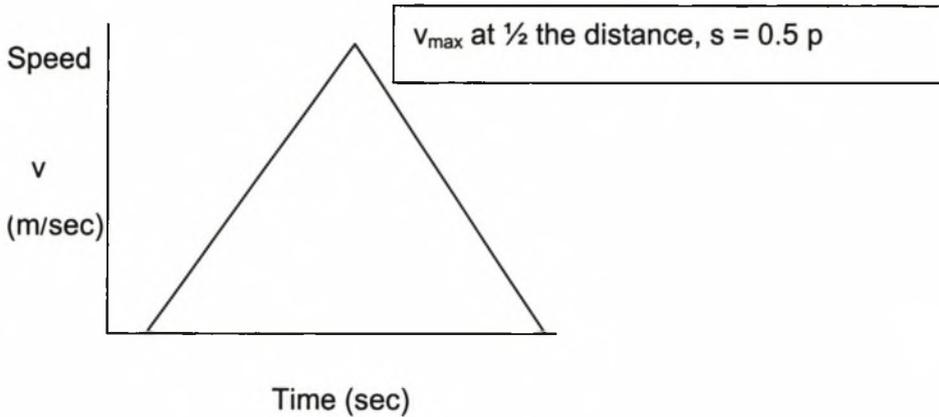


Figure 8.1.1.10 Speed – Time relationship when axis never reaches programmed speed

The speed - time curve above has an acceleration part and a deceleration part, which is identical because of the assumption that the deceleration rate is the same as the acceleration rate. It then follows that the average speed for the acceleration part of the curve is the same as for the deceleration part and of the whole curve. The displacement (s) at which the maximum speed occurs, is therefore half of the path lengths (p).

$$v^2 = 2 a s \quad s = 0 \dots \frac{1}{2} p \dots 0 \quad p = \text{path length (can be } \ell \text{ or } b)$$

$$\begin{aligned} v_{\text{max}}^2 &= 2 a (\frac{1}{2} p) \\ &= ap \end{aligned}$$

The average speed by using the area under the curve therefore is:

$$v_{\text{ave}} = \frac{1}{2} \sqrt{ap} \quad \text{where } p \text{ could be either } \ell \text{ or } b \text{ depending whether it is a lengthwise cut or a width wise cut.}$$

Returning to Fig 8.1.1.10, the proportion of the time used to do width cuts vs. lengthwise cuts must be determined:

The area of the two end triangles in the diagram:

$$A = \frac{1}{2} b \cdot h$$

$$A = \frac{1}{2} (b) (\frac{1}{2} b)$$

$$A = \frac{1}{4} b^2$$

$$A \text{ (both triangles)} = \frac{1}{2} b^2$$

In the case where the cavity to be milled is square in plan view, therefore

length = width the total area is ℓ^2 or b^2 . The result of $\frac{1}{2} b^2$ is then the correct proportion, which gives credibility to the expression.

Therefore: For width wise cuts: $\text{Area}_b = \frac{1}{2} b^2$

$$v_{\text{ave}(b)} = \frac{1}{2} \sqrt{ab}$$

 For lengthwise cuts: $\text{Area}_\ell = b \cdot \ell - \frac{1}{2} b^2$

$$v_{\text{ave}(\ell)} = \frac{1}{2} \sqrt{a\ell}$$

$$\text{Overall average speed } (v_{f \text{ ave}}) = (\text{Area}_b \cdot v_{\text{ave}(b)} + \text{Area}_\ell \cdot v_{\text{ave}(\ell)}) / (\text{Area}_b + \text{Area}_\ell)$$

$$v_{f \text{ ave}} = \{ [\frac{1}{2} b^2] [\frac{1}{2} \sqrt{ab}] + [b \cdot \ell - \frac{1}{2} b^2] [\frac{1}{2} \sqrt{a\ell}] \} / \{ [\frac{1}{2} b^2] + [b \cdot \ell - \frac{1}{2} b^2] \}$$

$$= (\frac{1}{4} a^{1/2} b^{2\frac{1}{2}} + \frac{1}{2} a^{1/2} b \ell^{1\frac{1}{2}} - \frac{1}{4} a^{1/2} b^2 \ell^{1/2}) / b\ell$$

$$= [\frac{1}{4} a^{1/2} (b^{2\frac{1}{2}} - b^2 \ell^{1/2} + 2b \ell^{1\frac{1}{2}})] / b\ell$$

Recalculating the roughing time in Step 19 as an example:

First consider the A type cavities but with the hypothetical machine data:

Length (ℓ) = 29, with \emptyset_c subtracted, $\ell = 23 \text{ mm} = 0.023 \text{ m}$

Width (b) = 9, with \emptyset_c subtracted, $\ell = 3 \text{ mm} = 0.003 \text{ m}$

Acceleration (a) = $0.7 \text{ g} = 6.87 \text{ ms}^{-2}$ (0.7g is the specification for the Mazak Super Mould Maker)

$$\begin{aligned} V_{f \text{ ave}} &= [\frac{1}{4} a^{3/2} (b^{2/2} - b^2 \ell^{1/2} + 2 b \ell^{1/2})] / b \ell \\ &= [\frac{1}{4} (6.87 \times 1000)^{3/2} (3^{2/2} - 3^2(23)^{1/2} + 2(3)(23)^{1/2})] / 3 \times 23 \\ &= [(20.72) (15.59 - 43.16 + 661.8)] / 405 \\ &= 190 \text{ mm/sec} \\ &= 11\,400 \text{ mm/min} \end{aligned}$$

Compared to the programmed feed rate of 24 000 mm/min this will have a serious effect on the machining time. The time is inversely proportional to the average speed – In this hypothetical case the speed is just more than halved which means that the time will be just more than doubled.

In paragraph 8.1.1 the effect of acceleration and deceleration on machining times was discussed. It is clear that depending on the situation especially the values of the length and width of the cavity, the axis speeds, and the acceleration rate of the axes, there may be significant effect on machining times and thus the Material Removal Rate (“Spanvolumen”). It is therefore clear that the model will have to incorporate the axes' acceleration into the machining time calculation. Due to this rather lengthy calculation of the effects of axes acceleration, the terms of the model is only presented in general terms as the time for roughing being a function of the diameter of the cutting tool (and the segment size as well as the machine parameters e.g. the axes' accelerations). When the model is programmed the calculations of the case study will have to be followed and generalised.

8.1.2 Description of the semi-finishing term of the model

$$K_{sf} f_{\text{delta}} k^m \sum_k t_{sf}(A_k d_k)$$

- K_{sf} - Correction constant for semi-finishing
- $f_{\text{delta}1}$ - Correction factor for tool \emptyset change from rough cut to semi-finish cut
- k - Number of segments for semi-finishing with an own cutting strategy
- m - Compensation exponent for multi - strategy, multi - segment semi-finishing
- A_k Area to be covered in the segment
- d_k Diameter of tool used for segment k (tool \emptyset)
- t_{sf} - Time to semi-finish machine the segment

This specific case study did not have a semi-finishing phase. The process went directly from roughing to finishing. The same approach as with finishing to obtain an estimation of the surface area (A_k) to be covered and then dividing the surface area of the segment by the area coverage rate for the specific tool used, will be followed.

8.1.3 Description of the finishing term of the model

$$+ K_f f_{\text{delta}2} \ell^p \sum_{\ell} t_f (A_{\ell} d_{\ell})$$

- K_f - Correction constant for finishing
- $f_{\text{delta}2}$ - Correction factor for tool diameter change from semi-finish cut to finish cut
- ℓ - Number of segments for finishing with an own cutting strategy
- p - Compensation exponent for multi - strategy, multi - segment finishing
- t_f - Time to finish machine the segment
- A_{ℓ} Area to be covered machining the segment

In this term the usual HSC milling practice is followed as in the usual process planning. The emphasis is now on surface finishing and not on material removal.

The primary inputs to the process therefore are the size of the surface to be covered, the rate at which the machine covers the surface and other factors, which may influence this process. These other factors include factors like the geometry of the final surface. If the geometry is such that the cutter path is not an even curve within the acceleration capabilities of the machine tool, the path becomes longer and the average speed is lower exerting a large influence on the time per path completion. This potential inaccuracy will be covered with the K_f factor discussed below. Another factor is the unevenness of the material left to be removed with the finishing cut, which will be covered by the $f_{\text{delta}2}$ factor discussed below. It is general practice to use one tool for finishing the whole final surface. This was the way the case study was programmed. A more advanced way of programming the finish cut would be to divide the surface into discrete surface areas using the optimum tool diameter for that part. Larger areas may be productively finished with larger ball nosed tools ("Kugelfräser") utilising the advantage of the smaller scallop height with the same stepover ("Bahnabstand") of a large diameter tool. The features, requiring small diameter tools usually for (but not limited to) corners, can then be finished in separate steps where only the necessary areas are machined. For a state of the art surface finish the surface should also be separated in different areas to use not only the optimum tool diameter but also the direction of cut (Refer Fig 7.4.1.). The Gibcam software does this and then links the segments together. It was not specifically evaluated whether Gibcam fully utilises all the newest machining strategies for the best surface finish attainable.

K_f - Correction constant for finishing

The K_f factor is used to finally correct the value of the time calculated for the finishing operation. The factors that need compensation are typically controllers putting in delays between segments and also between cuts. Some of the CAM software systems include G00 or moving to a safe position away from the work piece commands between segments. This is a waste of machining time and the K_f factor can effectively provide such compensation. The operation personnel at SFM were successful in using the options in Gibcam to eliminate both delays and the unnecessary moving away from the work piece commands (G00).

$f_{\text{delta}2}$ - Correction factor for tool diameter change from semi-finish cut to finish cut

This factor is used where there is a significant difference between the tool used for semi-finishing and the one for finishing. This could lead to the finishing cut having to make more than one pass if there is more material to be removed than can be removed with one cut. If the semi-finishing is done with an 8 mm ball nose (“Kugelfräser”) tool and the finishing is done with a 2 mm tool there will be more material left in the corners than can be removed with one pass. This factor is intended to compensate for this. The factor could be set to a default value with the process planner able to change it according to his judgement.

l - number of segments for finishing with an own cutting strategy

It is the modern technique to divide the surface into segments with similar cutting conditions e.g. angle of contact between the cutter and work surface and feed direction. Every separate segment needs some cutting overlap with the previous segment and lead-in path segments and lead-out path segments. These “extra” cutting path segments causes relative inefficiency to achieve the optimal surface finish.

p - compensation exponent for multi - strategy, multi - segment finishing

The number of segments discussed above is raised to the power *p* to accommodate the increase in machining time when the finish surface is divided into a large number of segments. It is considered that the time consumed to do the final cut increases exponentially with an increase in the number of segments. This factor will have to be practically determined in a specific environment. It therefore gives the opportunity to customise the model for the style of machining in a particular company. A company with highly skilled CAM personnel may have a low K_f factor (efficient programmers/operators) together with a relatively high *p* value (preference for smooth leading of the cutter in to the surface and getting the axis up to speed before the surface is reached, causing unproductive cutting time). This advanced strategy will however give a superior surface finish.

It can also be concluded that the Paso machine tool with the relatively high acceleration together with the Andronic controller is an efficient combination for small mould manufacture in light materials e.g. aluminium and tooling composite. It could give some insight into the machine’s capability to work through a model exercise like the one in this chapter for tool steel and determine theoretically whether this fast agile machine is capable of machining tool steel. In spite of the machine personnel being convinced that the machine is not capable machining tool steel, the author is of the

opinion that with extremely careful process planning (and a gradual building of the knowledge base) this will be possible. It is the opinion of the author that a high performance milling machine (“Hochleistungs – Fräsmachine”) will be much better suited for roughing than this pure HSC machine. Refer to par 5.6 for a discussion on high performance milling machines. The pure HSC machine (Paso) can effectively be used for finishing if the roughing work is done with a high performance milling machine or “Hochleistungs – Fräsmachine”.

8.2 Example of the use of the Model for a Tool Steel Variant of the Case Study

For the purpose of the example some of the features of the item were changed, so as to require a minimum radius of 2 mm.

8.2.1 Determine the Potential Process Chain

The flow diagram in Fig 7.3.1 is used. The flow diagram as customised for the specific firm should be used. It is presented here as fig 8.2.1.1.

Material: Tool steel, normal (“Normale Werkzeugstahl”)

Min Feature radius: R2

Tool required: \varnothing 4 ball nose, solid carbide, TiAlN coated
 (“ \varnothing 4 Kugelkopf Fräser, Vollhartmetall, TiAlN beschichtet”)

Max depth of feature 42 mm

Clearance between chuck and work piece: 2 mm

Tool length required: 44 mm

Tool ℓ/d ratio 11

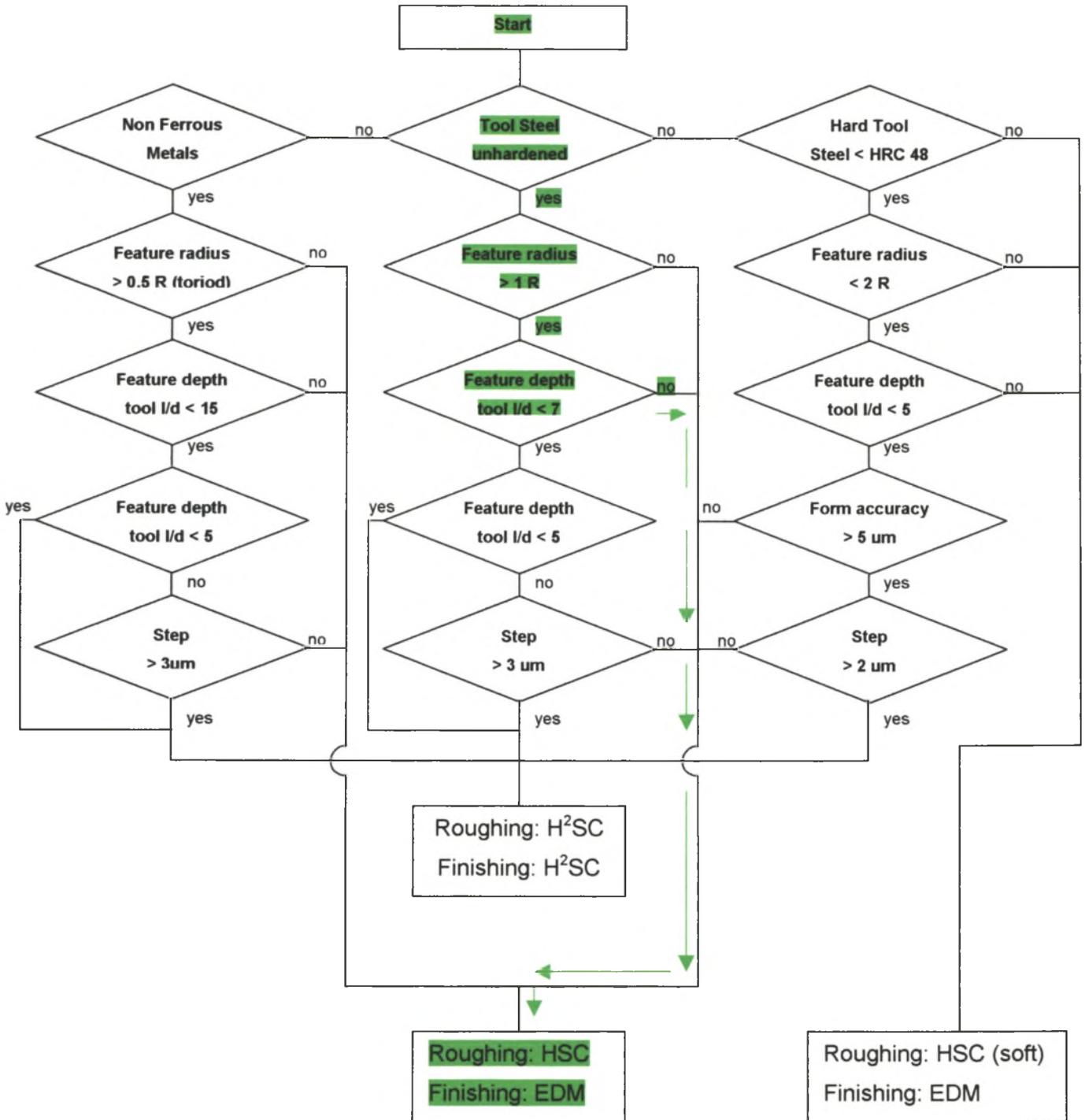


Figure 8.2.1.1 Application of Process Chain selection flow diagram on Ampoule Holder

It can be seen that the combination HSC / EDM process makes it possible to handle this project even in a machining workshop where the expertise in HSC is limited. The high-risk HSC operations with either small diameter tools or large l/d ratios are eliminated to suit the expertise level of the company.

The rest of the application of the model will be similar to the one discussed in detail for the aluminium machining.

8.3 The Implementation of the Decision Model for a Process Planning Tool

The next paragraph shows a schematic flow diagram how the decision model could be implemented to achieve the goal of a low human input / valuable output process planning tool.

8.3.1 Use of the Decision model for determining the HSC / EDM changeover point

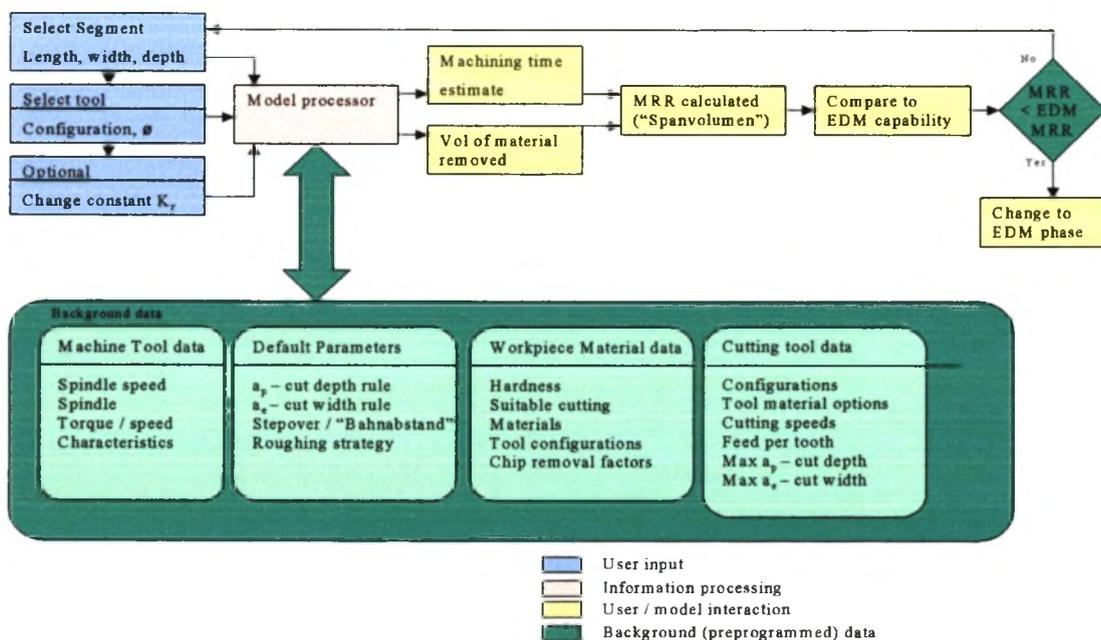


Figure 8.3.1.1 Use of the Decision Model for HSC / EDM changeover

In this application the model is used with the smallest amount of user input. It is required for this low user input that the user requirements should allow for an EDM final surface finish.

HSC is employed first to do the bulk material removal and EDM is used to finish all the surfaces of the work-piece. There is no need for HSC finishing; therefore HSC is used only in roughing mode. The EDM tool will therefore be the total final (negative) shape of the required work-piece. The total final work-piece surface will have an EDM ("Erodieren") surface finish.

The user will select a segment to be machined and enter the length, width and depth dimensions of the segment. The decision model will respond to ask the user to select a milling tool. Optionally the user will be able to adjust the constant K_r . The computer will calculate the estimated machining time for the segment, the volume of material removed and the material removal rate (MRR). Thereafter the computer will compare the MRR achieved in the segment with the MRR achievable with EDM. If the MRR is still higher (for HSC Milling) than the MRR the computer will ask the user to enter the next segment's data. When the segment becomes so small, forcing a small diameter HSC milling cutter and short cutting paths, so that the MRR becomes lower than the MRR achievable with EDM, the computer will give feedback to the user that the recommended change-over point is at the end of the previous segment. This change-over point then becomes the key input for further process planning and programming.

8.3.2 Use of the decision model where HSC is used for partial finishing

The model is used as in Fig 8.3.1.1 but without the decision loop to record the changeover point between HSC and EDM. The process iterates until the roughing is finished.

The model is used to estimate the time used for semi-finishing as described in the Fig 8.3.2.1, below. For semi-finishing the area to be covered is estimated. The path length in the length dimension and the width dimension of the surface to be machined is estimated and entered into the model. The constants that can be corrected include K_{sf} , $f_{\Delta 1}$ and m . K_{sf} is the correction constant for irregular surfaces that will cause a large amount acceleration time losses ($K_{sf} = 1$ for smooth surfaces, $K_{sf} = 2$ for moderately irregular surfaces). $f_{\Delta 1}$ is the factor to correct the extra time necessary when the semi-finishing tool is a considerably smaller diameter than the roughing tool. The compensation is for areas where the semi-finishing requires more than one pass to remove all the material necessary. $f_{\Delta 1}$ will vary from 1 for a smooth surface and a minimally smaller for semi - finishing to an expected value of 1.5 where the difference is large. The value of m depends on how much "lead in" and "lead out" cutting is done. When the final work-piece surface is divided into a number of surfaces each with its own cutting direction to optimise the cutter life and surface finish the cutter spends a large proportion of its time approaching and leaving the surface (in air). This loss of cutting time is compensated for with the m factor with the time effectively multiplied by k^m . k is the number of separate surfaces that are programmed. The value of m is expected to be between 1 and 2. The default values for these three factors could be set at 1,2.

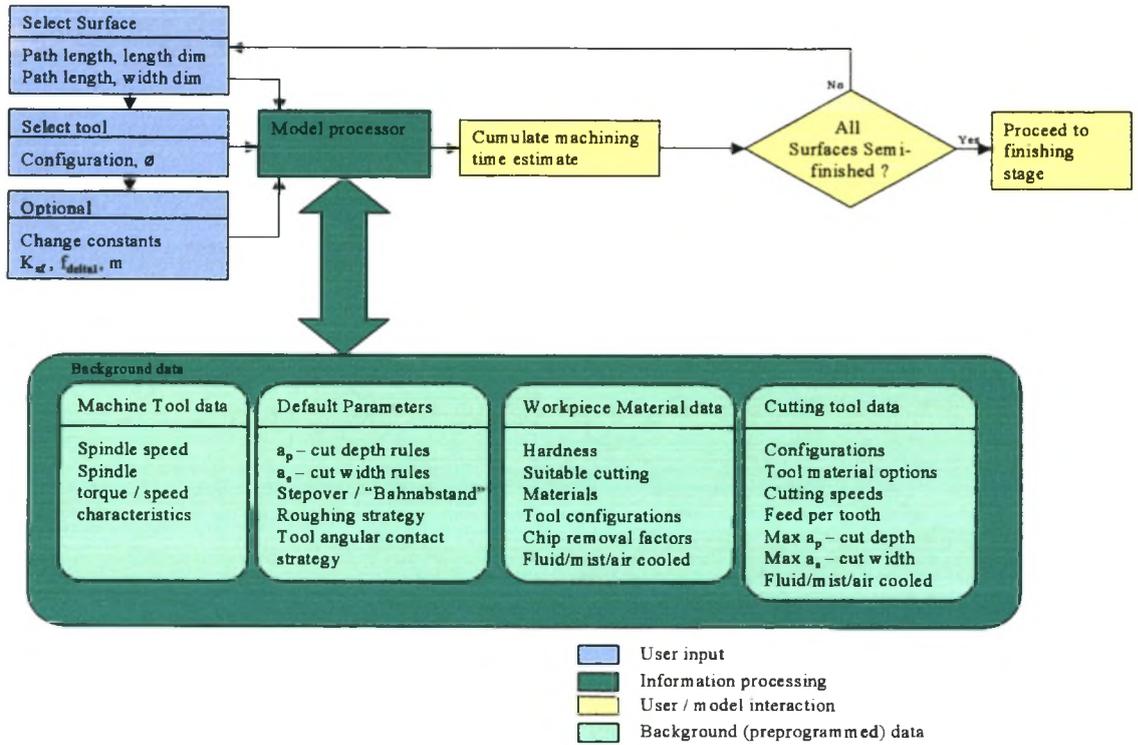


Figure 8.3.2.1 Use of the Decision Model for HSC semi - finishing

The finishing phase is detailed with a similar diagram to the semi-finishing because it is also based on a surface to be covered rather than an amount of material to be removed.

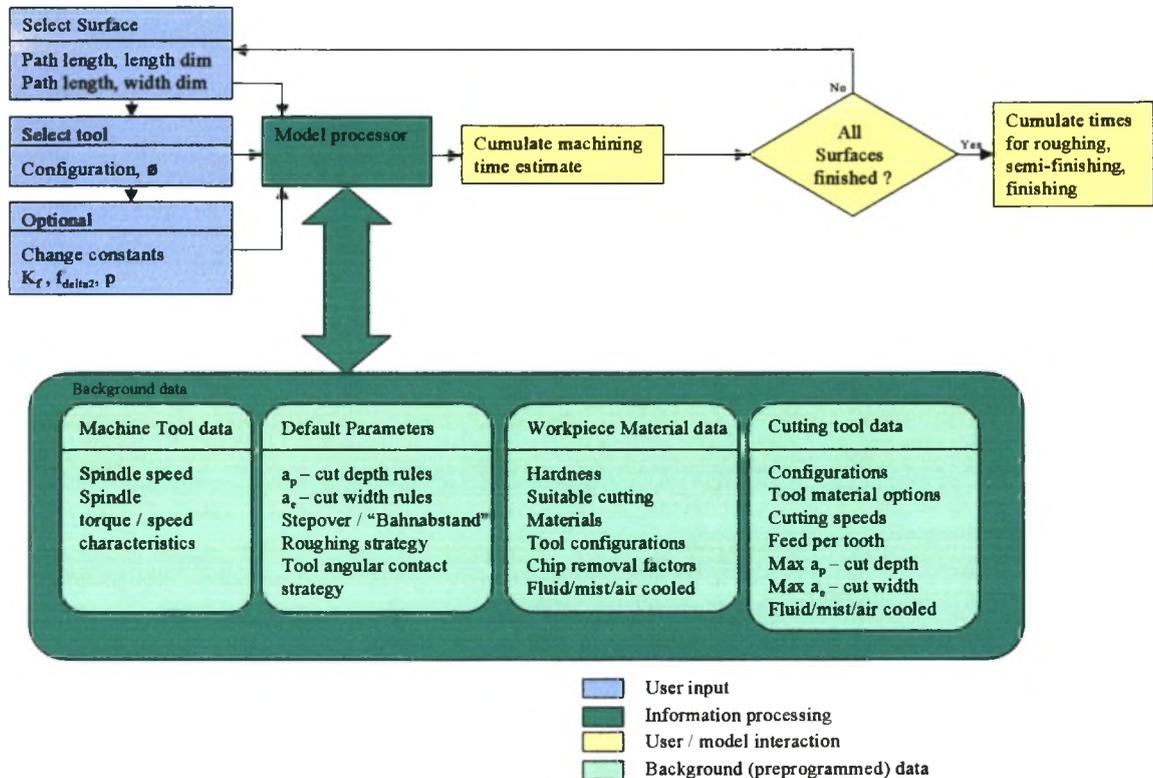


Figure 8.3.2.2 Use of the decision model for HSC Finishing

Similar to semi-finishing, the model is used to estimate the time used for finishing as described in Fig 8.3.2.2. For finishing the area to be covered is estimated. The path length in the length dimension and the width dimension of the surface to be machined is estimated and entered into the model. The constants that can be corrected include K_f , $f_{\text{delta}2}$ and p . K_f is the correction constant for irregular surfaces that will cause a large amount acceleration time losses ($K_f = 1$ for smooth surfaces, $K_f = 2$ for moderately irregular surfaces). $f_{\text{delta}2}$ is the factor to correct the extra time necessary when the finishing tool is a considerably smaller diameter than the semi-finishing tool. The compensation is for areas where the finishing requires more than one pass to remove all the material necessary. $f_{\text{delta}2}$ will vary from 1 for a smooth surface and a minimally smaller tool for semi - finishing to an expected value of 1.5 where the difference in tool diameter is large. The value of p depends on how much "lead in" and "lead out" cutting is done. When the final work-piece surface is divided into a number of surfaces each with its own cutting direction to optimise the cutter life and surface finish the cutter spends a large proportion of its time approaching and leaving the surface (in air). This loss of cutting time is compensated for with the p factor with the time effectively multiplied by ℓ^p . ℓ is the number of separate surfaces that are

programmed. The value of p is expected to be between 1 and 2. The default values for these three correction factors for finishing could be set at 1,2.

In the above mentioned case the model is used to estimate the total HSC machining time. Only the features that cannot be machined with HSC will then be machined and finished with EDM. An example would be small holes deep in a mould cavity and possibly small radius corners deep in the mould cavity. The EDM tool will be made only to finish the necessary surfaces, thereby limiting the EDM heat affected areas. The output of the model enables the process planner to compare the time for the combination process and his estimate from experience for the equivalent EDM only process.

8.3.3 Use of the decision model where HSC is used on an development basis

The situation is foreseen where the process planner estimates that the first part of the project is well within the established HSC capability of the company, but a second part with fine detail is technically feasible but that it is unknown whether it will be quicker to do this with HSC. If the HSC/EDM complementary process is used, this point will be the default changeover point from HSC to EDM. The decision model can also be used to support the decision whether this part of the process, which is considered an unknown HSC application, could be done effectively with HSC. The boundaries of HSC application can therefore be developed with less risk that it is less effective than EDM.

The first step is to ignore the part of the cavity or convex shape that will be done by HSC milling anyway.

The model should then be used to estimate the HSC machining time from the default change-over point to EDM for that part of the HSC milling that has not been done before (problems are e.g. long slender tools, small diameter tools, hard materials). The constants in the model will need adjustment for these specific situations. The application of the model for this purpose will be the same as in paragraph 8.3.2.

A comparison with the time estimated for EDM for this specific area will enable the decision to be made before investments are made in programming.

8.4 Summary of the Decision Model Refinement

A relatively simple test case for the decision model was chosen, namely the ampoule holder.

The detail calculations were shown in this chapter. These detail calculations will take the place of the general mathematical expressions presented in the previous chapter and follow the path of detail process planning. The process is intended to require substantially less detail and effort than actual process programming. These calculations will be done in the background without effort from the process planner.

It was also briefly shown how the use of the decision model could be expanded from the aluminium application described in paragraph 8.1 to the steel application in paragraph 8.2.

The final part of the model refinement described conceptually shows how the model could be implemented in software.

9 Conclusion

9.1 The combined HSC / EDM Process Chain

- 9.1.1 The HSC process suffers of a number of limitations. The main limitations are that deep cavities with small dimensions become difficult if not impossible to machine. HSC hard milling or H²SC has reached a level of development where it can be used in commercial operations. The hardness of the material is however still a challenge making HSC machining more difficult and risky.
- 9.1.2 EDM is a rather suitable complementary process. It can machine deep cavities and is insensitive to hardness of the work material. The main disadvantage that EDM is a time consuming process, can be supplemented well by HSC preparing the work piece up to the near finished state.
- 9.1.3 Opponents of the process strategy of using HSC and EDM as complementary processes focus on the following disadvantages:
- a. Using two processes requires two set-ups, which has a major time and cost implication. They use the processes in an either/or manner. If the process can be completed with HSC, HSC only is used. If the process cannot be completed with HSC, EDM only (conventional milling with EDM finishing) is used.
 - b. HSC is not the ideal process to do the initial roughing i.e. for heavy, fast metal removal.
 - c. Process security of H²SC milling is considered suspect.

- 9.1.4 The technology has developed sufficiently for these problems to be considered as surmountable challenges now.
- a. The fixturing technology, notably pallets (e.g. Erowa, 3R) has developed sufficiently for a work piece to be mounted on a pallet early in the manufacturing project and then the pallet is transferred from one machine tool to the next even if these are very different processes like initially HSC milling and finally EDM.
 - b. In the HSC field H²SC (HSC Hard Milling) is adequately developed to be used in industry. Another development in HSC is that of High Performance Milling (“Hochleistungsfräsen”) where the process is optimised for speed as well as cross sectional area of the cut. The HPM machine tools are also generally well suited for H²SC. This HPM focus yields machine tools with good roughing capabilities together with relatively good surface finish abilities. The application will determine where on the speed scale the ideal machine tool lies. It could even be possible that with the pallet technology used, the milling phase could be done on two different machines, the first a HPM machine optimised for heavy roughing, the second stage on a true HSC machine to semi-finish and finish the accessible surfaces and the final stage with EDM finishing the sharp corners and high ℓ/d cavities.
 - c. The Mould and Die companies should invests in people and continuous development training. The goal should be to have a work force who regards machining projects as opportunities to apply relatively advanced knowledge and not only experience. In such an environment HSC can be a secure industrial process. SFM GmbH is far advanced towards this goal with recently trained machine tool personnel. There is however room for further development. It could be beneficial to form a HSC machining technology development group consisting of the machine personnel and an engineer interested in machining technology. This group needs to be exposed to leading developers of the technology on a regular basis possibly quarterly, like the Fraunhofer Institute in Chemnitz. The difference in the levels of the technology in SFM and at the Institute is such that very valuable learning can take place. This group should also undertake capacity building projects to develop the HSC machining capability of the company further. It is even more important that the attitude of basing decisions on experience of the past should make way for an attitude of continuously working to remain up to date with a fast moving technology and to base decisions on this technology. These machine personnel should be developed to regard their reference as a changing technology.

9.2 Development of a Decision Model

- 9.2.1 A mathematical model was developed to aid the process planner to plan the complementary use of HSC and EDM. The intended output of the roughing part of the model is feedback to the planner of the estimated time spent and the material removal rate ("Zeitspanvolumen") for every successive machining step using the next smaller tool size. The process planner can then decide at which point in the process it is better to change over to EDM.
- 9.2.2 If the finishing part of the model is included the HSC machining time for whole sections of a job (roughing and finishing) can be estimated. Comparing this estimate to the time needed for EDM that can be calculated simply, sound quantitative decisions can be made guiding the complementary use of HSC and EDM.
- 9.2.3 The model is supplemented by a decision flow diagram to show whether the process is a candidate for the conventional EDM process chain, HSC and EDM as complementary processes or HSC only.
- 9.2.4 The model is developed in concept only. For practical use the model will have to be implemented in computer software.
- 9.2.5 The model is in an early stage of development with the roughing process detailed in this thesis. The development of the detail calculations was done based on a case study. The actual machining and the collection of the data for the case study were done during a capacity building visit to Dresden. The model can describe the real roughing process with adequate accuracy.

9.3 Future Implementation of the Model

- 9.3.1 The finishing process needs to be detailed similar to the roughing process. The data is available and this can be done.
- 9.3.2 The semi – finishing process is similar to the finishing also being surface based. Although the case study did not have a semi – finishing phase, the results of the finishing phase analysis can be used for an initial approximation.
- 9.3.3 Ultimately the model will have to be implemented as a computer application. This will be done depending on the continuation of this research focus.

10 Appendices

10.1 Appendix A: Visit to the Fraunhofer Institute, Chemnitz

10.1.1 Contact Information

Address of Institute:

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Dipl.-Ing. Carsten Hochmut Hochleistungsfertigungsverfahren

Dr.-Ing Andrea Stoll Fachgruppenleiterin, Hochleistungsfertigungsverfahren

Dr.-Ing Eberhard Kunke OBERINGENIEUR

10.1.2 Introduction

The institute is currently active in research in the field of manufacturing technology finding prominent applications for the automotive industry. High pressure hydraulic forming, deep drawing, cold forming, and tooling manufacture are the areas focused upon. The centre of gravity of the machining research is probably focused on the requirements of the sheet metal forming and forging tooling. The deep drawing research also being done in the same institute is creating an environment for the High Productivity Machining Group where true customer requirements are fed back quickly and reliably.

It is interesting to note that the "Hochleistungsfertigung" or High Power / High Performance / High Effectiveness Machining group include HSC and EDM.

10.1.3 HSC and EDM Equipment

The institute uses a Mikromat Hexapod and a conventional HSC 5 axis-milling machine. The Hexapod has one linear axis on the table and the other 5 axes in the head. The other machine is a standard 3-axis configuration with a rotating C-axis on the table and the head rotating as a B-axis. Mr Hochmut pointed out with higher speed machining the conventional machines are not capable of full 5 axis machining at elevated speeds and the corresponding high feed rates. The rotational axes are too slow. The hexapod configuration is currently the configuration best suited for the machining of large free form surfaces to a high quality surface finish. The surface finish achieved is of such quality that no manual finishing is required for the tooling for external automotive body parts. The Fraunhofer Institute developed this Hexapod concept and this configuration has been given to Mikromat to manufacture and to develop commercially. The current development workpiece is a segment of a car roof with curvature in both the x and the y-axes. The machine spindle is capable of 30 000 rpm, a feed rate of 30 m/min and an axis acceleration of 1g. The institute's solution for high productivity is in this specific case to move away from ball nose tools to a torus tool (tip carrier, "Fräskörper, Wendeplattenträger"). The tool used is a $\varnothing 42$ toroid tool with a 5 tip radius. In this specific case round tips are used.

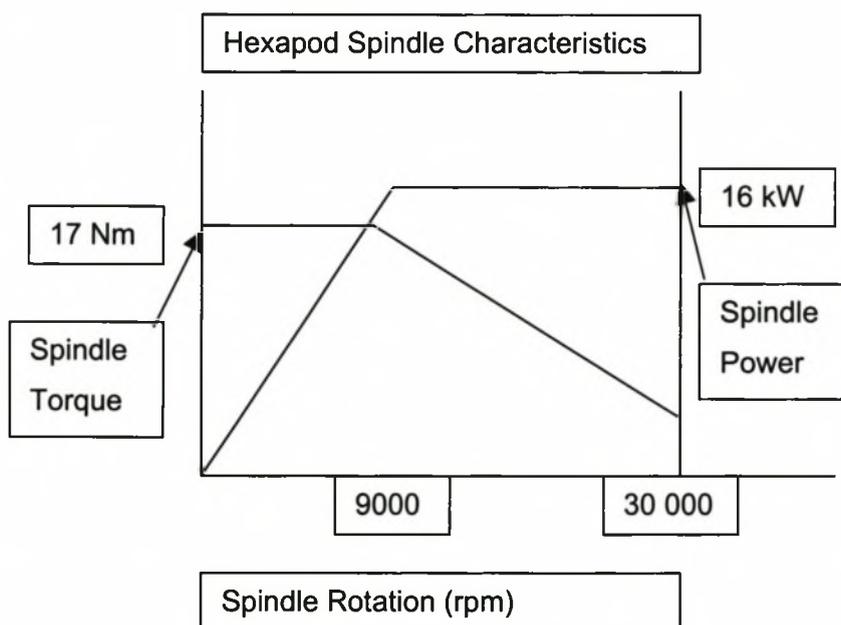


Figure 10.1.3.1 Mikromat Hexapod Spindle Torque / Speed characteristics

10.1.4 Tool Holding

There are largely three categories of tool holding devices:

10.1.4.1 Collet Chucks

In the field of HSC, collets are the least accurate type of tool holding device and are now rarely used by facilities employing the newest technology. Collets are not really suitable for speeds higher than the low range of HSC, namely 5 to 15 000 rpm. They were previously extensively used before the prices of the more accurate devices became competitive.

10.1.4.2 Hydraulic clamping chucks

The hydraulic chuck has a chamber around the tool shank, which is filled with a hydraulic fluid. This fluid is pressurised and the tool is clamped by a screw and piston displacing the hydraulic fluid to force fluid into the chamber around the tool. The screw and piston is balanced by excess material on the other side of the chuck. The balancing is corrected during manufacture.

The hydraulic chucks have considerably better balancing and alignment properties and are suitable for Mould and Die type machining over the entire spindle speed range used for this application. Due to complexity they are relatively expensive.

10.1.4.3 Crimp type clamping

Heating with hot air expands the crimp (shrink) type of tool holder; the tool inserted, and allowed cooling. The heating is performed in a heating station where no specific experience or skill is required.

The crimp type of tool holder has the highest rotational accuracy of all. This tool holding method is used extensively and is the preferred method at the Institute. Both small diameter milling tools e.g. end mills, ball nose mills as well as the large diameter tip carriers are mounted in this way.

The accuracy is such that extensions supplied by the suppliers of the crimp tool holders have become a reliable option. Tools can now be lengthened with these factory balanced tool holders and extensions. The Institute does not balance nor have tools balanced.

With the solid carbide tools it is easy to reheat the holder and remove the tool from the holder. With HSS it is not reliable to remove the tool simply by reheating and may be very difficult to remove the tool. A HSS steel tool therefore has to be considered mounted permanently once it is in the crimp type holder.

To utilise the higher accuracy of the crimp type tool holding fully cylindrical tools therefore without the flat part to accommodate a fixing screw is used.

Initially, after their introduction crimp type tool holders were prohibitively expensive. Hydraulic chucks are now approximately US\$ 350 and crimp type tool holders approximately US\$ 135.

10.1.4.4 Tool holder/Machine Interface

HSK is a hollow cone taper interface. It is the only type to be considered. Proprietary interfaces offered by machine tool manufacturers are not recommended. The standard sizes of 25, 32, 40, 50, 63 and 100 are available. Tool holder availability for HSK 40, 50 and 63 are the widest. The sub categories indicate the allowable speeds and torque. The HSK / Form A, B and C has additional positive lock in the form of cutouts on the taper surface as shown in the diagram. Form E has the highest alignment accuracy specification and is therefore suited for the higher speed applications.

10.1.5 Tools Used

For free form surfaces where the sidewalls of especially cavities are curved near vertical surfaces going over to near horizontal surfaces the Institute have moved away from end mills for roughing to toroid tools in the tip carrier configuration. The round tip approximates the curved surface better and improves productivity.

The octagon shaped tips are also often used. They are useful for vertical or horizontal surfaces and give a relatively long life by turning the tip to expose a new cutting surface.

These tips ("Wendeplatten") are available in different cutting angles also for softer materials such as plastics and aluminium.

The tips used are fine grain solid carbide coated with TiAlN as the outside coat with softer undercoatings to absorb machining shocks / damping. The TiAlN's heat resistance is one of the reasons for the good performance. The institute does not use Cermet any more for milling. Cermet used to be the best tool material for finish milling because of its fine grain. The new generation TiAlN however delivers better performance. Cermet continues to be used in turning where a good surface finish is required.

TiN is used for roughing.

10.1.5.1 Overview of tools used

Ball Nose	0.8 – 10 dia	Solid Carbide, coated
	Ø8 – Ø25	tool Tip carriers
Torus cutters	0.5 – 2 radius	Solid carbide, coated
	Ø4 - Ø12	tool
	Larger than 2 radius or Ø12 tool:	Tip carrier
For tool > Ø12	Tip carrier	
	Tip radius	2.5 - 10

With these tip carriers the spindle speeds are not normal HSC spindle speeds. HSC is defined by the cutting speed. This is therefore still HSC as indicated by the cutting speed but due to the large diameter (42 in the demonstrated car roof section case) the spindle rotation speed is low, well below 10 000. These tip carriers also carry a rotation limit which normally does not exceed 10 000. The other conclusion is that with this emphasis on HSC, the HSC machine cannot have a high-speed low torque only spindle for work in the die and mould category.

10.1.6 Cutting Parameters

10.1.6.1 Cutting Speeds

A cutting speed of 200 m/min is used up to HRC 55 tool steel.

Aluminium is machined at very high speeds. Tests have been done up to 5000 m/min. The experience is that other factors limit the cutting speed, not the tool / material interface. The maximum rotation speed, spindle power or the tool (tip) carrier is usually the limiting factor.

10.1.6.2 Cutting strategies

The two different strategies of a deeper but narrow cut as opposed to a shallow wider cut were discussed.

The institute normally uses a wide cut for roughing limiting the depth of cut. The breadth (stepover / "Bahnabstand") of 0.8-0.9d is commonly used. Tool length, diameter, torque and power then limit the depth. With toroidal tools being the preferred tool for the roughing of free form surfaces, the depth is frequently at the limit of 0.4 tool radius. At over 0.5 tool radius a ridge is left. Several CAM systems do not allow this high productivity practice of 0.9d stepover / "Bahnabstand". The limit is often 0.5d and 0.4d recommended as the preferred value.

The strategy of approximately 0.2d stepover with depth of 1.0d or even 1.2d has its merit. Where the situation (most often a long spindle) is prone to vibration and machining is done with an end mill a tool is selected with multiple (spiral) cutting edges. With a long side face cutting there is always more than one cutting surface in contact with the work piece. In the case of a shallower cut there would be only one cutting surface in the case of a two cutting surface tools in contact with the material. This fluctuating tool load is the primary driver of vibration.

10.1.6.3 Roughing strategies

The institute uses a contour parallel roughing strategy. For the sake of an example a concave mould cavity is considered. The tool path is calculated from the outside, but physically executed by the milling machine from the inside. The principle of constant z level is therefore used in combination with contour parallel strategy.

10.1.7 Electric Discharge Machining (EDM)

The institute is also involved in EDM research on an Ingersoll machine. The research is aimed at finding optimum z direction speeds. The cycle of the machine is such that the tool is moved towards the work piece until the erosion process starts. The erosion is then continued for some time where after the tool is rapidly extracted from the work piece. The dielectric flowing in to replace the removed volume of the tool flushes the waste material. The institute is experimenting with much higher speeds than current EDM machines and achieving specifically in the order of three cycles in the same time a conventional machine can do one cycle.

The downward speed and the retract speed is roughly the same in conventional machines but in the high productivity situation the downward speed is higher and the retract speed

much higher resulting in the higher flushing frequency. In the case of shallow cavities forced flow flushing is used. In the order of EDM die size that this research is focusing on namely 300 x 300 and smaller the EDM specialist regards the z-axis progress rate to be a constant, independent of the area of the die that is actively eroding. He therefore regards a displacement rate model more valid than a material removal rate model for EDM for this specific limited size of electrode. The average value is given as 0,25 mm per minute. There is however a difference between the speeds used for roughing and for finishing.

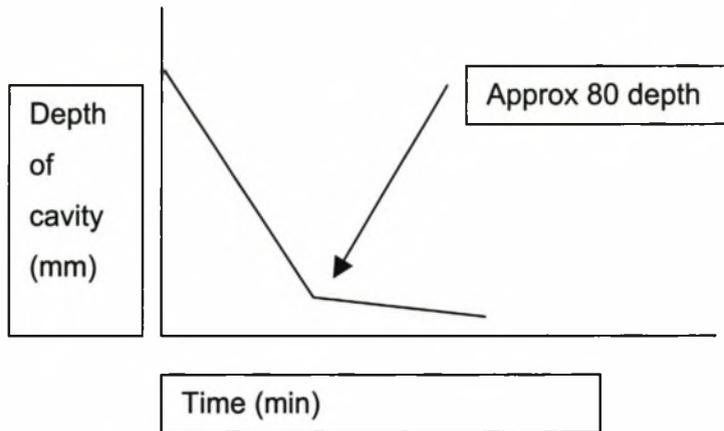


Figure 10.1.7.1 EDM Rate of Progress related to the depth of the cavity

The process now used most in industry is the die sinking process where the tool shape resembles the cavity to be machined. This is in contrast to the (Planetary) Electric Discharge Milling process where the tool resembles a milling tool which is moved around in the x, y and z axes as in milling. Initially, the tool is only moved in the Z – direction (roughing). In the finishing stage of the machining the tool is displaced in small planetary movements to compensate for minor tool wear and to hold close tolerances.

In figure 10.1.7.1 it is shown that typically at 80-mm depth the z-axis feed rate is drastically reduced.

In a discussion with the HSC and EDM specialists together they agreed that when a surface roughness of $R_a < 0.5$ required, EDM is the preferred process.

In the institute the internet site www.industrienet.de is found useful for technical articles.

10.1.8 Confidentiality

The Institute does the research on a contract basis for industrial partners. The results are confidential and the above report is based only on oral communication with the researchers. No reports, computer simulation or test results could be made available in hard copy format.

10.2 Appendix B: Interview with the MD of Paso HSC Machine Tools

Paso is the manufacturer of the HSC machine the author had the opportunity to work on during the capacity building visit in Dresden at the company SFM GmbH. There was an opportunity to meet the managing director, Mr. Schäfer and discuss the recent developments in the machine tool industry. Certain opinions that he had which has a bearing on this work are detailed here.

The tooling companies publish cutting conditions data that tend to be on the optimistic side. A short-term marketing strategy for these companies could be to publish very progressive values for cutting speeds and feed rates to create the impression that this company's tools are superior to the competition's products. It is indeed so that if a specific brand of cutting tool has superior characteristics it will be possible to cut and feed the tool faster. The German cutting tool market is extremely competitive creating market pressure to publish optimistic values. The end result of too optimistic values being used for process planning is a relatively short tool life causing unhappy customers.

The value, which is an acceptable tool life, varies from company to company and is therefore a very difficult criterion to use to objectively judge cutting tool performance.

Paso often receives complaints from machine tool users that the machine tool is not capable of machining especially the hard materials because of premature cutting edge failure. Mr Schäfer is of the opinion that the SFM HSC machine personnel is not quite correct in their perception that the Paso machine is not suitable for tool steel milling.

It should be the user's goal to use full capacity of the machine. This does not happen when an HSC machine is used at low speed. Most of the machines have a more or less constant torque curve resulting in lower power ("Leistung") available at lower speeds. The machine tool application and characteristics should be matched with care for the machine capacity to be productively utilised by the majority of the work performed on it.

The Paso machine is a pure HSC machine with the spindle, the lightweight, stiff structure and the axis drives optimised to work at high spindle speeds and relatively high feed rates. The machine is utilised well with the high cutting speeds and feed rates used for Aluminium and tooling composite. However, if the application is planned well to carefully match the machine tool characteristics with job demands the machine can be used for the machining of hardened tool steel.

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