Environmental aspects of sheet metal forming

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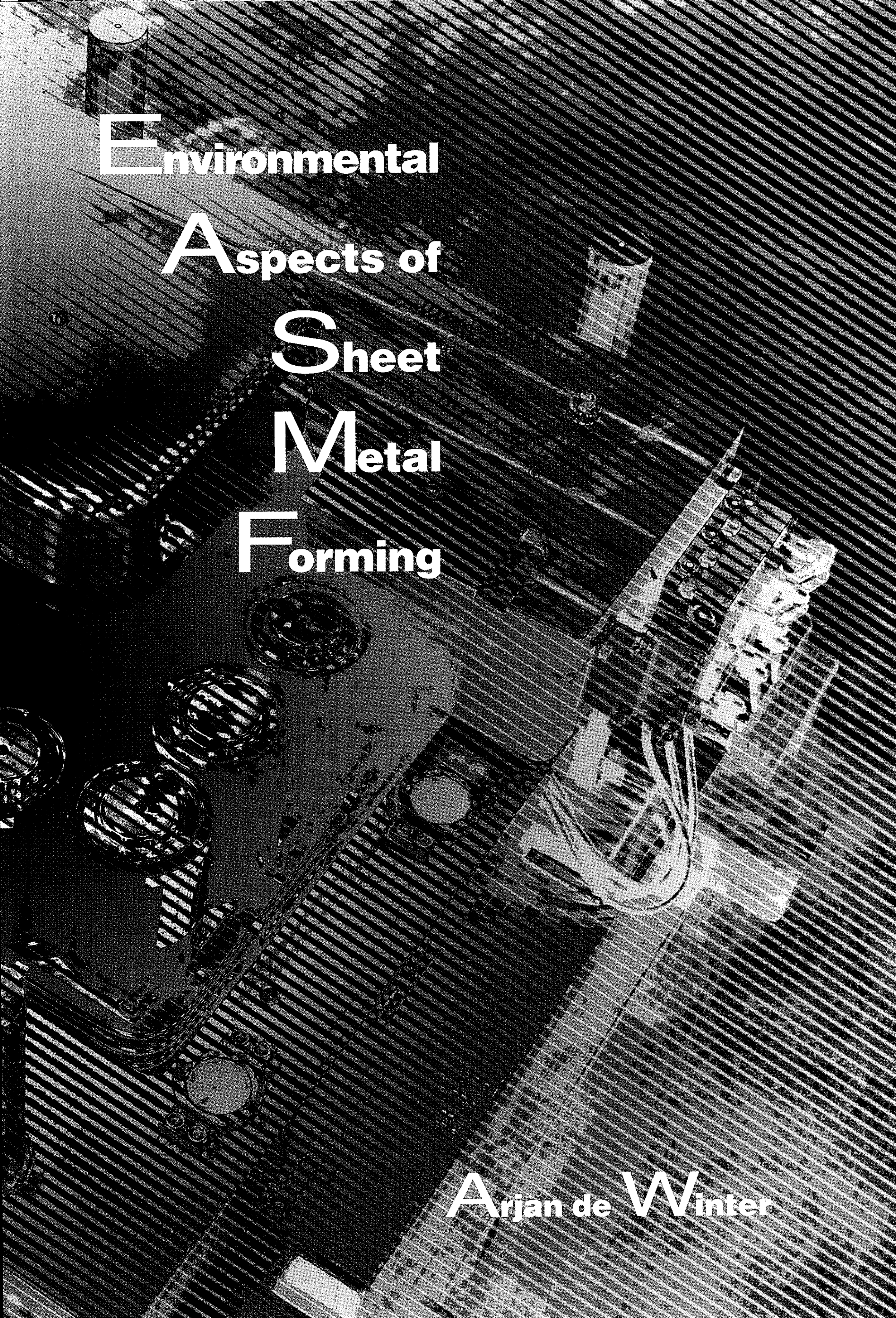

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Environmental Aspects
of
Sheet Metal Forming

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan
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door

Adrianus de Winter

geboren te Geldrop

Dit proefschrift is goedgekeurd door de promotoren:

prof. ir. J.A.G. Kals
en
prof.dr.ir. J.E. Rooda

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Eindhoven, March 1998,

Arjan de Winter.

Summary

The environmental relevance of **sheet metal forming** processes is mainly based on their application in **mass production**. The total environmental impact of these processes is larger than could be expected on basis of the impacts of a single part. The research presented in this thesis concentrates on two different environmental aspects, viz. the process-related and product-related aspects. The **process-related aspects** involve the use of auxiliary materials, energy consumption and material waste during manufacturing. The **product-related aspects** involve the environmental impacts which are caused by the manufactured products. The research can be divided into three parts: An environmentally directed main line and an elaboration of two technological subjects, each representative for one of both aspects.

In the **environmental analyses** different technical alternatives are valued based on quantitative and qualitative methods adapted for the specific situation. In an industrial orientation two alternatives are selected, which are, besides being environmentally-friendly, also technically and economically interesting. The selected alternatives are 'environmentally-friendly lubricants' and 'tailor-made blanks' (TMBs). The analyses following this orientation, result in clear environmental objectives for the subsequent technological research.

- In addition to the requirement that the **lubricants** themselves are environmentally-friendly (i.e. particularly without harmful chemical dopes), the lubricants should especially be easy to remove. The total environmental load of the forming process is namely largely determined by the cleaning process. Therefore the lubricants should have a good cleanability in alkaline processes and they may not affect the cleaning fluids.
- The environmental load of **TMBs** (blanks which are composed out of two or more welded blanks, which may differ regarding their thickness or quality) is particularly related to the product mass in automotive applications. The product mass largely determines the life-cycle energy consumption of a car. The influence of the waste (scrap) mass is relatively unimportant, though interesting in itself,. The product mass is determined, amongst others, by the weld position in the TMB. The environmental analysis results in a relation between the weld position and the life-cycle energy consumption of a TMB applied in a vehicle. This results in interesting new design insights.

The technological research on the applicability of environmentally-friendly lubricants is directed at the prevention of **tool wear**. Since the application of most alternative lubricants leads to unacceptable tool wear, special attention is given to alternative tool materials and PVD-coatings. The test methods used are based on a standing nipple over which a strip is drawn. The resulting stress situation is comparable to the stress situation at the die radius in deep drawing. Both short and long-term wear effects are studied. The visual judgement of the tools (both by SEM and the naked eye) gave the best representation of the resulting wear. The 'long-term' test led to the looked for ranking of alternatives. In general the PVD-coatings perform better than the tested tool

materials. However, the alternatives showed different wear mechanisms, which complicates mutual comparison. Within the group of PVD-coatings significant differences are observed. These differences can largely be assigned to the coating suppliers. The results of the laboratory tests are confirmed by a number of practise tests.

The technological research on the TMBs is particularly directed at their **formability**. The weld position again plays an important role in this research. The standardised tests, which are normally used to determine the formability of unwelded sheets, are not suitable to describe all aspects of the TMB forming behaviour. The design and realisation of a new test tool meets the found shortcomings. The tests with this tool, give insight into the formability of TMBs for different material and thickness combinations under two stress situations: deep drawing and stretching. The weld displacements and the subsequent failure types play an important role. The test results give a relation between the weld position and the deep drawability. In combination with the results of the environmental analysis, design guidelines for product designers are derived.

In conclusion, it can be said that the technical optimisation of sheet metal forming processes can contribute to the reduction of environmental impact by both the manufacturing processes themselves and the manufactured products. The resulting contribution however is limited to a **reduction of the environmental impact** and does as yet not lead to truly sustainable manufacturing processes.

Samenvatting

De milieurelevantie van **omvormprocessen** komt voornamelijk voort uit de toepassing van deze processen in **massafabricage**. Hierdoor is de totale milieubelasting groter dan op basis van de belasting per enkel onderdeel zou worden verwacht. De milieuaspecten van omvormprocessen kunnen worden verdeeld in twee groepen, namelijk de proces-gerelateerde en de produkt-gerelateerde aspekten. De **proces-gerelateerde aspekten** hebben betrekking op het gebruik van hulpstoffen, energieverbruik en het produktieafval tijdens de produktie. De **produkt-gerelateerde aspekten** hebben betrekking op de milieubelasting van de geproduceerde produkten. Het onderzoek heeft zich gericht op beide aspekten en valt uiteen in drie onderdelen: de milieugerichte hoofdlijn van het verhaal en twee technische uitwerkingen, die elk representatief zijn voor één van beide aspekten .

In de **milieugerichte hoofdlijn** worden verschillende technische alternatieven beoordeeld met behulp van voor de specifieke situatie aangepaste kwalitatieve en kwantitatieve methoden. In een industriële oriëntatie zijn twee alternatieven geselecteerd, die naast milieuvriendelijk ook technisch en economisch interessant zijn. De geselecteerde alternatieven zijn milieuvriendelijke smeermiddelen en 'tailor-made blanks' (TMB's). De op deze oriëntatie volgende milieuanalyses, concentreren zich op de milieu-impact van beide alternatieven en resulteren in duidelijke milieurandvoorwaarden voor een verdere technische uitwerking.

- Behalve dat de **smeermiddelen** zelf milieuvriendelijk moeten zijn (d.w.z. voornamelijk zonder schadelijke chemische dopes) is het vooral belangrijk dat ze eenvoudig te verwijderen zijn. De totale milieubelasting van het omvormen wordt namelijk grotendeels bepaald door het schoonmaakproces. Daarom moeten de smeermiddelen eenvoudig (alkalisch) schoon te maken zijn en mogen ze het reinigingsmiddel niet aantasten.
- De milieubelasting van **TMB's** (blenks die zijn samengesteld uit twee of meer aan elkaar gelaste blenks, welke kunnen verschillen voor wat betreft dikte en kwaliteit) is vooral gerelateerd aan het produktgewicht. Deze parameter bepaalt grotendeels het totale energieverbruik van een voertuig. Ten opzichte hiervan speelt de, op zichzelf interessante, invloed van het produktieafval een ondergeschikte rol. Bepalend voor produktgewicht is de laspositie in een TMB. De milieuanalyse resulteert in een relatie tussen de laspositie en het energieverbruik van een TMB over de gehele levenscyclus van een voertuig. Hierdoor ontstaan interessante nieuwe ontwerpinzichten.

Het onderzoek naar de toepasbaarheid van milieuvriendelijke smeermiddelen richt zich op het voorkomen van **gereedschapsslijtage**. Omdat de toepassing van de meeste alternatieve smeermiddelen leidt tot bovenmatige slijtage, is tevens aandacht besteed aan alternatieve gereedschapsmaterialen (gesinterd snelstaal en hardmetaal) en PVD-coatings. De gebruikte testmethoden zijn gebaseerd op een stilstaande nippel waarlangs onder belasting produktmateriaal wordt getrokken. Deze belastingsituatie is vergelijkbaar met de belastingsituatie die bestaat in de afronding van een

dieptrekmatrijs. In de proeven zijn zowel korte - als langetermijn effecten bestudeerd. De visuele studie van de teststukken (onder de SEM en met het blote oog) maken een beoordeling van de optredende slijtage mogelijk. De 'langetermijn' tests resulteren in een ranking van de verschillende alternatieven. Over het algemeen bleken de PVD-coatings beter te presteren dan de geteste gereedschapmaterialen. Beide alternatieven toonden echter verschillende slijtage mechanismen, zodat een onderlinge vergelijking niet zonder meer mogelijk is. Ook tussen de verschillende PVD-coatings zijn grote verschillen waargenomen. Deze kunnen grotendeels worden toegeschreven aan de coatingproducent. De resultaten van de laboratoriumtests zijn bevestigd in een aantal praktijkproeven.

Het technische onderzoek van de TMB's richt zich voornamelijk op de **omvormbaarheid**. Hierbij speelt de laspositie een belangrijke rol. De tests die normaal gebruikt worden voor het bepalen van de omvormbaarheid van plaatmateriaal geven weliswaar een indruk van omvormbaarheid van TMB's, maar zijn niet geschikt om het omvormgedrag volledig te beschrijven. Door een nieuw testgereedschap te ontwikkelen en te realiseren is geprobeerd aan de tekortkomingen tegemoet te komen. De tests met het gereedschap geven inzicht in de omvormbaarheid van de TMB's voor verschillende materiaal - en diktecombinaties voor twee belastingsituaties (dieptrekken en strekken). Hierbij spelen de verschuiving van de las en de daarmee samenhangende faaltypen een belangrijke rol. De proeven resulteren in een relatie tussen de laspositie en de dieptrekbaarheid. In kombinatie met de resultaten van de milieuanalyse zijn ontwerprichtlijnen voor TMB-ontwerpers afgeleid.

Concluderend kan worden gesteld dat het technische optimaliseren van omvormprocessen bij kan dragen tot het terugbrengen van de milieubelasting van zowel de processen zelf als van de geproduceerde produkten. De uiteindelijke bijdrage is echter beperkt tot een **reduktie van de milieubelasting** en leidt vooralsnog niet tot volledig duurzame productieprocessen.

Contents

Symbols

a	[m/s^2]	acceleration
A	[mm^2]	area
h	[mm]	weld position relative to product wall
s	[mm]	weld position relative to hole centre
r	[mm]	product radius
r_{blank}	[mm]	virtual blank radius
C	[N/mm^2]	strength coefficient
e	[%]	engineering strain
e_{neck}	[%]	engineering strain at necking
e_{neck}^*	[-]	normalised engineering strain at necking
e_{frac}	[%]	engineering strain at fracture
e_{frac}^*	[-]	normalised engineering strain at fracture
F_{bp}	[N]	back pull force
$F_{\mathrm{bp,\ galling}}$	[N]	load bearing capacity
g	[m/s^2]	earth gravity
H	[MJ/l]	combustion value
H_{p}	[mm]	product height
$H_{\mathrm{p,\ max}}$	[mm]	maximum product height
i	[%]	percentage of road km at constant speed
M	[kg]	mass
n	[-]	strain hardening coefficient
n^*	[-]	normalised strain hardening coefficient
P_{bh}	[N/mm^2]	blank holder pressure
R	[mm]	hole radius
R_{m}	[N/mm^2]	tensile strength
R_{m}^*	[-]	normalised tensile strength
R_{p}	[N/mm ^{2}]	yield strength
R_{p}^*	[-]	normalised yield strength
s	[m]	travelled distance
v	[m/s]	speed
W_{acc}	[N·m]	work required for acceleration
W_{rf}	[N·m]	work required to overcome rolling friction
W_{ar}	[N·m]	work required to overcome air resistance
W_{m}	[N·m]	work required to overcome mounting
α	[l /100km·kg]	mass sensitivity of fuel consumption
β	[l /100km]	mass insensitive part of fuel consumption
β	[-]	deep drawing ratio
γ	[rad]	degree of inclination
ε	[-]	logarithmic strain
ε_1	[-]	major strain
ε_2	[-]	minor strain
ρ	[kg/m^3]	mass density
ρ_{punch}	[m]	punch radius
ρ_{die}	[m]	die radius
η	[-]	efficiency
μ	[-]	coefficient of friction

Chapter 1
Introduction

As a Dutch saying goes: "Waar gehakt wordt, vallen spaanders". The literal translation would be "Where one chops, wood chips fall". The saying refers to the inevitable consequences of doing things and is used as an excuse in situations where valuable goods are wasted, due to human mistakes. This conventional wisdom expresses the acceptance that work is accompanied by unintentional side-effects. In particular when one actually makes things.

The saying connects to the actual discussion on environmental issues. In this discussion the attitude towards the side-effects of human activities is one of less understanding. The side-effects of making things are no longer accepted, let alone the wasting of valuable goods. Hence, manufacturers are facing new challenges.

During the past few years the discussion on environmental issues has intensified. The manufacturer is increasingly viewed as somebody whose responsibility goes beyond mere manufacturing. In particular when the manufacturer is also the product designer. The manufacturer is not only held responsible for the side-effects of his own manufacturing processes, but also for the side-effects caused by the actual products he or she manufactures. The reason for this is that the products' environmental effects are largely determined once the product specification leaves the design department. Therefore the manufacturer/designer has to evaluate the environmental consequences of the complete product life-cycle. This includes the life-cycle phases prior to and following manufacturing.

In this thesis the possible contribution towards environmentally-friendly manufacturing techniques is studied for sheet-metal forming processes. The thesis focuses on aspects that are directly related to these manufacturing processes, as well as indirect aspects, related to manufacturing by the impact during the product's life-cycle. However, the resulting research area is too big and complex to deal with in all its variety and detail. In this work an effort has been made to outline the field, on the basis of industrial examples.

1.1 Aim of the project

Starting point for the project has been the observed discrepancy between society and manufacturers regarding environmental issues. Society, represented by an environmental establishment, tends to get stuck in philosophical discussions, whereas the manufacturers tend to ignore 'soft' arguments like ecological considerations. Although this discrepancy may be less relevant for higher management levels and governmental policy makers, it is pertinent in daily manufacturing practice. An outline of the field is necessary to promote a new way of thinking.

The objective of the project is to connect the existing philosophical ideas with manufacturing practice. The project therefore aims to deduce a basic philosophy that suits the industrial world and gives a classification of the research field. From the manufacturing perspective the project aims at tangible results, which contribute to environmentally-friendly manufacturing without affecting competitiveness in a negative way.

These aims are first and foremost positioned as to make a contribution to manufacturing technology. Contributions to the environmental world are not aimed at, although the necessity to communicate the results as feedback to environmentalists is recognised.

1.2 Scope of the project

As this project is, as far as I know, one of the first in the field of 'environment and manufacturing', it has an orientating character. This demands a broad approach to gain an overview of the entire research field. The resulting overview should serve as a basis for future research. To obtain this overview an approach is used that can be characterised as 'going the distance'. The idea being that while working in the field of 'environment and manufacturing' all relevant aspects will be encountered. This determines the scope of the project which ranges from the determination of possible environmental improvements to their realisation in the industrial practice.

Sheet metal forming

The scope of the project is limited to sheet metal forming processes, as it is impossible to reach the set aims for all manufacturing processes simultaneously. It is however expected that the results are representative for other forming processes and possibly other fields of manufacturing as well. Sheet metal forming processes are typically shearing, bending and deep drawing processes. Their common denominator is plastic deformation to obtain the required shapes. The processes are generally applied for series and mass production and require mostly specific tools for individual parts or part categories. The processes can be applied to most metals, but this work is limited to steels.

Environmental aspects

As the aim is not to contribute to the understanding of ecological interactions themselves, existing methods are applied. The scope is to use ideas developed by ecologists, to create new entries in manufacturing research and to contribute eventually to environmentally friendlier production. To avoid discussions on the direct work environment of employees, the scope of the thesis is limited to ecological aspects in a broader sense. Although closely related, these exclude working circumstances, like noise nuisance, or safety regulations.

1.3 Structure of this thesis

The thesis is organised along two lines of thought (Figure 1.1). The environmental line formulates rough objectives and translates these into concrete technical demands. The technological line studies the technical possibilities to realise the set demands. The thesis is concluded with a summary of the results and a feedback of the technical results to the environmental demands. Within this structure a secondary structure can be recognised, which follows the first phases of a design process, i.e. orientation, specification and realisation.

The introduction on environmental aspects of manufacturing (Chapter 2) outlines the present situation by means of a literature review, which is placed in a historical context. This inventory of activities leads to a refinement of the set aims and results in the definition of two objectives, which serve as guidelines for further research. As these objectives result from environmental considerations the ideas are first confronted with practical situations in an industrial orientation (Chapter 3). This involves basic ecological, economic and technical considerations. Next, two practical examples are selected. Each example is representative of one of the set objectives. In the environmental analyses (Chapter 4) these examples are worked out to result in concrete technical demands. This chapter focuses on the environmental aspects. Technical and economical aspects are disregarded.

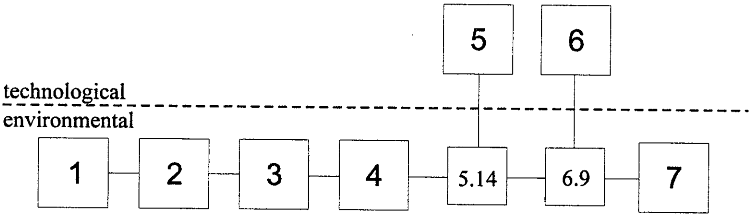

***Figure 1.1** Flow chart of thesis and division in technological and environmental chapters*

Chapters 5 and 6 each deal with one of the selected technical subjects and are therefore representative of one of the set objectives. These chapters represent the actual engineering research that consists of a series of laboratory experiments. Both chapters conclude with a test of the experiments' outcomes in practise, as a first step towards realisation. This provides feedback (Sections 5.14 and 6.9) for the original ideas formulated in the environmental orientation. A separate chapter (Chapter 7), which includes a summary of the obtained results, forms the conclusion of this thesis. This chapter includes recommendations for future research and industrial development.

Chapter 2
Environmental aspects of manufacturing

Chapter 2 demonstrates the differences between the product and process based approaches by means of a literature review. Manufacturers are concerned with factory processes, while designers concentrate on environmental aspects of products. Although this initially seems a logical situation, the question can be raised whether or not an integration of both approaches could contribute to the environmental optimisation of manufacturing and could result in an interesting synergy. The manufacturing process is, after all, one of the factors that determines product quality. This idea can be captured in two objectives, which set the goals for environmentally-based research in manufacturing.

2.1 Brief history

During the past few years environmental issues have gained an important place on the political agenda of countries across the whole world. Not only in wealthy nations, but also in third-world countries these issues are now of general importance. People experience these issues as a potential threat to the quality of their life. Nevertheless the problem is not typical for this age. The negative side-effects resulting from human activity are as old as humanity itself. The same thing holds for the side-effects of manufacturing. Hence, to put this thesis in perspective, this section gives a brief history of the environmental aspects of manufacturing using a number of examples, taken from European history [Zon89].

Early times

As early as the end of the twelfth century Europe reached the borders of its growth. The increase in population led to diseases and scarcity of energy. At that time questions were raised comparable to those of today. However solutions were either based on faulty scientific assumptions, or not found at all. In the end the problems were solved by a decimation of the population.

Two centuries later Europe again faced the same problems. This time the role of manufacturing was more pronounced. Steel production led to a scarcity of wood. This was the first time that the full-scale effects of production were experienced. Unlike today the areas in which the problems arose were limited to certain parts of Europe. Around this period other environmental issues, similar to those we know today, were reported as well. One of them was noise pollution resulting from forging processes. This led then to the concentration of production in ‘industrial areas’, separate from the living space of people.

Industrial revolution

In the middle of the nineteenth century the effects of the industrial revolution began to have an impact. The industrialisation had led to a concentration of the population in the cities. This meant a major change in the agricultural Europe of that time. Not only did many people's place of residence change, their working circumstances changed too. Workers had to work long hours in an often unpleasant and unhealthy environment. Prosperity was measured by the number of smoking chimneys, polluting the air for miles around. The effects of industrial activity of that time on nature can still be seen in former industrial areas. Especially the mines and the consequent mounds of waste that piled up besides them, are still evidence of our past (and even present) industrial activity. The industrial revolution was also important as it marked the change of our energy provision, which changed from renewable - to finite energy sources. This change enabled the intensification of energy consumption and led to the energy intensive society we know today.

Until the final decades of the twentieth century, all efforts were directed towards economic growth. History had shown that industrialisation and the resulting prosperity resulted in an improvement in the living conditions for everybody. Environmental issues were seen as minor side-effects that could be dealt with relatively easily. After the second world war this led to a limitless trust in the future.

This image was shattered by the publications of the Club of Rome in 1973. Their publication 'The limits to growth' [Mea72] can be seen as a turn-about. It was the initiation of the present attitude towards environmental issues. For the first time people realised that if we continue to use the earth's natural resources at the same rate as we are doing today, the limits of the earth will be reached within a few generations. This implies that the present day environmental issues have a global character.

Sustainability

The ideas presented by the club of Rome found a sounding board in society. The ideas were discussed and worked out at frequently. One of those was the commission under chairmanship of Brundtland, which published its final report 'Our common future' (Brundtland report) [Wor88] in 1988. The report gives long-term strategies for 'sustainable development' from the year 2000. The importance of the report is based on a definition of the term sustainability. The report characterises 'sustainable development' as a development that fulfils the needs of present generations, without endangering the possibilities for coming generations to fulfil their needs. Sustainable development is based on economic growth, according to the commission, but this growth should be realised under high-quality demands and by activities requiring less materials and less energy. The report describes several 'common challenges', ranging from growth of the world population and industrial development to peace and safety. The strongest limits for global development are linked to the availability of energy sources and the ability of the biosphere to absorb the waste products of energy consumption.

Sustainable development can be seen as the state-of-the-art in environmental consciousness and as such the basis for most activities. In this thesis too, the starting point is the fact that products and functions are demanded by society. Our challenge is to design and produce these products by the highest ecological qualities possible.

2.2 Product and process related activities

Environmental activities can be divided into two different categories, i.e. process directed activities and product directed activities. Stevels [Ste96] has characterised both categories as each other's opposites (Table 1.1).

	Environmental improvements of **products**	Environmental improvements of **processes**
Since	+/- 1990	+/- 1965
Character	prevention	correction
Profession category	designers	technologists
Place of action	labs, desks	factories
Contribution to product quality	yes	no
Geography	international	national
Financial	often cost neutral	costs often money
Initiative	often own initiative	often based on regulations

Table 1.1 *Characterisation of environmental improvements of products and processes [Ste96]*

In this section the process and product directed activities are discussed in relation to the discrete part manufacturing. The suggested division is largely confirmed by the reviewed literature.

Process directed activities

The process directed activities originated in the process industry. The chemical plants were the first to be under environmental criticism. Their environmental relevance is symbolised by chimneys and they are owned by large companies that are easy to target. The situation in the discrete part manufacturing however is different, as the manufacturers usually are less visible and represented by many smaller companies. Environmental activities in this area are therefore of recent date and in a preliminary stage.

An indication of the first steps in the field of manufacturing and environment was the symposium 'Milieubewust Omvormen' (Environmental Forming) [Con94]. This symposium can be seen as representative for the Dutch situation at the time in this specific field and can be characterised by five remarks:

1) Special laws provide the incentive for four out of six papers.
2) The approaches to determine environmental problems are not systematic.
3) All problems that are dealt with have a chemical nature.
4) The properties of the manufactured products are not under discussion.
5) Although the problems are recognised, the solutions are still under development.

The symposium was one of the few public activities in this specific field, where environmental aspects were the main theme in manufacturing process development. Another comparable example can be found in Germany [Zib--]. Many other publications mention the environmental relevance of the presented research subject, but do not go into detail as far as the environmental relationships are concerned. All publications found in this period only deal with the problem of chemical substances in forming.

The above examples show that the emphasis is placed on processes and that the nature of the activities is mainly re-active, based on laws and regulations. This situation resembles the scheme drawn by Stevels: Re-active correction and performed in factories by engineers.

In recent years the situation has changed. Present activities have a broader perspective and follow new methods that are developed in the environmental sciences [Gei95, ICE95, ICE96, ICE97, Kiu93, Tön96]. The presented work has been performed in close contact with the activities referred to. These activities can be characterised by the following remarks:

1. Recognise both the product and the process aspects.
2. Use a more general approach to determine environmental problems.
3. Energy and material consumption are recognised as relevant.
4. The problem is also interpreted in terms of process selection.
5. The influence of manufacturing on the product life-cycle is not yet explored.
6. Almost no references are made to the work of predecessors or colleagues (except in the work of Alting [Alt92]).

The work is still concentrating on the processes itself, but operates more on a 'pro-active' level, since more than the minimal demands of the laws are discussed. The minimisation of the environmental effects themselves is seen as relevant and more than just the chemical aspects are evaluated. The influence of the product on the environmental impact is mentioned, but is not yet dealt with and forming processes are still underrepresented.

Parallel to these activities in manufacturing itself, there are two developments that are relevant to manufacturing. One development is the 'Integral Chain Management'

[Cra93] for realising environmental improvements in production. The method is a step-by-step trajectory that is executed by a multi-disciplinary team of chain participants and finally leads to technically and economically feasible environmentally (mainly process) directed improvements. The other activity concerns the developments in standardising an 'Eco-audit' by, amongst others, the ISO. The intention of the Eco-audit is comparable with quality standards, as the ISO-9000 series, and aims at the continuous improvement of the environmental performance of the factory. These audits however are still under development. Publication of audit results have been limited. In the field of metal forming no results have been found.

Product directed activities

Recent developments in the approach of environmental issues have taken place with an emphasis on the role of products. The attention of the environmentalists shifted from processes to products. The central idea is that the environmental impact of products should be minimised over its entire life-cycle, covering all effects from cradle to grave. This has led to the development of tools that are able to measure the environmental load of a product over all life-cycle phases. Initially, based on minimisation of consumed energy [IFI74], the tools have been developed to instruments that deal with all concerned extractions and emissions. They are usually referred to using the term Life-cycle Assessment or Life-cycle Analysis, abbreviated as LCA [SET90]. The tools require an inventory of all life-cycle extractions and emissions and value the environmental impact of the product, based on a mathematical description of the society's value judgement, regarding the different environmental problems.

Some of the successful projects that use a life-cycle approach are the 'EcoDesign'-projects in the Netherlands. These projects involve the re-design of products to minimise the consequences for the ecology. In some of the examples [Rie94] manufacturing processes are adapted. Mostly other raw materials are chosen. The newly introduced manufacturing processes generally involve the conventional techniques applied to alternative materials.

The contribution from the product directed research towards environmentally-friendly development of manufacturing is low. Results mainly concentrate on material extraction and use phase and relative new aspects concerning industrial 'end-of-life' scenarios. The manufacturing of discrete products is generally only mentioned briefly in LCAs and does not have the ability to innovate manufacturing.

2.3 An integral approach for manufacturing

Section 2.2 showed the existing split between process and product-based activities. Section 2.3 deals with the overlap of both activities and tries to combine them in an integral approach. This leads to the definition of two objectives, which are relevant for manufacturing, and involve both process and product qualities. The first objective concerns the environmental aspects that are directly related to the manufacturing processes. The other objective concerns the indirect environmental aspects, which are related to the processes indirectly via the product.

Definition of objectives

The situation is schematised in Figure 2.2. The axes represent the level of anticipation regarding environmental issues, divided into three categories viz. re-active, pro-active and innovative on both the product- and the process axis.

The vertical axis represents the product dimension. The activities that take place along this axis are aiming at the design of a 'green product'. Good examples are given by the EcoDesign projects and by most LCA-projects. The attitude towards manufacturing processes is here re-active in nature. The processes are approached as fixed or given parameters.

The horizontal axis represents the process dimension. The final aim of the activities along this axis is the 'zero-emission option'. This option focuses on a total stop to all emissions. Terms like 'end-of-pipe' and 'process integrated' solutions are relevant in this context. The activities in this direction accept the product as a given quantity. The activities on the product axis therefore are on a re-active level.

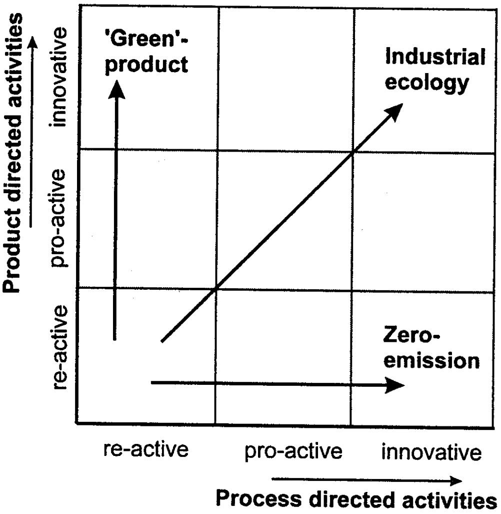

Figure 2.2 Aims in the process and product directed environmental activities

The ideal situation is represented by the arrow bringing both the process and product directed activities on an innovative and integrated level. This situation can be characterised as 'Industrial Ecology' [Soc94]. This can be seen as the final aim, in which all activities are on an innovative level.

From the perspective of manufacturing two objectives can now be discerned. Both objectives are characterised by their innovative attitude towards the processes.

- **Objective 1 : 'Act innovative with respect to the processes'**
  The manufacturing design should aim at the minimisation of the environmental load caused by the manufacturing processes itself. This aim is directly related to the manufacturing processes and will be referred to as 'process-related aspects'.

- **Objective 2 : 'Act innovative with respect to the processes and products'**
  The manufacturing design should aim at the minimisation of the environment load caused by the manufactured product as a whole. This includes environmental impacts in the life-cycle phases outside the manufacturing-phase itself. This aim is indirectly related to manufacturing and will be referred to as 'product-related aspects'.

For both objectives it holds that success is not reached by meeting regulations and laws, but can only be reached by continuous improvements.

In this definition of objectives the 'product-related aspects' cover a larger scope and include the 'process-related aspects'. Still the two objectives are stated separately, because not all situations require the larger scope. A tighter scope enables one to concentrate on the effects for manufacturing itself. Furthermore, the separate objectives connect to specific disciplines in the industrial practice. This is explained further on.

Environmental outline of manufacturing

The scope of both objectives can be represented as the 'life-cycle-crossing' (Figure 2.3). This figure shows that manufacturing forms the interaction between the means-of-production life-cycle (mp-LC) and the product life-cycle (p-LC). Both life-cycles are composed of the same phases, but stand perpendicular to each other. In the resulting life-cycle-crossing (LCC) both life-cycles intersect at the use-phase of the means-of-production and the manufacturing-phase of the product.

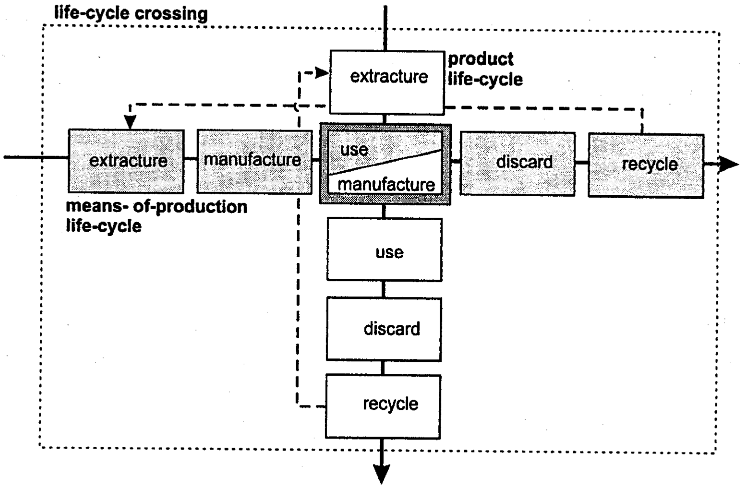

Figure 2.3 Environmental relevant outline of manufacturing including means-of-production and product life-cycle [Roo97]

The presentation in Figure 2.3 is highly simplified. The recycling loops shown are only a few of the possible recycling or re-use possibilities. The life-cycles are often bundles of life-cycles that are spread over different companies. The individual processes, represented as life-cycle phases, often are process chains. This broader definition of life-cycles and processes is also referred to in this thesis.

Process-related aspects

The 'process-related aspects' of manufacturing are covered by the mp-LC, represented by the vertical axis in Figure 2.3. The mp-LC not only includes machines and tools, but also the required energy and auxiliaries like water, lubricants, cleaning fluids, etc. Just like for other products, the environmental impact of the means-of-production is determined over the entire life-cycle. Although the environmental impact is spread out over the life-cycle, it is determined through manufacturing design. Examples are process selection, lubricant selection, and part nesting. Generally the environmental impact of these process-related aspects can not be inferred from the product itself.

The 'process-related aspects' of manufacturing are independent of other p-LC phases like the use or discard-phase. In the approach of 'process-related aspects' the product qualities can be regarded as given and play a passive role. The product is the starting point of optimisation. This is the work field of the process engineers and its environmental implications are relevant for all production companies, independent of their size. Activities in the direction of 'zero emission' can be undertaken by this group of engineers.

Product-related aspects

The manufacturing design can potentially influence the environmental performance of the product itself. These 'product-related aspects' of manufacturing require a design approach in which both the product and the process parameters are under discussion.

The starting point is the functional demands of the product. To deal with the environmental consequences of these activities the mp-LC alone is not sufficient. The scope of the environmental analysis has to be extended with the p-LC. The total LCC, as given in Figure 2.3, determines the environmental performance of the various manufacturing alternatives. The results can usually be deduced from the product. Examples are the processing of recycled materials, the development of new processes, the overcoming of geometric constraints, etc.

The consequence of this enlarged scope is that it exceeds the borders of small production companies. These companies usually are suppliers of a certain product or part, that is manufactured in accordance with the given product specifications. The responsibility for product-related aspects of manufacturing processes therefore lies with larger companies that design parts and products. Contrary to the process-related aspects, there often is no particular group of people in the industrial practice that is held responsible for the total LCC. It is the joint responsibility of the process engineers and the product designers. Action with respect to the processes and products is therefore a multi-disciplinary task.

Mass production

Sheet metal forming processes are generally used for series and mass production. Product series of tens of millions are not uncommon in, for instance, the electronic parts and light bulb industry. In this field the 'law of large numbers' is relevant. The environmental impact of each individual part may be negligible, but the total number of produced parts is so large that the sum of all individual contributions is significant. The effect of mass production is even more pronounced for active products, which have an environmental impact during the use-phase.

In this perspective the emerging markets (like China, Indonesia, Korea, India, South America, etc.) play an important role [Hor93]. These markets try to catch up with the western economies and life-styles. This gives the mass production of formed parts a new boost, as millions of households demand consumer goods and means of transportation. The environmental impact of the manufacturing processes required to fulfil these demands is considerable. Especially because the production is often located in these newly developing and third world countries where the environmental regulations are not as strict as in large parts of the western world.

The mass production character of most sheet metal forming processes underlines the importance of the research field. Therefore, this thesis intends to contribute to a first step in the direction of the larger concept of 'sustainable mass production'.

Chapter 3
Industrial orientation

Chapter 2 gave a theoretical outline of manufacturing regarding its environmental context and the resulting relevance for mass production. A further theoretical elaboration for specific processes proved to be a dead-end [Win94], as environmental performance is largely determined in industrial applications. Therefore an approach is chosen in Chapter 3, in which the environmental performance of actual industrial practice is encountered. Initially not only environmental, but also technical and economic considerations are evaluated. Chapter 3 is concluded with a confrontation with the model presented in Chapter 2. This results in a rough division of relevant environmental issues and a selection for further research.

Two cases are studied, one at the press workshop of DAF Trucks NV and one at the Automated Presses division of Philips PMF. Both cases are based on existing parts. The DAF-case is a pilot-study to determine the environmental impacts and improvements in manufacturing. The Philips-case is a verification of the environmental impacts found earlier for another products range and another production type. This case is approached with a method based on environmental costs.

3.1 The DAF-case

The objective of this case [Pol94] is to determine the material flows in the manufacturing of metal parts that are relevant from an environmental point of view. Additionally, possible solutions are formulated to reduce the impact of these flows.

Case circumstances

The case is conducted at the press-workshop of the motor-truck producer DAF Trucks NV. The workshop consists of six hydraulic and nine mechanical presses ranging from 60 to 2000 tons. In this shop the metal parts of the cabin and the chassis are manufactured. The input material is supplied by the cutting shop and consists of steel sheet varying in thickness between 0.8 mm and 13 mm. Part sizes range from 0.01 to 4 m^2. Approximately 250 different parts, all with their own specific set of dies, are manufactured in the workshop. These dies are designed and maintained by DAF. After being pressed in the workshop, parts are welded, sand blasted, cleaned, painted and/or assembled.

Objective of the case has been to realise reductions of the environmental load of the press-workshop, giving effect to economic constraints. This striving reflects the commitment by the DAF management which underlines the importance of environmentally-friendly products. For the press-workshop itself, it was the first confrontation with environmental criticism.

Approach

For this case a method is used that will be referred to as the MEA-method (Manufacturing and Environmental Assessment-method) to distinguish it from the method used in the second case. The method is based on research carried out in the Netherlands [Cra93] and is intended to achieve the successful introduction of new and environmentally-friendly alternatives in a production situation (see also Section 2.2). The method is slightly adapted to fit the specific manufacturing situation.

The method consists of the following steps:

1) Selection of representative products
2) Description of the process chain of the products
3) Description of the material and energy flows
4) Detection of environmentally relevant flows
5) Determination of possible 'improvement options'
6) Decision on the 'feasibility' of the improvement options
7) Decision on the 'desirability' of the improvement options
8) Final choice of the improvement options

The method is carried out by a team of specialists, employed by the manufacturer and is guided by a facilitator who collects the necessary information, takes care of the communication and monitors the progress. The composition of the team intended to include all disciplines which are involved in the manufacturing of the parts. In the DAF case the team consisted of an environmental co-ordinator, a technologist, the involved engineers and the responsible production manager. The facilitator was a TUE research assistant.

Results

The first step is to select products that are representative for different processes and process combinations. In this case the selected products are: axle half (13 mm thick, hot rolled, unstained), chassis cross beam (6 mm thick, hot rolled, stained), door outer panel (0.9 mm thick, cold rolled, uncoated) and cabin cross beam (1.2 mm thick, cold rolled, thermal zinc coated).

In the second step the process chains are determined for the different products. Special attention is given to the determination of the analysis boundaries and the detail in which the chains are set up.

In the next step the material and energy streams that connect the different processes in the chains are quantified. The quantification requires information which is sometimes difficult to obtain. For instance the information about the used energy was solely available for the workshop as a whole and over a longer than desirable period of time, not for a single press or specific period. This problem was experienced for many quantities. As a consequence this step takes a considerable amount of time. A 'black box' approach (material streams not linked to certain products or processes) would have simplified this step considerably.

	Environmentally relevant areas	Additional remarks
A.	The use of lubricants	• The lubricant must be removed from the part • The lubricant must be extracted from the earth • The material waste contains lubricant
B.	Cleaning of the axle half	• High energy use • Use of hazardous fluids • Bath fluids have to be treated as chemical waste
C.	Cleaning of the chassis cross beam	• Use of hazardous fluids • Bath fluids have to be treated as chemical waste
D.	Cleaning of the dies, in particular when forming zinc coated or unstained sheet	• Use of hazardous and/or volatile cleaning fluids
E.	Material waste of outer door panel	• Over 50% loss of material
F.	Phosphates in degreasing	• The waste water of the electro coating pre-treatment contains phosphates
G.	Passivating of the chassis cross beam	• The waste water of the passivating bath contains chromium
H.	Phosphating	• The waste water of the electro coating pre-treatment contains zinc

***Table 3.1** Recognised environmental relevant areas*

In step four the environmentally relevant material flows and problem areas are indicated (A to H, Table 3.1). In this case this has been done in close co-operation with the environmental co-ordinator and literature sources. The expectation is that in the future this step can be performed using more detailed and reliable information.

For the appointed problem areas possible improvements are suggested. This was done by the multi-disciplinary team in a brainstorming session and worked out by the facilitator. This results in a list of improvement options for each of the recognised problem areas (A.1 to H.1, Table 3.2).

Next, the options are ranked based on their desirability (des). This quantity is based on the valuation of the technical (tech), economical (eco) and environmental improvement (env) of an option. Each of these aspects is valued by the specialist in the team (Table 3.2). The environmental improvement is interpreted as a combined measure for the weight of the environmental load and the potential reduction resulting from the improvement. The values vary from 0 (bad) to 4 (good). This method is analogue to the DIN 2225 standard for designers, which compares different design alternatives.

Improvement options	**eco**	**tech**	**env**	**feasibility**	**desirability**
A.1 Reduction of lubricant quantity	*2*	*3*	*0*	1.5	**0**
A.2 Use of PVD/CVD coatings on dies	*3*	*4*	*3*	3.0	**2.3**
A.3 Use of unstained sheet	*2*	*2*	*0*	1.0	**0**
B.1 Reduction of lubricant quantity	*2*	*3*	*3*	1.5	**1.1**
B.2 Water cleanable, non-water soluble lubricant	*3*	*3*	*3*	2.3	**1.7**
B.3 Alternative cleaning fluid	*3*	*4*	*3*	3.0	**2.3**
C.1 Reduction of lubricant quantity	*2*	*3*	*2*	1.5	**0.8**
C.2 Phosphating before forming, soap lubricant	*2*	*3*	*0*	1.5	**0**
C.3 Use of phosphated sheet	*3*	*3*	*0*	2.3	**0**
D.1 Use of PVD/CVD coatings on dies	*3*	*4*	*3*	3.0	**2.3**
D.2 Use of stained sheet	*4*	*4*	*1*	4.0	**1.0**
D.3 Protection of zinc coated sheet	*2*	*2*	*1*	1.0	**0.3**
E.1 Use of 'Tailor-made Blanks'	*2*	*3*	*3*	1.5	**1.1**
E.2 Re-use of material waste	*2*	*2*	*2*	1.0	**0.5**
E.3 Hydro forming of door-jamb	*1*	*0*	*2*	0	**0**
F.1 Phosphate free degreasing	*2*	*1*	*4*	0.5	**0.5**
F.2 Neutral degreasing of zinc coated sheets	*2*	*1*	*3*	0.5	**0.4**
G.1 Cr-free passivating	*2*	*1*	*4*	0.5	**0.5**
H.1 Fe-phosphating	*2*	*1*	*3*	0.5	**0.4**

***Table 3.2** Improvement options and their valuations.*

The technical and economical aspects are combined in the feasibility (Formula 3.1).

$$\text{feasability } [0\text{-}4] = \frac{\text{economical valuation } [0\text{-}4] \cdot \text{technical valuation } [0\text{-}4]}{4} \qquad (3.1)$$

The feasibility and the expected environmental improvement together determine the desirability of an improvement option (Formula 3.2).

$$\text{desirability } [0\text{-}4] = \frac{\text{feasibility } [0\text{-}4] \cdot \text{environmental improvement } [0\text{-}4]}{4} \qquad (3.2)$$

The results of the DAF-case are given in Table 3.2 and Figure 3.1.

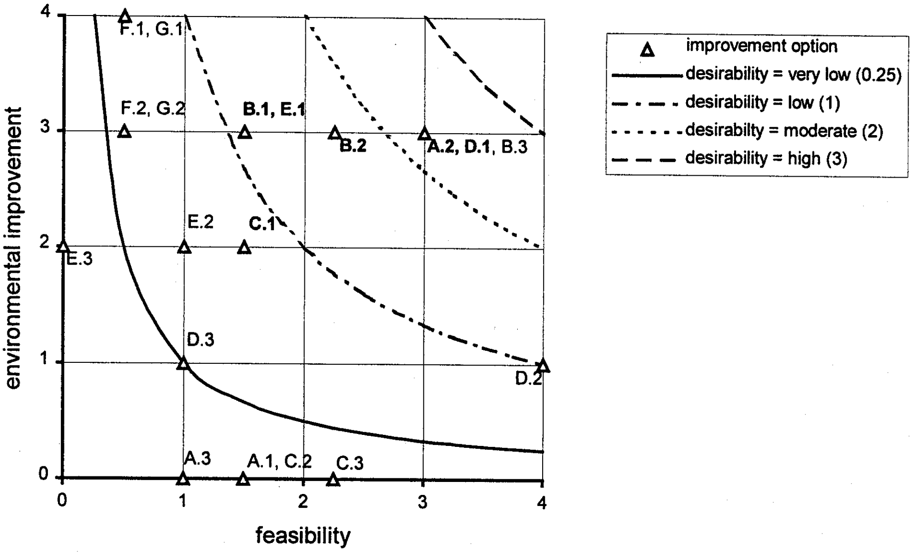

Figure 3.1 The feasibility and environmental improvement of the different options

Based on the valuation the decision can be made which improvement options are to be introduced directly (high feasibility and high environmental effect) and which options are suitable for further research (high environmental effect but low feasibility). In this case [Pol94] the team chose to change the used lubricant (B.1, B.2, C.1) in combination with a surface coating on some heavily loaded dies (A.2, D.1). Technical details (based on comparable cases) are worked out in Chapter 5. Further research is performed (Chapter 6) to reduce material waste in manufacturing through the introduction of 'tailor-made blanks' (E.1) .

Evaluation

Regarding the used method the following conclusions can be drawn:

- The advantage of the method used is the involvement of all relevant people. This contributes to a general awareness of the existing environmental issues and creates the internal support required to solve them. Broad involvement is also the weakness of the method as the results depend on the quality and the completeness of the project team.

- The method worked satisfactory in a production environment, but it lacks a valuation aspect. There is no objective environmental quantity that values the alternatives. This deficiency is magnified as some improvement options reduce more than one environmental problem.

- Although data gathering used up the majority of the time available for this case, the resulting depth of information was far from optimal.

The DAF case revealed three characteristic environmental aspects:

- The majority of environmental issues were related to lubrication. Not only lubricants themselves have an environmental impact, but also the cleaning fluids which are used to remove them. In addition to the general effect on the environment, the used lubricants are also polluting the working environment. The lubricants drip from the products during handling, they smell bad and spoil the air quality due to their volatile character. The pollution related to these substances is not only caused during the manufacturing processes itself, but also during the production and discard of these lubricants. The character of the pollution is mainly related to their chemical structure.

- Apart from the auxiliary materials the 'material waste' has an environmental impact. The waste stream (mainly steel) is less definable by its chemical content, because it is almost 100% recycled. Only a minimal percentage of the steel will end up outside the recycling loop. The waste stream therefore has a more definable energy content, required for the production and recycling of the material [Kop94].

- The 'energy consumption' of manufacturing itself is the third environmental aspect that is encountered in this case. The energy consumption is mainly caused by the forming presses and partly by the cleaning processes as mentioned earlier.

Some of the activities that are excluded from the analysis are production and maintenance of dies. These activities (include honing and grinding) are performed in a separate workshop and contribute to the environmental performance of the forming process. Since the frequency of these activities is low compared to the lubrication or punching frequency, it is assumed that the environmental impact is negligible [Cha83]. Although it is not fully proven that this assumption holds, the production and maintenance of dies is also excluded from the following chapters.

3.2. The PHILIPS-case

This case is set up to check the results of the DAF-case in a different situation and to try to solve one of the problematic points of the MEA-method, viz. the lack of possibilities to measure the environmental load. The solution to this problem is sought in assigning costs to environmentally loaded streams and to use the resulting 'environmental costs' as a first indicator for the size of the environmental loads.

The case circumstances

In the Philips PMF Automated Presses metal parts are manufactured for the electronic industry, for Philips as well for other producers. The parts are manufactured in mass production. Series range from 10^5 and 10^7 per year. The sizes of the parts range from

10^{-4} to 10^{-2} m². The input material consists of rolls of metal strips that are previously sized. Thickness ranges from 0.1 mm to 2 mm. After deforming, parts are cleaned and dried depending on the used lubricant and the requirements of the purchaser.

Approach

To assign the environmentally loaded streams to costs a model is introduced which will be referred to as ECM (Environmental Cost Model). The model is based on the idea that the industry is stimulated and discouraged in an environmentally-friendly direction by subsidies and levies. Environmentally unfriendly actions will, in this model, have negative financial effects and increase the manufacturing costs of a product. The size of the financial effect is taken as a measure for the unfriendliness of the action. Another assumption is that costs incurred to recycle a certain material to its original state can be qualified as environmental costs. To make this model effective a clear distinction has to be made between environment related costs and non-environment or production related costs. Hence the processes and efforts in production have to be divided in two parts:

- processes to produce the required products
- processes to fulfil the environmental demands.

As an economic measure of the efforts to recycle production waste to its original state the difference between buy and sell prices are taken. In addition the energy costs are fully accounted for as environmentally related.

Results

The ECM-method is applied to a small metal part, a brace. This brace is produced in a process chain of punching, bending, PER-cleaning and drying. The part has a surface of approximately 2.5 10^{-3} m² and is irregularly shaped. The batch size is approximately 10^7 parts.

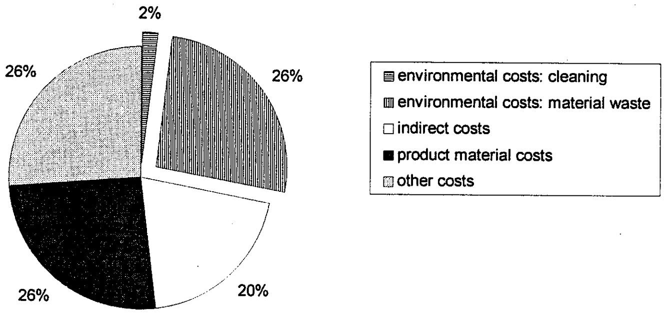

Figure 3.2 Environmental costs of a small metal part

The results of the analysis are given in Figure 3.2. Approximately a quarter (28%) of the total costs could be related to environmental issues. This is mainly (26%) a result of material waste. This is approximately equal to the costs of the material that actually is contained in the part.

Another 2% of the environmental costs are caused by the cleaning process. The costs distribution of the cleaning process is enlarged in Figure 3.3.

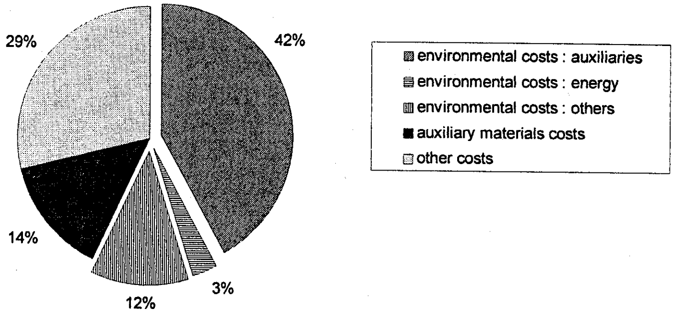

Figure 3.3 Environmental costs of solvent cleaning process

More than half (57%) of the cleaning costs are environmentally related. The largest portion (42%) is connected with the cleaning fluid that has to be discarded after use. This has to be done in accordance with environmental laws and regulations. Another substantial part (12%) is connected with energy consumption, used to heat the cleaning fluid. Another 3% of the environmental costs are made in connection with fluid proof floors, research and personnel.

Evaluation

Although different from the DAF-case, the Philips-case leads to similar results. Material waste, cleaning fluid in relation to the used lubricant and energy consumption are the main environmental issues. The environmental costs are approximately a quarter of the total costs needed to manufacture a metal part. The lion's share of the environmental costs is caused by material waste. The costs related to energy consumption, lubricants and cleaning fluids are relatively low. However if the cleaning process is reviewed separately, the environmental costs account for approximately half the costs related to this process.

The used environmental cost model is simple, but enables the identification of material streams that have an environmental impact, based on the costs that have to be made to comply with the environmental regulations. In some cases it is difficult to decide whether costs are made in relation to the environment or not. This concerns the materials in particular. The difference between the buying price of the raw material and the selling price of the waste is used as an indicator for the environmental load of the materials recycling process. This indicator is clouded by market influences. However, if the price of waste is high it is wanted by the market and will apparently be used again, which is environmentally positive. This is in agreement with the lower accounted environmental costs.

The model is further developed by economists. Though this has resulted in different models, the results are comparable.

3.3 Conclusion

The cases generally agree with the impression developed in Chapter 2. Manufacturing plants mainly have a process focus and engineers are held responsible for process control. Product optimisation is considered an option for exceptional situations, if demands exceed process capabilities. In general the product is regarded as given. This observation supports the proposed division between 'process' and 'product-related aspects' of manufacturing.

Section 3.3 gives a summary of the experiences with the used methods and draws conclusions regarding the 'process-related aspects'. For both objectives (Section 2.3) subjects are selected for further research.

Methods

The presented methods are useful for factories to start and monitor their environmental activities.

- The MEA-method is proposed as a practicable, unpretentious method to obtain environmentally-friendly developments in production, which are technically realisable and commercially acceptable. It helps to direct research for future environmental restrictions. An advantage of this method is the involvement of different disciplines. This contributes to the implementation of the proposed improvements in a later stadium. Conversely this means that the quality of the results is determined by the skills and knowledge of the team members. The methods have a limited integration of environmental knowledge, particularly on aspects outside the manufacturing process. In part this can be solved by including an environmental specialist and a product designer in the team.

- The ECM-method is a rough indicator to indicate environmentally relevant material streams. It needs more research to establish the relationship between costs and environmental loads. The method supports to discussions with the management.

Process-related aspects

Both cases yielded largely comparable results, independent of the different production processes. From these cases the 'process-related aspects' can be divided into three main categories:

- **Auxiliary materials**
  The main representatives in sheet metal forming are lubricants and cleaning fluids. Dependent on the cleaning processes water consumption can play a role.
- **Energy consumption**
  The main energy consumers in sheet metal forming processes are the presses and heating of cleaning fluids. Drying of products after the cleaning process can also contribute significantly to the energy consumption, dependent on the used cleaning process
- **Material waste**
  The material waste results from the material efficiency. Forming processes are

generally known for their high material efficiency compared to other working processes as cutting or milling. The industrial orientation however shows that in individual cases the absolute waste due to punching can be significant.

This list can probably be applied more generally then only in the limited field of sheet metal forming. The three categories can be recognised in most manufacturing processes and cover a larger environmental scope. Working circumstances and tool production and maintenance are excluded as they fall outside the scope of this project.

The use of auxiliary materials has been selected for further research on 'process-related aspects'. The material waste and energy consumption are also connected to the 'product-related aspects' and are therefore integrated in the corresponding sections.

Product-related aspects

The 'product-related aspects' of manufacturing are mostly related to the product material. This varies from the material used, the surface structure, the product mass, etc., etc.. In the DAF-case above two improvements are mentioned that are related with life-cycle phases outside manufacturing and are therefore representative for the product-related aspects: a) tailor-made blanks and b) hydro-forming.

These two examples are mentioned based on the potential environmental improvements within manufacturing processes themselves. If the scope of the cases would have been broader, more options regarding the 'product-related aspects' could have been named.

The tailor-made blank (TMB) process is a suitable example to deal with the 'product-related aspects' of manufacturing. As mentioned before, the analysis can include some of the 'process-related aspects', like energy consumption and material waste. This combination makes the TMB process an appropriate example to study the total 'Life-Cycle Crossing'.

Chapter 4
Process and product-related aspects

In the industrial orientation (Chapter 3) the environmental aspects of sheet metal forming are discussed in relation to technical and economic aspects. This resulted in a selection of topics that are relevant from both the environmental and industrial point of view. The results are however not detailed enough to direct further technical research. This requires a more detailed environmental evaluation of different technical alternatives. This evaluation is performed in Chapter 4. The 'process-related aspects' are examined through auxiliary materials (Section 4.1). The 'product-related aspects' are dealt with in the 'tailor-made blank'-process (Section 4.2). The analyses in Chapter 4 have a broader scope then the analyses in Chapter 3. This has been done to make the outcomes as general applicable as possible.

4.1 Environmental aspects of auxiliary materials

From the industrial orientation it follows that one of the relevant environmental issues in forming processes is the use of auxiliary materials, in particular lubricants and cleaning fluids. The environmental aspects of these materials are process-related, since they are neither found in or deductible from the finished product. The main part of their environmental impact is therefore related to the means-of-production life-cycle (mp-LC). Interaction with other life-cycle phases of the product is limited. As a result the product quantities are taken as given.

In Section 4.1 the relevant auxiliary material streams are determined and their effects on the environment are classified. Different lubrication and cleaning alternatives are examined on this classification (Section 4.2). Consequently environmental priorities for technological research are set (Section 4.3).

Method

A life-cycle analysis (LCA) of auxiliary substances in metal forming processes requires two types of information : a) data on substances bought from suppliers and b) data on material streams within the factory. Presently the available information for both types is insufficient.

The added value of suppliers of auxiliary materials, in particular the lubricant suppliers, is the mixing of a number of chemical substances. Since all these substances are commercially available, the composition of the mixture is kept secret. This makes it impossible to include the mp-LC of the auxiliaries outside the factory itself.

Within the factory boundaries, the administrative systems are not yet adapted to the requirements of an environmental analysis (see also Section 3.1). Therefore it is impossible to generate the normal required mass balance of the in- and out going material streams of a specific factory, on the basis of available data. The information depth found in industry was limited to the mass quantity of the different lubricants, cleaning fluids and the chemical waste over a certain period. None of the administrated material streams had been assigned to particular products. In addition, the reliability of the available data was often doubtful. Quantitative or qualitative information was not available on:

- the composition of the chemical waste;
- the evaporation rates of cleaning fluids and lubricants;
- the chemical contents of the lubricants or cleaning fluids (only generally);
- the corrosive preventives on the product materials;
- the energy consumption of processes and
- the lubricant discarded with the material waste.

Attempts to make a mass balance were not successful. This stands in the way to make a quantitative LCA, or even an LCA-scan. Nevertheless the systematic approach of an LCA was chosen to evaluate the environmental aspects of auxiliary substances in metal forming processes. The scope of the analysis had to be limited to qualitative statements. In spite of its limitations, this pragmatic approach helps to reach technical sufficient solutions.

Goal setting and determination of system boundaries

The objective of the analysis is to review lubricant and cleaning alternatives as to their relative environmental performance. Environmental performance is valued using a classification of impact types. Based on this valuation, the environmental demands are set for the lubricant alternatives which are tested in the technical research (Chapter 5).

The system boundaries are confined to steel supplier and manufacturer. This implies that the actual production of the chemical substances is disregarded and that the mp-LC is largely neglected. This significantly narrows the scope of the analysis and limits the results to qualitative statements.

The product design is accepted as given, just like the demands on the cleanliness and dryness of the part. The material streams related to the material production itself are disregarded as these are irrelevant as to the application of auxiliaries.

Inventory analysis

The inventory is based on a simplified flow model of the production facility for sheet metal parts (Figure 4.1). The process chain starts with the melting of incoming ore and scrap. Scrap recycling is relevant for this case as the applied lubricant is returned as well. The next step is the rolling of the solidified melt to a sheet. This sheet then enters the manufacturing processes itself. The manufacturing process consists of a number of forming steps followed by a cleaning step. The cleaning process may be followed by a process that separates the cleaning fluid, water and other substances from the cleaning sludge. Subsequently, the cleaning fluid can be recycled. This process is called 'upgrading'. The final step of the manufacturing process is the drying process.

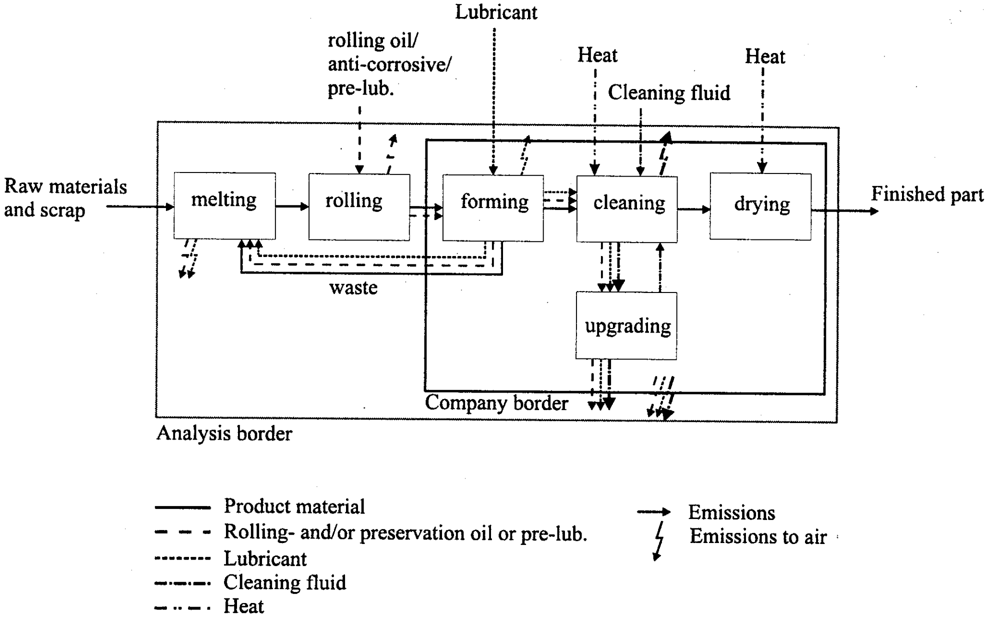

Figure 4.1 Life-cycle of auxiliary substances in deforming for a general situation

Three types of auxiliary materials are used as part of the forming process:

- **preservation- or rolling oil**, which is applied during or after the last rolling step of the sheet. Its primary function is to protect the sheet during storing and transportation against corrosion. The preservation oil is normally present during the forming process and contributes to the lubrication system. The preservation oil is removed together with the lubricant;
- **lubricant**, which is applied just before the forming process and is intended to reduce the friction and/or tool wear. The lubrication frequency can vary from every single product to once every ten products;
- **cleaning fluid**, which is not applied as a fixed quantity per product, but as a bulk quantity that is used for a number of products, often in the form of baths or tanks. These baths have to be renewed after a certain time.

The above is a general description. Actual situations may vary. For example in cases where pieces of dirt lead to visible spots, the sheet is cleaned before the forming process. These special cases are not included in this analysis. Also not included are the hydraulic oils of the presses, as they fall outside the scope of this work. In some case the waste of these oils is significant due to leakages. This deserves extra attention from the manufacturers, at least in the form of 'good-house-keeping'-practices.

Impact assessment and distribution

Several material streams have an impact on the environment. They can be divided into five groups, viz. evaporation, burning, discard, waste and consumption of water and energy. These categories are discussed separately below.

- **Evaporation of preservation oil, lubricant and cleaning fluid**
  The evaporation of the auxiliaries leads to emissions into the air, due to the volatile character of some substances. This effects the work circumstances in the factory (sensitive skin, irritated eyes, stench, etc.) and the air quality in general (changes of climate etc.).
- **Burning of preservation oil and lubricant during melting of scrap**
  The oil or other layers that are applied on the sheet before the forming step, will partly be returned together with the scrap to a steel producer, where they are burned. This has a certain advantage since the energy content of the substances is used. If the burning of oils is uncontrolled, hazardous gasses can originate that effect the air quality.
- **Discard of used lubricant, preservation oil and cleaning fluid after cleaning**
  The used auxiliaries have a limited recycling potential. Especially for those whose functioning is based on chemical reactions (like doped lubricants and alkaline cleaning fluids) re-use is very difficult. Therefore many auxiliaries have to be treated as hazardous waste or must be burned. It is also possible that the discarded sludge, in addition to auxiliaries themselves, contains metal parts. This is especially relevant when the product or tool material is an alloy based on heavy metals.
- **Waste/spill of preservation oil, lubricant and cleaning fluid**
  In some cases, especially in the case of small batches and manual application, a substantial part of the auxiliaries is wasted during its application. This has a negative influence on the internal factory environment (slippery floors, possibilities for evaporation, accumulation of dirt, etc.) and on the soil underneath the factory building (effecting ground water and public health) .
- **Consumption of water and energy**
  During the processes clean water and energy is used. Depending on the local situation this leads to a variety of unwanted effects and should therefore be reduced to a minimum.

The final effect of these impact categories depends on the selected auxiliary, the applied quantity and the treatment. In the following analyses the auxiliary selection is the subject of research. It is therefore assumed that the used quantity and treatment are state-of-the-art.

4.2 Valuation of auxiliary materials

In Section 4.2 a number of alternative auxiliaries (lubricants and cleaning fluids) are presented and discussed. This discussion is based on the impact categories presented in Section 4.1. Although the required cleaning effort is taken along in the valuation of the different lubrication alternatives, the different cleaning alternatives are also evaluated separately.

Lubrication alternatives

Common lubricants are (cl-)doped oils, greases and non-doped oils. The greases have a small advantage over the non-doped oils as they generally tend less to evaporate or drip (spilling). The doped oils have of course the environmental disadvantage related to their chemical composition, regarding evaporation, discard and waste. The non-doped oils have usually the best cleanability of these three alternatives. The better the lubricant sticks to the material during the forming process, the more difficult it is to remove it later. This makes the doped lubricants and greases generally more difficult to clean, resulting in a corresponding larger environmental impact of the cleaning process.

Suppliers offer two kinds of lubricants that are claimed to have an improved environmental behaviour: volatile lubricants and emulsions.

- Volatile lubricants, which evaporate directly after deforming, reduce the demands on the cleaning process considerably. Although this reduces the cleaning effort, it also diffuses the lubricant, making it difficult to handle. This is not in the interest of the environment and can form a serious threat to employees' health. In some special cases the volatile character can be used in a harmless way, when the forming process is followed by a heating step (e.g. controlled oxidation). The lubricant evaporates and can be sucked up and treated. The remaining rolling oil and anti-corrosive oil however, can form an obstacle. The risk remains that temperatures during the forming process rise to such an extend that early evaporation of the lubricant occurs.
- A special group of lubricants are emulsions. These lubricants can be, but not necessarily are, diluted in water. Their environmental advantage is that they can be cleaned with water and that they can be applied in a diluted state. This reduces the required lubricant quantity, but has an application range that is limited to less severe sheet applications. A major disadvantage is that the separation of lubricant and water requires other chemical substances to settle the lubricant along with the increased risk of corrosion of the product.

An alternative lubrication method is the use of 'pre-lubricated' sheets. These sheets contain a layer applied instead of the preservation oil. This alternative ranges from oil layers to permanent coatings. A distinctive advantage of this alternative is that the layers reduce the total conservation- and lubrication quantity and can be applied in large amounts, allowing optimal process control and minimal waste. A disadvantage of more permanent coating types (the non-permanent, the half-permanent and the permanent coatings) is that all material is coated, including the production waste. This increases the applied quantity and the impact of the production scrap. For these coatings it is also not possible to choose the optimal coating for a particular process.

- The simplest example is provided by pre-lubricated sheet. These sheets are supplied with an oil layer that has reasonable lubrication qualities. The disadvantages are non specific lubrication for separate operations and a limited application range, since they are only applicable for light sheet drawing [Sch94].
- Non-permanent coatings are made of waxes or ester polymers and are currently under development. A major advantage is improved performance compared to pre-lubricated sheets, because non-permanent coatings function as a solid lubricant. Non-permanent coatings are more expensive and can not be changed for small series.
- Half-permanent coatings can additionally be used as primer for lacquering after the forming process. The function of these coatings can be compared to conversion layers used for extrusion. These layers replace the normal corrosion oil, the lubricant and the pre-paint conversion layer.
- A permanent coating is a kind of paint and has the disadvantages of both the half - and non-permanent coatings. In addition the layers can break during forming. The half-permanent and permanent coatings are not compared to the other alternatives, because their effects are outside the set analysis boundaries.

Environmental valuation of lubrication alternatives

Table 4.1 displays the discussed lubrication alternatives and their effect on the impact categories and substance types. The alternatives are firstly ranked according to the number of 'strong negative'-effects they cause. This is not an absolute ranking as effects may vary for individual cases.

		Lubrication alternatives						
Impact category	**Substance type**	Cl-oil	oils	greases	volatile lubs	emulsions	pre-lub	non per/waxes
Evaporation	preservation oil	-	-	-	-	-	o	o
	lubricant	- -	-	o	- -	o		
	cleaning fluid	- -	-	- -	o	o	-	o
Burning	preservation oil	o	o	o	o	o	-	-
	lubricant	- -	+	+	o	o		
Discard	preservation oil	o	o	o	o	o	-	-
	lubricant	- -	-	-	o	o		
	cleaning fluid	- -	-	- -	o	o	-	o
Waste/spill	preservation oil	o	o	o	o	o	o	o
	lubricant	- -	-	o	-	o		
	cleaning fluid	- -	-	- -	o	o	-	o
Consumption	water	-	-	-	-	- -	-	-
	energy	-	-	- -	o	- -	-	-
Total score	number 'str. neg. eff.'	7	0	4	1	2	0	0
	number 'mod. neg. effe	3	9	3	3	1	7	4
	ranking	**7**	**3**	**6**	**4**	**5**	**2**	**1**

- -	strong negative effect
-	moderate negative effect
o	negligible effect
+	small positive effect

***Table 4.1** Lubricantion alternatives and their effect on the impact categories*

Based on this valuation the environmental aspects of lubrication are least harmful for pre-lubrication and non-permanent coatings or waxes. If a certain flexibility in the application is required (non-doped) oils are the best alternative.

However, from a technical perspective the environmentally-friendly alternatives have limited lubrication qualities. Their introduction in severe forming processes, like e.g. the working of stainless steel, requires other measures to guarantee tool life. Possibilities to improve tool life are the application of :

- adapted normal tool steels (surface treatments)
- alternative tool materials
- self-lubricating coatings
- hard coatings.

These alternatives reduce lubricant requirements, allowing a simpler lubricant, less lubricant or a even a complete refraining from lubricant application (dry conditions). The technical possibilities of these options are discussed in Chapter 5.

The given alternatives also influence the environmental impact. Although the impact of the tool production falls outside the scope of this analysis, it is mentioned that particularly the coating process can have a relevant environmental impact [Löf93].

Cleaning alternatives

From the environmental point of view the variety of cleaning processes can roughly be divided into two main process technologies, viz. solvent cleaning and aqueous - or alkaline cleaning. These technologies are also applied in combination. Section 4.3 is based on [ASM76, Fre95, Kil89, Nac85, Plo94].

- Solvent cleaning removes contaminates by immersion in organic solvents. The vapour degreasing process uses partly the same chemicals, but the products are exposed to solvent vapour. These processes do not require any rinsing or forced drying, are applicable for a wide range of substrates and contaminations and are easy to maintain in production. Recycling of the solvents is possible in closed systems by distillation.

- Aqueous- or alkaline cleaning processes are based on other principles. The main principles are:
  - Saponification, the cleaning fluid converts animal or vegetable oils into soluble soaps;
  - Emulsification , the cleaning solution reacts to the mineral oils and greases and forms an emulsion and
  - Dispersion, the surface active materials in the cleaning solution decrease the concentration of dirt on the product surface.

  These processes use water based cleaning solutions ranging from pure water to combinations of water, (synthetic) detergents, corrosion inhibitors etc., etc.. The processes are followed by rinsing and forced drying. Aqueous cleaning requires process maintenance (process control) during utilisation and adaptation to the specific situation. This makes them less suitable for production facilities with different parts and lubricants. The recycling of the cleaning fluids and lubricants is unusual, because of contamination and irreversible reactions. Due to these reactions some lubricants have a destructive character and reduce the bath lifetime considerably. Aqueous cleaning is particularly good for cleaning inorganic or polar materials. For this reason it is advisable to covert to water- or organic based lubricants instead of oil-based. The performance of these systems is, more than solvent based systems, improved by ultrasonic agitation.

Environmental valuation of cleaning alternatives

The major environmental issue related to solvent cleaning systems is, apart from direct health and safety risks, emissions to air and soil.

- Evaporation of these (chlorinated) solvents fall under (inter-)national regulations on halogenated hydrocarbons. The losses in an open system can be up to 90% of the solvent [Fre95]. The use of vapour degreasing in combination with a closed system and solvent recycling by distillation, reduces solvent emissions to nearly zero. To meet a prospective EC requirement of 20 mg/m^3 even these systems have to meet high requirements.
- The waste streams (discard) of these processes are regarded as chemical waste (see Table 4.2).

The major environmental issues related to aqueous systems are discard of the bathes, energy and water consumption (including hazardous wastewater discharges) :

- The discard of the bath residues can be divided into two situations, viz. the bath is characterised by a solvent/emulsion or by layers. To separate the water the bathes are ultra-filtered or skimmed respectively. This leaves water and a composition of conservation oil, lubricant, small metal parts and other dirt combined with or chemically reacted to the cleaning substances. The environmental load of the remaining slurry is dependent on the applied cleaning fluid and lubricant. The presence of non-biological degradable detergents, metal parts with heavy metals, phosphates etc. increases the hazardousness of the waste.
- The water consumption is relatively high. Good bath control and careful water treatment can reduce this impact.
- The energy consumption is considerable due to the elevated bath temperatures and the substantial bath volumes. The temperature can be lowered by the use of heavier detergents (leading to an increased discard load), or the application of an agitation mechanism or other special techniques. The forced drying is another energy consumer.
- The evaporation is less problematic than for processes based on solvents. Only for hot processes evaporation is relevant.

The cleaning methods are valued based on these considerations (Table 4.2).

	Cleaning alternatives			
Impact category	Solvent cleaning	Vapour degreasing	Closed system	alkaline cleaning
Evaporation	- -	-	-	o
Discard	- -	- -	o	-
Water consumption	o	o	o	-
Energy consumption	o	-	-	-

- -	strong negative effect
-	moderate negative effect
o	negligible effect
+	small positive effect

Table 4.2 Environmental effects of cleaning alternatives

The valuation confirms the environmental impact of solvent cleaning systems in general, but suggests also that a vapour degreasing process in a closed system could be competitive with alkaline processes. A comparison of both systems requires a more detailed, quantitative analysis [Lei95].

Quantitative examples of lubricant use

To give an impression of the lubricant use in the metal working industry an example is taken from the car industry (Table 4.3). The presented numbers are estimated by a lubricant supplier [Str96] and are based on the production of an average passenger car.

PROCESS STEP	PROCESSED PART	
Material production[1]	hot rolled sheet	40 gr.
	cold rolled sheet	120 gr.
Pre-lubrication[1]	pre-lub. sheet	250 gr.
	washed blank	100 gr.
Drawing[1]	outer panels	120 gr.
	inner panels	350 gr.
	suspension parts	200 gr.
Machining and grinding	transmission emuls.	800 gr.
	transmission neat	400 gr.
	engine emuls.	1000 gr.
	engine neat	250 gr.
	bearings and others	200 gr.
Others	several	250 gr.
TOTAL		**4080 gr.**

[1] Based on a medium size car with a body-in-white of 300kg that requires 400 kg steel.

Table 4.3 Lubricant use for the production of an average passenger car [Str96]

The numbers show that the production of an average passenger car requires some 4 kg of lubricant. Approximately 25% of this quantity (1 kg) is related to the sheet metal forming processes. The major part is required for machining and grinding processes. A provisional conclusion is that sheet metal forming processes have a lower contribution to the environmental load than machining processes, apart from other environmental aspects as material waste.

As the annual car production adds up to millions of cars the lubricants consumption for sheet metal forming constitutes a significant amount. This holds also for other product types manufactured by sheet metal forming processes, since mass production is typically used for these processes. In these cases the law of big numbers holds. This can be illustrated as follows. One imaginary electronic component that is manufactured in an annual series of 10 million pieces and is lubricated by 1 gram oil per 10 components requires 1000kg lubricant a year. The environmental aspects related to the used auxiliaries are often unnoticed by the outside world, because production is spread over many small and medium sized companies.

The quantities applied during the manufacturing-phase are small compared to the oil consumption during the use-phase. Where as the manufacturing requires 4 kg, the used motor oil and transmission oil add up to approximately 40 kg and 10 kg respectively, over the car lifetime. These numbers are on their turn small compared to the fuel consumption, that lays in the order of $2 \cdot 10^4$ litre over the car lifetime. This illustrates the relative importance of the lubricant use in metal working processes.

4.3 Evaluation of auxiliary materials

Although an overview is given of possible lubrication and cleaning alternatives, the analysis is far from complete. The reason for this is, besides the lack of data availability, the generality of the reviewed situation. Nevertheless some conclusions can be drawn:

- The cleaning process causes the major environmental load. Particularly the solvent cleaning fluids have a bad environmental reputation. Up to now, the alternative is an alkaline process. This process has other negative aspects like increased energy- and/or water consumption. Determination of the optimal environmental solution requires quantitative analyses.

- Although the cleaning fluid is responsible for the major environmental load, the lubricant selection is particularly important. The lubricant determines to a large extend the environmental performance of the total process chain, including the cleaning process. Therefore the selection of a suitable lubricant is the key issue in the environmental process design. The main lubricant requirements are: a) chlorine free; b) removable and c) not effecting the cleaning bathes.

- The environmentally-friendly lubrication alternatives proposed by some lubrication suppliers (volatile lubricants and emulsions) have the potential to reduce the required cleaning effort, but overall environmental performance is not automatically improved. The general disadvantage of almost all environmentally-friendly alternatives is their mediocre lubrication performance. This means that in practice problems can be expected for stainless steel and hard alloys, due to increased tool wear. The application of alternative tool materials and tool surfaces can support a successful implementation of these environmentally-friendly lubricants.

- The environmental load also depends on the system equipment and the efforts made to prevent unwanted leaks to the environment. An example is the difference between the open - and closed installation for volatile fluids, that use the same fluids, but have an essentially different environmental effect. This means that 'good house keeping' is important.

4.4 Environmental aspects of tailor-made blanks

In Chapter 2 it is stated that the environmental impact of manufacturing is not limited to the manufacturing processes itself. Environmentally friendly manufacturing design should therefore include other life-cycle phases than manufacturing alone. This leads to the aimed for integration of 'product' and 'process-related aspects'.

In the industrial orientation (Chapter 3) the material waste is recognised as one of the environmentally relevant material streams in manufacturing. The effects of the material waste extends to other life-cycle phases. One of the suggested improvement options in the automotive industry is the application of tailor-made blanks (TMBs). TMBs are blanks which are welded together from several smaller blanks, with varying thickness and material quality. TMBs not only have the potential to reduce the material waste, but also to reduce the product mass [Aut94, Bay93, Pra95, Sie95]. The product mass influences the environmental impact of the use-phase of car or truck. Therefore TMBs are a suitable example to study the impact of manufacturing design on the environmental impact over the total life-cycle crossing (Section 2.3).

Although literature mentions the main environmental advantages of TMBs [Del95, Hib95, Pra93, Raz94], viz. the reduction of both the waste and product mass, the relative importance of these advantages or their absolute impact have not yet been discussed [Hav96]. In Section 4.2 the life-cycle of an automotive body part is modelled, based on the life-cycle energy consumption. The model is applied on a TMB-door and compared to the conventional door. In addition to the effects of waste and product masses, the distribution over different life-cycle phases is studied. The results include the influence of the weld position, as this parameter determines the formability of the blank. The weld position can therefore not be freely chosen.

Automotive life-cycle energy model

A model describes the environmental impact of an automotive body part by its life-cycle energy consumption. The model is based on the 'cradle to grave' approach of LCA-methods. The use of energy as a measure, makes it possible to compare the environmental impact of different aspects, like fuel consumption and material use, without weighing factors. This allows the valuation of the TMB-alternatives and avoids discussions which are outside the scope of this thesis. The disadvantages of a direct energy measure, is that it disregards the effects of extraction and emissions like material wastes, dust and CO_2. A quick LCA-scan of steel production showed that the energy consumption covers approximately 80% of the accounted environmental measure [Dec96]. The model based on energy consumption gives therefore only a first order approximation.

The energy models found in literature are mostly applied to compare different materials [Fus91, Hei92, Sch91]. In automotive applications the discussion in this respect concentrates on the question whether aluminium or steel has the most advantages [IIS94, Sin94]. Only few studies are presented that compare different manufacturing processes. Kuzman compares the required energy to produce a metal cup by forming and cutting, based on the energy requirements of the material production [Kuz90]. In this work the product-related contributions in the use-phase are disregarded.

The used life-cycle is represented schematically in Figure 4.2 and includes the material production, manufacturing, use and discard phase.

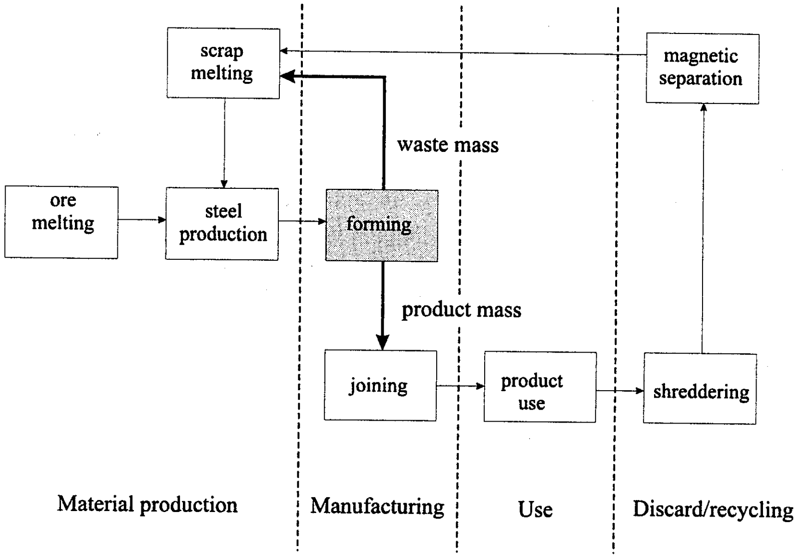

Figure 4.2 Life-cycle of steel automotive part with the environmentally relevant parameters which are determined by the manufacturing design

The TMB alternatives determine the input parameters of the model: waste mass and product mass. Both parameters are mass quantities. The waste mass is the mass of the material waste or scrap that results from the production. The product mass is the mass of the part as it leaves the manufacturing.

- **Use-phase**
  To describe the use-phase with respect to the energy consumption, the mass dependence of the fuel consumption is required. The values found in literature [Sch91, IIS94, Fus91] differ significantly. Therefore this relation is studied in more detail. The work performed by a vehicle is the summation of the work that is required to accelerate (W_{acc}) , to mount (W_m) and to overcome rolling friction (W_{rf}) and air resistance (W_{ar}). These contributions can be described mathematically by Formulas 4.1 to 4.4:

$$W_{acc} = M\,a\,s \tag{4.1}$$

$$W_{rf} = \mu\,M\,g\,s \tag{4.2}$$

$$W_{ar} = \tfrac{1}{2}\,C_w\,A\,\rho_{air}\,v^2\,s \tag{4.3}$$

$$W_m = M\,g\,s\;\sin\gamma \tag{4.4}$$

To obtain the required energy the performed work is multiplied by an efficiency factor (η) that accounts for the internal losses. The energy supply of the engine is given by the fuel consumption multiplied by the combustion value H and the travelled distance s. To discern the mass sensitivity from other mass independent influences, the fuel consumption is written (Formula 4.5) as a linear function of the product mass (M).

$$(W_{acc} + W_{rf} + W_{ar} + W_m)/\eta = H\, s\, (\alpha M + \beta) \qquad (4.5)$$

The parameter α represents the dependence of the fuel consumption with the mass. The determination of α ($\alpha \sim \mu$, g, a, γ, s) can be done theoretically. This requires however assumptions about accelerations, speeds etc. that can not be made sufficiently correct. It also requires efficiency numbers for combustion, transmission, etc. The parameter β is related to the work required to overcome air resistance W_{ar} and does not influence the mass dependence of the fuel consumption. Therefore this parameter is left out of consideration.

For passenger cars the parameter α is determined by fuel consumption values of production cars [Sch91], based on information found in car tests [Rok94]. These tests give fuel consumption numbers for a constant speed ($a=0$ m/s^2) of 90 km/hour, 120 km/hour and for city trips (with acceleration, $a \neq 0$ m/s^2) according to ECE. With this data α can be determined for constant speed (α_{90} and α_{120}) and regular acceleration (α_{city}). For cars running on petrol, the fuel consumption data are collected for 7 European brands available in 1995 and set out against the car mass (Figure 4.3).

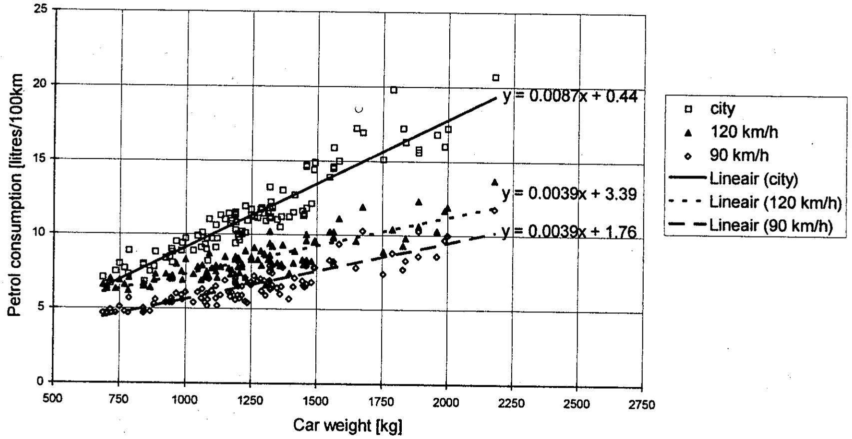

Figure 4.3 *Fuel consumption(ECE) versus the car mass for all models of seven European brands available in 1995*

The points are fitted with a linear approximation, from which can be derived that $\alpha_{90}=\alpha_{120}=3.9\ 10^{-5}$ l/km·kg and $\alpha_{city}=8.7\ 10^{-5}$ l/km·kg. For constant speed this means that for each 1kg extra mass, the fuel consumption increases with 3.9 10^{-5} litre/km. Analogue holds for city traffic an increase of 8.7 10^{-5} l/km for each kg extra mass. The total increase of fuel consumption can now be written as Formula 4.6 in which '*i*' is relative share of road km at constant speed.

$$\alpha = \frac{3.9i + 8.7(1-i)}{10^5} = \frac{8.7 - 4.8i}{10^5} \tag{4.6}$$

The diesel oil consumption figures for trucks (Formula 4.7) are based on route simulations performed at DAF Trucks [Hak96]. The resulting figures differ from those for passenger cars. The influence of mass is lower. The computed numbers are $\alpha_{85}=$ 0.57 10^{-5} l/km·kg and α_{city} =0.75 10^{-5} l/km·kg for respectively constant speed (v=85 km/hour) and city traffic. In the route simulations it is assumed that the driver has an economical behaviour.

$$\alpha = \frac{0.57i + 0.75\ (1-i)}{10^5} = \frac{0.75 - 0.18i}{10^5} \tag{4.7}$$

The combustion values H for diesel oil and petrol are respectively 35,49 MJ/l and 38,18 MJ/l [Cre87].

- **Material production phase**
  In order to deal with recycling, the material production phase is split in three. The steel is melted from ore or from scrap and successively formed to the final steel sheet (data according to [IIS94]). The processing of the ore into the melted steel is the most energy intensive step (22.5 MJ/kg). The recycling step requires less then a quarter of the raw material production (5 MJ/kg). The final processing of the melt into the sheets requires another 7.5 MJ/kg.

- **Manufacturing phase**
  The manufacturing phase is represented by the energy consumption of the stamping and spot welding processes, which are respectively approximated [IIS94] by respectively 3.6 MJ/kg and 0.3 MJ/weld.

- **Discard phase and recycling rates**
  The discard- and recycling phase is represented by a crushing- and a magnetic separation step. According to Mauch [Mau94] the breaking and sorting requires 212 MJ/ton of primary energy. According to NOH [Hei92] the shredding and magnetic separation are require respectively 10 and 3 MJ/ton. In the model the average of both figures has been used.

  The efficiency of the discard processes determines the recycling rates. A differentiation must be made between recycling rates of new scrap and post-consumer scrap. Most of the new scrap is recyclable, because of the ease of collection, sorting and the continuous availability at high quality and constancy of composition [IIS94, Kas95]. This recycling rate is set to 95%. Recycling rates for the post consumer scrap are considerably lower, and differ depending on the source consulted. Kassem gives the lowest number 10-50% [Kas95]. The highest found numbers are 86- 95% [IIS94]. The recycling rate of post consumer scrap has been set to an average of 80%.

The model disregards the transportation between the different phases since this has an effect of less than 0.3% [Het96] and is not significantly changed by the introduction of TMBs.

4.5 Valuation of a TMB-door

The TMB-design enables the designer to place strength where it is needed and omit reinforcements. Because the welds are continuous, instead of spot welded as in the conventional process, the product mass can be reduced. Under the assumption of unchanged material efficiency this also leads to a reduced waste mass. In some cases the material efficiency can be improved by the 'enclosure' of unused sheet and by better nesting possibilities of the smaller blanks.

For this quantitative example an inner door (excluding the unchanged outer panel) has been taken (Figure 4.4). This example is chosen, because doors are commonly applied as TMBs [Hav96]. The design aims at omitting the door hinge reinforcements. Since the enclosure of unused sheet (the window opening) is not economically feasible in this case (due to required number of welds), optimisation of material efficiency is not particularly aimed at.

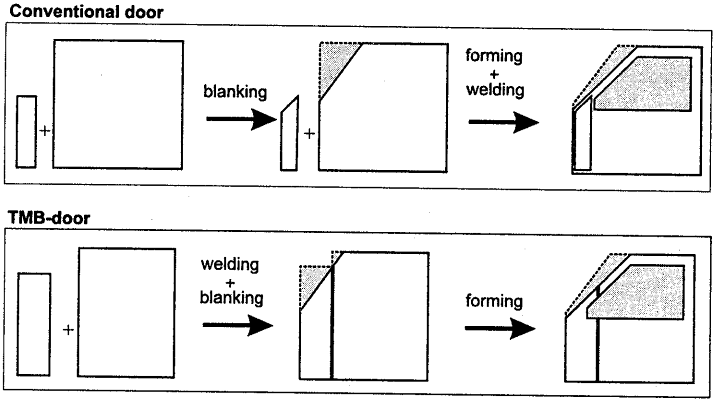

Figure 4.4 The conventional and TMB process steps and their material efficiency for an automotive door

The conventional door is made from a 0,75 mm thick sheet. The initial sheet measures 1175mm by 195mm and weights 8,3 kg. The final panel is 4 kg ($\eta_{\text{over all}}$=0,48). The panel has been reinforced with two door hinges, weighting 2 kg made with an overall efficiency of $\eta_{\text{over all}}$=0,70. The TMB-door design is based on literature examples [Aut95, Bar93, Bro93, Sch92] and is composed of 1,75 mm thick steel sheet on the front-side and 0,75mm for the rest. The blanks are connected by a straight weld.

The forming can be represented by two steps (Figure 4.4): blanking of the outer contours and the forming process itself. Both processes have their own material efficiency (η). In the analysis it is assumed that the efficiency of the forming step is equal to the conventional process (η=54%). The blanking process is computed on basis of the actual measurements, since better nesting possibilities can result in a higher material efficiency.

Product and waste mass

The parameter investigated is the weld position ('h' [mm], see Figure 4.5). This parameter determines the product and waste mass. It is assumed that at least the side of the door is made of the thicker material, as this is a minimum strength requirement [Kem96]. This position is defined as h= 0 mm.

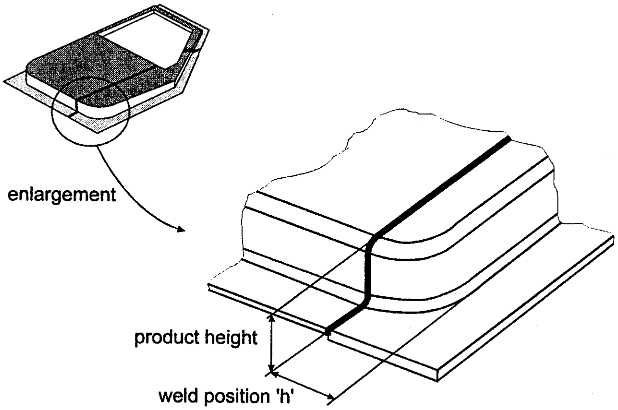

Figure 4.5 The weld position 'h' in an inner-door and enlargement of the corner radius

The resulting weight figures are given in Figure 4.6 as function of weld position. The horizontal axis represents the weld position 'h'. The vertical axes represents the assembled door and the waste mass.

When the weld of the TMB door is positioned at larger distance from the side, the product and waste mass increase because additional thick material is included. The minimum mass is therefore achieved when the weld position is not limited by the forming process (h=0 mm). In that case the door and waste mass are reduced to respectively 80 and 90% of their original values. The waste mass surpasses the conventional waste mass for weld position h>150 mm. In those cases the product mass is reduced to 90% of its original value.

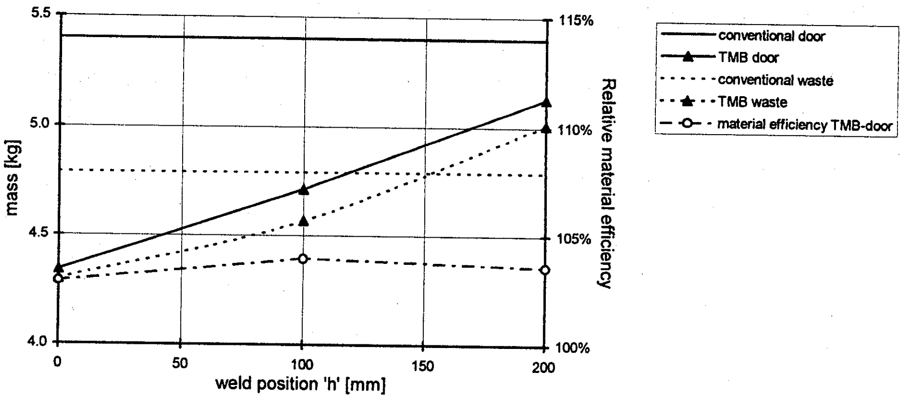

Figure 4.6 *Mass of the inner-door as function of the weld position 'h'*

Initially the material efficiency (the right scale in Figure 4.6) increases as 'h' increases, but after a certain point the efficiency starts decreasing again. The material efficiency is maximally 104% compared to the conventional door and therefore accounts for only a small part of the material waste reduction. The material waste is directly related to the product mass. In other cases, in which holes can be enclosed, material efficiency can play a more important role.

Life-cycle energy consumption

The calculated mass figures are the input parameters for the energy model. Assumptions are made regarding the car- and truck lifetimes. The results are represented in Tables 4.4 and 4.5.

- Annual mileage car 15 10^3 km/year; truck 100 10^3 km/year
- City use car i=20%; truck i=5%
- Welding of the inner-door requires 100 spot welds per door

The results of the energy calculations for this 'door'-example are given in Figure 4.7. The horizontal axis represents the weld position 'h' and the vertical axis represents the reduction of the life-cycle energy consumption relative to the conventional situation. The lines represent the car and the truck case, respectively.

Figure 4.7 shows that the energy reduction decreases for weld positions farther away from the door-side. The maximal energy reduction is realised for h= 0mm, corresponding with the lowest product- and waste mass. For this weld position the reduction ranges from 200 to 350 MJ over the product life-cycle. The energy reduction is positive over the whole range, but drops to values below 100 MJ for weld positions exceeding 160mm. The differences between cars and trucks are small.

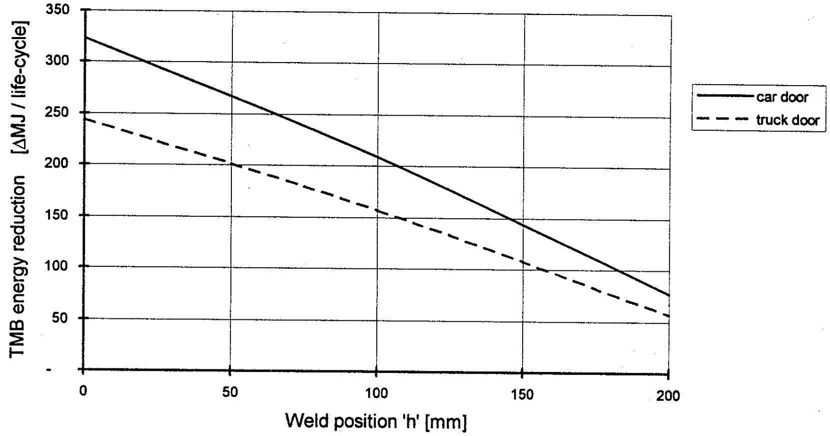

Figure 4.7 Reduction of the energy consumption of a TMB-door relative to the conventional door as function of the weld position 'h'

Relative contribution of life-cycle phases

The impact of the different life-cycle phases on the energy consumption is presented in Figure 4.8. The use-phase is responsible for 80-90 % (dependent of the assumptions) of the life-cycle energy consumption. The next largest contribution, approximately 10%, is made by the material production. The manufacturing itself is only responsible for a few percent of the life-cycle energy consumption. For trucks the distribution of the energy consumption over the life-cycle phases is almost equal.

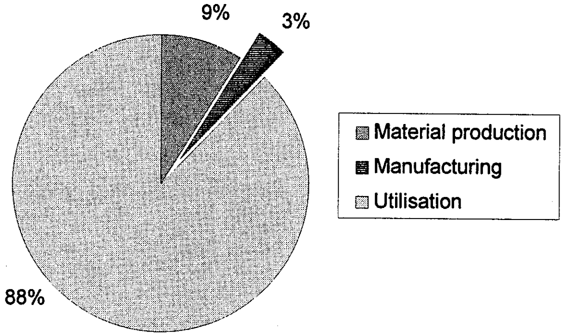

***Figure 4.8** Distribution of the energy consumption over the life-cycle phases of a passenger car*

Consequently the reduction of product mass, which is effective during the product's use-phase, has a stronger effect on the life-cycle energy consumption then the reduction of the waste mass. Calculations for this example show that the reduction of the waste mass by 1 kg has an effect on the energy consumption equal to the reduction of the product mass by 0.06 kg and 0.08 kg for the passenger car and the truck respectively. This sets the objective for the environmentally-friendly design of TMBs.

PASSENGER CAR Energy [MJ]	**conventional**	**TMB** h=0	**TMB** h=100	**TMB** h=200
ore melting	30	24	26	29
scrap melting	44	38	41	44
sheet production	76	65	70	76
material production	**150**	**127**	**136**	**149**
forming	26	22	24	26
spot welding	30	30	30	30
manufacturing	**56**	**52**	**54**	**56**
utilisation	**1503**	**1208**	**1311**	**1428**
crushing	0	0	0	0
magn. separation	0	0	0	0
recovering	**0**	**0**	**0**	**0**
transportation	**2**	**2**	**2**	**2**
TOTAL	**1711**	**1389**	**1503**	**1635**

Table 4.4 Energy consumption for a conventional and a tailor-made door over its life-cycle in a passenger car

TRUCK Energy [MJ]	**conventional**	**TMB** h=0	**TMB** h=100	**TMB** h=200
ore melting	30	24	26	29
scrap melting	44	38	41	44
sheet production	76	65	70	76
material production	**150**	**127**	**136**	**149**
forming	26	22	24	26
spot welding	30	30	30	30
manufacturing	**56**	**52**	**54**	**56**
utilisation	**1100**	**884**	**960**	**1045**
crushing	0	0	0	0
magn. separation	0	0	0	0
recovering	**0**	**0**	**0**	**0**
transportation	**2**	**2**	**2**	**2**
TOTAL	**1308**	**1065**	**1152**	**1252**

Table 4.5 Energy consumption for a conventional and a tailor-made door over its life-cycle in a truck

4.6 Evaluation of tailor-made blanks

The energy model allows for the environmental comparison of the TMBs with the conventional manufacturing process. The results must be regarded with some caution as some environmental aspects are disregarded, like emissions to air and landfills. The analysis has led to TMB design guidelines and insight into the environmental impact of the weld position.

- The reduction of the product mass in cars has a 12 to 18 times larger effect on the life-cycle energy consumption than the reduction of the waste mass. This holds both for passenger cars and trucks. The environmentally-friendly design of the TMB should therefore aim at the reduction of the product mass. The reduction of the waste mass also contributes to the environmental friendliness, but is negligible compared to the effect of the product mass. In some cases an increase of the waste mass can even be acceptable, if this allows a reasonable reduction of the product mass.

- In the door example the reduction of the product mass is reached by omitting reinforcements. A significant improvement of the material efficiency could not be realised. Consequently the material waste varied in proportion to the product mass. For other examples this may differ, as more holes can be enclosed.

- In the door example the weld position has a significant influence on the life-cycle energy consumption. The closer the weld can be placed next to, or in the door radius, the smaller the usage of thick material and the lower the life-cycle energy consumption. This is a challenge for the forming process design.

4.7 Conclusion

The environmental analyses succeeded in the intention to set demands for the technical research. The analyses further confirmed the effect of mass production on environmental impacts. Environmental loads that are negligible at first, can have a significant impact when they are encountered in mass production. For active products this effect is even more pronounced. This underlines the necessity to optimise manufacturing processes and to use the potential in manufacturing to improve the environmental performance of the manufactured products.

Environmental aspects

Although the means-of-production life-cycle (mp-LC) is indicated as relevant for the 'process-related aspects', the mp-LC is hardly taken into account in the environmental analysis performed. The major reason is the lack of available data on the supplier chain, particularly on lubricants and other chemical compositions. As a consequence the impacts in the mp-LC could not be assessed. The analysis concentrates on the impacts of the manufacturing itself. Furthermore the analysis shows that the 'process-related aspects' can not be reviewed fully independently of the product life-cycle (p-LC), as assumed earlier. The lubricants applied on the material scrap, for instance, are returned to the material supplier to be re-melted. Subsequently the lubricants are burned, causing an environmental impact. The relation with the p-LC however is limited and relatively independent of the product design.

The environmental analysis of the 'product-related aspects' corresponded to the expectations. The integrated approach of the life-cycle crossing showed the influence of manufacturing design on the over-all environmental product performance.

Environmental measure

The analyses also showed that the usability of the environmental analysis is largely determined by the environmental measure. In the TMB-case the energy consumption proved to be a valuable measure, although the completeness of the measure can be questioned. The energy approach regards materials as energy carriers [Kop94]. Their use can therefore be compared with respect to the energy consumption in the manufacturing and use-phase. This provides quantitative results that can be used in mathematical comparisons.

In the case of the auxiliaries such a quantitative measure was lacking. It is not so much the energy contents, but the toxic or global environmental impact of these materials that is of interest. Qualitative results make the analysis outcomes less unambiguous.

Auxiliaries

Environmental relevant auxiliaries in forming are preservation or rolling oil, lubricants and cleaning fluids. As these substances are closely related to each other, they should be dealt with using an integral approach.

In the environmental analysis five different impact categories are recognised :

- Evaporation of preservation oil, lubricant and cleaning fluid.
- Burning of preservation oil and lubricant during melting of scrap.
- Discard of used lubricant, preservation oil and cleaning fluid after cleaning.
- Waste/spill of preservation oil, lubricant and cleaning fluid.
- Consumption of water and energy.

Based on these categories, different cleaning and lubrication alternatives are valued. The cleaning process causes the major environmental load. The solvent cleaning fluids have a particularly bad environmental reputation. The alkaline process has other negative aspects like increased energy and/or water consumption. Because the required cleaning process is determined by the applied lubricant, the lubricant selection is an important factor.

Based on these results the selection of a suitable lubricant is the subject of research in Chapter 5. The environmental demands on the lubricant are that it be a) chlorine free, b) removable, and c) that it does not effect the cleaning bathes. The technical demands mainly concentrate on wear prevention.

Tailor-made blanks

As a car is an active product, its energy consumption in the 'use'-phase dominates the life-cycle energy consumption. The energy consumption during the 'material extraction' and the 'manufacturing'-phase are approximately 10% and 1% respectively of the energy consumption in the 'use'-phase. In spite of the small contribution of manufacturing, the production of TMBs can save up to 20% of the total life-cycle energy consumption related to a part. This confirms the environmental potential of TMBs and of manufacturing in general. The fact that these products are manufactured in mass production increases the significance of this conclusion.

Based on these results the technical research (Chapter 6) concentrates on the formability of TMBs for situations in which the product mass can be influenced by process and product optimisation. The weld position will again be a key parameter.

Chapter 5

Lubrication systems and tool wear

From the environmental analysis in Chapter 4 follows that environmentally-friendly forming processes require special lubricants. Unfortunately increased tool wear restricts their utilisation. To ensure a reasonable tool life, the process design requires an optimal combination of lubricant and tool material. This optimisation process is the subject of research in Chapter 5. This chapter deals with measuring methods which enable the selection of suitable lubricants and tool materials.

The research topics are based on industrial cases that have a potential to improve environmental friendliness. In the selected cases the effect of lubricant and tool material is separated. One case, referred to as 'Automatic presses'-case, deals with the selection of a lubricant based on available tools (Sections 5.3 to 5.7). The other case, referred to as 'SBX'-case, deals conversely with the situation that an environmental lubricant (called SBX) is available, but its application leads to unacceptable tool life (Sections 5.8 to 5.12). In both cases product material and tool design are taken as given. The cases are preceded by an introduction in wear phenomena and a presentation of the used test methods (Sections 5.1 and 5.2). The chapter is concluded with the first steps of the realisation phase, as promising tool alternatives are tested in production (Section 5.13).

5.1 Physical background of tool wear

The wear phenomena in metal forming are complex and extensively discussed in literature. An overview has been given by Schey [Sch83]. Schey states that no basic laws of wear have yet emerged and that only some trends can be discerned, which can be systematised regarding wear as a tribo-system. In this thesis an insight in the wear phenomena is required to select and test promising alternatives. Therefore this section deals with the relevant wear mechanisms and the way to recognise them.

Wear is a result of the established tribo-system in the interaction zone between the contacting surfaces. Three physical partners can be distinguished, viz. the tool material, product material and the lubricant. Since the product material is taken as given in the selected cases, the possible alternatives are limited to choice of lubricant and tool material.

Wear

Wear is the change of volume as a result of contacting surfaces. In metal forming processes two major types of wear can be recognised, viz. abrasive- and adhesive wear. Fatigue wear is another wear mechanism that can play a role in intermitting or repeating processes like the stamping process. This wear mechanism is less important for the studied cases and is dealt with shortly in Section 5.9. Other wear mechanisms like corrosive or chemical wear can play a role, but are disregarded here since they are of minor importance.

Adhesive wear results from junctions (e.g. cold welds) between product- and tool material (Figure 5.1). If the junctions have strong bonds, fracture of the junction takes place either above or below the interface of the asperities [Nac85]. The appearance of adhesive bonding is supported by a high similarity of the contact partners (qua chemical composition, structure, etc.), the absence of an intermediate layer like oxides and high roughness, pressure and sliding length. Severe cases of adhesive wear are referred to as 'galling'.

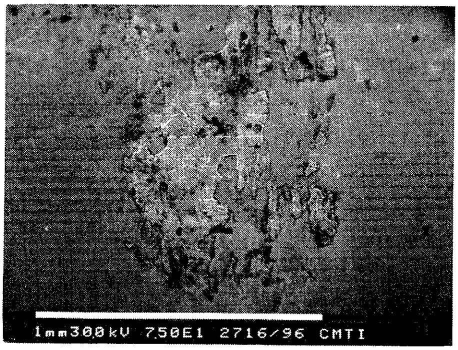

Figure 5.1 *Adhesive wear; Zinc galled to the tool*

Figure 5.2 *Abrasive wear; ploughing through softer contact partner*

Abrasive wear or ploughing is a mechanical phenomena. A projection of the harder partner (two-body type) or a hard particle (three-body type) ploughs through the softer counter part, resulting in a groove (Figure 5.2). Abrasive wear is increased with higher surface roughness, higher hardness difference between the partners, the presence of hard particles and higher normal loads.

Discussion on the physical processes that cause adhesive wear is still going on. To avoid this discussion, the term adhesive wear is defined as the wear behaviour in which material is transferred from one partner to the other, as opposed to the abrasive wear in which the material surface is damaged without the appearance of material transfer.

In most cases the occurring wear constitutes a combination of abrasive and adhesive wear on both tool and product. Galled spots (adhesive wear) on the tool plough through the workpiece material (abrasive wear). This results in increased local pressure and consequently greater adhesive wear. Finally, the pressure becomes so high that the transferred workpiece material breaks, forms a hard particle (Figure 5.3), and initiates new abrasive wear.

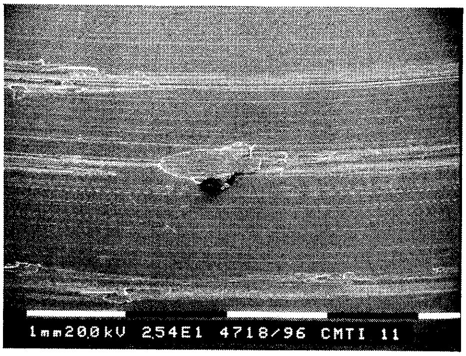

***Figure 5.3** Broken off galled particle on product*

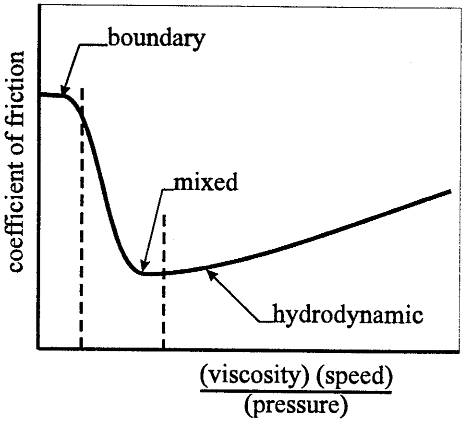

***Figure 5.4** Stribeck curve*

In both selected cases the adhesive wear plays an important role. In the 'SBX'-case the applied material, called INVAR, has a tendency to adhesive bonding due to its high Nickel contents and the absence of oxide layers [Het94]. In the 'Automatic Presses'-case a variety of materials and processes require the application of chlorinated lubricants to prevent adhesive wear. Especially stainless steels and galvanised steels are sensitive to this wear mechanism, as their components tend to adhere to the tool surface. Another category where adhesive wear mandates the application of Cl-lubricants is the processing of thick sheets of Low Carbon Steel (t>1.5mm). For these sheets the normal forces become so high that bonds can occur.

Tribosystems

To describe the behaviour of tribological systems the Stribeck curve is mostly used. This curve recognises three lubrication phases, viz. hydrodynamic-, mixed-, and boundary lubrication, which are characterised by their global coefficient of friction and represented as a function of viscosity of the lubricant, sliding speed and normal pressure (Figure 5.4).

From the wear perspective not the global phenomena (like the coefficient of friction), but the local contact situations determine the resulting wear. In particular when locally the lubrication system breaks and boundary or even dry- or metal-metal contact occurs. In this situation adhesive wear occurs. The lubricant and the tool material play their own role in this perspective.

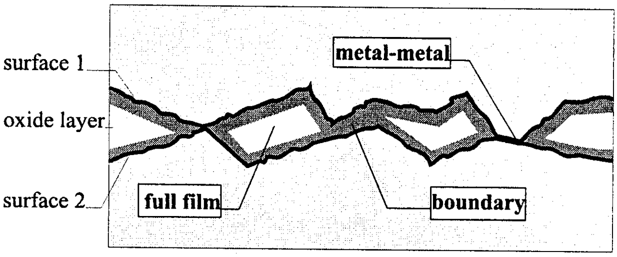

Figure 5.5 The different local contact situations in mixed lubrication regime

Each contact zone can be regarded as a form of mixed lubrication that is composed of a combination of one or more of the following three contact types: full film, boundary and/or metal-metal contact (Figure 5.5). Each contact type has a typical wear behaviour (Figure 5.6) and can be described separately.

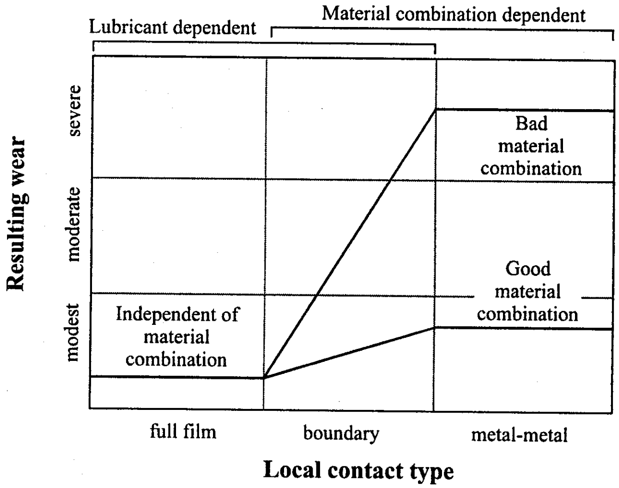

Figure 5.6 Local contact types and the resulting wear in mixed lubrication

The wear in full film contact will be low as the surfaces are separated from each other and are not able to bond or plough. The wear is maximal when the virgin metals touch each other and pure metal-metal contact exists. In this lubrication situation the material combination characterises the wear and thereby the maximum occurring adhesive wear of the system. This is independent of the applied lubricant.

For boundary contacts the wear will be somewhere in between the wear of the full film and metal-metal contact. In this contact situation shearing takes place in the surface layers, like oxides, reacted lubricant dopes, dirt etc..

From this classification of contact situations and wear, the demands on alternative tool materials and lubricants can be derived. The material combination determines the maximum occurring wear in tribological systems. A good tool/product combination has a low wear rate in cases that metal-metal contacts occur, for instance during dry sliding. The lubricant influences the transition from one contact type to an other. A good lubricant will postpone the loss of film separation and prevent the metal-metal contact, by improving the boundary contact, for instance under increasing normal load.

In addition to the used lubricant or material combination other parameters exist, like the material roughness, contact pressure etc., that influence the occurrence of (adhesive) wear. To limit the scope of this work these parameters are kept constant in all tests.

5.2 Test methods to rank tool and lubricant alternatives

The aim is to select a series of tests that enable the selection of an alternative tool or lubricant for industrial application. This requires test methods that discriminate the alternatives as to their wear behaviour as described in Section 5.1. The final result does not require a strict quantitative determination of the options, but requires a judgement about the ranking of alternatives. In this section the realisation of a suitable contact situation and the measurement of the resulting wear are discussed.

Creation of a suitable contact situation

Recent work at Eindhoven University of Technology by Sniekers [Sni96, Tol96] has resulted in a test method to study the tribological aspects of metal forming. The proposed test methods have some advantages over the classical tribological methods to measure wear:

- The imposed stress situation resembles the one during the actual forming conditions;
- The work piece material is not repeatedly passing the tool (like for instance the pen on disk test);
- The work piece material is subject to plastic deformation in the bulk material next to the contact surface;
- The contact situation can be maintained for a contact length corresponding with tool lifetimes ('long-term' tests).

The test methods are capable of generating severe contact situations such as those which occur in deep drawing or bending. The analogy with punching is lower since the intermitting character of the load can not be simulated. The assessment of wear behaviour in punching must therefore be made with some caution, as the possibility of fatigue wear is not incorporated in the tests.

Two different test machines are used for different drawing lengths. In both situations, a metal strip is drawn over a quarter circle length, called the nipple. The load severity can be changed by the back-pull force F_{bp} (BPF, see Figure 5.7).

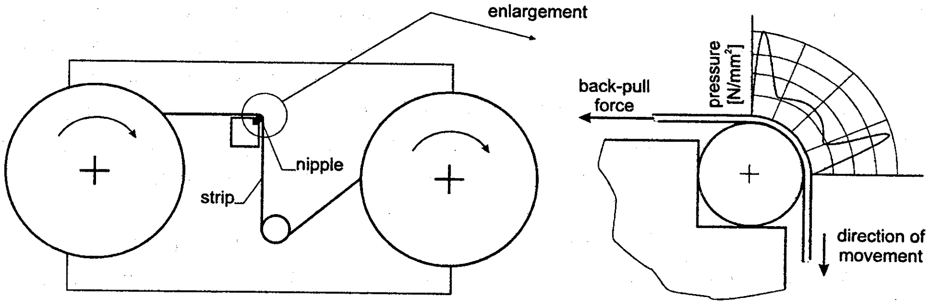

Figure 5.7 *'Long-term' test machine; enlargement of nipple and pressure distribution over the contact area [Sni96, Tol96]*

Figure 5.7 provides a schematic representation of the 'long-term' test machine and the stress distribution over the nipple radius. The sliding length in this test is only limited by the size of the spools. The draw speed is 80mm/s. The forces are measured every second. The imposed test circumstances (sliding length and imposed loads) differ for the tool and lubricant alternatives and are discussed in the accompanying sections. In the 'short-term' tests the drawing length is 60mm and the draw speed is 10mm/s. During the drawing the resulting forces are measured 1500 times. The coefficients of friction are determined by the average value of the measurements.

The measurement of the occurring loads and hence the determination of the coefficients of friction were not optimal at the time of the tests, as the machines are still under development. Therefore the absolute values should be regarded with some caution. However, the reproducibility was reasonable and enabled the ranking of alternatives.

Measurement of the resulting wear

The simultaneous occurrence of different phenomena (like galling) makes it hard to quantify wear. An often used measure is the mass difference (Δm) [Gla93, Jas92, Shu94], because this has a direct relation to the definition of wear (change of volume). But for example a combination of abrasive and adhesive wear may suggest the absence of wear. Schey [Sch83] mentions several other measurement techniques as radioactive tracer techniques, acoustic emission techniques etc. However Schey also mentions that for galling the wear can best be examined visually.

For the visual, qualitative measurement the Scanning Electron Microscope (SEM) is mentioned as the most suitable device [Sch83]. The SEM pictures can be complemented with EDAX (Electron Defraction Atomic X-ray) scans that show the element distribution of a certain area. This enables the detection of product material (e.g. in the SBX-case represented by Nickel) bonded to the tool (e.g. represented by Chromium or Titanium). The SEM pictures are made from both tool- and product surfaces. The interpretation of the pictures is qualitative and requires a certain experience with these pictures.

As indicated before, the coefficient of friction (CF) is a global variable and may therefore have a limited relationship with the resulting (local) wear. Nevertheless, the CF gives a good impression of the development of wear in a defined lubrication situation. In this work the CF is measured to support the visual observations and to examine the relationship between friction and wear behaviour. The CF has been defined as the required drawing force divided by the average normal force.

Another measure to characterise the quality of the tribo-system is its load bearing capacity (LBC). This measure has been defined as the maximum load, in this case the maximal back-pull force $F_{bp,\text{ galling}}$ that the tribo-system can bear before the lubrication system fails and metal-metal contact occurs. The LBC is used to characterise the ability of a lubricant to prevent these metal-metal contacts, and hence the occurrence of severe wear.

5.3 Alternative lubricants

Sections 5.3 to 5.7 deal with the possibilities of environmentally-friendly lubricants. The research is based on the 'Automatic Presses'-case (see also Philips-case, Chapter 3). This case is representative for a manufacturer of many different parts using a variety of materials. Some of these materials put high demands on the lubricant/tool system. Especially stainless steels require frequent lubrication with chlorinated lubricants (Cl-lubricants).

Alternative lubricants are all commercially available. The selection is made based on the supplier's advise for the specific situation. The minimum demands are (Section 4.7): chlorine free, easy to clean by an alkaline process and not destructive to the cleaning fluid. The alternatives are tested on their expected cleanability and lubrication performance. The original Cl-lubricant is used as a point of reference. The research questions are:

1) Are the presented test methods suitable to test lubricants on their wear-preventive qualities and if so, what qualities should be used to rank the alternatives?

2) Are there commercially available, Cl-free, alternatives that perform satisfactory with respect to both anti-wear performance and alkaline cleaning behaviour? If so, are they also satisfactory in practice. If not so, what are the problems?

The subsequent sections deal successively with the lubricants themselves (Section 5.3), their cleaning possibilities (Section 5.4) and the short - and long-term test methods (Sections 5.5 and 5.6). In Section 5.7 the results are discussed, followed by a conclusion.

Lubricant composition

Lubricants in metal forming are functional in full film and boundary contacts and should prevent the occurrence of metal-metal contact under severe loads (Section 5.1). In the full film contacts, the film thickness is sufficient to avoid metal contact. The physical and macroscopic properties (principally viscosity) are important. In more severe contacts the film thickness is reduced to the order of molecules. In these boundary contacts the chemical and physicochemical properties of the lubricant are addressed. The last blockade before lubricant breakthrough is formed by the extreme pressure (EP-)lubrication. The lubricant behaviour is (on a micro-scale) comparable to solid lubricants. If this mechanism fails metal-metal contact and the accompanying wear occurs.

Lubricants generally consist of a carrying oil and a number of chemical additives that enhance the lubricant qualities. In [Nac85] 22 different kinds of additives (each with several active chemical variants) are mentioned, amongst other things emulsifiers, solid additives, thickeners, detergents, antioxidants, odour masks, corrosion inhibitors and Extreme-Pressure (EP-)dopes. All of them effect both the lubricating- and cleaning qualities in their own way. Discussion of all these substances falls outside the scope of this work.

Lubricant selection

The reference lubricant is doped with chlorine additives. This makes it suitable for severe forming processes, in particular for forming of parts made of stainless steel and thick low carbon steel (uncoated and galvanised). Ten alternative lubricants (represented as lub. 1 to lub. 10) are selected. All alternatives are recommended by the supplier for severe stamping processes and are chlorine free. The lubricants are produced by seven different suppliers (represented as sup. 1 to sup.7).

Lubricants		µg **Cl** /ml	µg **F** /ml	µg **S** /ml	**C.C.**	**Description**
Sup. 1	**lub. 1**	≤100	$1,2\cdot10^3$	$120\cdot10^3$	Mo	mineral oil
	lub. 2	≤30	$1,4\cdot10^3$	$80\cdot10^3$	Mo	mineral oil
Sup. 2	**lub. 3**	≤1	$1,6\cdot10^3$	$10\cdot10^3$	-	vegetable oil, S-fatty acid
	lub. 4	≤50	$1,5\cdot10^3$	$16\cdot10^3$	Zn	vegetable oil, S-fatty acid
Sup. 3	**lub. 5**	500	≤300	$18\cdot10^3$	-	par. mineral oil, EP-dopes, anti corrosives.
Sup. 4	**lub. 6**	200	≤300	$10\cdot10^3$	Ca	par. mineral oil, EP-dopes, polar additives, anti oxidants, fatty acid ester
Sup 5	**lub. 7**	≤5	≤2	$8\cdot10^3$	-	
Sup. 6	**lub. 8**	18	190	14	B	oily fats + amine salts
Sup. 7	**lub. 9**	11	≤1	≤1	-	par. mineral oil, fatty acids
	lub. 10	12	≤1	1	-	par. mineral oil, fatty acids
reference	**ref.**	$510\cdot10^3$	-	-	-	-

***Table 5.1** Selected lubricants, including the amount of the Cl-, F- and S-dopes, the major chemical components and the supplier description of the lubricant composition.*

The quantities of the Cl, F and S-dopes, given in Table 5.1, are based on ion-chromatografy. Samples of the lubricants are also investigated on their chemical contents (colomn C.C.). In the last column a description of the lubricant is given by the supplier. Remarkable is the indefinite and inconsistent use of terms.

5.4 Cleanability of lubricant alternatives

The lubricants are tested on their solvent and alkaline cleaning properties and on their effect on the alkaline bath [Pri96]. In addition the evaporation rate is determined (represented in the second column of table 5.2). This rate is determined based on the mass loss after ageing (30 minutes at 150°C) of the samples (two stainless steel variants). None of the lubricants has a clearly volatile character, although the evaporation rates reach up to 22% (lub. 9) and 35% (lub. 8). Just like lubricants 1, 2 and 5 (17%) the in house circumstances for these lubricants should be monitored. Comparison of these results with the cleaning tests reveals that a higher evaporation rate not necessarily means easier cleaning.

	Lubricant evaporation rate	**Solvent cleaning**	**Alkaline cleaning**			
			Sup. 6 (sample 1)	Sup. 6 (sample 2)	Uniclean	Polluting effect on bath
lub. 1	17%	++	-	+	- -	destructive
lub. 2	17%	++	-	+ +	++	destructive
lub. 3	2%	+	-	- -	++	polluting
lub. 4	4%	++	- -	+	- -	destructive
lub. 5	17%	++	-	+		
lub. 6	5%	++	-	++	+ +	small
lub. 7					+ +	small
lub. 8	35%	- -	++[1]	++[1]	+ +	polluting
lub. 9	22%	++	- -	- -	- -	destructive
lub. 10	5%	++	- -	- -	- -	destructive
ref.					- -	polluting

[1] The lubricant- and cleaning fluid supplier are the same.

***Table 5.2** Results of the tests on the lubricant cleaning (- - = very bad, - = bad, + = reasonable, ++ = good).*

The two stainless steel samples are subsequently cleaned by solvent cleaning. This is done using three different solvent cleaning methods (vapour cleaning, vapour cleaning with additional plunging and vapour cleaning with additional ultrasonic plunging). The differences among these three methods are mostly negligible for these lubricants and are jointly represented in column 3. The differences between the two different stainless steels are also negligible. This confirms the ease of the solvent cleaning method regarding the process conditions and product variants. Nevertheless some lubricants are difficult to clean in this solvent. Lubricant 3 shows stains after cleaning and lubricant 8 is even still visible as small drops.

The stainless steel samples are also cleaned in an alkaline cleaning fluid supplied by the supplier of lubricant 8 (supplier 6). The cleaning is performed under mild plunging. The results for the two sample materials are given in column 4 and 5. The results show the possibility to adapt the cleaning process to a specific lubricant, as lubricant 8 is the only lubricant that is trouble-free cleaned by the cleaning fluid. The results with the other lubricants and steel sheets are less univocal. No conclusions can be drawn whether the cleaning fluid works for a certain material or a certain lubricant. The results suggest that a cleaning method works for a particular combination of both. This confirms, as opposed to the solvent cleaning, necessity to control the cleaning process and to adapt it to a specific situation. This suggests that a single lubricant in production would ease alkaline cleaning considerably, although different product materials can still cause cleaning difficulties.

Besides the alkaline cleaning by an adapted cleaning fluid the lubricants are also tested in a standardised (Philips) test method. The steel samples are cleaned in a common cleaning fluid (Uniclean). The results of this test are given in column 6. The polluting effect of the lubricants on the cleaning bath is also investigated (column 7). Again these results have a low similarity with the results of the other alkaline cleaning situations. In general lubricant 2, 6, 8 and possibly 7 make the best over all score. If the effect on the bath quality is taken into consideration, lubricant 6 and 7 have the best potential to improve the environmental performance.

The majority of lubricants are taken along in the wear tests, because the tests suggest that an adapted cleaning fluid will enable alkaline cleaning for most lubricants. Only the lubricants of supplier 7 (Lub. 9 and 10) have been excluded, because their alkaline cleaning is insufficient in all cases and their effect on the cleaning bathes is destructive.

5.5 Short-term wear effects of lubricant alternatives

The lubricants have been tested by the short-term wear tests. This is done on three different product materials, e.g. stainless steel, thick low carbon steel (LCS) and galvanised LCS. All of them are normally lubricated with Cl-doped lubricants. The material samples are cleaned with a solvent prior to lubrication to avoid influence of the preservation oil. The tools were made of standard tool steel. During the experiments the coefficient of friction (CF) has been measured. This results in an average value of the CF over the drawing length [Sni96]. The experiment has been repeated 3 times. Mean values are represented in Figure 5.8.

The short-term tests are not suitable to rate the alternative lubricants satisfactorily. The drawing distance is to short to initiate wear which can be judged visually. Although some lubricants show lower CFs for a certain product material (Figure 5.8), there are no clear trends. None of the lubricants perform better or worse on all points then any other one. According to this test all lubricants could be suitable to replace the reference lubricant.

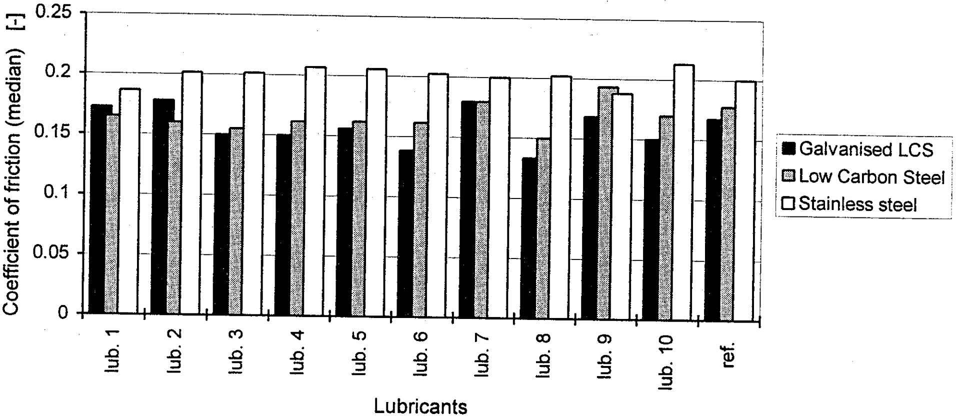

Figure 5.8 *The measured coefficient of friction for the different lubricant alternatives and three product materials*

The test results do suggest significant differences among the product materials. The CFs for stainless steel are some 10% higher then those for LCS. The CFs of galvanised sheets are some 5% lower. In spite of the unclear relation between the CF and wear this reflects the difficulties encountered in practice with the lubrication of stainless steels. The low CFs of the galvanised sheets, in spite of the tendency of zinc to adhere, are probably caused by another mechanism. The zinc layer has a lower shear stress. Asperity deformation requires therefore less force, resulting in lower CFs.

5.6 Long-term wear effects of lubricant alternatives

To limit the number of tests the long-term tests have been performed only on stainless steel (x12 CrNi 17 7, 450 HV). This material showed the highest CF on the short-term tests and is known for its problematic contact behaviour. The tool is again made of the standard tool steel. The tests are performed under an increasing normal load. This load is realised by a step-by-step increased back-pull force (BPF). The maximal BPF is in the order of 3.5 KN. During the tests the strip is controlled on the appearance of wear particles and the forces are measured to deduct the CF. The tools are observed visually after the tests.

Visual observations

The visual observations show galled spots of product material stuck to the tool steel. (see also Section 5.1). These observations can be made by naked eye examination of the tools. The tests show the superior qualities of the chlorine doped lubricant (Figure 5.9). The matching tool does not show signs of wear. Only one single track on the tool indicates the effects of the tests. Few alternative lubricants approximate the wear-preventive qualities of this reference oil. The lubricants of supplier 1 (lubricant 2 and to a lesser degree lubricant 1) performed best (Figure 5.10). The tool shows a limited number of wear tracks. The remaining surface outside the picture is similar to the reference tool. All other alternatives show many tracks of bonded product material (Figure 5.11).

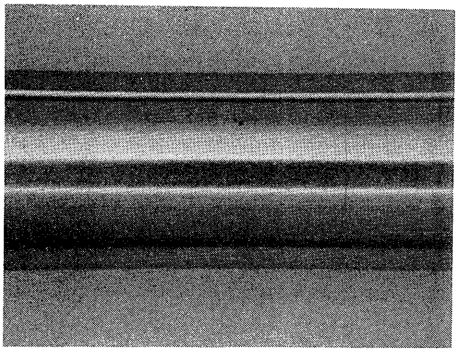

Figure 5.9 *Absence of tool wear for reference lubricant (Cl-doped)*

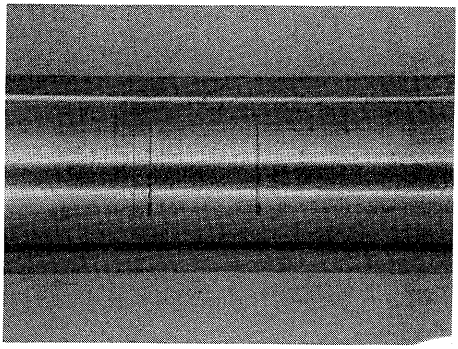

Figure 5.10 *Limited tool wear for lubricant 2*

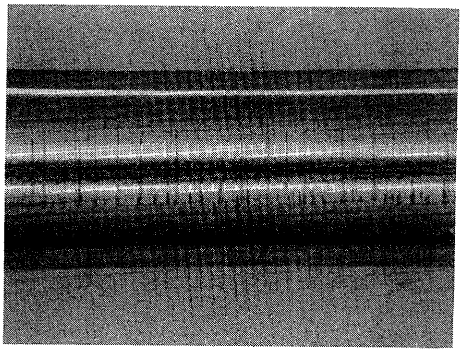

Figure 5.11 *Excessive tool wear, representative for most lubricant alternatives*

The SEM pictures confirm the undamaged surface for the reference lubricant and lubricant 2 (Figure 5.12 and 5.13). Lubricant 2 performs almost equally well as the reference lubricant.

Figure 5.12 *Undamaged tool surface of the reference lubricant (cl-doped).*

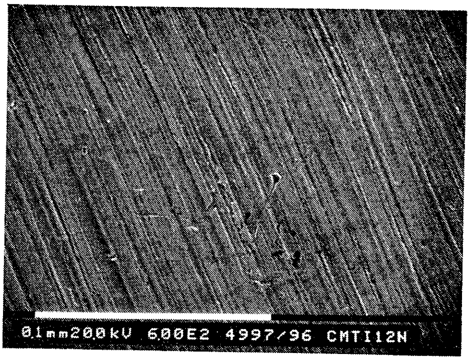

Figure 5.13 *Tool surface comparable to the reference (lubricant 2)*

Although these pictures are representative for the major part of the surfaces, both samples show local spots of adhesive wear (Figure 5.14 and 5.15). The spots lay on otherwise undamaged surfaces. The two wear spots are remarkably different in their appearance. The Cl-doped reference shows a thin layer of adhered product material, which is almost invisible to the naked eye. The wear spot on the tool surface lubricated with lubricant 2 is thicker and less spread out. This wear appearance is comparable to that observed for other lubricants. The deviant wear of the reference lubricant can possibly be explained by the chemical bonding of the Cl-additive to the tool surface.

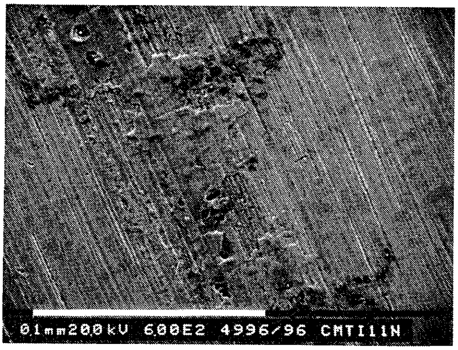

Figure 5.14 *Incidental wear spot on the tool surface lubricated with the reference lubricant (Cl-doped)*

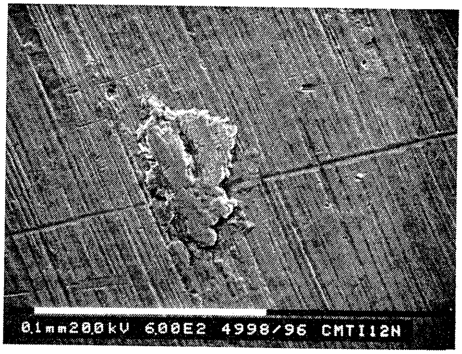

Figure 5.15 *Wear spot on the further undamaged tool surface lubricated with lubricant 2*

All other alternative lubricants (Figure 5.16 and 5.17) show thick spots of galled product material. In Figure 5.16 the orientation of the wear tracks in the direction of movement of the strip is clearly recognisable. Figure 5.17 shows the damaged surface of the tools. The pictures represent the later stages of adhesive wear. Bonded material is visible at several spots. Around these, the surface has a pockmarked structure. This is a result of galled particles braking off, along with a bit of tool material. This is an example of severe tool damage.

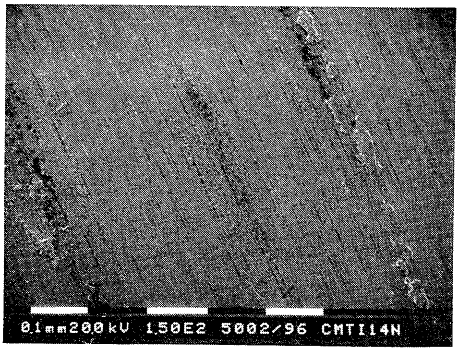

Figure 5.16 *Survey of galled tracks, representative for most alternative lubricants*

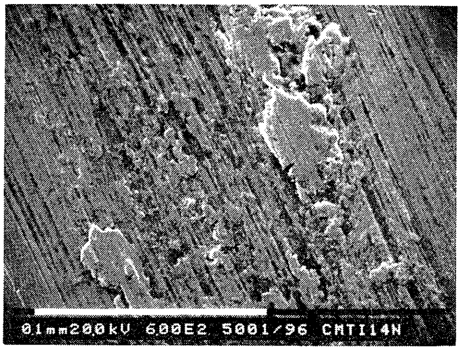

Figure 5.17 *Magnification of galled spot and the heavily affected tool surface around it*

The ranking of alternatives (Section 5.7) is based on these visual observations. The observed mutual differences are confirmed by other measures as the load bearing capacity and the coefficient of friction.

Load bearing capacity

The 'load bearing capacity' (LBC) is the normal force, in this case represented by the back-pull force $F_{bp,\ galling}$, at which the first tracks of galled material are observed. This is a measure that characterises the ability of a lubricant to prevent failure through metal-metal contact. The given numbers are only representative for the applied test conditions. Consequently their validity is limited to cross-comparison. Translation to normal loads is impossible due to the irregular load distribution over the tool (Figure 5.7).

The measurements (Table 5.3) show that the reference lubricant has the highest LBC-value. This matches the expectations, because the Cl-dope is known for its ability to prevent metal-metal contact under severe contact pressures. The second best lubricant is lubricant 2. This corresponds with the visual observations, which led to a similar conclusion. The other lubricants all show a lower LBC.

	$F_{bp, galling}$ [N]
reference	2000
lubricant 1	1000
lubricant 2	1400
lubricant 3	1000
lubricant 4	900
lubricant 5	1200
lubricant 6	1000
lubricant 7	1000
lubricant 8	400

***Table 5.3** LBC of the lubricants*

From the tests the LBC-value emerged as a relevant value for the quality characterisation of lubricants. More than the coefficient of friction the LBC-value relates fundamentally to the demands that are made to the lubricant regarding wear prevention.

The tests as they were performed in this project lacked the refinement to measure small differences in LBCs. As a result the performance of some lubricants can not be distinguished clearly from others. The reason is the course steps of the load increase and the limited measuring precision of the testing equipment. The expectation is that an improved measuring and testing system will result in discriminating values, which are adequate to characterise lubricants.

The coefficient of friction

The fundamental difference between the CF and wear is that wear is a local phenomenon, whereas the measured CF represents the entire contact area. Therefore the coefficient of friction is not a suitable measure to describe the lubricant's ability to prevent wear. Nevertheless the test results show a resemblance between the CF and the results of the visual observations and the measurements of the LBC.

The CFs are measured [Sni96] during the strip drawing under increasing normal load. The values (Figure 5.18) are given as an average values over a period of constant load.

The CF tends to increase under severer loads. A trend change can not be recognised at the moment wear is observed (LBC-value). This indicates that the CF is not the best variable to measure wear. Nevertheless, the lubricants that show the smallest wear in the visual observations correspond with the lubricants with the lowest CF. The CF of the Cl-doped lubricant ranges between 0.07 to 0.13, as does the CF of lubricant 2. All other lubricants have a higher CF.

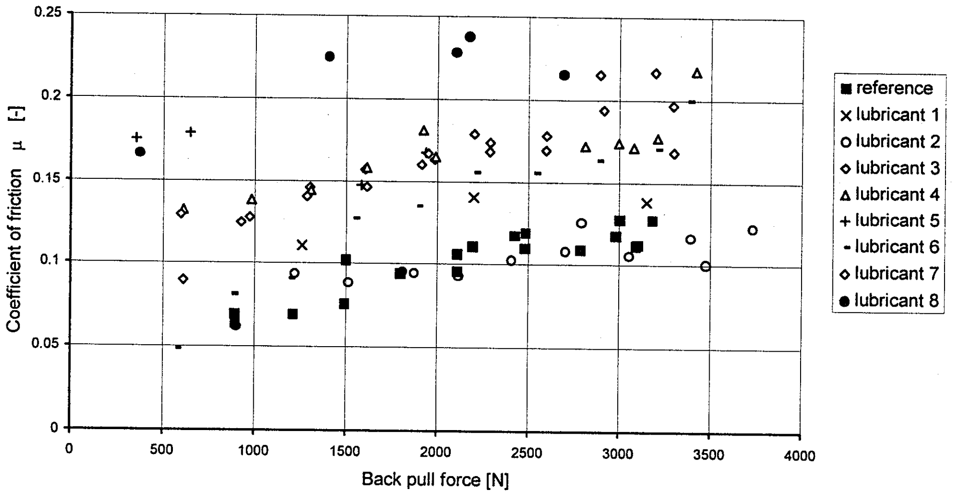

Figure 5.18 The coefficient of friction plotted against the average back-pull force on the strip material for stainless steel to tool steel

5.7 Ranking of the lubricant alternatives and conclusion

The short-term tests are not suitable to study the wear preventing capacity of the lubricants. The visual observations of the worn tools from the long-term tests give the best indication of the wear behaviour. The measurement of the 'load bearing capacity' (LBC) and the 'coefficient of friction' (CF) supported these observations. For future research the LBC is an interesting measure to test lubricants on their ability to prevent wear. The measure is quantitative and represents the demands that are made to the lubricant. The definition of the CF is not related to the occurrence of wear and is therefore less suitable to measure the wear preventing capacity of a lubricant, though the results are in line with the wear observations.

- None of the tested lubricants performs better then the conventional Cl-doped lubricant. Only one lubricant has a comparable performance (lub. 2). All other lubricants perform worse. This conclusion has been based on visual observations, and agrees with the LBC and even the CF. Interpretation of the LBC-values leads to the suggestion that lubricant 5 will perform relatively well (but worse then lubricant 2) and lubricant 8 extremely bad.

- The cleaning tests showed that the alkaline cleaning process is situation dependent, but can be adapted to a particular lubricant-material combination. The solvent cleaning process on the other hand is successful almost independent of the used lubricant-material combination. A number of lubricants perform satisfactorily in the cleaning tests (numbers 6, 7 and 8). The other lubricants can be removed, but require more effort (numbers 1, 2, 3, 4 and 5). Two lubricants could not be removed at all (numbers 9 and 10) and were not used in the long-term performance tests.

The conclusion is that none of the tested commercially available lubricants combines all qualities that make up a good and environmentally-friendly lubricant. Only one lubricant comes close to the reference Cl-doped lubricant, but has a destructive effect on the cleaning bath. The lubricants that have a satisfactory cleaning behaviour showed an unacceptable tool wear. Therefore the economical implementation of an environmentally-friendly lubricant requires a combined approach ensuring better wear resistance of the tools.

5.8 Alternative tool materials

The previous sections showed that environmentally-friendly lubricants generally have inferior lubrication qualities. The application of these lubricants leads therefore to higher demands regarding the wear-preventive qualities of tools. These qualities have been studied on basis of the SBX-case. In this case an environmentally-friendly lubricant is available. This lubricant is called SBX and is a pure mineral oil with a very low viscosity. However, its application leads to unacceptable tool wear if INVAR material is processed. This material has a high Nickel content (36%) and lacks an oxide layer, the combination of which makes it sensitive to adhesive wear. The solution is sought in an alternative tool material.

Sections 5.8 to 5.11 deal with alternative tool materials that possibly perform better than the present tool steel. Next to alternative tool materials the possibilities of coatings are considered [Fra89, Kön95, Sch86]. The aim is to obtain a ranking of and a ranking method for commercially available tool alternatives. The ranking should be based on wear resisting qualities. The research questions are:

1) Are the presented testing methods suitable to test tool alternatives on their wear resisting qualities? If so, what quantities can be used to rank the alternatives?.

2) Do commercially available tool alternatives exist that are satisfactory according to the tests? If so, are they also satisfactory in practice? If not so, what are the problems?

Section 5.8 presents the possible alternatives and makes a selection of suitable materials and (PVD)-coatings [Fid97]. Before the alternatives are tested on their wear behaviour (Section 5.10 and 5.11) the PVD-coatings are characterised by a number of tests (Section 5.9). These tests are a first filter, as the worst coatings fail. In Section 5.12 the results are discussed and concluded with a ranking of the alternative tool materials.

Reference tool steel

The conventional Chromium (12%) steel (denoted as tool steel) is used as a reference to rank the alternative tool materials. This steel is a AISI D_2 variant with special hardening capabilities and is commonly used by Philips for the fabrication of forming tools. This steel is within the range of tool steels an almost optimal choice, due to its good workability, toughness, resistance against push, shock and bend loads and rust-resistant characteristics.

The alternatives are limited to two groups, viz. uncoated steels and PVD-coated tools. Other alternatives are suggested in literature. Especially in the improvement of tool surfaces. These alternatives are less promising in this situation and therefore not included in the tests. Their disadvantages are discussed briefly.

Alternative materials

The alternative materials are Sintered Carbide Metals (SCM) and Sintered High-speed Steels (sintered-HSS). SCMs are composed of hard oxide particles that are bounded in a softer binder. The material qualities can be optimised by choosing the right particle- and binder type and their relative proportion. The general advantages of SCM are the high hardness, reducing the tendency of abrasive wear, and the divergent material structures, reducing the tendency of adhesive wear. The technical disadvantages are the reduced toughness and workability of the material. The latter leads to high tool costs. For working with dynamic loads a Co binder and WC carbides are advised. For this case the GT30 (10-15wt% Co, average WC grain size 1-3μm) is chosen. This SCM-type is a compromise between the desired hardness and toughness. Sintered-HSS steels are more comparable to the reference tool steel regarding their chemical contents and hardness. The advantage of the sintered variant is the homogeneous structure of the tool and a high heat resistance. Their structure reduces the similarity between tool and product material, and hence the adhesive wear. The selected sintered-HSS variants are Mo, W, Cr and V alloyed tool steels, supplied by two different suppliers (called CPM 10V and ASP23).

Coating alternatives

PVD-coatings are known for their high hardness and amorphous like (very fine grains and almost crack free) structure [Vij96]. This combination results in a high wear resistance. A critical aspect of these coatings is the bonding to the substrate.

The coatings are thin (2-10μm) and hard (1000-3000 Hv) layers that are applied on steel surfaces. Different application methods are magnetron sputtering, ion-plating, or vacuum evaporation. The PVD-coating follows the roughness of the substrate. The roughness increase is approximately R_a=0.04μm [Hou92]. The deposited materials are diverse and may consist of metals, carbides, oxides, nitrides, etc.. The PVD-coatings can be divided into two groups, the wear resistant coatings and the non-wear resistant or self-lubricating coatings. The self-lubrication is similar to solid lubricants since the layers in the coating are able to shear.

The application of a coating is a complex totality. The selection of the coating material is not the only determining parameter. Many production parameters influence the final quality. The production optimisation, required for an acceptable coating, falls outside the scope of this thesis. The selection is limited to commercially produced coatings that have a guaranteed availability. The production optimisation is performed by the supplier based on the given manufacturing situation. To study the mutual differences between the suppliers the coatings are acquired from three different companies, indicated as x, y and z.

The selected wear resistant coatings are : CrN (x, y, z), TiN (x, y, z), TiCN (x, z), TiC (z), TiAlN (z), ZrN (z). For the self-lubricating coatings a MoS_2(z) and DLC (z)-coating are selected. The DLC (z) coating is applied in a combination of different layers, of which the under laying have a wear resistant behaviour.

Other alternatives

Several other alternatives are mentioned in literature to improve wear resistance of forming tools. These alternatives are not included in the tests for different reasons. CVD-coatings have largely the same advantages as PVD-coatings, but are above that chemically bonded to the substrate. The application of CVD-coatings requires process temperatures, that exceed the tempering temperature. The succeeding hardening process results in change of geometric qualities. These changes are unpredictable and therefore unacceptable for these stamping applications, as the required die clearance in this case is less then 10μm (5% of the sheet thickness of 0.2mm). Surface improvements like nitrating and ion implementation would require a separate study, because of the number of different possibilities. In addition, these techniques have some disadvantages. Ion implementation results in a very thin layer and nitrating requires temperatures around the tempering temperature. Hard chromium plating is not suitable for stamping application as these layers are not able to with-stand fatigue loads. Their application is limited to deep drawing dies.

5.9 Coating characterisation

Preceding the wear tests, the coatings are tested on their mechanical properties [Fid97]. This is required because the coating qualities are, unlike the materials, not standardised. Primary quality requirements are the coating thickness, bonding strength and hardness. These parameters are respectively tested by the 'ball wear scar'-technique, the scratch test and micro and macro hardness indentation. The results of the scratch test are discussed extensively as they appear to be discriminative.

Scratch test

The scratch test gives an indication of the adhesive and cohesive bonding failure from the coating/substrate combination under the particular load situation [Val86, Per83, Ste88]. The tests have been performed by moving a diamond headed pin over the test piece under an increasing (1-80N) vertical load (Figure 5.19). During the test the acoustic emission is measured. The emission is zero as long as the coating is unbroken. The bigger the travelled way/vertical load (*s*) at coating fracture, the better the adhesive and cohesive bonding of the coating/tool combination.

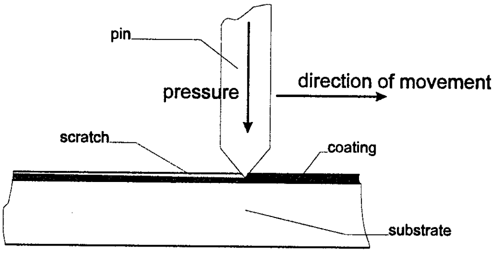

***Figure 5.19** Principle of the scratch test method*

In this case the interpretation of the parameter s is problematic, as the coating thickness varies for the different samples. More important than the load at fracture is the fracture type [Hed90]. From the tests it appeared that there are three categories. Most coating/tool combination have no zone next to the indentation trench in which cracks can be observed (see Figure 5.20). These coatings have a good bonding to the substrate. The TiN (z) coating shows a cracking zone (see Figure 5.21), which can be interpreted as a lesser quality of the bonding. The TiAlN (z) and the CrN (y) coating show a bad cracking behaviour (see Figure 5.22 and 5.23), with large brittle cracks next to the trench and the coating flaking off.

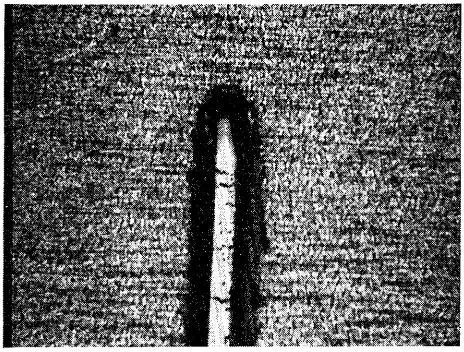

***Figure 5.20** Representative trench with hardly any fractures*

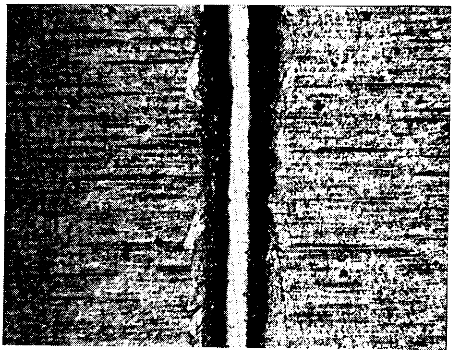

***Figure 5.21** Cracking of TiN (z) coating next to the trench*

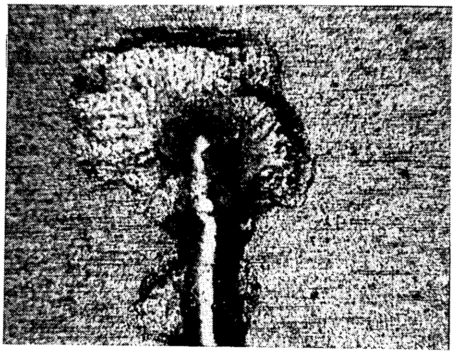

***Figure 5.22** CrN (y) coating flaking off at the end of the trench.*

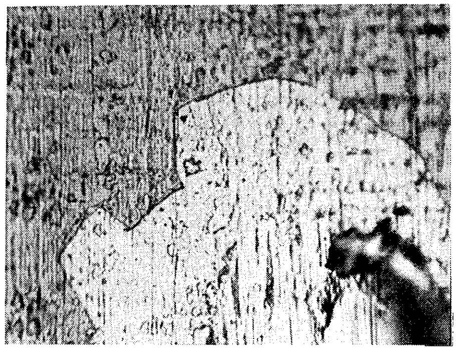

***Figure 5.23** TiAlN (z)-coating flaking off at the end of the trench.*

The conclusion drawn from these tests is that the TiAlN (z) and the CrN (y) coating and to a lesser degree the TiN (z) coating will fail at lower frictional loads, resulting in higher wear. Considering the test situation (a hard ploughing pin) the expectations are that these coatings will fail particularly under abrasive wear conditions.

Thickness

The coating thickness is determined by the 'ball-wear-scar' technique on round coated tools. A rotating ball removes a part of the coating. The resulting surface shows patterns of ellipses from which the coating thickness can be measured. The test could be performed, except for the DLC coating for which the pattern was difficult to distinguish. The resulting numbers are given in Table 5.4.

	sup. x			sup. y		sup. z						
	CrN	TiN	TiCN	CrN	TiN	CrN	TiC	TiAlN	TiCN	TiN	ZrN	DLC
$HV_{0.025}$	2300	2400	3200	2300	2700	1900	2400	2200	2800	3100	2600	1700
thickness [µm]	3.9	3.6	2.1	7.9	4.9	2.4	4.0	3.1	3.7	3.7	3.0	3.5

***Table 5.4** The average micro Vickers hardness (25 gf) and coating thickness for the coatings of supplier x, y, z*

Micro hardness

The micro hardness has a limited validity. The indentation exceeds the ISO 6507 limit of 10% of the coating thickness. For larger indentations the substrate hardness influences the test results. For low indentations depths the variation of the results is unacceptable. The chosen hardness measurement is an approximation that is acceptable according to [Meh85], as the coating thickness is at least equal to the indentation diagonal. The average figures, rounded off to the nearest hundred, are given in Table 5.4. The MoS_2 is not taken along as the thickness (1µm) to low for acceptable values. Mutual comparison of the results and ranking of the coatings is difficult due to differences in coating thickness. Thicker coatings are less influenced by the substrate, resulting in a higher hardness, then thinner coatings.

Nano hardness

The indentations required for the nano hardness are low enough to fulfil the ISO 6507 standard (less then 10% of coating thickness). The nano hardness is measured under a continuously increasing load. The load increases in 60 steps from 40mN to 500 mN. Each load is kept constant during 1 second. A disadvantage of the continuous measurement is that the elastic deformation is not accounted for [Mül95]. This differs from the micro hardness indentation which is measured after the load is removed. Comparison of both hardness measurements is therefore impossible. The nano hardness indentation is measured and translated to Vickers values. The measurements are corrected for shape deviations of the pyramid body at low indentations.

The measurements are performed on stainless steel, as the difference between coating and substrate hardness is to low for the tool steels to distinguish the measured values.

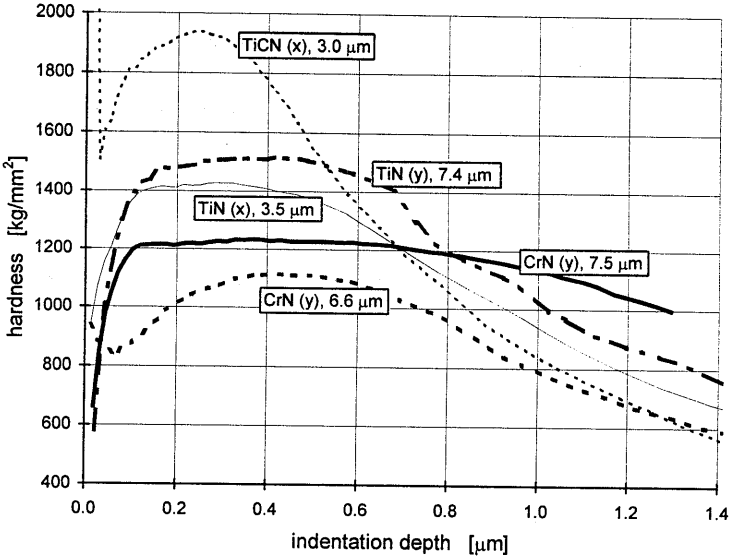

Figure 5.24 The hardness course for increasing indentation depth of some of the coatings

Figure 5.24 shows some initial divergence, but after an indentation of approximately 0.2µm the measurements reaches a constant value. This is the representative hardness. If the indentation exceed a certain value the hardness converges to the substrate hardness. This occurs at approximately 10% of the coating thickness, which is in accordance with the limit given in the mentioned ISO standard. The hardness values show a significant scatter over the measurements, due to samples flatness and other irregularities and contamination.

Fracture toughness

The fracture toughness is an other quality requirement that is related to fatigue wear and contributes to the translation from the wear test to the stamping application. This quality is studied by a micro-Vickers fracture toughness analysis. This method is based on fracture propagation on the corners of a Vickers indentation. All coatings performed well, but the test is difficult to perform and the results are not consistent. Therefore the results are not discussed.

5.10 Short-term wear effects of tool alternatives

The short-term tests provide a first impression on the wear behaviour of the various tool systems. The tests are performed on the strip draw machine (Section 5.2) under dry and lubricated conditions [Fid97]. The used lubricants are the conventional and the environmentally-friendly alternative lubricant (SBX). Each test is repeated three times. The strip material consists of the INVAR Iron-Nickel alloy. The strip width is 30 mm and its thickness is 0.2 mm. The nipples have a radius of 6 mm and are made of the tool materials and surface layers presented in Section 5.8.

The tests were to short to the study the wear behaviour. The tool surfaces showed neither signs of abrasive nor adhesive wear. The strips were only slightly scratched, but not sufficiently to enable ranking of alternatives. The results are therefore limited to the coefficients of friction (CF). The measured average CF value ranges from μ=0.18 to μ=0.49 and has a reproducibility over the three repetitions of approximately 0.01. This points to mixed/boundary conditions. The only exceptions are the MoS_2 (μ_{dry}=0.14) and TiN (y) (μ_{dry}=0.54 and η_{sbx}=0.78). The measurements are presented in Figure 5.25.

The application of the alternative lubricant (SBX) results in higher CF values than for dry conditions. This confirms the limited possibilities of the alternative lubricant. The lubricant apparently worsens the tribological system. The results can be explained by the idea that the alternative lubricant destroys the possibility of the surface layers to establish boundary condition by cleaning the material surface. The alternative lubricant is very thin and volatile and possibly removes the preservation oil applied by the steel manufacturer. This situation is representative for almost all tool systems, except for CrN (y). The lubrication with the conventional lubricant shows the expected decrease of the CF compared to the dry situation (not represented).

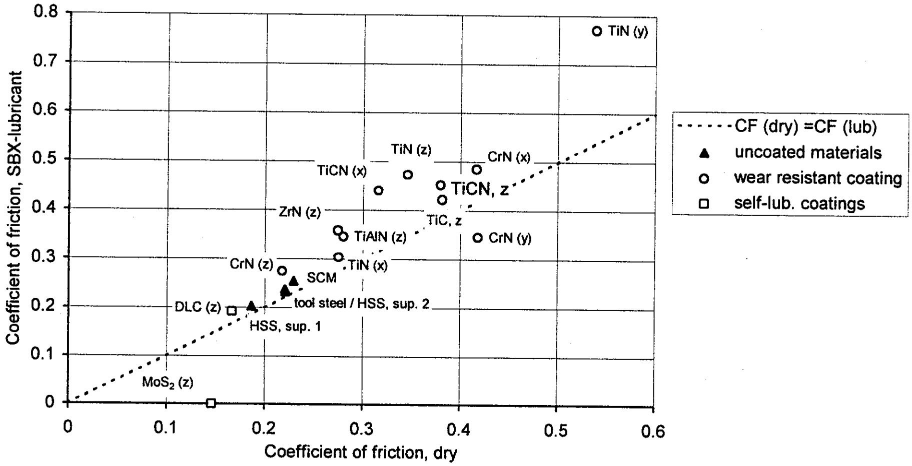

Figure 5.25 Measured coefficients of friction on the short-term (drawing length 60 mm) strip draw machine under dry and lubricated (SBX) conditions.

The CF value for the different uncoated tools under dry friction conditions lays between $\mu_{dry}=0.2$ and $\mu_{dry}=0.25$. Only slight mutual differences are observed. The measured average values for the CF of coatings are significantly higher. The range for coated tools under dry conditions is from $\mu_{dry}=0.22$ to $\mu_{dry}=0.42$, The higher CFs compared to the uncoated tools can be explained by the hardness difference between coating and strip material. Adhesion of the uncoated tools and a subsequent high CF-values can not be established within a 60 mm drawing length. The only exception is formed by the TiN(y) coating that showed a $\mu_{dry}=0.54$. A possible reason for this exceptional CF is maybe found in the small metal particles that originated during this test.

The self-lubricating coatings (DLC and MoS_2) showed an aberrant friction pattern, as their CFs were lower than those of the uncoated steels ($\mu_{dry}<0.2$). This is explained by the 'self lubricating' characteristics of these coating types, as shearing takes place in the coating. The tool surfaces did not show signs of wear over the sliding length of 60mm. The lubrication of the DLC-wear coating with the conventional lubricant did not show a divergent CF compared to the dry tests. This means that the shearing mechanism dominates the tribological system, even in a lubricated situation. For this reason the test with MoS_2 (also developed for its self-lubricating qualities) is only performed under dry conditions.

Based on the results of the short-term tests it is not possible to rank or exclude tool alternatives. A CF could be determined for the applied conditions. The results pointed towards differences in the friction mechanisms between uncoated tools, coated tools and non-wear resistant coated tools. The validity of the CF in absolute terms has not been investigated.

5.11 Long-term wear effects of tool alternatives

The long-term experiments have been carried out under dry and lubricated conditions [Fid97]. For the lubrication the alternative pure mineral oil has been used (called SBX). As a reference one experiment has been carried out with the conventional doped lubricant in combination with a standard tool steel nipple. The experiments have been carried out during a fixed period of time and a fixed back-pull force (BPF). The duration and severity of the experiments is chosen such that wear is observed for the best test combinations without complete worn out surfaces for the worst combinations. This has led to 5 minute tests under dry conditions with a BPF of 800N and 15 minute tests for the lubricated combinations with a BPF of 1000N.

Tool steels

The uncoated tools showed tracks of strip material bonded to the tool. This adhesive mechanism dominates the wear and results in ploughing of the galled particle in the strip. This is schematically represented by Figure 5.26. The wear/galling is initiated at the location of the highest pressure peak, just before the strip leaves the nipple. As the test proceeds the INVAR builds up in the direction opposite to the strip movement.

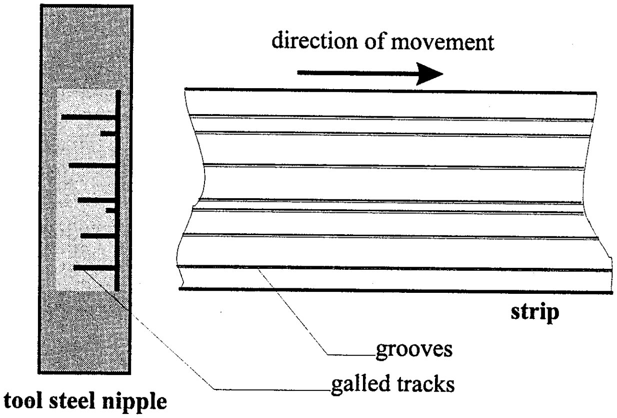

Figure 5.26 Schematic representation of tool and strip wear for uncoated tool steels

A representative example of this mechanism has been observed for the standard tool steel under lubricated conditions, and is earlier encountered during the tests with the alternative lubricants. The nipples (Figure 5.27) show a limited number of wear tracks that consist of galled strip material. This is confirmed by the EDAX, that proves the presence of INVAR through the detection of Nickel. The track width increases for more severe wear. The galled tracks tend to grow longer and broader. The tracks width for normal tool steel are in the order of 0.1 to 0.3mm after the tests. An important observation is that the galling is always a local phenomenon. It is assumed that the strip is carried on the galled particles. This reduces the pressure on the rest of the tool surface, leading to reduced wear between the galled tracks. The local character of wear causes the discrepancy with the measured, global CF.

The galled INVAR particle causes deep ploughing grooves in the strip (Figure 5.28). It is observed that, although the galling takes place at specific spots, the position of the ploughs can vary during the tests. This indicates that galled particles disappear and re-appear somewhere else. This results in intermitting values of the CF.

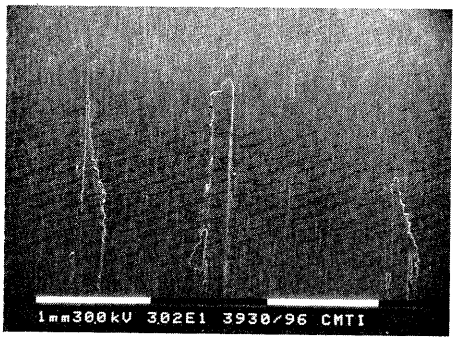

Figure 5.27 *Wear tracks of galled strip material on tool steel nipple*

Figure 5.28 *Wear tracks in the strip after sliding on tool steel nipple*

The dry wear on the conventional tool steel is so strong that the strip breaks before the test conditions are reached, at a back-pull force of 600 N. In the 30 seconds it takes to reach this load the galled spots grow to a width of 0.3 mm (Figure 5.29). The picture gives an impression of the plastic deformation that takes place in the galled material.

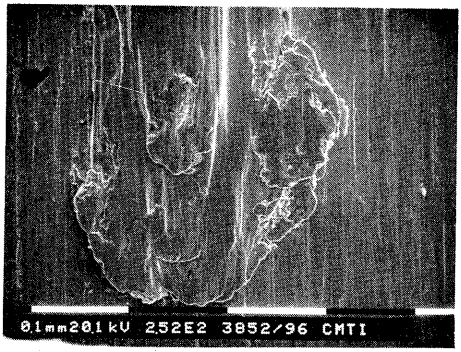

Figure 5.29 *Excessive galling of INVAR on uncoated tool steel*

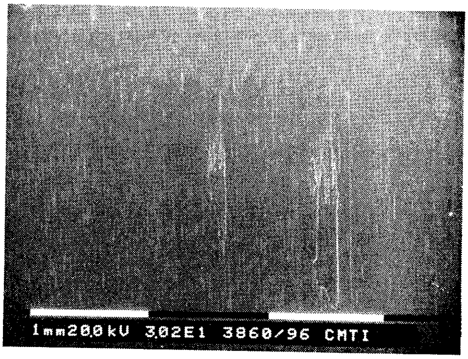

Figure 5.30 *Galled tracks of INVAR on sintered-HSS tool*

The tested sintered-HSS nipples (Figure 5.30) show mild adhesive wear under test conditions. Only a few galled tracks are observed. The sintered carbides (SCM) do not show any wear at all, neither in the lubricated nor the dry test conditions. Even the SEM pictures do not show any sign of wear. These pictures are not included here, because the surface is nearly immaculate. The adhesive wear mechanism of these SCM tools is only observed under extreme test conditions.

These observations confirm the better performance of the SCM and sintered-HSS tools compared to the normal tool steel, as mentioned in the material selection.

Coated tool steel

The visual observations of the coatings show a wear mechanism that differs from that of the uncoated tool steels. The abrasive wear mechanism dominates the wear behaviour of the coated tools. The adhesive wear mechanism is only observed at a micro scale. The typical wear mechanism of the coated tools is schematically represented by Figure 5.31.

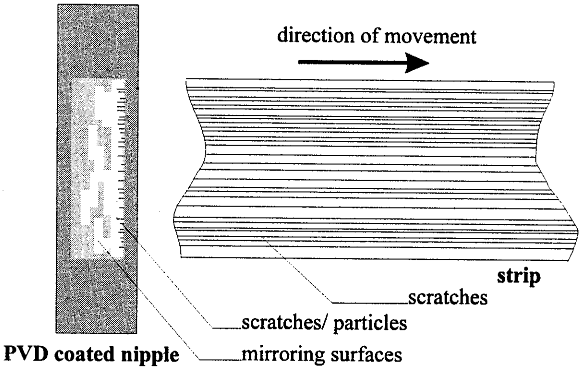

Figure 5.31 Schematic representation of tool and strip wear for coated tools

A representative example of this mechanism is observed at the TiN (x) coating, lubricated with the pure mineral oil (Figures 5.32 and 5.33). The strips show shallow scratches that are spread over the contact area. The performance of different coatings can be evaluated through the severity of these scratches and the coating surface appearance. The coating surface shows an increasing mirror effect with increasing wear accompanied by fine particles. The particles and a large number of scratches concentrate in the high pressure area where the strip leaves the nipple.

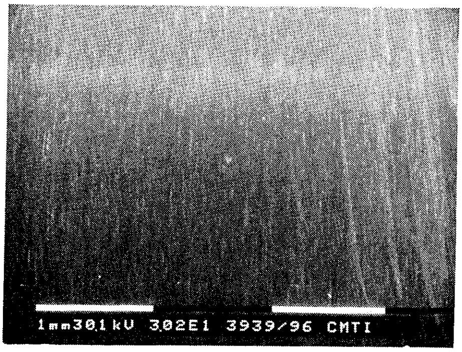

Figure 5.32 Hardly worn TiN (x)-coated tool after lubricated sliding to INVAR strip material

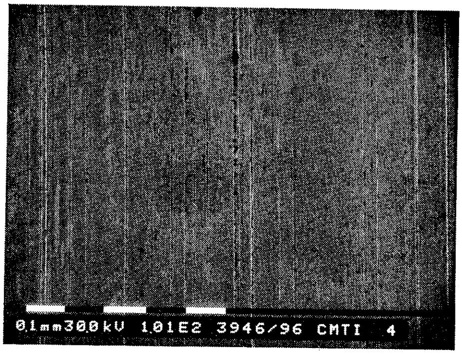

Figure 5.33 Light abrasive wear on an INVAR strip after sliding to TiN (x)-coated nipple

Adhesive wear, like the forming of visible tracks at tool steel nipples, has not been observed. The coatings show local spots of material transfer (Figure 5.34). This adhesive wear takes place on a micro scale. The bonded particles are the light grey spots on the picture. The size of the particles is in the order of magnitude of 5μm to 15μm (appr. 10 to 20 times smaller than the typical adhesive wear for uncoated tool steel). This micro scale bonding of strip material to the coated nipples is spread over the total contact area. This phenomenon has been observed for almost all coatings. It can be assumed that these particles are responsible for the scratches on the strip.

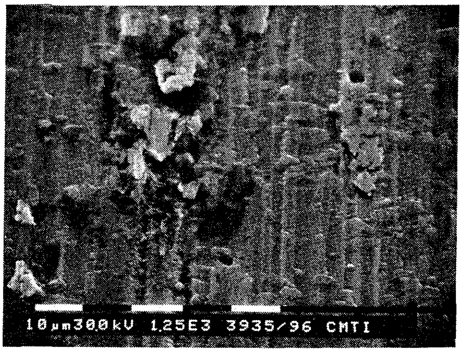

Figure 5.34 *Micro scale adhesive wear on TiN (z) coated nipple after dry contact with INVAR*

Some coatings show different wear patterns as a result of coating failure. The TiAlN (z) coating is locally worn away (Figure 5.35). Where the coating has disappeared tracks of bonded strip material can be observed. This resembles the wear behaviour of the substrate material. These piled up tracks grow until their thickness exceeds the coating thickness. Subsequently the strip is carried by these tracks. This situation prevents further wear of the coating itself. It is unclear whether the coating failure is a result of global coating wear or of local failure of the bonding between substrate and coating.

The TiN (x) coating showed local failure of the bonding between substrate and coating, without substantial global coating wear (Figure 5.36). The coating has disappeared in a circular area with a diameter of approximately 40 μm. The hole in the coating shows the substrate material with the original finishing grooves. The substrate has probably not yet contacted the strip material, as no new signs of wear are observed. This wear mechanism is not common. The shown spot is the only one found, for any coating. Initially it was expected that this failure mechanism would play an essential role in the failure of coated tool systems. This has not been confirmed by the tests.

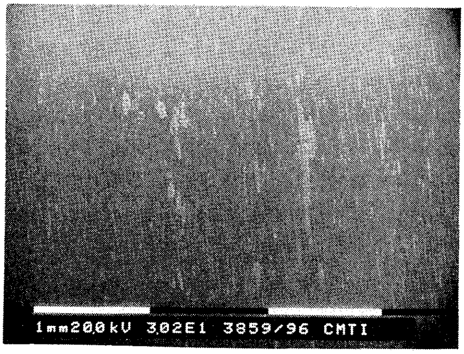

Figure 5.35 *Failure of the TiAlN (z) coating and resulting adhesive wear*

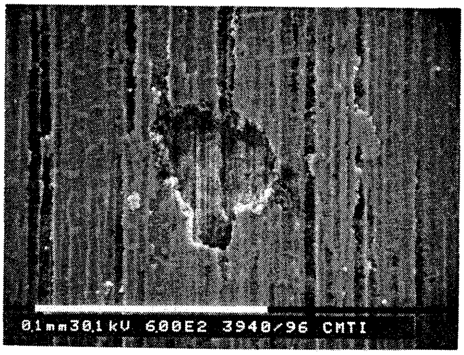

Figure 5.36 *Local failure of the TiN (x) coating without adhesive wear*

Self -lubricating coatings

The short-term tests confirmed the low CF that characterise the self-lubricating coatings, DLC and MoS_2. This is a result of shearing of the layer and therefore self-lubricating character. The long-term tests show that due to this mechanism the wear coating disappears. The effect of the wear coating itself is limited to a few meters strip displacement, for as well the DLC as the MoS_2 coating. When the self-lubricating layer has disappeared the underlying surface dominates the wear behaviour. The underlying surfaces differ for the tested coatings. The MoS_2 coating is directly applied to the uncoated tool steel. The DLC coating lies on a previously applied hard coating (a TiCN) that corresponds more or less to the other coatings.

Figure 5.37 *DLC-coated nipple with worn off upper coating (DLC) and micro scale adhesive wear on under coating*

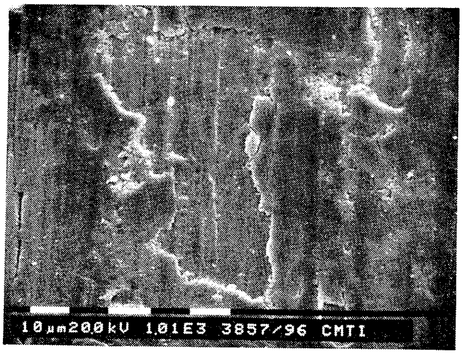

Figure 5.38 *MoS_2 -coated nipple (sliding length 8 meter) with flaking off coating and large areas of uncoated tool material*

The wear of the MoS_2-coating is so severe that the strip broke after a few meters drawing length. Figure 5.38 shows the broken and largely disappeared rests of the coating. The central area shows the substrate material. This pattern dominates the total tool surface. The general appearance of the strip corresponds to the results of the uncoated tool steel. The DLC coated tool (Figure 5.37) shows elongated spots of

INVAR (light grey/white), which are present on the rests of the DLC layer. The size of these spots is of the same order of magnitude as the micro adhesive wear, observed at the other coatings. The elongated shape of the spots is probably caused by the confinement of the INVAR particles in the grooves that originated due to the wear of the layer. These wear grooves are perpendicular to the finishing grooves. The INVAR spots are probably the cause of the relative deep grooves in the strip material.

Coefficient of friction

Figure 5.39 shows the measured coefficients of friction over the drawing length. The dry tests are drawn over a length of 24 metres, the lubricated tests over 72 metres. The tool steel under dry condition is an exception, because the wear was so severe that the maximal force could not be reached and the strip broke after approximately 20 meters. The shown lines are an approximation of the measured values.

The dry contacts result in higher CFs then the lubricated contacts. In contrast to the short time strip draw test this holds also for the SBX lubricant The sintered-HSS tool in combination with the SBX lubricant performs particularly well, as the resulting CF is lower than the reference situation.

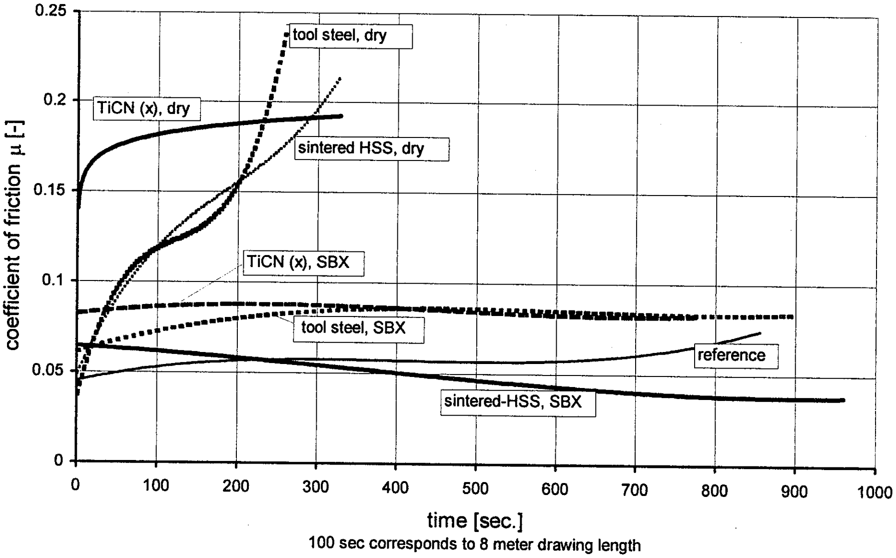

Figure 5.39 Development of the CF in time for different tool materials under dry conditions

The absence of an unambiguous relation between the CF and the wear is again confirmed by Figure 5.39. The uncoated tool shows a similar CF as the coated tool under lubricated conditions, whereas the wear patterns are completely different. Another example is that the mentioned low CF-value of the sintered-HSS tool is not accompanied by the lowest wear. A high CF should therefore not necessarily be interpreted as severe wear. This confirms the distinction between the local character of the wear mechanism and the global character of the CF. The CF is therefore unsuitable for the prediction of wear and life time expectation and is definitely no suitable measure to rank the tool alternatives.

In certain situations the development of the CF through time is more meaningful. An increasing CF can generally be explained through the occurrence of severe wear. For situations in which the wear is moderate or almost absent, the CF-value stabilises at a certain level. But even this suggestion of a relationship between CF and wear must be regarded carefully. The relationship will e.g. not hold in a situation where a coating (large real contact area, high CF and a low wear) fails and changes into sliding on locally adhered product material (small real contact area, low CF and a high wear).

Influence of lubrication

The experiments suggest that the wear mechanisms do not change by the application of the alternative lubricant. The effect of the lubricant lies in the reduction of the wear severity. Even for the alternative lubricant, that showed a higher CF in the short-term experiments then under dry conditions, the reduction of observed wear was considerable.

The observations under lubricated conditions are closer to each other than the observations under dry conditions, which makes it more difficult to evaluate the tool alternatives on their relative performance. Ranking of the tool alternatives can therefore best be done using the results under dry conditions.

5.12 Ranking of alternatives and conclusions

It is possible to rank the tool alternatives on their ability to prevent wear under poor lubrication circumstances on basis of the test results of the long-term strip draw tests. The visual observation appeared to be sufficiently distinctive, but the test results do not allow a quantification of the relative positions in the ranking, nor do they allow a translation into tool lifetimes. The coefficients of friction proved to be inadequate to rank the alternatives on their wear-preventive qualities.

Ranking

The ranking has been based on dry conditions, since these give the clearest differences among the alternatives. The ranking has been performed by direct mutual comparison of the tools and strips. The pictures presented in Section 5.11, are useful to determine the wear mechanism, but lack the oversight of the complete tool.

Due to the different wear mechanisms the coatings and tool steels can not be ranked in one group. Generally coatings perform better then uncoated tool steels. The self-lubricating coatings tested in this tests performed worst. The ranking of the tools steels, the coatings and the self-lubricating is as follows:

- In the group of the uncoated tools the sintered carbides (SCM) perform best, followed by the sintered High-speed Steel (sintered-HSS). The reference material showed the highest wear. The tests did not provide differences among suppliers of the sintered-HSS tools.

- The ranking of the coating systems is presented in Table 5.5. Although the difference between best and worst coatings is significant, mutual differences are sometimes small. Therefore the ranking is presented in four categories. The coatings in category 1 hardly show signs of wear. The category 2 coatings show modest wear on nipple or strip and category 3 coatings show wear on both contact surfaces. The coatings in category 4 failed and show heavy wear.

RANKING					
cat.	**category description**	**coatings**			
1	hardly any wear	TiN (x)	CrN (x)		
2	modest wear on tool or strip	TiCN (x)	CrN (y)	CrN (z)	
3	modest wear on tool and strip	TiC (z)	ZrN (z)		
4	severe wear	TiAlN (z)	TiN (y)	TiN (z)	TiCN (z)

***Table 5.5** Ranking of the coatings*

The ranking suggests that the coatings of supplier ‘x’ perform better than the comparable coatings of the other suppliers. The TiN (x) is ranked in the best category, while the TiN coatings of supplier ‘y’ and ‘z’ are ranked in the worst category. A similar conclusion can be drawn for the TiCN-coating. These results lead to the remarkable conclusion that the selection of a supplier is more decisive then the selection of a coating type. The CrN coating of all suppliers performs better than the average, although supplier ‘x’ also supplies the best CrN coating.

- The self-lubricating coatings are not included in this ranking as their wear mechanism differs too much. Both the DLC and the MoS_2 coating showed to be incapable to withstand the applied loads. The coatings wear too fast, due to their shearing characteristics. This makes them, at least for the time being, unsuitable for forming applications. Under the given load situations the DLC coating performed better then the MoS_2, but this is not necessarily valid for the entire application range of these coatings. The underlying coating layer is responsible for the relatively good performance of the DLC-coating.

Conclusions

The ‘long-term’ tests are an useful measuring method to study the development of wear for a particular stress condition. Product and tool material combinations can be tested under constant load and for a fixed time. The scratch test excludes unsuitable coatings, based on the resistance against abrasive loads. The coefficient of friction is not a suitable parameter to rank tool material alternatives, as the measured global coefficient of friction does not capture the local friction and wear situation.

In the tests, PVD-coatings show a wear pattern which is essentially different from uncoated tool steels. This makes it impossible to compare a single coating to a single tool steel. Within the separate groups a ranking can be made based on visual observations. In general PVD-coatings show a better resistance against galling then tool steels.

The results of these tests show that the quality of a coating system depends more on supplier selection than on coating type selection. This emphasises the complexity of PVD-coating application. The self-lubricating coatings confirm their ability to replace the lubricant, but failed because of their high wear rates.

5.13 Production tests

The laboratory tests showed that environmentally-friendly alternatives meet the technical demands. The environmentally-friendly lubricants proved to be too poor to be applied without an adaptation of the tool material. The tests of the alternative tool materials gave successful results. Nevertheless, there are some technical constraints regarding application and selection. The question remains whether the laboratory tests are predictive for production application. Section 5.13 is therefore aimed at production tests. Since the performance of the alternative lubricants in the laboratory tests was poor, the production tests are focused on the alternative tool materials.

Test circumstances

Tests are carried out on a die that cuts the product loose from the strip material. The cutting length is approximately 5mm. The die is made of the reference material (AISI D_2) and two alternatives, viz. a sintered-HSS and a coated tool steel. The sintered-HSS was chosen for its high wear resistance, which is better than the reference tool steel according to the long-term strip drawing test. As both sintered-HSS variants performed equally well, the choice was made via the supplier relation. The applied coating, a TiCN, is acquired from the supplier that had the best overall performance. This coating is selected prior at the expense of the coating with the best test result (TiN). The consideration for this decision is that the stamping process also requires a high hardness to withstand peak loads. The TiCN coating combines a good resistance against adhesive wear with a high hardness. The top of the coated tool is removed so that the test situation is comparable to the practice of maintained tools.

In spite of the good ranking in the laboratory tests, the SCM alternative is not taken along. It was not possible to make the required screw thread using this material. Other disadvantages are: high working costs, high surface roughness and an unacceptable lack of toughness for the specific stamping process.

The dies were tested in normal production runs of approximately 2.0 10^5 strokes. The product material is the Fe-Ni alloy (INVAR). The die-clearance was measured and set to 5% of the sheet thickness (0.2mm), according to the tool design. The tests were performed with the conventional lubricant. Lubrication with the environmentally-friendly alternative requires a tool set in which all critical parts are made from the alternative material. This was not achievable. Lubrication with the conventional lubricant means that the test results do not allow judgement of the applicability of the alternative SBX lubricant. The results demonstrate the performance of the alternatives relative to the conventional tool steel under stamping conditions.

Results

The performance of the alternatives was ranked by visual observation of the wear mechanisms and of the burr height of the product's cutting edge. The visual observations are supported using SEM pictures. Figure 5.40 shows the view perspective of these pictures.

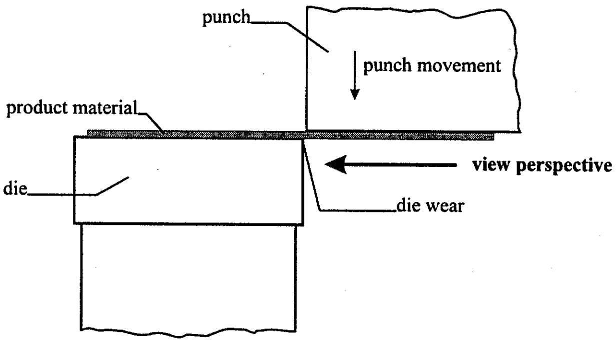

Figure 5.40 Stamping situation of the production tests and the view perspective of the SEM-pictures

The observed wear mechanism differs for the coated and the uncoated tools. This resembles the observations from the long-term strip draw tests. All tools show edge wear, since the edge has changed from a sharp to a rounded shape. Moreover, the uncoated tool steels show abrasive side wear, which is indicated by grooves on the side of the tool over approximately half the sheet thickness. This side wear is not observed for coated dies. Consequently, the wear area on the coated tools is limited to a fraction of the sheet thickness.

A characteristic observation for both uncoated tool steels is the spots of product material on the tool, which mark the transition of edge wear to side wear. These spots are bonded to the tool and form the head of dams that separate the grooves. It is expected that these adhered spots, though relatively insignificant relative to the total surface damage, mark the initiation of abrasive wear and hence the wear severity. In no situation wear is observed at the top of the die.

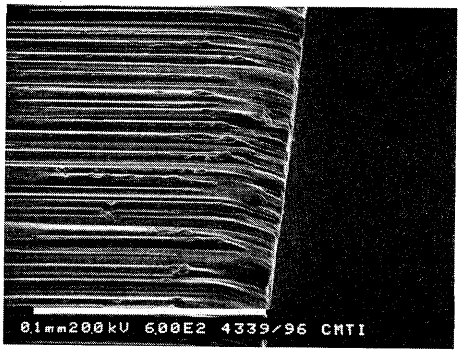

***Figure 5.41** Wear of the conventional tool steel die*

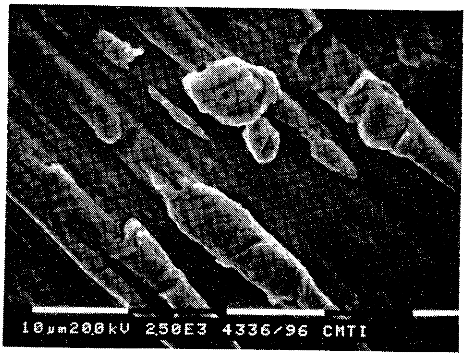

***Figure 5.42** Enlargement of the bonded product material at the transition of edge wear and side wear (conventional tool)*

The resulting wear of the reference tool steel after 2.0 10^5 strokes is shown in Figure 5.41. The cutting edge is situated on the right side of the picture. The product material moved along the die from right to left. The picture shows the edge wear, the zone of abrasive wear, and the adhesive bonded INVAR particles, which are enlarged in Figure 5.42.

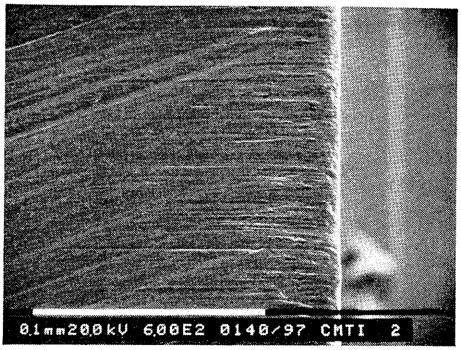

Figure 5.43 *Wear of the sintered-HSS die*

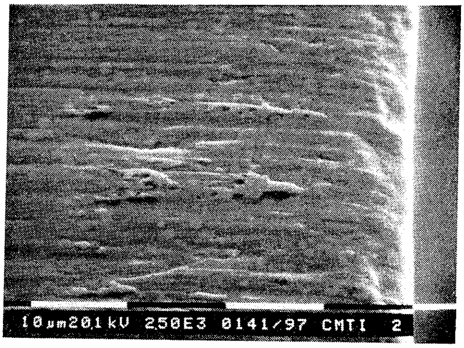

Figure 5.44 *Enlargement of the bonded product material at the transition of edge wear and side wear (sintered-HSS).*

Figure 5.43 shows the wear on the sintered-HSS die after $1.7 \cdot 10^5$ strokes. The cutting edge is situated on the right side, the material moved from right to left. Compared to the conventional tool steel the abrasive grooves are less severe. The adhesive bonded particles are smaller, as can be seen in Figure 5.44.

Although all circumstances considered to be relevant for the occurrence of abrasive wear (surface roughness, hardness difference, die clearance, etc.) are equal for both uncoated tools, the occurring abrasive wear differs significantly. Therefore it is assumed that the different inclination to adhesive wear, as observed in the laboratory test, is responsible for the difference in abrasive wear between the uncoated tools. This idea is supported by the presence of adhered spots of product material on the tool, since the spots on the sintered-HSS are smaller than the spots on the reference tool steel. This has an effect on the abrasive wear.

Figure 5.45 shows the wear of the PVD-coated die after $1.7 \cdot 10^5$ strokes. The cutting edge is situated on the right side; the material moved from right to left. Compared to the conventional tool steel the wear is negligible, as only the tool edge is worn. The wear at the sides of the die does not occur. The die side shows the vertical tracks of the die finish. Figure 5.46 shows an enlargement of the edge wear. The cutting edge is the top of the picture; the material moved downwards. This enlargement shows the local removal of the coating. This is confirmed by the EDAX. The substrate material (the conventional tool steel) emerges at the surface. This results in adhesive bonding of the product material to the die, comparable to the tool steel dies. In this stage the wear has a mild character, but in longer production runs this process can possibly reduce the tool life of the coated tool.

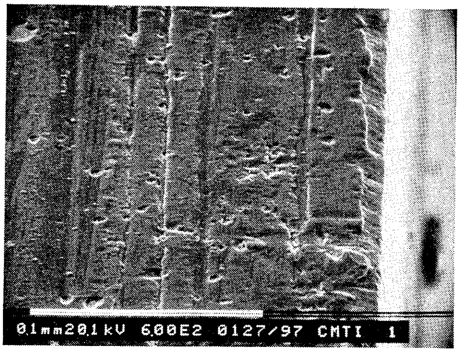

Figure 5.45 Wear of the PVD coated die

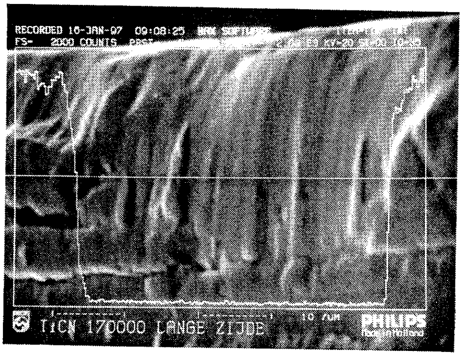

Figure 5.46 Enlargement of the die edge wear (PVD coated die)

Burr height

In practice the tool wear during punching is often monitored by measurement of the burr height. This is also done in these tests. In Figure 5.47 the maximum measured heights are given for different numbers of strokes. It is assumed that the initial burr height of the reference tool steel is equal to the burr height of the other initial burrs. The number of measurements are too few to characterise the burr development through time. To obtain some idea, the measurements are fitted with a linear approximation.

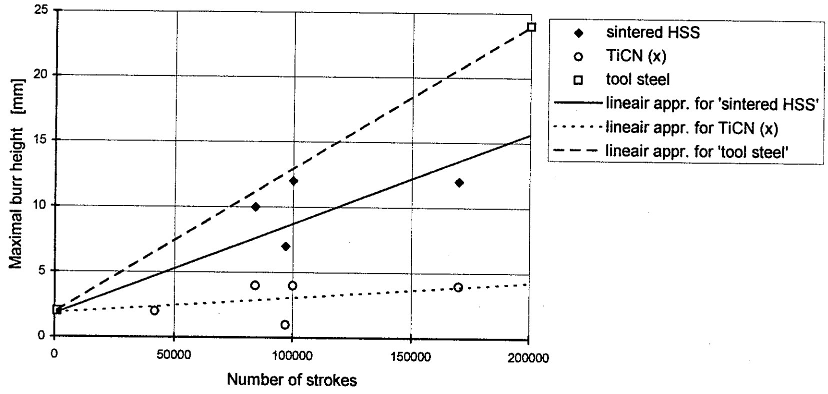

Figure 5.47 The wear resistance of the alternative tool steel and coating is confirmed by the burr heights measured during punching

The measurements are in agreement with the visual observations. Both the sintered-HSS tools and the PVD-coated tool perform better then the reference tool steel. Of all alternatives the PVD-coated tool performs best. For these tools the burr height after $1.7 \cdot 10^5$ strokes is increased from 2 µm to 4 µm. At that point, the reference tool steel has a burr height close to 20μm and the sintered-HSS tool has a burr height of approximately 12 μm. By this standard the PVD-coating performs very well, at least up to this number of strokes. Extrapolation of the results is not possible for the PVD-coating, as the SEM-picture shows the occurrence of a different wear pattern at the end of these tests, as the substrate emerges at the surface of the tool.

Conclusion

The production tests confirm that the laboratory tests have a predictive character. The alternatives that performed best in the laboratory tests, performed accordingly in production. As only a small number of alternatives were tested in production, the validity of this conclusion is still limited. It is therefore too early to draw conclusions on the correctness of the detailed ranking that could be reached by the laboratory tests. It is however expected that the application can be extended beyond these production tests, as the observed wear mechanism of the different alternatives resembles the wear mechanisms of the test situations.

The sintered-HSS tools are a good alternative to the conventional tool steel and impose lower demands on lubricants. This enables the application of environmentally-friendly lubricants. The coated tool shows a strong resistance against wear in production. Brittleness and bonding failure of the coating to the substrate are not observed as limitations to the life-time of the coated tools, but newly emerging surfaces at the tool-edge can endanger tool lifetimes in longer production runs. In this area the adhesive character of the substrate tool steel appears. This makes it impossible to estimate tool lifetimes for the PVD-coatings. The lifetimes of the sintered-HSS tools can be estimated to be up to 1.5 times higher than the reference tool steel.

5.14 Feedback to environmental expectations

The technical research presented in Chapter 5 was performed using one of the environmental improvements suggested in Chapter 4. The question can now be asked to what extent the alternatives can effectively contribute to the set expectations. This feedback is difficult to quantify, because the conclusions of the environmental analysis have a qualitative character. Therefore the feedback is limited to qualitative statements.

The tested alternative, environmentally-friendly, lubricants are not able to replace the conventional lubricants. Particularly in situations where higher demands are placed on the lubricant, for instance in cases of high alloyed product materials or high process loads, the environmentally-friendly alternatives fail regarding their wear-preventive qualities. The application of these lubricants therefore is initially limited to low-loaded processes and wear-insensitive product materials. It is to be expected that the same conclusions apply to simple pre-lubricants, which replace anti-corrosives. This conclusion does not necessarily hold for the more permanent coatings, which are also discussed in the environmental analysis. The lubrication mechanism of these coatings is not comparable.

The alternative tool materials ('sintered high-speed steels' (sintered-HSS) and 'sintered carbide metals' (SCM)) and PVD-coatings improve the wear resistance of the tools. This leads to longer tool lifetimes. The PVD-coatings have the largest expected lifetime increase, followed by the SCM and sintered-HSS respectively. Regarding the PVD-coatings the tests showed that not all coatings performed equally well. The coating suitability is influenced by the coating composition and especially the coating supplier.

The increased tool lifetime of the alternative tool materials itself, does not improve the environmental performance of the process. But the alternative tool materials are also able to maintain the normal tool lifetimes for the environmentally-friendly lubricants. This does contribute to the environmental performance of the process. A disadvantage of the application of the alternative tool materials, particularly the SCMs and coatings, is that the processes are more sensitive to disturbances and more difficult to design.

The research on 'lubrication systems and tool wear' was performed as an example of 'process-related aspects' of environmentally-friendly sheet metal forming. The technical problems could indeed be dealt with independent of the product design. The research did results in environmental improvements, but to a limited extent. The aim of 'zero emission' is still far away.

Chapter 6
Formability of tailor-made blanks

The environmental analysis on automotive body parts made from tailor-made blanks (TMBs) resulted in a relationship between the position of the weld and the environmental impact of the part over its total life-cycle. The weld position can however not be freely chosen to allow maximal environmental performance. The part's formability amongst others, is a limiting factor. Therefore the formability of TMBs is subject of research in Chapter 6.

The formability behaviour of TMBs differs significantly from that of normal, unwelded sheets. Therefore the standardised tests, which are generally used for unwelded sheets, are insufficient. Hence the research is extended with a newly developed test method for TMBs. Together, both tests methods enable the description of the formability of TMBs, which is characterised by local concentration of deformations and reduced formability of the weld itself.

Since the standardised tests impose a specific deformation path, the results of these tests only focus on the formability of the weld zone (Sections 6.1 through 6.4). The effect of the changed deformation path is studied in the sections on 'tailor-made blank adapted tests' (Sections 6.5 through 6.8). Finally, Section 6.9 links the technical research with the outcomes of the environmental research. This results in design guidelines which unit environmental and manufacturing demands.

6.1 Standardised tests

The 'standardised test' determines the forming characteristics and formability limits of materials. The mechanical material properties of a sheet are usually measured by the tensile test. Other tests are used to determine the formability limits for different strain situations. The results of these tests are normally represented through a Forming Limit Curve (FLC).

The tests are standardised for unwelded sheets. For welded sheets no standards have yet been derived. These sections deal with the possibilities to use these standardised test for welded samples. Emphasis is put on the properties of the weld itself, since this distinguishes the TMB from the base materials. The research questions are:

1) Is the tensile test suitable to determine the mechanical material properties of the weld? If so, which parameters can be used and how do they relate to the original materials?

2) Is it possible to determine the forming limits of the weld with the standardised tests? If so, what is the effect of the weld on the forming limits?

The sections deal with the test set-up and weld characteristics, the mechanical properties and the forming limits, respectively. In Section 6.4 the results are discussed followed by a conclusion.

Tested materials, combinations and welds

The tests were performed on two materials and three material combinations. The two materials are commonly used deep drawing steels (FeP06, and FeP06G (galvanised)), with a thickness of 0.7mm. The combinations are: a) steel to steel, b) steel to galvanised steel and c) galvanised to galvanised steel (Table 6.1).

Tested combinations	**Abbreviation**	
	laser weld	mash seam weld
FeP06 to FeP06	06-06, L	06-06, MS
FeP06 to FeP06G	06-06G, L	06-06G, MS
FeP06G to FeP06G	06G-06G, L	06G-06G, MS

Table 6.1 *Tested material combination and used abbreviations*

All tests were performed for laser and mash seam (MS) welded samples The weld qualities were tested on their geometrical properties according to the prEN 1419-standard of Soudronic AG in Germany. A number of samples did not meet the standards. For these samples the observed failure is checked against the weld quality. In most cases the weld did not fail as a result of poor weld quality. In some cases however a relationship between failure and the weld quality could not be dismissed.

Weld characteristics

Before the results of the formability test, a short description of the laser and mash seam weld is provided. The typical width of a laser weld is 0.5 to 1mm, whereas the mash seam weld is approximately 3 to 5mm. Both welds have an increased hardness compared to composing materials. To give an indication of the hardness course over the weld measurements are taken perpendicular to the weld.

The tests (Figure 6.1 and 6.2) show the width of the weld and heat affected zone (HAZ) and demonstrate the difference in the hardness of the welds itself. The hardness of the mash seam weld is in the order of 200-250 HV, over a distance of 4-5mm. The hardness of the laser weld has a local peak of 350-400 H over a distance of 0.5-1 mm. The hardness of the basis material is approximately 90-110 HV. An increased hardness is accompanied with a decreased toughness, which will result in higher maximal stresses and lower maximal strains.

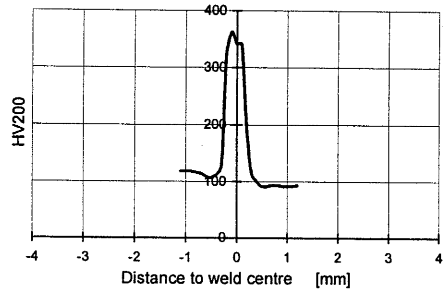

Figure 6.1 Hardness course over the cross-section of the laser weld

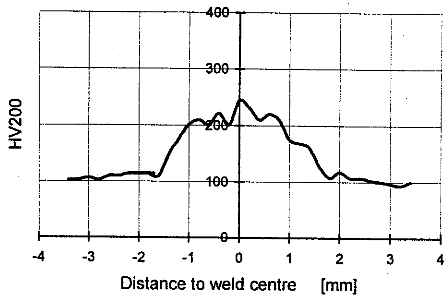

Figure 6.2 Hardness course over the cross-section of the mash seam weld

6.2 Mechanical properties

The measured mechanical properties of the TMBs [Sie95, Sie97, Bar93, Wat93] are not necessarily true material properties. The measurements describe the properties of the sample. In few cases the properties of the weld itself can be computed from the measurement data. In other cases the values are only representative for the chosen samples and are able to indicate a trend. In the discussion of the results special attention is given to the computation of the true weld material parameters. Another point of attention is the influence of the galvanic zinc layer. The discussion focuses on the effect of the galvanic surface layer on the formability of the weld and is related to the normal effect of these surface layers.

Tensile tests

The tensile test results in a characteristic stress-strain relation from which the mechanical material properties can be determined (see Figure 6.3). The yield strength (R_p) is the stress at which the material behaviour is considered to change from elastic to plastic. With increasing stresses the deformation initially shows an uniform elongation. For stresses higher then the tensile strength (R_m) the elongation is no longer uniform and necking occurs. The strain that accompanies the transition is the strain at necking (e_{neck}). Finally the imposed distortion becomes critical and fracture occurs. This is called the strain at fracture (e_{frac}). The measured strains in the tensile tests are represented as engineering strains. The stress-strain relation can be characterised by the strain hardening exponent (n) and the strength coefficient (C).

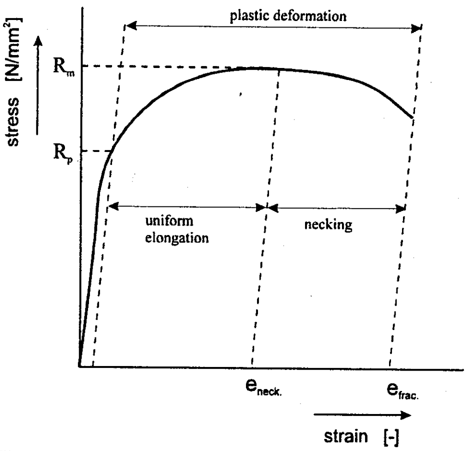

Figure 6.3 *Typical stress-strain relation with the relevant measures*

All experiments have been executed in three different directions relative to the rolling direction and also repeated three times. The reported values are average values.

Influence of the welding method

Although all samples failed in the weld, the measured values are generally representative for the samples as a whole. The tensile strength and the strain at fracture of the weld itself can however be derived from the measurements. This is discussed along with the test results of individual parameters. Table 6.2 contains the measured and computed values.

Measured quantity	unwelded material	sample *(measured)*		weld material *(computed)*	
		laser	ms	laser	ms
R_m [N/mm²]	297	309	345	537	489
R_p [N/mm²]	146	174	250	*(706)*	*(562)*
e_{neck} [%]	23.8	21.6	19.2	-	-
e_{frac} [%]	44.3	32.5	35.3	32.5	35.3
n [-]	0.211	0.211	0.173	-	-

Table 6.2 *Measured mechanical properties of the welded (06-06, L and 06-06, MS) and unwelded specimens (thickness 07.mm, ungalvanised)*

The measurements show that the tensile strength (R_m) increases for the welded samples. The sample measurements suggest that the R_m of the laser welds is less influenced by the welding compared to mash seam welds. If the surface ratio in the cross section of the test samples is taken into account the relationship is the other way around, as the surface ratio of the laser- and mash seam weld are 3.5 % and 25% respectively of the sample's cross section.

Formula (6.1) was used to determine the weld's tensile strength from the sample's and material's tensile strength, by taking into account the surface of the weld (A_{weld}) and the base materials ($A_{mat.}$).

$$R_{m,\,weld} = \frac{R_{m,\,sample}\,(A_{weld} + A_{mat}) - R_{m,\,mat}\,A_{mat}}{A_{weld}} \qquad (6.1)$$

Thus the corrected figures give an estimation of the weld's tensile strength. The computed figures show that the tensile strength of the laser weld is larger then of the mash seam weld. This corresponds with the expectations, since the laser weld is considerably harder.

The average yield point (R_p) of the tested samples also increases due to the hard and brittle character of the weld. Unlike the tensile strength it is impossible to extract the yield point for the weld itself from the measured data. The transition from elastic to plastic deformation in the area surrounding the weld is so complex that it is impossible to assume that the weld deforms plastically at the moment the test strip as a whole shows plastic deformation. The computation of the yield point (analogue to (6.1)) confirms this assumption, as the calculated values are not realistic. The computed yield point is higher then the tensile strength. In spite of this incorrectness of the computation the results give a better representation of the effect on the yield point as it relates to the welding method. The computed values for the laser weld show a higher yield point then the mash seam welds, which is in accordance with its harder and more brittle character.

The strain at fracture (e_{frac}) measured on the samples represents the weld properties themselves, as the tested strips failed in the weld. The strain at fracture of the laser welds are reduced by approximately 27% compared to the unwelded materials. The mash seam welds have a higher toughness, and show a reduction of 20%. This corresponds with the lower hardness of the mash seam welds.

The strain at necking (e_{neck}) is lower for mash seam welded samples than for laser welded samples. Apparently the material behaviour in the small flanges on both sides of the mash seam weld becomes unstable more easily and changes to local deformation. The results are difficult to apply to practical situations.

The measurements of the average strain hardening exponent (n) indicate a reduction of 0 to 12% for the laser samples and 18 to 24% for the mash seam samples compared to the unwelded specimens. These values are again strongly influenced by the relatively large contribution of the wide HAZ of the mash seam weld. The values are highly disputable an cannot be used as parameters in constitutive models.

Influence of the galvanic surface layer

The question is whether or not the galvanic zinc layer influences the weld quality and therewith the material parameters of the weld. To answer this question different material combinations are compared. In the comparison the normal differences between the non-galvanised and the galvanised sheets (Table 6.3) need to be excluded.

	FeP06	FeP06G
R_m [N/mm^2]	297	321
R_p [N/mm^2]	146	182
e_{neck} [%]	23.8	22.5
e_{frac} [%]	44.3	40.9
n [-]	0.229	0.214

***Table 6.3** Mechanical properties of bare and galvanised (unwelded) sheets*

To exclude the normal differences between non-galvanised and galvanised sheets, normalised values were derived. These values represent the property of the welded sample relative to the unwelded sample. Consequently, the values are dimensionless numbers. As an example of the calculation method, the normalised tensile strength, R^*_m, is given in formula (6.2) to (6.4). The computation of R_p^*, n^*, e_{neck}^* and e_{frac}^* the computations for the mash seam welds follows the same logic.

$$R_m^*{}_{,\,06\text{-}06,\,L} = \frac{R_{m,\,06\text{-}06,\,L}}{R_{m,\,06}} \tag{6.2}$$

$$R_m^*{}_{,\,06\text{-}06G,\,L} = \frac{2\,R_{m,\,06\text{-}06G,\,L}}{R_{m,\,06} + R_{m,\,06G}} \tag{6.3}$$

$$R_m^*{}_{,\,06G\text{-}06G,\,L} = \frac{R_{m,06G\text{-}06G,\,L}}{R_{m,\,06G}} \tag{6.4}$$

The computed dimensionless values are given in Table 6.4. The values are derived from the samples, except for R_m^* and e_{frac}^* which represent the welds. In addition, the average values, the average deviation and the relative average deviation are given for each weld process.

Based on these results, it can be concluded that the material parameters of the weld are hardly influenced by the galvanic surface layer. The computed normalised values are almost equal for the three material combinations. The mash seam and laser weld influence the material parameters by a certain percentage of the original, unwelded, values. This is confirmed by the small relative average deviations, which are between

1 and 6%. The only exception is the tensile strength of the laser welded samples. This is due to the results for the 06G-06G combination.

[-]	R_m^*		R_p^*		n^*		e_{neck}^*		e_{frac}^*	
	laser	ms	laser	ms	l	ms	laser	ms	laser	ms
06-06	1.81	1.65	1.19	1.71	0.92	0.76	0.91	0.81	0.73	0.80
06-06G	1.78	1.61	1.15	1.49	0.92	0.80	0.91	0.82	0.74	0.84
06G-06G	*0.81*	1.62	1.14	1.54	0.92	0.76	0.93	0.80	0.79	0.75
average	*1.47*	1.63	1.16	1.58	.91	0.77	0.91	0.81	0.76	0.79
av. deviation	0.44	0.01	0.02	0.09	0.01	0.02	0.01	0.01	0.02	0.03
av. dev./av.	29.7%	0.8%	1.8%	5.5%	1.6%	2.6%	0.9%	1.0%	3.2%	3.9%

Table 6.4 *Computed normalised values for the different mechanical properties*

It was not possible to verify this idea with other materials then the tested FeP06-series. Therefore it is not yet possible to extend the validity of the values to a characteristic value for a certain weld mechanism.

Furthermore, the normalised values confirm the earlier suggested increase in strength (R_m^* and R_p^* -values larger then 1) and the decrease in toughness (e_{neck}^* and e_{frac}^*-values lower then 1) of the welded samples.

6.3 Forming limits

For the determination of the FLCs [Lan93, Szi91, Vol95, Azu96, Hoe94, Wat93] the required deformation path can not be applied to combinations of unequal sheets. The strains concentrate in the weaker/thinner partner, which finally fails as a result. The resulting measurements describe the weaker material instead of the weld and are therefore useless to describe the forming behaviour of the TMB as a whole. To avoid this effect, all tests have been limited to combinations of sheets with equal strength and thickness.

The orientation of the weld and the weld position are not standardised. In the performed tests the weld was placed in the symmetry axis of the sample, in the direction of the maximal strain. This ensures fracture of the weld. To get an impression of the sensitivity for the weld position a hole expansion test is also performed for asymmetrically welded samples. This results in a new FLC, that describes the formability of TMBs.

Forming limit curves

The Forming Limit Curve (FLC) is used to describe the forming limit of sheets. The FLC gives the borders of local plastic stability for sheet metals under various strain situations. If the strains exceed these limits, the material behaviour becomes unstable and fails. Because the observation of necking is difficult in most test situations, the presented measurements are based on fracture. The curve is represented in the Forming Limit Diagram (FLD). The axes represent the major and minor natural strains (ε_1 resp. ε_2, $\varepsilon_1 > \varepsilon_2$).

Figure 6.4 gives a typical example of an FLC for deep drawing quality steel sheet (FeP06). The graph can be divided into three areas. The flange stretch area ($\varepsilon_2 < 0$), plane strain ($\varepsilon_2 = 0$) and the bi-axial stretch area ($\varepsilon_2 > 0$). The minimal formability is typically reached near plane strain.

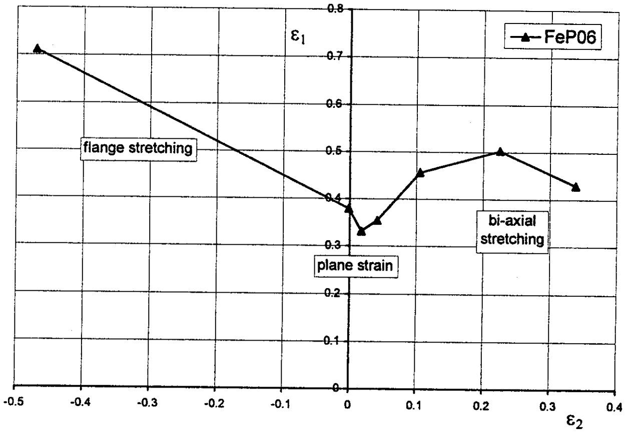

***Figure 6.4** Characteristic FLC for an unwelded sheet (FeP06)*

The FLCs have been experimentally determined by a combination of tests, that each impose a defined strain situation and results in a single point on the FLC. A variety of tests is available. In this work three tests have been selected. The hole expansion test determines the point on the left side of the graph in the flange stretching area. The drawing test results in a point on or just left of $\varepsilon_2 = 0$ in the flange stretching area. The Nakazima tests determine the forming limits in plane strain and the stretching area The sample shapes are given in Figure 6.5

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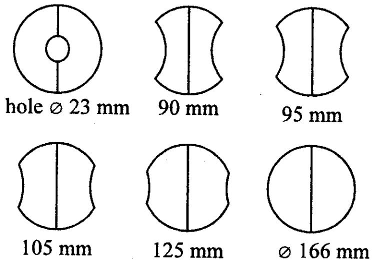

***Figure 6.5** Shapes of the hole expansion test sample (upper left) and the Nakazima test samples*

The tests have been performed on a normal Erichsen test bench. The blank holder is adapted to prevent wear due to the hard welds. In order to measure the strains, a grid of squares is applied to the test samples. This special grid is recorded by two camera's, which are connected to a computer. The measured deformations are translated into natural strains.

Test results

For most specimens fracture appeared, as intended, in the weld itself. As a result the FLCs indicate the formability behaviour of the weld. This provides however not enough measurements to make conclusive statements. The presented results just give an indication. The measurements are less accurate then for unwelded sheets, because the strain distribution around the weld is less evenly. It was only possible to measure general strains, that average a larger area (2 by 2mm).

The general tendency for welded sheets is represented in Figure 6.6, by means of the FLC measured on the FeP06-FeP06 laser welded combination. Its FLC has been compared to the unwelded material. The effect of the welds is considerable. In the bi-axial stretching area ($\varepsilon_2>0$), the effect of the weld on the forming limits is most significant. The typical 'bulge' that characterises the FLC of the unwelded sheets disappears. The critical strain for bi-axial stretching is reduced in the order of 50 to 70%. For plane strain ($\varepsilon_2=0$) the effect is smaller. The average reduction is in the order of 40%, with peaks to 70%. The influence of the weld is lowest in the flange stretching area ($\varepsilon_2<0$). In this region the decrease in formability is in the order of 20 to 25%.

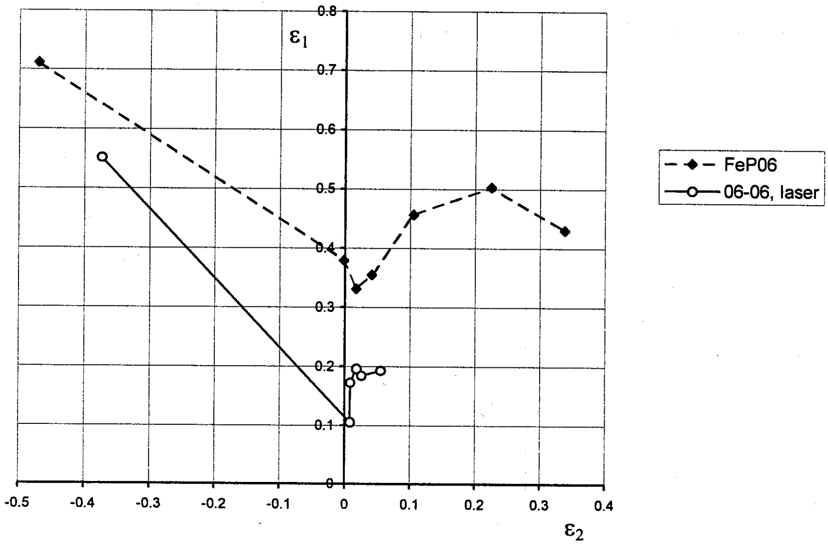

__Figure 6.6__ The forming limits of an unwelded and a laser welded sample (0.7mm, FeP06)

Influence of the weld process and galvanised surface layer

In Figure 6.7 the forming limits for the laser and mash seam welded blanks are compared. The mutual differences between the weld processes are moderate and smaller then expected on basis of the tensile tests. This holds for both the non-galvanised and galvanised sheets.

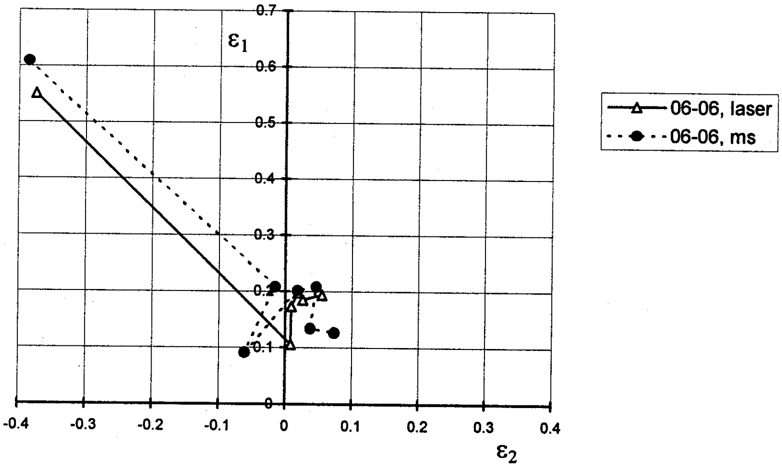

Figure 6.7 Comparison of the effect on the FLC between laser and mash seam welded samples

Figure 6.8 compares the FLCs of non-galvanised and galvanised sheet combinations. The graph shows the results for the laser welded samples.

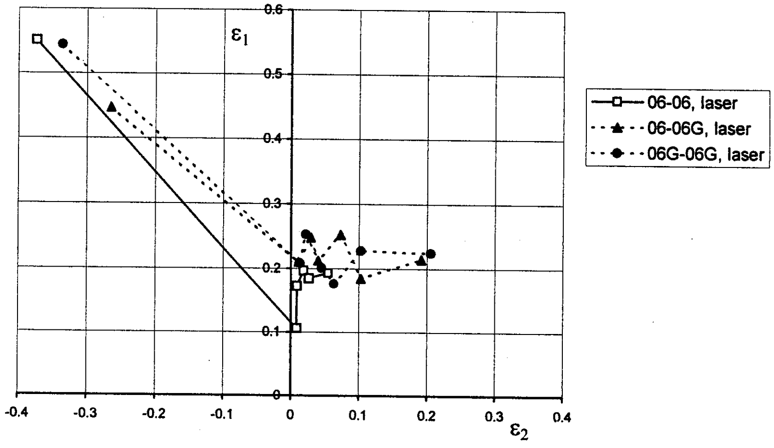

Figure 6.8 Comparison of the forming limits for bare- and galvanised sheets (0.7mm, FeP06)

The points for the non-galvanised sheets gather around plane strain area. These sheets do not show a bi-axial stretching behaviour. The maximal strain in this area is reduced by 65-75% compared to unwelded sheets. The Fe06G-FeP06G and the FeP06-FeP06G combinations show a bi-axial stretching behaviour which is more like the unwelded situation. The reduction of the maximal strain in this area is around 40% to 50% compared to unwelded sheets. This tendency is seen for as well laser- as for mash seam welded sheets. There is no clear cut explanation for this phenomenon. Possibly the lower coefficient of friction for galvanised sheets plays a role, enabling a better all sided displacement.

In areas other than the bi-axial stretching area, the galvanised and non-galvanised sheets do not show significant differences. The galvanised sheets tend to have a slightly lower forming limit in the flange stretching area, which is similar to the unwelded materials.

Orientation dependent FLCs

The strains represented in a Forming Limit Curve (ε_1 and ε_2) are the major and minor strains. These strains do not relate to a fixed orientation on the specimen. Therefore, the line $\varepsilon_1=\varepsilon_2$ is in fact a line of symmetry in all FLCs, assuming (quasi-)isotropic material. As a consequence strains measured at different spots at the hole edge in the hole expansion test result in the same strain ratio. This does not hold for welded sheets. Not only is the strain distribution around the hole uneven, the strain distribution also depends on the position of the weld. This is tested using a number of hole expansion tests with asymmetric welds. Figure 6.9 gives the four weld positions that were investigated.

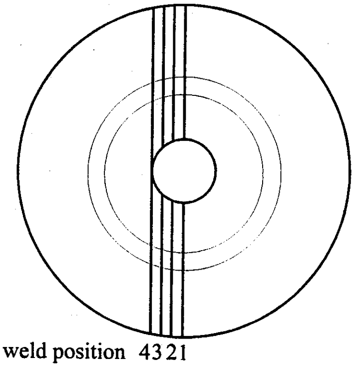

Figure 6.9 Weld positions for the asymmetric hole expansion test.

Position '1' equals the situation in which the weld is placed in the middle of the sheet, just like in the symmetric tests. In position '4' the weld just touches the hole. Position '2' and '3' are in between.

The results of the tests are given in Figure 6.10. Compared to the symmetric hole expansion tests the measurements show a similar deformation path combined with a reduced critical strain for positions which are more asymmetric. The critical strain drops to values equal to 50% of the unwelded sheets and equal to 35% of the symmetric weld positions.

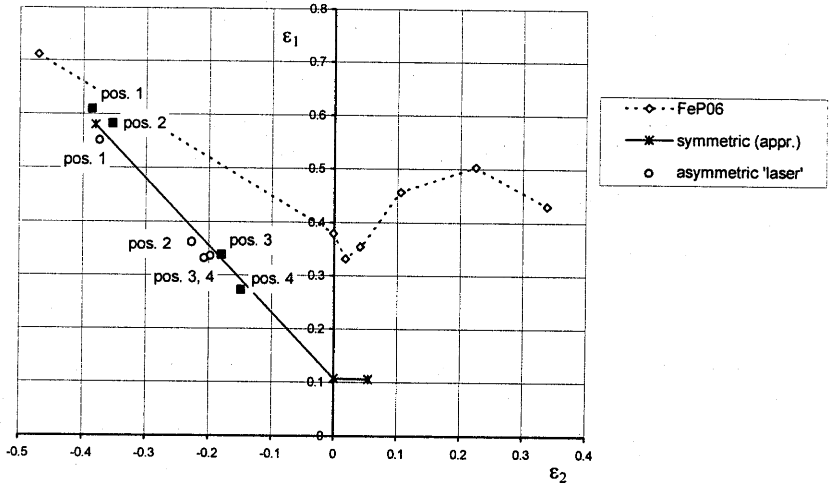

Figure 6.10 Strains at fracture for the asymmetric welded hole expansion test, represented in the laser- and mash seam FLC and unwelded FLC (0.7mm, FeP06)

Although the measured deformation path is hardly different, the orientation of the deformation relative to the weld has been changed completely. In the symmetric situation (position '1') the weld has been compressed parallel to the weld and stretched perpendicular to the weld. For position '4' the situation is inverted. The weld is stretched parallel to the weld and compressed perpendicular to the weld. This difference can not be represented using a normal FLD. An alternative would be to measure the strains relative to a fixed orientation, viz. the weld. The corresponding FLD has axes that represent the strains perpendicular and parallel to the weld.

Figure 6.11 shows such an orientation-related FLD for several material combinations including the measurements of the asymmetric welds (position '4') and the unwelded material. The essential difference is the measuring point of the symmetric hole expansion test, whose co-ordinates are inverted. They are replaced by the measure point of the position '4' of the asymmetric hole expansion test. The figure needs to be regarded with some reservations, because the points are based on the normal FLC measurements, and the orientation is therefore a rough estimation. The measurements of position '2' and '3' are not included, as their strain orientation can not be converted to strains parallel and perpendicular to the weld.

The orientation-related FLD shows that a weld is particularly sensitive to elongation. Formability in this area decreases up to 70% compared to the unwelded situation. Combination with compressive strains perpendicular to the weld show only little improvement. This conclusion corresponds with the hard and brittle character of the weld (Section 6.1). The welds are less sensitive to compressive strains in combination with elongation perpendicular to the weld. The formability decrease with respect to these deformations is in the order of 20%.

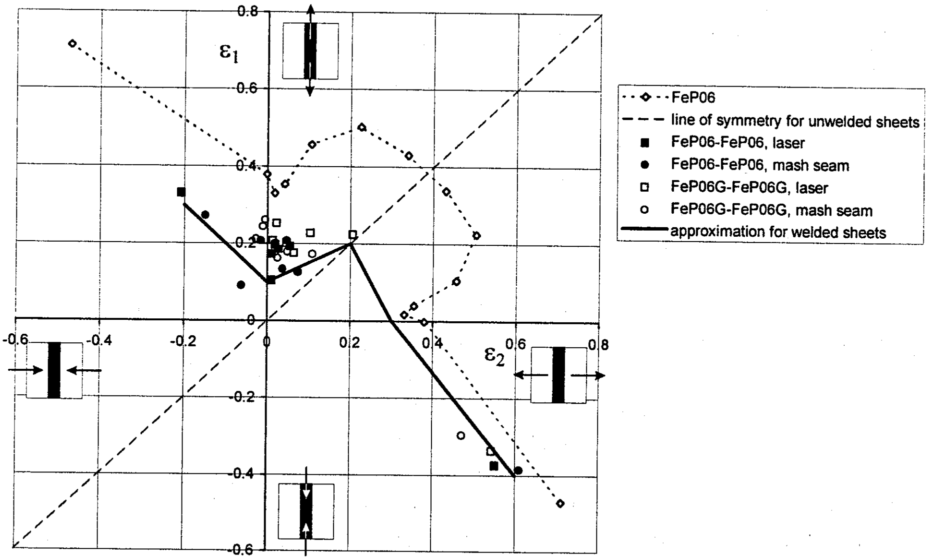

Figure 6.11 Forming Limit Curve for welded sheets; the x- and y-axis represent resp. the strains perpendicular and parallel to the weld

6.4 Conclusions

The standardised tests have a limited application range since they are restricted to combinations of identical sheets. This restriction is required to meet the requirement of a fixed strain distribution. Tests on combinations of unequal sheets provide undefined results. In spite of this limitation, the standardised tests contribute to the determination and description of the TMB forming behaviour. Their added value lays in the ability to investigate the forming behaviour of the weld itself, regarding both its material parameters and forming limits.

- From the tensile test the material parameters 'strain at fracture' and the 'tensile strength' can be deducted for combinations of identical sheets. The measurements can be translated to values representative for the weld itself. The measured 'strain at necking', the 'yield point' and the 'strain hardening coefficient' can not be deducted for the weld itself. These measurements only give a qualitative indication of the weld properties. In general the mechanical properties of the welded samples are dominated by the hard and brittle character of the weld, resulting in higher maximal stresses and lower maximal strains. The tests show a higher tensile strength and a lower strain at fracture for the laser weld (characterised by a higher hardness peak) then for the mash seam weld. The formability of welded samples is hardly influenced by galvanised surface layers.

- The series of Nakazima and hole expansion tests resulted in a first indication of the formability limits of TMBs. Unlike the FLCs of normal sheets, the FLCs of TMBs show to be more valuable if the strains are related to their orientation. The test results show an over-all reduction of the formability, but the welds are especially sensitive to elongation of the weld, particularly to bi-axial stretching.

  The FLCs of welded blanks show a larger scattering then those of unwelded balnks. This is possibly explained by local stress concentrations around the weld and occasional irregularities in the weld itself. This gives rise to extra caution in the interpretation of the results.

The tests in these sections on ‘standardised test’ have led to the impression that the formability behaviour of TMBs is dominated by the hard and brittle character of the welds. The formability of TMBs is limited, particularly for elongation of the weld. This effect is most significant under bi-axial stretching and plane strain. Although the tests are limited to combinations of identical sheets, it is expected that the reduced formability is also encountered in combinations of unequal sheets. For these cases the strain concentration in the weaker partners also plays a role. Since these effects are not dealt with in the ‘standardised tests’, they are subject of research in the next sections.

6.5 Tailor-made blank adapted tests

The 'standardised tests' (discussed in section 6.1 to 6.4) show a formability decrease for welded sheets and a dependence of the formability on the weld orientation. In these standardised tests the effect of the weld displacement during the process is largely prevented to fulfil test requirements. Therefore the standardised tests are mainly limited to combinations of identical sheets. However in the production practice weld displacements can not be ignored. Free movement of the weld allows local deformation, leading to early (local) fracture. The weld displacement is therefore a relevant factor in the determination of the formability of TMBs. The research questions are:

1) How can the formability of TMBs be tested for different material combinations and weld positions under realistic production conditions, including weld displacements?

2) To what extend is the formability of TMBs influenced by the position of the weld, the material combination and the welding process?

To deal with these questions, the 'formability of the TMBs' has been quantified by the deep drawability [Sie95, Sie97, Azu96]. The deep drawability is defined as the maximum, fracture free, height that a certain product can be drawn to under defined test conditions. The requirement is that these test conditions conform with the production practise. Realistic production conditions means that the test samples have a size similar to normal automotive parts and that the weld is allowed to move over the punch during the forming process. The consequence of this weld displacement is that the stress situation is defined less strictly than in the standardised tests. Therefore the tests are divided into two general processes: deep drawing and stretching.

Conceptual tool design

In the concept phase [Abe97] the possibility is considered to combine both processes (deep drawing and stretching) in one testing product. The difficulty of this concept is that both processes influence each other. This is unwanted, since it complicates FEM simulations in a later stadium of research (though outside the scope of this thesis). As a consequence the tests require two different products and therefore two different tools. To limit production costs the two tools are combined as much as possible. This has lead to a modular testing tool design in which parts can be exchanged to form two different products. The products have the shape of a square bowl. In the deep drawing situation the height of the bowl is gained by drawing the flanges. The product used in the stretching test is basically the same bowl, except that a circular hole is made in the bottom. In this case the product height is gained by stretching the bottom. The flanges can not flow since they are fixed by draw beads.

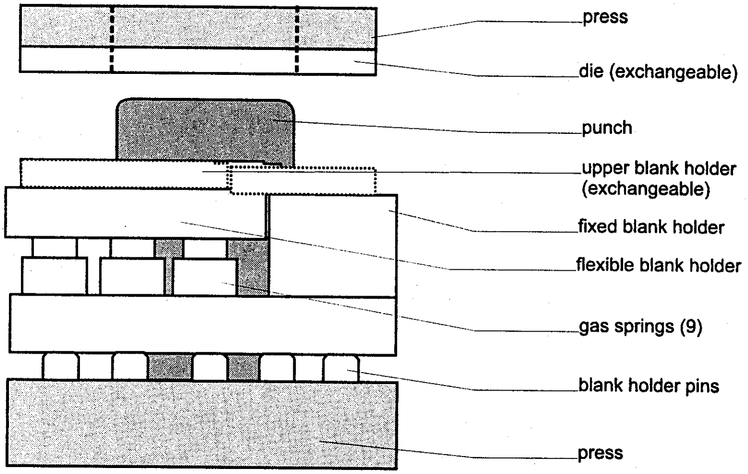

***Figure 6.12** Schematic representation of the tool set*

In addition to the combination of two products in one tool, the realisation of different weld positions was another requirement for the tool design. The combination of unequal sheets requires multistage blank holders and separate blank holder pressure (BHP). If the thinner material is not supported sufficiently by a blank holder the sheet will wrinkle.

The easiest way to realise this, is a series of blank holders with a fixed step to overcome the thickness difference of the TMB. Each blank holder is then characterised by the place and the size of its thickness step. The disadvantage is that each weld position and each thickness combination requires another blank holder. Besides, the blank holder pressure can not be adjusted for the individual sheet thickness, nor can the blank holder be adapted for deviations in the thickness step, due to thickness deviations of the individual sheets (maximal two times the individual sheet deviation of 10%).

The solution is found in the realisation of two separate blank holders, one fixed and one flexible (see Figure 6.12). This set-up requires separate sets of upper blank holders for different weld positions. The thickness step is flexible. One part of the blank holder is directly supported by the normal blank holder. The other part is supported by gas springs, which are placed between the normal blank holder and the movable blank holder top. The resistance of these springs can be adjusted separately. This enables the adjustment of the optimal blank holder pressure for both material partners. With this set-up, thickness deviations can also be adapted by gas springs.

Product dimensions and process conditions

Firstly the two different products are described. Figure 6.13 shows a deep drawing product (optimised blanks) and Figure 6.14 shows the stretching product (2mm) with the hole in the middle. The drawing rills affect the outer-sides of the product.

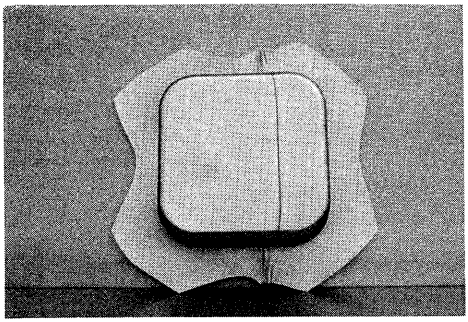

Figure 6.13 Deep drawing product

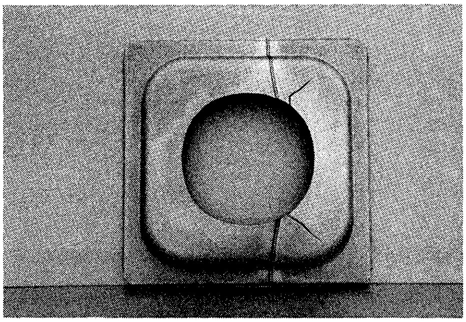

Figure 6.14 Stretching product

Both products are square shaped. The corners radius 'r' measures 80mm, which corresponds to common measures in automotive products (Figure 6.15 and 6. 16). The wall length of the product measure 4.5 times the corner radius. This guarantees a flange area that can move freely into the product wall, without being effected by the flange upsetting in the corners. The product measures therefore 360mm. The hole in the stretching products R measures 80mm.

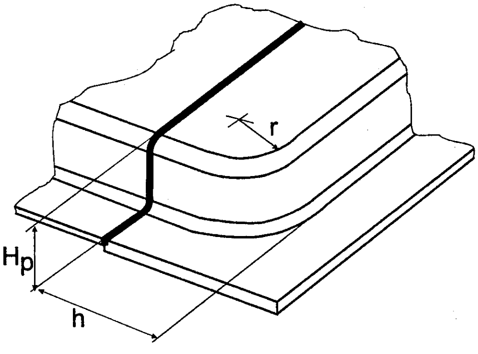

***Figure 6.15** Definition of the weld position (h), corner radius (r) and the product height (H_p) for the deep drawing tests*

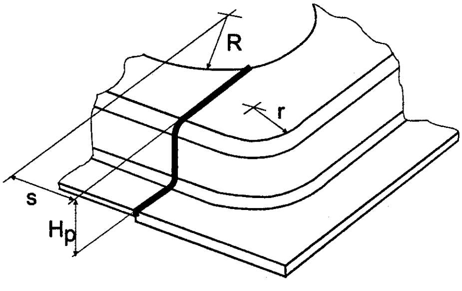

***Figure 6.16** Definition of weld position (s), hole radius (R), product height (H_p) and corner radius (r) for the stretching tests*

In the deep drawing product the weld position h is given as the distance between the product wall and the weld. In de stretching situation the weld position s is given as the distance between the hole middle and the weld.

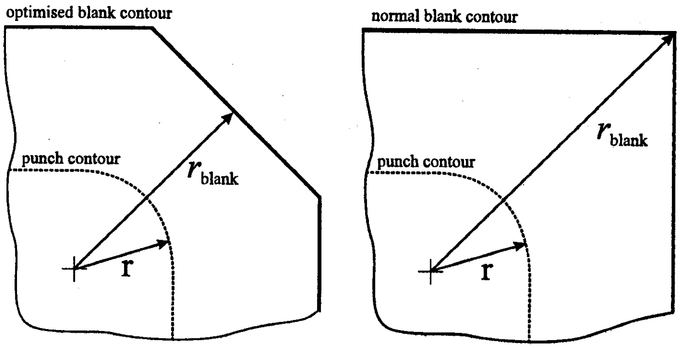

***Figure 6.17** Quart of the deep drawing blanks showing the product radius and the edge cut of the optimised blank*

In the deep drawing situation the measurements are strongly influenced by the deep drawing ratio (β), defined as β=r/r_{blank} (Figure 6.17), the blank holder pressure (BHP) P_{bh} and the lubrication. Therefore two different situations are tested, one under optimal conditions (low β and low BHP, good lubricant) and one under harsher conditions (high β and high BHP, normal lubricant). Both the BHP and the optimised β are chosen based on initial experiments. In the stretching situation the lubrication is optimised to allow maximal stretching and the BHP is maximal to prevent slip of the flanges.

	β [-]	P_{bh} [N/mm^2]			
		FeP04 0.7mm	BHS 0.7 mm	FeP04 1.5mm	Warm rolled 2.0 mm
Normal	4.0	3.6	3.6	2.5	1.8
Optimal	2.7	1.6	1.6	1	0.5

***Table 6.5** Used blank holders pressures P_{bh} for the different materials*

Tool dimensions

The punch and die radius are chosen to be respectively ρ_{punch} =20mm and ρ_{die} =10 mm. This is bigger than normally necessary for the used sheet thickness', especially the thinner sheets, but is required to enable FEM simulations in a later stadium of research. The die clearance is based on the thickest sheet and measures 3.5mm. Figures 6.18 and 6.19 give an example of the tool set for the stretching situation.

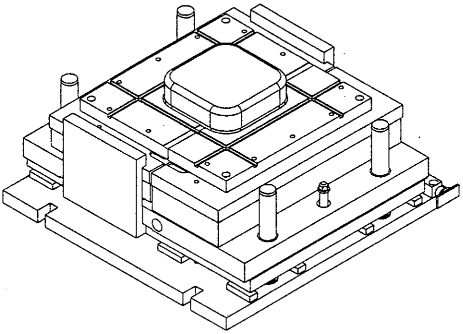

***Figure 6.18** Punch (middle) and the divided blank holder (draw bead side)*

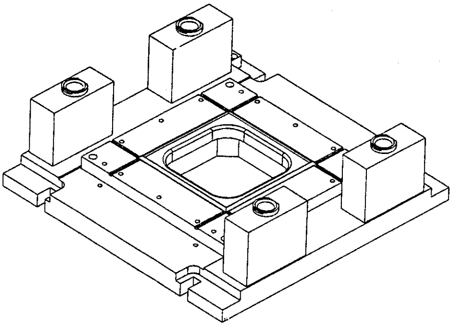

***Figure 6.19** Die with the draw beads*

The tool is executed with 10 blank holder sets, facilitating weld positions at an interval of 20mm The blank holders set are made of 60mm steel plates. Grooves are spared in the blank holder to enable the thicker material to move towards the thinner material (Figure 6.20). For combinations of identical sheets the grooves are filled with strips.

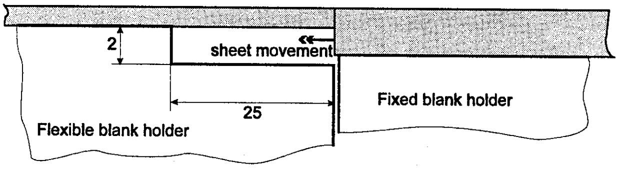

***Figure 6.20** Movement of the thicker material partner in the space excavated from the blank holder*

Since the thickness step is adapted by the blank holder, the die has been constructed as a flat surface The punch is also made flat, although it holds the thickness jump. Considering the large forces on the bottom surface there is however no risk for wrinkling or other faults in this area.

The tests have been performed on a 400 ton hydraulic, SMG press, placed in a lab environment (Figure 6.21 and 6.22). The maximal blank holder force has a limitation of 160 ton and 63 ton for the press and the gas springs respectively. The tool displacement is limited to 107 mm.

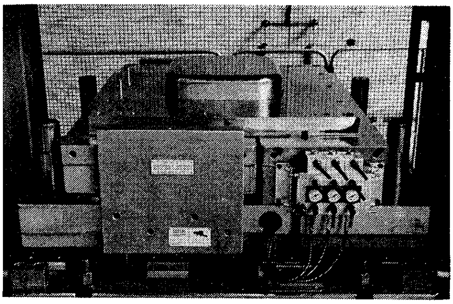

Figure 6.21 Tool build-in in the press with in front the pressure control unit of the gas cylinders

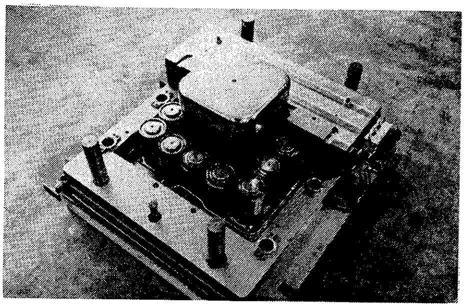

Figure 6.22 Open tool with visible gas cylinders

Tested material combinations

The tested materials and material combinations are based on commonly used combinations in the industrial practice. The tested materials are: a 0.7mm and 1.5mm deep drawing steel (FeP04), a 0.7 mm rephosphorised bake hardening steel (BHS) (0.7 reph.) and a 2.0mm hot rolled steel. The materials are tested separately and in the combinations 0.7-0.7, 0.7-0.7reph., 0.7-1.5, 0.7-2.0 and 2.0-2.0. All combinations are laser welded. The 0.7-1.5 combination is also mash seam welded (overlap 1.8 mm).

6.6 Deep drawing tests

In this section the results of the deep drawing tests are given. Before attention is given to the deep drawability itself, the occurring weld displacements and the consequent failure types are presented.

Weld displacement

The literature mentions the weld displacements as a result of local strain concentrations in TMBs. These displacements are particularly important for the tool design as the thicker partner tends to seize up in the blank holder. This requires savings in the tool geometry. On the other hand the displacements also determine the measurements of the final product.

The displacements are measured in the horizontal plane perpendicular to the original weld. The measure points are schematically represented in Figure 6.23. The absolute values of the measurements should be regarded with some caution, as the displacements are influenced by the drawn product height.

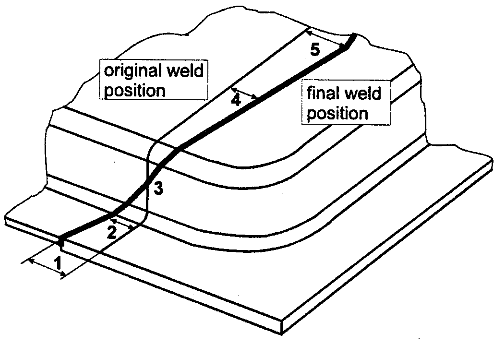

Figure 6.23 Definition of the weld displacement measure points for the deep drawing product (point 1' to 4' are mirrored on the other side)

Before the displacements of the TMBs are discussed, the displacements in the unwelded deep drawing processes are presented. These displacements are not so much relevant for the formability of normal products, but they give a better understanding of the displacements which are characteristic to the deep drawing process itself.

In the deep drawing situation the displacements in a product are dominated by the compressive strains in the corner areas. The surplus of material in these areas is pushed towards the sides, into the flanges of the walls. Straight lines on a blank, as imaginary welds, will bend away from the corners.

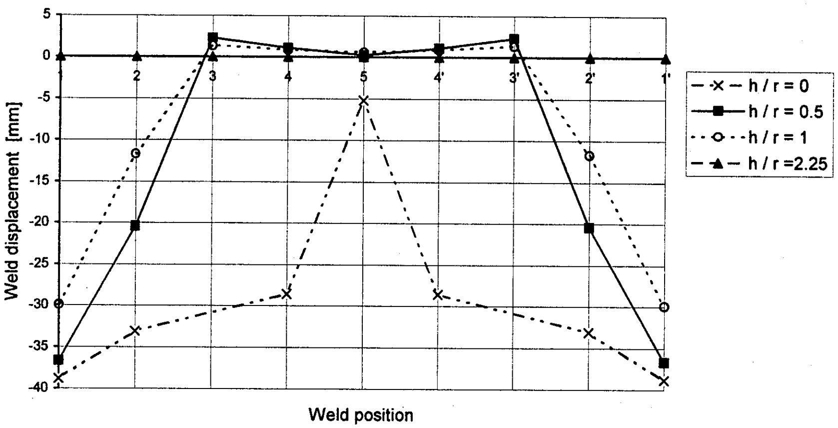

Figure 6.24 Displacement of straight lines (h/r=0, 0.5, 1 and 2.25) on 1.5 mm sheets during deep drawing (product height 107 mm)

The displacement of imaginary (weld) lines on the 1.5 mm sheets is represented in Figure 6.24. The part is symmetric so that no displacement in the middle of the product (h/r=2.25) occurs. For positions closer to and in the product corner the lines show the displacement in the flanges as a result of the compressive stresses. The displacements on the punch (measure point 3, 4, 5, 4' and 3') are negligible. The product does not move on the punch. The line along the side of the product (h/r = 0) shows an aberrant pattern as the lines are able to curve around the product corner. The displacement pattern shown in Figure 6.24 is representative for displacements in unwelded materials and welded identical materials. In the latter case the change in coefficient of friction and weld strain can lead to minor deviations in this pattern.

The 0.7-1.5 combination (Figure 6.25) shows the weld displacements of an unequal combination TMB. The displacements are asymmetric, bi-directional and the material on the punch is not longer fixed.

Due to the resistance of the thicker material to deform, the weld moves over the punch in the direction of the thicker material (measure points 3, 4, 5, 4' and 3'). This holds also in the case that the weld is placed far from the corner area, e.g. at the axis of symmetry (h/r=2.25). The direction of the movement at the punch is opposite to the direction of weld movement in the flanges (1, 2, 2', 1') which are subject to compressive stresses in the flange corners.

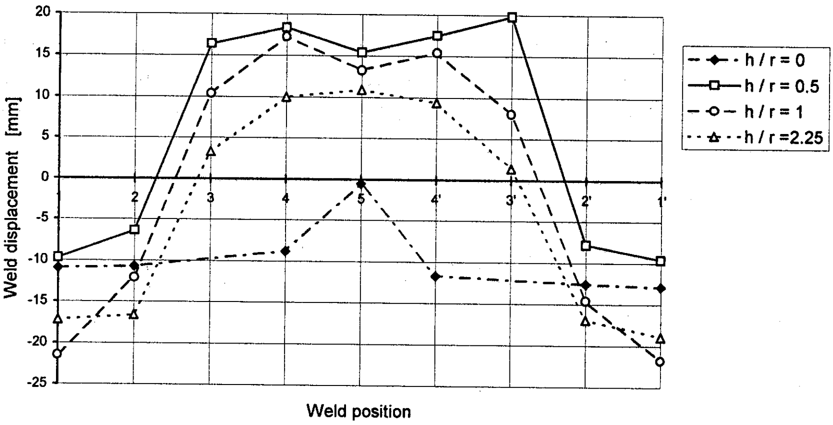

Figure 6.25 Weld displacement in product and flange for deep drawing of the 0.5-1.5 laser welded combination ((different product heights)

The absolute weld displacements of the h/r=2.25 position can be compared to the displacements of the product drawn form the 1.5 mm sheet, since these two products have equal heights ($H_{p,\,max}$=107 mm). This shows that the weld displacement at the end of the flanges (measure points 1 and 1') of the thick/thin combination is smaller then that of the unwelded sheet. The relative displacements (between measure points 1 (or 1') and 5) have the same order of magnitude as those of the unwelded sheets.

It can be concluded that the weld displacements in TMBs are fundamentally equal to those of the unwelded situations, except that the weld as a whole shifts away. The weld displacement in TMBs is therefore not only characterised by movements of the weld in the flanges, but also by movements of the weld on the tool.

Typical failure mechanisms

Weld displacement is not the only effect of the changed strain distribution. The local strain concentrations also lead to failure mechanisms that are typical for TMBs. The tests showed six different failure types, represented in Figure 6.26. Each type is representative for a particular situation. Failures that occurred due to irregularities in the welds are not taken along in this classification.

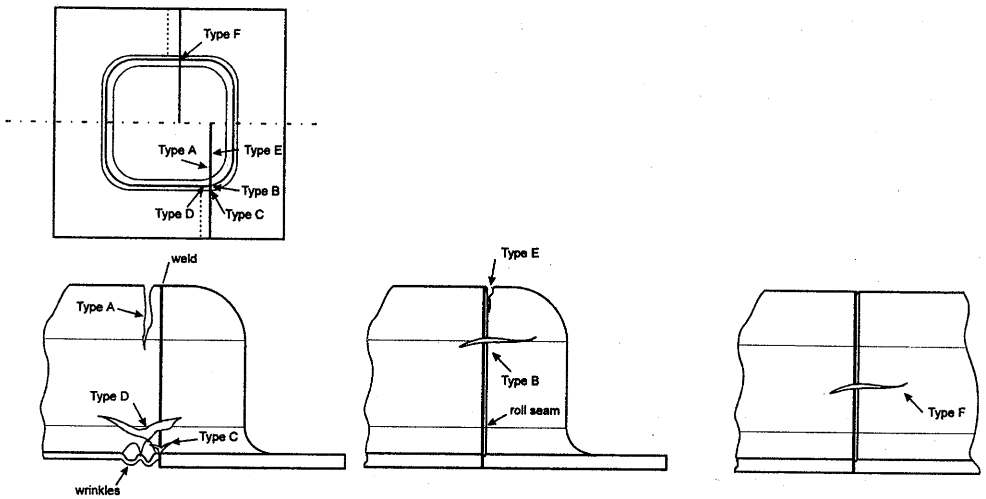

Figure 6.26 *Typical failure types in deep drawing of welded sheets*

During the deep drawing tests the following failure types were encountered:

- Failure Type A is a fracture in the thinner/weaker partner, parallel to the weld, outside the HAZ. Fracture is initialised at the top of the punch, close to one of the corners. Fracture is a result of stresses perpendicular to the weld, initiated by the resistance of the thicker/stronger partner to deform. This fracture type occurs for combinations of unequal sheets for weld positions close to or in the product corner, where the weld is allowed to slide off the punch corner.

- Failure Type B stands perpendicular to the weld and occurs at the transition of punch radius and product wall in cases of equal sheet thickness. Fracture is a result of critical plane strain in the thinnest cross-section of the wall. This failure type is also common for unwelded specimens.

- Failure Type C arises at the transition of the blank and the die radius. The fracture is mainly limited to the weld itself. This failure type is found for combinations with extreme thickness differences (0.7-2.0). Fracture takes place due to stresses parallel to the weld, but is initialised by bending over the radius.

- Failure Type D arises at the end of the wrinkles at the transition of die radius and the product wall. The fracture occurs for situations in which the wrinkles get stuck in the space that is meant to allow movement of the thicker partner. The wrinkles get so sharp that the peak stress result in fractures at the end of the wrinkles.

- Failure Type E occurs in the roll seam parallel to the weld, in cases of laser welded identical sheets. The location is similar to failure Type A. Fracture is a result of stresses perpendicular to the weld. The weakest spot is the thinned path next to the weld in the partners where the roll has passed. This fracture type is related to the used weld method. It is to be expected that this failure type can be prevented in the near future, due to weld process optimisation.

- Failure Type F stands perpendicular to the weld and occurs in the product wall, for weld positions further away from the corner area. This type is similar to Type B, except that there is no critical thinnest cross-section. The location of the fracture is inconsistent.

The observed failure types for the different weld positions and material combinations are represented in Table 6.6.

	h/r =0	**h/r =0.25**	**h/r =0.5**	**h/r =1**	**h/r =1.5**	**h/r =2.25**
0.7-0.7, laser	E	E+F	F	F*	F*	F*
0.7-0.7 reph., laser	A	A	F	B+F	B	-
0.7-1.5, laser	A	A	A+C	A+C+F	B	-
0.7-1.5, mash seam	A	A	A	A	B	-
0.7-2.0, laser	A	A	A+C	A+C+F	A+C+F	-
2.0-2.0, laser	-	-	-	-	-	-

***Table 6.6** Observed failure types for the different material combinations and weld positions*

In respect to the formability of TMBs tested in this chapter the failure types can be divided in two main categories:

A) Failure in the material, due to strain concentration in the thinner/weaker partner (Figure 6.27)
B) Fracture in the weld, perpendicular to the weld orientation due to elongation of the weld (Figure 6.28)

These two categories correspond to failure type A (and it derivative type E) and B (and its derivatives type C, D and F), respectively. Table 6.6 can now be divided into two parts. The bottom-left part (unequal sheets close to the product wall) is dominated by category A failures, whereas the upper-right part (identical sheets close to the axis of symmetry) is dominated by category B failures. This division is determinative for the deep drawability of TMBs.

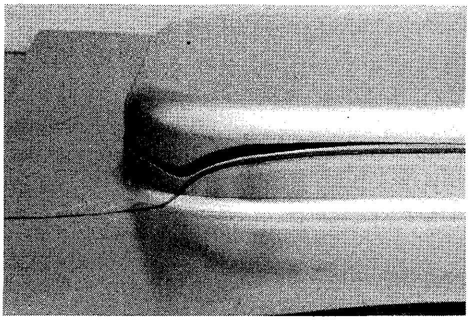

Figure 6.27 Fracture in the thinner/weaker partner parallel to the weld (type A)

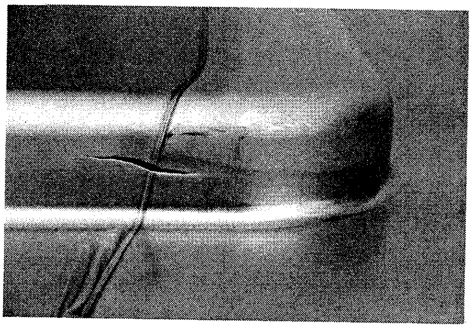

Figure 6.28 Fracture in the weld perpendicular to the weld (type B)

Deep drawability of unequal sheets

The maximal product height, representing the deep drawability, is determined on the basis of the measured force maximum. This measure showed to be adequate. All test are repeated three times. The three consecutive repetitions have a small mutual aberrance. The maximal average deviation is 5 mm, but is generally lower that the reading exactness of the measure equipment (in the order of 1mm).

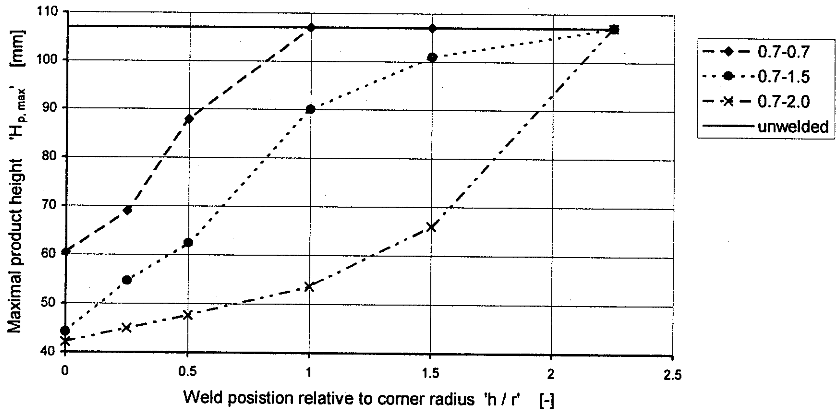

Figure 6.29 Deep drawability as function of the weld position for different material combination (0.7-0.7, 0.7-1.5 and 0.7-2.0) under optimal process conditions

In Figure 6.29 the deep drawability of the different material combinations is represented in a single diagram. The horizontal axis represents the position of the weld. The position h/r =1 corresponds to the transition of the product corner to the straight product wall, position h/r=2.25 corresponds to the middle of the product. The vertical axis represents the maximal product height ($H_{p,\ max}$). The deep drawability of the unwelded specimens is represented as a horizontal line. The tests are performed under optimal conditions.

The maximal product height for weld positions close to h/r=0 is more or less independent of the material combination. Failure at this position is a result of resistance of the stronger partner to deform, because the support of the punch is not enough to force it to deform. The imposed stresses are entirely passed on by the weaker partner. The resulting maximal product height is therefore dependent on the strength of this weaker partner. This is in all cases 0.7 mm FeP04. This corresponds to failure type A, fracture of the weaker/thinner material partner parallel to the weld. The 0.7-0.7 combination gives a marginally better performance as the strain can be distributed over both partners. Eventually however, the load perpendicular to the weld is fatal.

As the weld is placed further in or past the product corner, the stresses on the thicker/ stronger partner are increasingly passed on directly by the punch. The weaker partner is relieved, resulting in a better deep drawability. This is confirmed by the failure mode and the weld displacements. At larger 'h/r'-values the characteristic failure type changes. Not the weakest partner but the weld itself fails (type B). The transition can be accompanied by a dual failure mode. The weld position at which this transition takes place depends on the material combination.

The bigger the thickness/strength difference, the more the stronger partner is inclined to show a rigid character. As a consequence the formability is decreased over a larger 'h/r'-range, than for smaller thickness/strength differences. This can be represented by the minimal acceptable weld position $(h/r)_{Hp=90\%}$, defined as the weld position at which at least 90% of the original product height can be drawn. The minimal acceptable weld positions are given in Table 6.7 for the different material combinations.

Material combination	$(h/r)_{Hp,\ max=90\%}$
0.7-0.7	0.75
0.7-1.5	1.25
0.7-2.0	2.05

***Table 6.7** Minimum acceptable weld position to draw 90% of original product height (under optimal conditions)*

Distribution of strains over partners

In the former case the deep drawability of the individual materials are equal. In many cases this condition does not hold. The deep drawability of this category is studied by the 0.7-0.7reph. combination. The results are given in Figure 6.30 and are based on tests with laser welded samples tested under optimal conditions.

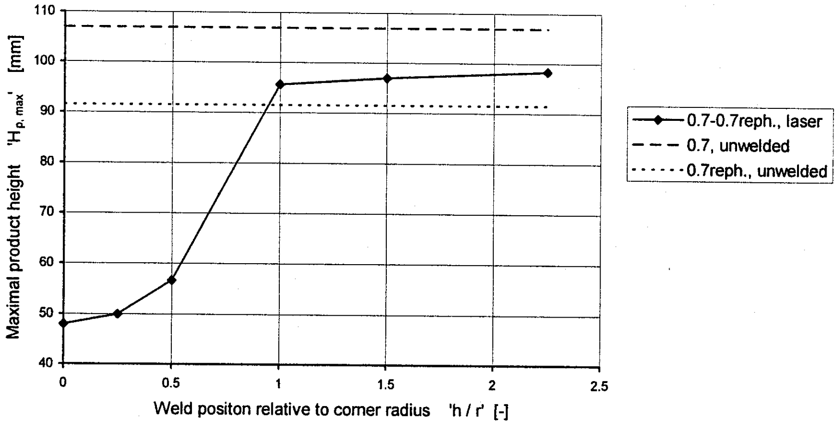

Figure 6.30 Deep drawability of a TMB (in this case 0.7-0.7reph) can exceed the deep drawability of one of the individual blanks

The figure shows the deep drawability of the 0.7 and the 0.7 reph. material as horizontal lines (at $H_{p,\,max}$ =107 and 92 mm respectively). The formability of the 0.7-0.7reph combination is again represented as a function of the relative weld position (h/r).

For weld positions close to the product wall (h/r < 1) the deep drawability is limited by the thinner partner, just like in the former example. For the other weld positions the 0.7-0.7reph. combination shows a divergent pattern.

For h/r = 0.9 the deep drawability of the TMB exceeds the deep drawability of one of the used materials (0.7reph), but the critical material does not fail as it would have in the unwelded situation (fracture in the corner area). Apparently the other partner (the 0.7mm) is able to take on some of the strain. The maximal deep drawability is finally reached somewhere in the middle between the deep drawabilities of the individual materials. Hence, the formability of the TMB may be better than that of the partner with the worst formability.

Effect of test conditions

In Figure 6.31 the deep drawability of the 0.7-0.7mm combination is given for two different test conditions. Both test conditions show the earlier observed drop in deep drawability in the corner area ($h/r < 1$).

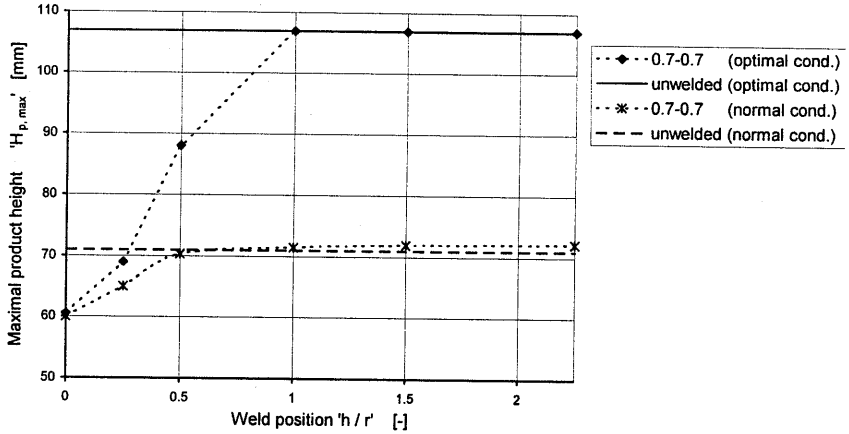

Figure 6.31 Influence of the process condition on the deep drawability

For weld position at $h/r = 0$ mm the deep drawability is independent of the process conditions. The relative decrease in deep drawability for weld positions in the corner area is therefore bigger if the process conditions are more optimal. As a consequence, the minimal acceptable weld position is $(h/r)_{Hp,\ max=90\%} = 0.45$ and $(h/r)_{Hp,\ max=90\%} = 0.75$ for the normal and the optimal conditions respectively.

Mash seam versus laser welds

The 0.7-1.5mm combination is also tested as a mash seam welded combination. This is done under the normal test conditions. The results of these test are given in figure 6.32, together with the matching results of laser welded samples.

The deep drawability of laser and mash seam welded samples are equal as long as the weakest partner forms the limitation, in this case for weld positions $h/r < 0.5$. If the deep drawability is limited by the weld ($h/r > 0.5$), the tests show that mash seam welded samples perform better. It can be assumed that this is due to the better formability of the mash seam weld, based on the lower and flatter hardness course. This corresponds to results of the standardised tests (Section 5.2), that show higher toughness for mash seam welded samples, compared to laser welded samples.

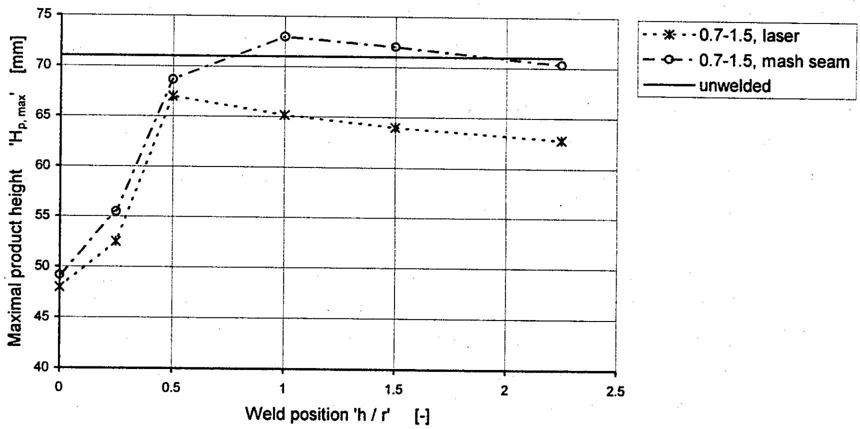

Figure 6.32 *Deep drawability of 0.7-1.5 laser- and mash seam welded material combination*

6.7 Stretching tests

The deep drawability of the stretching tests is determined by a series of tests. Each test is characterised by a adjusted height, which results in either fracture, necking or success. Each series required up to 10 tests. The resulting product heights are the values found at necking and represent the transition from acceptable to unacceptable products.

Weld displacements

The weld displacements in stretch situations are unidirectional. The weld in the flange shifts in the same direction as in the product itself. This is not effected by the introduction of welded blanks.

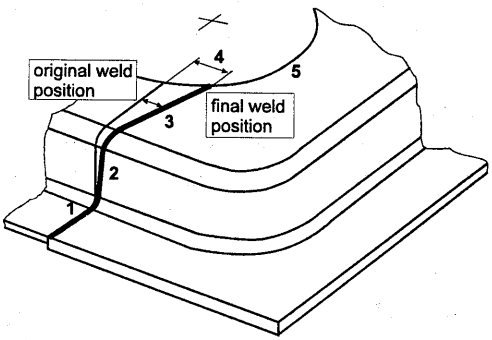

Figure 6.33 *Definition of the weld displacement measure points for the stretching product (points 1' to 4' are mirrored on the other side)*

The displacements are measured in the horizontal plane, perpendicular to the weld (Figure 6.33). The measures are taken from intact products, drawn to their maximum depth.
The weld displacements in the stretching situation are, more so then in deep drawing tests, geometrically determined. The strain distribution has a limited influence on the displacement pattern. This is not different for TMBs. The weld displacement is mainly determined by the product height (Figure 6.34).

The largest displacements are measured for the welds along the side of the hole (s/R=1). The movements in this area are perpendicular to the weld, just like the measured displacements. The displacements therefore follow the drawn product height, with an aberrance due to strains and tool radii. The other extreme is the central weld position in the middle of the hole (s/R=0). The weld movement in this area is parallel to the weld. The measured weld displacements, perpendicular to the weld, are therefore minimal. The small deviations are caused by strain concentration in the weaker partner.

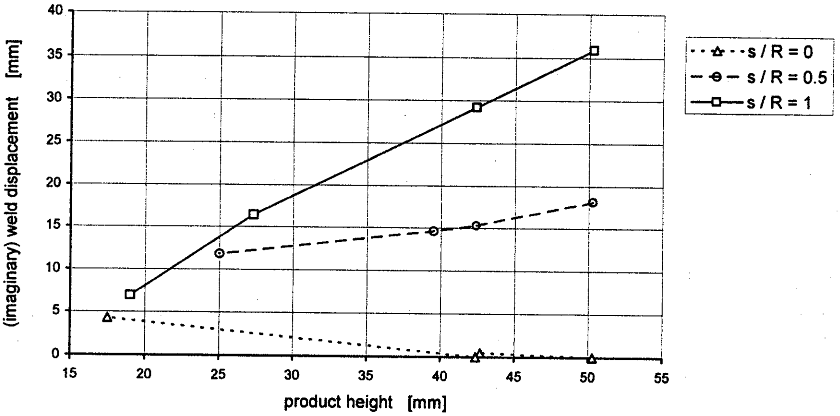

__Figure 6.34__ Weld displacement of four material combinations as a function of the product height (for unwelded samples displacement of imaginary welds are shown)

The displacement distribution over the product shows a corresponding pattern. The weld displacement of the 0.7-1.5 combination (Figure 6.35) can be seen as representative for welded unequal blanks in general. Unwelded blanks or combinations of identical sheets differ, since they do not show a weld displacement for the symmetric weld positions (s/R=0).

Figure 6.35 confirms the unidirectional character of the displacements, since all displacements are positive. The weld displacement is larger for points closer to the hole (points 3,4 and 5) and for weld positions closer to the edge of the hole (s/R=1).

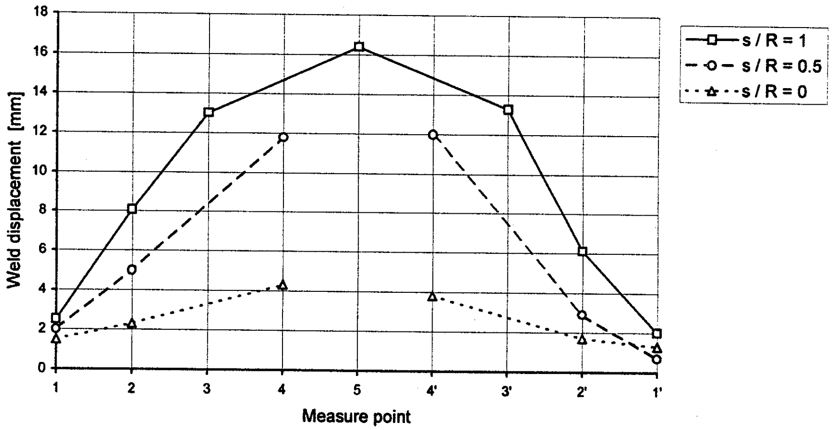

Figure 6.35 Weld displacement of the 0.7-1.5mm combination for different weld positions (s/R =0, 0.5 and 1)

Typical failure types

The stretching tests showed four different fracture types (Figure 6.36), referred to as failure type I to IV:

- The fracture type common for the unwelded blanks is type I. This fracture type occurs at the edge of the hole and develops in the direction of the bowl corners. In some cases the fracture is initiated in the material itself. This is caused by the strain concentration in the corner areas. For combinations of unequal sheets the thinner/weaker partner can show a comparable fracture type, which is referred to as I^*.

- Fracture type II, in combination with fracture type IIa/IIb, is representative for the combinations of unequal sheets in most weld positions. Type II, a fracture at the edge just next to the weld in the weaker partner, is typical for the central weld position. Type IIa/IIb are typical for the eccentric weld positions. The further the weld is placed towards the hole edge (s/R =1) the further the fracture occurs away from the hole edge (IIa resp. IIb). These fractures are initialised in the weld and develop in the direction of the weakest material.

- For the 0.7-0.7 combination fracture occurs in the roll seam (type III) due to the used weld process.

- If the weld is placed at the edge of the hole, the fracture occurs in the in the weld and develops into the material perpendicular to the hole (type IV), even when this is the stronger material.

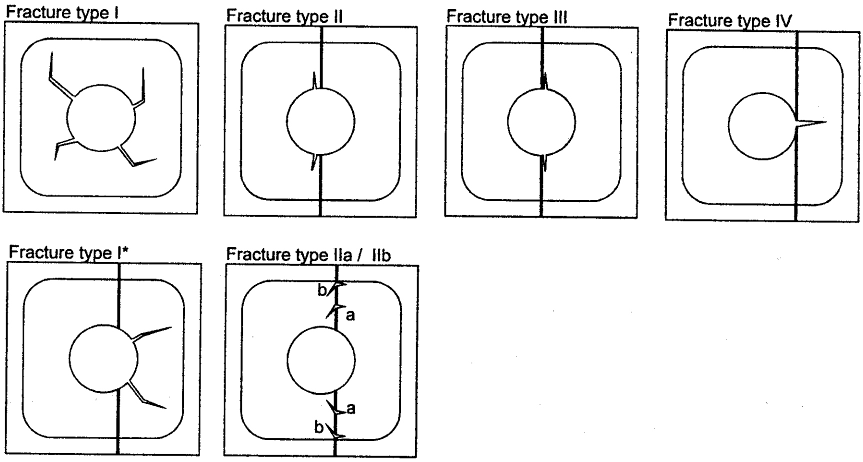

Figure 6.36 Typical fracture types of the stretching tests

Compared to the deep drawing test, the fracture types of the stretching test are less meaningful. The main failure type (type II) is comparable to the failure type of the unwelded samples (type I), except that the fracture is early initiated in or close to the weld or in the weaker partner. These small differences result however in large difference in deep drawability. In the situation that the weld is placed at the edge of the hole (s/R =1) a divergent fracture type (type IV) occurs. For this fracture type the elongation of the weld plays a role, comparable to fracture type B of the deep drawing tests.

	s/R =0	s/R =0.25	s/R =0.5	s/R =0.75	s/R =1
0.7-0.7, laser	I / Ia	-	III	III	IV
0.7-0.7Reph., laser	Ia	-	IIa	IIb	IV
0.7-1.5, laser	II	II	IIa	-	IIb / IV
0.7-1.5, mash seam	II	II	IIa	-	IIb / IV
0.7-2.0, laser	II	-	II / IIa	-	IIb
2.0-2.0, laser	I	-	I / Ia	-	I / Ia

Table 6.8 Observed failure type in the stretching tests

Deep drawability

The deep drawability of the stretching test is studied on basis of four different material combinations (Figure 6.37). The maximal product heights for the unwelded materials are given in Table 6.9.

[mm]	FeP04 0.7mm	Reph. 0.7mm	FeP04 1.5mm	Warm rolled 2.0mm
product height	46	39	54	46

***Table 6.9** Deep drawability of the unwelded materials*

The 0.7-0.7 combination shows that the deep drawability decreases as the weld is placed closer to the side of the hole (s/R =1). In this area the maximal strain is parallel to the weld. The weld is forced to extend, but this is impossible due to its brittle character. This leads to the fracture of the weld itself (type IV). The other combination of equal materials (2.0-2.0) shows a comparable behaviour.

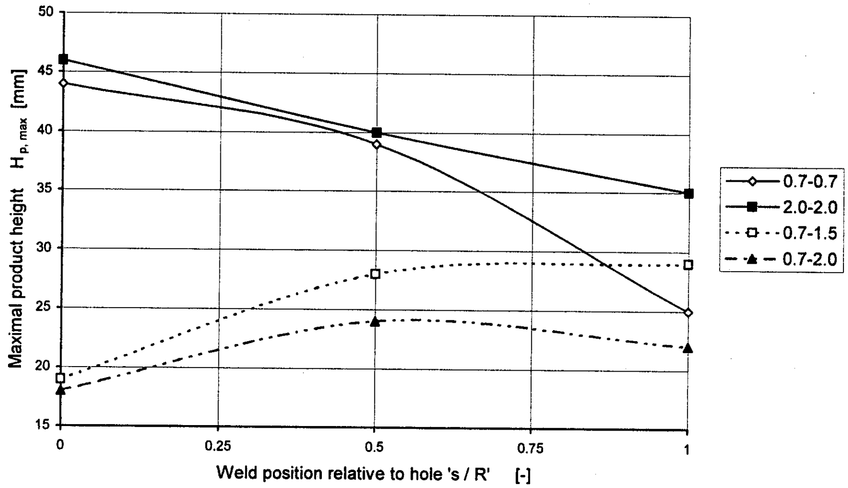

***Figure 6.37** deep drawability of thick/thin and equal thickness combination in stretching*

The thick/thin (0.7-2.0 and 0.7-1.5) combinations show a aberrant character. The lowest deep drawability for these TMBs is found for welds in the middle of the hole (s/R=0). Fracture occurs due to local strain concentration. The thicker partner behaves rigidly and the thinner partner is forced to deform. For welds closer to the hole edge, the entire hole is enclosed by the thinner partner. In this case the deformation of the thinner partner can be distributed over a larger area. The brittle character of the weld is the limiting factor. As a consequence, the situations where the weld is placed at the edge of the hole (s/R =1) the deep drawability is close to the values found for the 0.7-0.7-combination.

For all weld positions of the thick/thin combinations the maximal product height is lower than the addition of the die and tool radii (30mm). This means that the product fails even before a straight wall is formed.

Mash seam versus laser welded

The material parameters (Section 6.2) showed that the mash seam welds, for combinations of identical sheets, have a better strain at fracture (e_{frac}) then the laser welds. In the deep drawing tests (Section 6.6) the mash seam welds performed also better then the laser welds. In both tests the results are based on elongation of the weld. In the stretching test, the mash seam weld performs also better then the laser welded samples, but in a different strain situation (Figure 6.38).

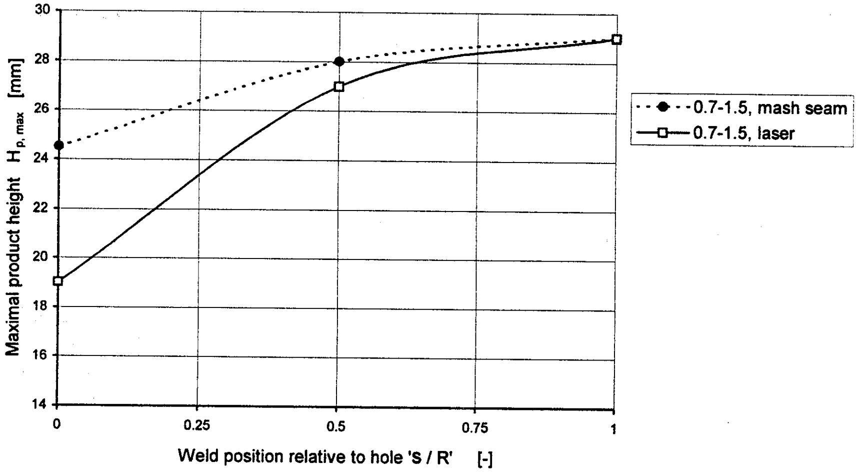

Figure 6.38 Influence of the weld method on the deep drawability in stretching (0.7-1.5 combination)

The mash seam weld performs better than the laser weld for weld positions close to the symmetry axis of the part (s/R <0.75). In this area the weld is compressed, while the two partners are drawn apart. Apparently the mash seam weld also has a better resistance for this particular strain situation. For the larger ‘s/R‘-values the difference between the mash seam and laser welds is negligible. This was unexpected. On basis of the earlier results it was anticipated that in this particular strain situation the mash seam weld would perform better also. No logical explication was found, except that maybe the failure is more affected by the surface finish of the hole then by the weld itself. For this particular weld position the finishing of the hole was difficult.

6.8 Conclusion

The developed tool has demonstrated its usefulness for different stress situations, weld positions and material combinations. The divided blank holder and the separately adjustable blank holder pressures have proven their adequacy. The advantage over the 'standardised tests' is that the weld can move over the punch and blank holder. These movements dominate the formability behaviour of unequal sheet combinations.

The forming behaviour of unequal TMBs can be divided in two typical situations, viz. strains and stresses perpendicular to the weld and strains and stresses parallel to the weld. This is comparable to the results from the standardised tests for identical sheets. But the effect is more pronounced for unequal sheets, since not only the weld, but also the weaker partner is critical.

- If the major strains stand perpendicular to the weld, the formability is dominated by strain concentration in the thinner/weaker partner. The thicker partner refuses to deform and the weakest partner fails. This situation is more critical for larger strength/thickness differences and is more or less independent of the weld method (laser or mash seam). The formability is determined by the extent to which the thicker material is forced to deform. Deformation of the thicker partner reduces the strain concentration and postpones failure. For example, the formability in deep drawing is improved for weld positions further away from a corner area. The more of the thicker partner is supported by the punch, the less likely it is that the thick material shifts off.

- If the major strains stand parallel to the weld the formability is dominated by the 'strain at fracture' of the weld. Strain concentration in one of both partners is excluded as the partners are loaded equally. In this case the laser and mash seam welds show a divergent behaviour, as the mash seam weld has a higher maximal elongation compared to the laser weld.

The test also showed weld displacements, both in the flange and on the punch. These displacements are relevant for both the tool and product design.

- The tool design has mainly to deal with weld displacement in the flanges. Particularly in the blank holder of a deep drawing product, where the weld line shifts over 20mm in the performed tests. Typical problems are wrinkling in the thinner partner and ripping of the thicker partner. In stretching situations the tool design needs only minor adjustments. The weld does not shift in the flange and the shifting of the weld at the punch is not critical for the tool design.

- The product design also has to take shifting of the weld line into account, since this influences the final product measures. In the tests the inclusion of thick material deviated up to 20mm from the initial blank. This holds for both stretching and deep drawing situations.

6.9 Feedback to environmental analysis

The environmental analysis (Section 4.4) of the TMB-door showed the relation between the weld position and the life-cycle energy consumption. The weld position can not be freely chosen as it affects the formability and hence the maximal product height (Section 6.6). Therefore, the designer of a TMB-door has to find a balance between required product height and the life-cycle energy consumption.

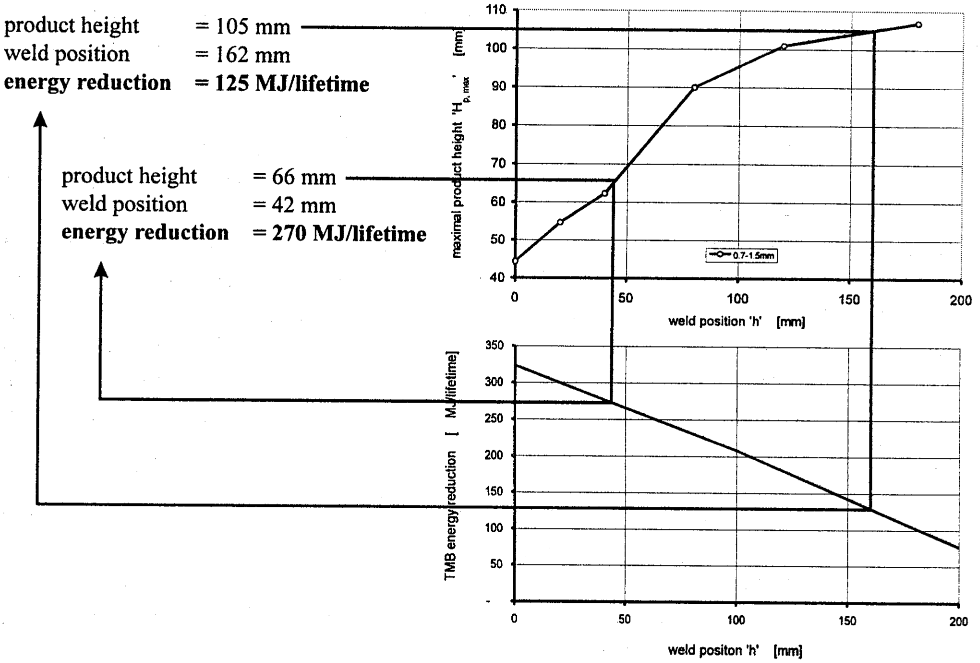

Figure 6.39 The combination of manufacturing and environmental information enables the designer to choose the weld position

Figure 6.39 (in which Figure 4.7 and Figure 6.28 are combined) gives an example based on the automotive inner-door, composed of 0.7mm and 1.5mm sheets. The horizontal axis in both graphs represents the weld position. The vertical axis represents the required product height and the resulting energy saving over the life-cycle relative to the conventional product, respectively.

The figure shows that a product height of 105mm requires a minimal weld position of 162mm. Weld positions closer to the product wall will result in early fracture of the door. This means the maximal life-cycle energy saving is 125 MJ per door. If the designer would accept a product height of 66mm, the minimal required weld position is 42mm. This means a life-cycle energy saving of about 270 MJ per door.

The example demonstrates that manufacturing technology can influence the environmental impact of the product. Until now this aspect of manufacturing has been underexposed. Therefore it is worthwhile to investigate the possibilities of new processes to manufacture environmentally friendlier products. In other cases other and maybe more parameters have to be taken into account to make a well-balanced decision.

Comparison of economical and environmental aspects

To compare the economic and environmental performance of TMBs, a number of different TMB-parts have been selected from the product range of three manufacturers. The selected parts are re-designed as a TMB and their environmental performance is reviewed according to the energy consumption as described in Section 4.4. Subsequently, the environmental performance is compared to the calculated cost prices. Both the cost prices and life-time energy consumption are related to the cost prices and life-time energy consumption of the conventional product.

The results are represented in Figure 6.40. The horizontal axis represents the relative cost price of the tailor-made part. The vertical axis represents the energy consumption over the lifetime of the tailor-made part. The environmentally-friendly alternatives are those in the lower part of the graph, the economically feasible alternatives are those on the left-hand side of the graph.

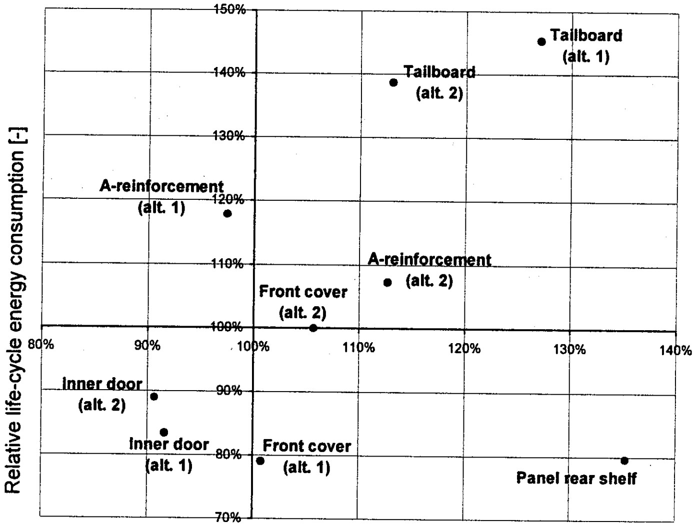

Figure 6.40 *Production costs versus life-cycle energy consumption for different tailor-made blank alternatives*

Most of the selected alternatives are more expensive than their conventional alternatives. Though it is not suitable to use TMBs for all parts, these results are affected by the fact that the TMBs are redesigned on the basis of the conventional parts. In a design starting from scratch, the advantages of TMBs can be used to a greater extent.

Two thirds of the economically feasible alternatives are also environmentally friendlier. This increases the chance that the environmentally-friendly alternatives will indeed be applied. The comparison between economic and ecological performance becomes particularly interesting in situations where economic feasibility is not optimal, like for instance the 'front cover' or the 'A-reinforcement'. In these cases the environmental benefit may result in the preference of the TMB over the conventional part.

Concluding remark

The presented TMB-case has shown to be a suitable example of a situation in which the process design requires an integrated approach of both 'process-related aspects' and 'product-related aspects'. This combination of influences is visualised in Figure 6.39. This figure also shows the importance of the weld position in TMB. In other cases, other parameters, characteristic for the specific situation, probably play a comparable role. An important topic for future research is therefore the determination of a parameter that is relevant for both the environmental performance and the process design.

Compared to the feedback of Chapter 5 the feedback in Section 6.9 is far more concrete. This underlines once more the necessity of reliable, quantitative methods to describe the environmental performance of manufacturing processes. Quantitative measures give unambiguous guidelines for the environmentally-friendly design of manufacturing.

Just like research on 'alternative lubricants and tool materials' (Section 5.14), the research on the TMBs has resulted in potential environmental improvements, but to a limited extent. The aim of 'zero emission' or 'industrial ecology' is still far away.

Chapter 7
Conclusion and recommendations

Environmental aspects of manufacturing can be divided into two categories: aspects that are directly related to manufacturing and aspects that are indirectly related to manufacturing. The direct aspects are related to the processes, whereas the indirect aspects are related to the products. Hence these aspects are referred to as process-related aspects and product-related aspects respectively. This concluding chapter goes back to this suggested division and gives an overview of the results. Section 7.5 focuses on the technical conclusions, followed by a feedback with respect to the environmental starting point (Section 7.6). The final section is dedicated to general recommendations for further research.

7.1 Relevance of sheet metal forming

Manufacturing in general and sheet metal forming in particular does not have first priority in the global strive for environmental friendliness. The impact of manufacturing processes in the sheet metal forming industry is, based on an energy consumption approach, about one tenth of the environmental impact that the processed materials cause during their extraction and production. For active parts, which are active during their use-phase (e.g. a car), the environmental impact of the use-phase is again ten times bigger than the environmental impact during the material extraction phase. The actual manufacturing effect for many products therefore is in the order of 1%. This thesis shows two reasons why the environmental optimisation of sheet metal forming processes is of general interest in spite of the limited direct impact: the processes are usually used in mass production and the processes have the potential to improve the manufactured products.

Mass production

Sheet metal forming processes are usually used in mass production. This means that although the impact is small from the product point of view, the impact is relevant from the process perspective. In Section 4.2 an illustration was given of the 'law of large numbers'.

From the perspective of mass production, emerging markets play also an important role. These developing countries are trying to catch up with our material prosperity, resulting in enormous demands for mass-produced products. Production facilities are often located in these countries, where environmental regulations and laws are not as strict as they could be.

Product improvement

Sheet metal forming processes have the ability to produce better and environmentally friendlier products through new and optimised processes or process chains. These new manufacturing processes should contribute to life-cycle phases beyond manufacturing itself, where the relevant environmental impact is caused. For example the processing of recycled materials. These materials have different qualities and require new or adapted manufacturing processes to enable recycling and hence the reduction of waste materials. Another example is transportation products, which are dealt with in this thesis. These products are active during their use-phase and their product weight determines largely their energy consumption. New manufacturing processes should therefore enable the production of lighter products. For these active products the mass production character of forming processes is particularly important.

7.2 Product and process-related aspects

The differentiation between product and process-related aspects is partly based on the split responsibility in companies between process engineers and product designers. The process engineer is held responsible for the processes that he utilises to manufacture a given product. This engineer is not authorised to change the product qualities, but is held accountable for the activities within the factory borders. A product designer on the other hand is held responsible for the product performance. One of the demands made to products concerns their environmental performance. The product designer therefore is interested in manufacturing processes that support his efforts to minimise the environmental impact of the product. However in practice the environmental impact of the manufacturing process itself is not his first priority, as this generally does not significantly influence product performance.

This split responsibility is embedded in company structures and differs for companies of different size. The small companies often are part suppliers and manufacture parts based to buyer specifications. The process is their product and their influence is therefore limited to process design. They are not allowed to influence part properties. Large companies on the other hand can influence both product and process aspects. However, due to their size, these responsibilities are divided among different people and different groups. This split is least prevalent for small companies that are just large enough to design their own products. In these companies product and process design often overlap.

Although the split is apparent in production practise, it is not based on fundamental ecological or physical differences. From the environmental point of view, process and product-related aspects are interrelated and their mutual distinction is vague. Therefore the main challenge is to bring the process and product designer together. A good example is the industrial collaboration in the TMB-project, in which suppliers, manufacturers and product designers co-operated. This project therefore is an example of the second objective (Section 2.3), ‘Act innovative with respect to the processes and products’.

The importance of the second objective does not diminish the importance of the first objective, regarding the ‘process-related aspects’. These aspects can be, more or less, independently dealt with by process engineers. The challenge in this field is the co-operation with suppliers and other players in the means-of-production life-cycle. Generation of the required data is an important part of this challenge. In the future the experiences in this field should be reflected in design guidelines. These guidelines then form an extension of 'design for manufacturing' guidelines and should incorporate the manufacturing consequences of design decisions.

7.3 Environmental assessment methods

The methods to determine the environmental impact of products and processes are still under development. One of the more fundamental discussions concerns how to measure the environmental impact. The scientific difficulty in this discussion is the weighing step, which has a subjective character. In this step different impacts, like for instance ozone depletion and acidification, are related to each other based on an assigned weight that expresses the relative importance of the impact category. The problem related to this weighing step falls outside the scope of the process and product design, but has to be solved before a final judgement on the environmental impact of manufacturing processes can be made.

A practical problem is the lack of environmental data. The available data on manufacturing processes is not detailed enough, in general, to analyse the environmental impact of manufacturing processes through quantitative measures. As mentioned in Section 7.2 this problem can partly be put on the desk of process engineers.

These problems made a solid environmental impact analysis of manufacturing difficult within this project. Since the determination of environmental impacts is an essential part of the project, the analysis has not been omitted, but its execution has been performed straightforwardly.

Industrial orientation

In the industrial orientation two methods are applied, one quantitative and one qualitative. The qualitative method is based on a step-by-step method that includes technical, economical and environmental issues. The method is suitable to determine improvement directions in a production environment. The shortcoming is the lack of quantitative information. The quantitative method is based on environmental costs. The method distinguishes costs related to environmental issues from other production costs. The method is suitable to discuss the environmental issues with management, but the results are not a direct measure of the environmental impact. Both approaches concentrate on the environmental impacts of production itself. Impacts outside manufacturing are addressed in brief. Though different methods are applied in different factories the outcomes are largely in agreement.

The activities had a one-off character. In future these activities should be integrated in production management. This can be supported by standards like the ISO 14000-series. Just like the quality standards, these environmental standards should aim at continuous improvement. Within these frameworks of activities the main environmental issues are listed, which are relevant for the specific company. Suitable evaluation methods are defined within the methods and the company's effort has to focus on gathering the required data.

Environmental analyses

The ecological impact of the topics selected in the industrial orientation (auxiliaries and tailor-made blanks (TMBs)) is analysed using a life-cycle assessment (LCA). The LCA on auxiliary materials has a low information depth and the results are qualitative. The main reason is the limited availability of environmental data on cleaning fluids and particularly on lubricants. The LCA-results are therefore limited to the determination of relevant material flows, classification of impact categories and the valuation of the material flows based on the obtained classification. In this stage of the research this was sufficient to formulate technical research questions. For the TMBs the LCA is based on an energy approach. The variable parameter is the weld position. The energy approach allows for quantitative results and avoids the weighing step. In this approach the material is represented by its energy content [Kop94, Kuz93]. The comparison of this approach with an LCA-scan shows that in this case it covers approximately 80% of the total environmental impact. The missing 20% consist of the impacts related to lubricants or other chemical substances that are not taken into account. Therefore this approach is sufficient for this case, since the TMB-process does not significantly influence the impacts related to these substances.

7.4 Relevant topics

The above mentioned methods have resulted in a global overview of the environmental topics relevant in sheet metal forming. The extension of results to the broader manufacturing is difficult, but it is expected that in all manufacturing processes comparable topics are of relevance.

Process-related aspects

The industrial orientation revealed three main aspects, which are directly related to the processes and which are largely independent of other product life-cycle phases. These process-related aspects are:

- auxiliaries
- material waste
- energy consumption.

A complete list of environmental impacts is larger because it includes items like production, maintenance, and discard of machines and tools [Cha74]. There are also some environmental impacts that fall outside the scope of this thesis, like for instance noise nuisance, which falls in the category of work circumstances.

In this thesis the auxiliaries are selected as exemplary for process-related aspects in sheet metal forming. The qualitative LCA shows three auxiliary material flows which determine the environmental impact:

- preservation oils
- lubricants
- cleaning fluids

Their impacts on the environment can be divided into five different impact categories:

- Evaporation of preservation oil, lubricant and cleaning fluid.
- Burning of preservation oil and lubricant during the melting of scrap.
- Discard of preservation oil, lubricant and cleaning fluid after cleaning.
- Waste/spill of preservation oil, lubricant and cleaning fluid.
- Consumption of water and energy.

Different alternatives are evaluated on the basis of these impact categories. The following conclusions can be drawn regarding the different material flows:

- As the results of the LCA are qualitative, it is difficult to give hard facts on the environmental impact of the different material flows. The results of the analysis give the impression that in most cases the cleaning and degreasing process is more critical than the lubricating process. The solvent cleaning processes suffer particular under ecological criticism, due to their destructive effects on air and soil. The preferred alkaline process on the other hand, also has negative effects like higher energy and water consumption and higher solid wastes. It is possible that in some cases the environmental performance of optimised solvent systems (closed systems with distillation recycling) is better than the performance of an alkaline system. This underlines the importance of 'good house-keeping'.

- Although most lubricants are seen as less dangerous to the environment than the cleaning fluids, the selection of a lubricant is equally important. The lubricants largely determine the ensuing cleaning process. Therefore the 'cleanability' of a lubricant is one of the relevant topics in the selection of an environmentally-friendly lubricant, in combination with its effect on the cleaning fluids. Besides that, some lubricants are enriched with additives that are harmful to the environment. A notorious example is the chlorine additive. Going forward, other additives like phosphates and sulphurs will probably be criticised as well.

- The environmental impact of the preservation oils themselves is limited. The quantities used are small and the oils are relatively pure. Nevertheless, the potential of these oils to achieve improvements is significant, as they can fulfil a function as a lubricant. These lubricants are the so called pre-lubs and are applied as a preservation oil.

Product-related aspects

The LCA of TMBs studies the influence of two parameters, the product mass and the waste mass of an automotive part. The mass of a car has to be accelerated during the use-phase and scrapped after discard of the car. The waste mass on the other hand is the quantity of material discarded during manufacturing, which has to be recycled subsequently. The analysis is limited to these two parameters and is applied to a car's inner door.

The analysis has shown that the use-phase is responsible for up to 90% of the energy consumption over a car's life-cycle. Therefore the environmental impact of the product weight is more important than the impact of the production scrap. The environmental impact of e.g. one kilogram weight in a passenger car has an impact equivalent to 16 kilograms of manufacturing scrap. The design of TMBs (and steel car parts in general) should therefore focus on reducing the product weight. In this perspective, the scrap reduction is of lesser importance.

The key-parameter in the design of TMBs is the weld position, as this parameter determines both product and waste weight. The environmental analysis resulted in a relationship between the weld position and the environmental impact of the part. The technical research results in a relation between the weld position and the formability. The formability is defined as the maximal depth of an inner door. The combination of both relations gives the product designer the possibility to optimise the door design based on both environmental and manufacturing information.

7.5 Technical specification

The conclusions drawn from the technical research were given at the end of each individual topic. Section 7.5 provides a short summary and does not address the test methods used into detail.

Auxiliaries in sheet metal forming

The technical research of auxiliaries is directed towards the different cleaning processes and the wear-preventive qualities of both lubricants and tool materials.

The solvent cleaning process is technically preferable to the alkaline cleaning process, because of the ease of maintenance and a broad number of parts and lubricants that can be handled in one installation. Though more difficult, an alkaline cleaning process can be adapted to a particular situation. Therefore the main requirement for an alternative lubricant is to guarantee wear-preventive qualities, without environmentally unfriendly (chlorine-)dopes.

The technical research also showed that none of the tested alternative lubricants has a better wear-preventive quality then the reference lubricant, which is Cl-doped. The tests show unacceptable wear for most lubricants, causing shorter tool-life times. The application of an environmentally-friendly lubricant should therefore generally be accompanied by the application of wear-resistant tools.

Two types of alternative tool materials were tested: uncoated steels (sintered carbides and sintered high-speed steels) and PVD-coated steels. In the group of uncoated steels the sintered carbides displayed superior wear preventive qualities, but they are difficult to use in practise. In some cases sintered high speed steels can give sufficient improvement compared to standard tool steels.

The wear pattern of the PVD-coatings differs from the wear pattern of the uncoated tools and gives the lower wear rate. Most coatings did not show the expected crumbling off. Since the quality difference among the suppliers exceeds the quality difference among coating types, the selection of a good supplier is an important consideration in the process design.

Finally, a sintered high-speed steel and a PVD-coating were selected and tested in production. The results are comparable to the results from the laboratory tests and show satisfactory results for punching. It is expected that results will be even better for less loaded processes like deep drawing.

Tailor-made blanks

The formability of TMBs was initially studied by means of tests that are standardised for unwelded sheet. Since these tests alone are not sufficient to describe the full forming behaviour of TMBs, a new test method was developed and applied.

In general the formability of the weld is characterised by a limited elongation. The measured maximal elongation is approximately 30%. This corresponds to a reduction of approximately 30% compared to unwelded sheets. The weld is less sensitive to strains perpendicular to the weld. Therefore the strain orientation relative to the weld is important in the formability of TMBs.

The alternative test tool developed gives us the ability to study the forming behaviour of TMBs on a full scale, including weld displacements, for two different processes: deep drawing and stretching. The test design is primarily directed at the study of the influence of the weld position and is suitable for dealing with different thickness combinations. The tests show several different failure types. The two main failure types are fracture in the weld and fracture in the thinner/weaker partner.

The most significant difference with normal forming is the displacement of the weld on the punch. The displacements are a result of strain concentrations in the thinner/weaker partner. Because the thicker material resists deformation, it slides off the punch. The larger the difference between the sheets, the larger its effect on the formability. In the deep drawing situation, this can be prevented by positioning the weld further on the tool, increasing the supporting punch area. In situations that strains do not concentrate in one of both partners (due to material combination or weld position) the weld is critical. In these cases the mash seam performs better than the laser welds, as demonstrated by a better elongation.

7.6 Feedback

The technical examples show that it is possible to realise environmental improvements in sheet metal forming. These improvements are not necessarily limited to the manufacturing process itself. Manufacturing processes can also be optimised to improve the environmental performance of the manufactured products. In both cases the resulting 'delta' is limited. The approach used leads to an evolution of the environmental load reduction. The TMB-case showed that the reached reduction of environmental impacts is 10-20% at most. However, that reduction can only be reached for a small part of the total environmental impact of a car. The reduction in the lubrication and cleaning case will not deviate significantly, but is causing an even smaller impact.

Though no complete reductions are reached, the methods used are worthwhile, because the technical research leads to economically feasible improvements. Since the improvements are an integrated part of manufacturing (process-integrated), they increase the technological level of manufacturing and contribute to the manufacturer's competitiveness. These process-integrated solutions therefore lead to environmentally friendlier production without increasing the production costs. End-of-pipe solutions, on the other hand, are added to the manufacturing processes and cost extra money. This does not mean that process-integrated solutions can eliminate the necessity of end-of-pipe solutions in all cases.

Achieving more significant reductions of environmental loads would require a different approach. This approach should be directed at the optimisation of the function fulfilment and not to the optimisation of existing processes and products.

The technical research emphasised the importance of quantitative measures to determine the environmental impacts. This enables the evaluation of the technical results and enables designers to select an optimum between technical and environmental aspects.

7.7 Recommendations

The research has shown that it is rewarding to include environmental considerations in new process and product developments. In research projects on new processes, evaluation of the environmental consequences is particularly useful. Up to now these considerations have been under-represented in daily practise.

Several comments can be made about the continuation of the work presented in this thesis. The mass-productive character and the ability to influence the product qualities make sheet metal forming processes sufficiently interesting for future research. The future environmental research requires a further co-operation with other disciplines. This co-operation should contribute to a better valuation of the environmental impacts and to a further optimisation of the environmental performance of manufacturing in the broadest sense of the word. On the other hand, the technical research topics dealt with in this thesis are only examples of environmental improvements. Many other possible improvements are not yet worked out. The recommendations focus first on the continuation of the technical research, before attention is given to possible co-operation with other disciplines.

- Since particularly the 'product-related aspects' contribute to an improvement of the environmental performance, future research should focus on these aspects. The presented TMB-project is a good example, in which technical and environmental considerations are brought together to support the product designer. Other examples of this kind, should mainly be sought in the range of active products, which use energy during their use-phase. The transportation industry is probably the best example of these active products, but household, heating, cooling or machining equipment are other examples. With respect to product-related aspects the manufacturing of recycled materials is also relevant. These materials can have divergent material qualities that complicate manufacturing. This recommendation implies an active search for new manufacturing processes that enable environmentally friendlier products.

- Although the environmental impact of 'process-related aspects' is less significant than the impact of the 'product-related aspects', these aspects are still interesting to research. In this thesis the research is limited to auxiliary materials, but the reduction of energy consumption and material waste are both aspects that have an interesting potential. Material waste has always had ample attention due to the economic impact, but even in this field new approaches should be able to further optimise material efficiencies. The energy reduction that can be realised in some cases is remarkable. Insulation of heat sources and the combination of energy consumers can lead to significant reductions of the energy consumption, especially for large energy consumers like the cleaning and drying processes.

  But here too it holds that prevention is better than treatment. This emphasises once more the importance of the lubricant optimisation and focus on the cleaning process. The example in this thesis can be extended with further research on pre-lubricated or coated sheets. These alternatives have a high environmental potential and are still under development. Combination of functions, like corrosion prevention, lubrication and (pre-)painting, is the key factor in these developments.

Almost all activities in the field of manufacturing and environment require co-operation with other disciplines. This co-operation should relate to three parties, viz. the suppliers in the means-of-production life-cycle (mp-LC), the environmental specialists and the industrial designers.

- The co-operation with the suppliers in the mp-LC should concentrate on the mutual matching of the different processes and substances. An example of the matching of processes is the combination of heat generation (e.g. the hydraulic presses) and heat use in different processes (e.g. the cleaning). An example of the matching of substances is the optimisation of cleaning fluid and lubricant. The research on the lubricant cleanability showed a good example of this tuning. Another aspect that has to be dealt with in the mp-LC is the mutual transfer of environmental data. Up to now the environmental information that is provided with the supplied products has been insufficient.

- The co-operation with environmental specialist is linked to this last remark. This co-operation should contribute to a further understanding of the environmental impacts of the different material flows in sheet metal forming. In addition to the acquisition of relevant data, the application of data in LCAs is an important challenge in the near future.

- The co-operation with industrial designers should focus on the optimisation of the manufactured products themselves and relates as such to the 'product-related aspects'. The true challenge in this co-operation will be the development of new ways of function fulfilment. This means that the existing process or product is not the starting point for optimisation, but the function as demanded by the consumer. For example in the case of a car not the 'deep drawing of a door', or the 'design of a car' is most important, but the broader concept of 'transportation' needs to be discussed. This larger scope should enable more significant environmental improvements than currently possible. The role of manufacturing in this approach is not yet completely clear, but new manufacturing techniques will certainly stimulate this future discussion.

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Glossary

Active product

Product that consumes energy during its use-phase. In some cases only a few parts of an active product are active.

Auxiliary materials

Materials which are used to manufacture a product, but which are not part of the final product.

Cleanability

Qualification of lubricant or other substance that indicates the ease with which it can be removed from a part to which it is applied.

Deep drawability

Measure that indicates to which degree a certain blank can be formed in a defined forming situation. In this thesis the deep drawability is measured by the maximal product height that can be drawn in a test tool under set test conditions.

Desirability

Qualification of an 'improvement option' that indicates its expected environmental, economical and technical performance

Environment

Totality of ecological circumstances that determines the living conditions of a person or group of persons.

Feasibility

Qualification of an 'improvement option' that indicates its expected economical and technical performance.

Formability

Qualification that indicates the extend to which the sheet can be deformed (see also deep drawability).

Improvement option

Alternative that possibly improves the existing situation regarding its environmental performance.

Life-cycle

Totality of all consequent life-cycle phases that a product or material passes during its life.

Life-cycle Assessment (LCA)

Environmental assessment of an product or material over its entire life-cycle (also life-cycle analysis).

Life-cycle phase

Characteristic part of the life-cycle, e.g. use-phase of discard-phase.

Life-cycle-crossing

The combination of the product life-cycle and a means-of-production life-cycle, which cross at the 'use of the means-of-production' and the 'manufacturing of the product'.

Life-cycle energy consumption

Measure of the environmental impact of a product on basis of the consumed energy over its complete life-cycle, including extraction, manufacturing, use, discard and recycling-phase.

Manufacturing

Combination of processes that convert raw materials into products. In this thesis it is used in relation to discrete products.

Material waste

Mass of the material that enters the factory, but is not part op the final product ('scrap').

Material efficiency

Percentage of the total required material that forms the final product.

Means-of-production life-cycle

The means-of-production life-cycle (mp-LC) is the life-cycle that includes all the means-of-production that are required to manufacture a product. Although stated as singular, the mp-LC is mostly a bundle of many different life-cycles. In other contexts then this thesis, a mp-LC can also refer to the mean-of-production necessary to dismantle a product or to recycle a certain material. As such it always stands perpendicular to the product life-cycle.

Process

Characterisation of the actual transformation that takes place during manufacturing, e.g. deep drawing or punching. Although stated as singular, 'process' often refers to a combination of several subsequent processes or a process chain.

Process-related aspects

Environmental aspects of sheet metal forming which are caused in the means-of-production life-cycle and can potentially be influenced by the manufacturing processes.

Product-related aspects

Environmental aspects of sheet metal forming which are caused in the total life-cycle crossing and can potentially be influenced by the manufacturing process.

Product weight

Measure that indicates the weight (mass) of the manufactured product.

Tailor-made blank

Blank composed of two or more sheets, that are welded together by a continuous weld before the forming process. The individual sheets can differ regarding thickness or quality.

Unwelded blank

Blank that is not welded, as opposed to a 'welded blank'.

Waste weight

Measure that indicates the weight (mass) of the waste material (scrap).

Weld position

Position of the weld in a TMB, stated as distance between the weld and the product wall or between the weld and the hole centre dependent on the product shape

Welded blank

Blank that is composed of two or more smaller sheets which are welded together

Abbreviations

BHP	blank holder pressure
BHS	bake hardening steel
BPF	back pull force
CF	coefficient of friction
Cl	chloride
CVD	chemical vapour deposition
DLC	diamond like carbon
EC	European Community
EDAX	electron diffraction atomic x-ray
EP	extreme pressure
FEM	finite element method
FLC	forming limit curve
FLD	forming limit diagram
HAZ	heat affected zone
INVAR	Fe-Ni alloy invariant for temperature changes
L	laser welded
LBC	load bearing capacity
LC	life-cycle
LCA	life-cycle assessment
LCC	life-cycle crossing
LCS	low carbon steel
lub.	lubricant
MEA	manufacturing and environmental assessment
mp-LC	means-of-production life-cycle
MS	mash seam welded
p-LC	product life-cycle
PVD	physical vapour deposition
SCM	sintered carbide metal
SEM	scanning electron microscope
Sintered-HSS	sintered high-speed-steel
sup.	supplier
TMB	tailor-made blank

Curriculum Vitae

Arjan de Winter was born in Geldrop, the Netherlands on September 10, 1969. He attended the Strabrecht College in Geldrop, where he obtained his VWO-diploma in 1987. In September that year he enrolled as a mechanical engineering student at the Eindhoven University of Technology. After a specialisation in manufacturing technology, he graduated on a research project on the modelling of sheet metal forming processes in 1993. Subsequently he started a PhD-project on 'environment and manufacturing' at the same university. During this period he was also technical secretary of the International Committee on Environmental and Manufacturing (ICEM). As such he organised a workshop on 'Ecology and Economy in metal forming and cutting' in 's Hertogenbosch, the Netherlands, in 1997.

Stellingen

behorende bij het proefschrift

Environmental Aspects of Sheet Metal Forming

1. Optimalisatie van bewerkingsprocessen ten aanzien van milieubelasting moet zich niet alleen richten op het ontwerp van de processen zelf, maar in gelijke mate ook op het ontwerp van de gefabriceerde producten.

2. De mogelijkheden om bewerkingsprocessen te optimaliseren ten aanzien van milieubelasting worden beperkt door het feit dat het product dat veel producenten leveren alleen het maakproces is.

3. Ook al kenmerkt het slijtagepatroon van PVD-coatings zich ogenschijnlijk door abrasieve slijtage, op microscopische schaal is hiervoor toch adhesieve slijtage verantwoordelijk.

4. Door het globale karakter van de wrijvingscoëfficiënt en het veelal lokale karakter van de optredende slijtage, is de in veel gevallen voorkomende samenhang tussen slijtage en wrijvingscoëfficiënt zeker niet algemeen geldend.

5. Bij de integratie van PVD-coatings in het procesontwerp is de keuze van de coatingleverancier belangrijker dan de keuze van het coatingtype.

6. Ook al worden slijtage-preventieve kwaliteiten van gereedschapsmaterialen en smeermiddelen op geheel verschillende wijzen getest, de beoordeling van de resulterende slijtage door visuele waarnemingen kan in beide gevallen niet worden gemist.

7. Het overgewicht van menig chauffeur is groter dan de gewichtsbesparing die met 'tailor-made blanks' in auto's kan worden bereikt.

8. Als met een globale milieuanalyse niet de milieuvriendelijkste van twee alternatieven kan worden bepaald, is een beter alternatief nodig en niet een betere milieuanalyse.

9. Economische groei leidt niet zonder meer tot milieuvriendelijke technologische ontwikkelingen, maar omgekeerd leiden milieuvriendelijke ontwikkelingen wel tot economische groei.

10. Ecologie hoort thuis in het rijtje ‘ecologie, economie en technologie’, ondanks het feit dat ecologie uitgaat van evenwicht en stabiliteit, terwijl de beide andere uitgaan van respectievelijk groei en vooruitgang.

11. De overeenkomst tussen het beoefenen van topsport en wetenschap, achtereenvolgens gebaseerd op prestaties van het lichaam en de hersenen, is de mentale druk die verbonden is met het neerzetten van een prestatie; het verschil tussen beide is gelegen in de onmogelijkheid om de hersenen na de geleverde prestatie, net als de spieren, aangenaam te laten masseren.

12. Indien men evenveel voldoening ontleent aan het modelleren van metaalvervorming als aan het modelleren van kunststofvervorming, vloeistofturbulenties of aardlaagverplaatsingen, rijst de vraag of men het modelleren niet mooier vindt dan het gemodelleerde.

13. De gewenste communicatie tussen produktiemedewerkers en ingenieurs wordt in sterke mate gehinderd door milieuvervuiling.

Arjan de Winter

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