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Defects and defect avoidance in cold forging.

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TUE-MSc thesis

maart 1993
Vfcode: D3 WPA reportnr.: 1485

Summary

The competitiveness of cold forging processes in relation to other manufacturing processes is good. To remain competitive, cold forging processes have to produce defect free products.

In practice there is a wide range of defects which occur during metal forming processes.

Fracture is in most cases the only defect that immediately is recognized as one. Cracking is also the defect that has been researched most extensively. The Okamoto-classification of cracks is used to discuss the cracks and their causes. The main cause for cracks is a wrong tool geometry.

Surface imperfections find their main cause in an inadequate lubrication. Although this kind of defect has not attracted much attention, it will become more important in future.

Flow imperfections represent a wide range of defects, but they can be divided in: dimensional inaccuracies, shape inaccuracies and positional errors. The main causes for these defects are a wrong designed tool and inadequate lubrication.

A method of dealing with these defects is of considerable interest, since the cost to industry in terms of lost time and material is essentially proportional to the percentage of products being rejected.

In literature there are several manners mentioned to avoid defects. Statistical process control and various physical modelling techniques are the methods that are already being frequently used in industry. Databases, expert systems and neural networks however, are not being used so often but they show great potential on defect avoidance.

A literature survey has been carried out on the subject of defects in cold forging. This survey initially encompassed the literature of the last decade. In addition other relevant literature was consulted.

Samenvatting

In vergelijking met andere produktietechnieken zijn (massief) omvormprocessen zeer concurrerend. Om concurrerend te blijven, moeten de omvormprocessen echter foutloze produkten produceren.

In de praktijk kunnen er een groot aantal fouten aan de produkten optreden. Breuk is in de meeste gevallen de enige fout die onmiddellijk wordt herkend als een fout. Daarnaast is breuk de fout waarnaar het meeste onderzoek is gedaan. De Okamoto-classificatie van breuken wordt gebruikt om de breuken en hun oorzaken te evalueren. De belangrijkste oorzaak van breuk is een verkeerd gereedschapsontwerp.

Oppervlakteafwijkingen worden meestal veroorzaakt door verkeerde smering. Alhoewel aan dit soort fouten niet veel aandacht is besteed, zullen ze belangrijker worden in de nabije toekomst.

Vloeiafwijkingen vertegenwoordigen een groot aantal fouten. Ze kunnen worden verdeeld in maatonnauwkeurigheden, vormafwijkingen en plaatsafwijkingen. De belangrijkste oorzaak voor deze fouten is een verkeerd ontworpen gereedschap en onvoldoende smering.

Een methode om afwijkingen te vermijden is van groot belang voor de industrie. De kosten in termen van tijd- en materiaalverlies zijn namelijk proportioneel aan de hoeveelheid afgekeurde produkten.

In de literatuur worden verschillende manieren genoemd om fouten te voorkomen. Statistische procescontrole en verschillende modellering technieken zijn de methoden die al regelmatig worden gebruikt in de industrie. Databases, expert systemen en neurale netwerken worden echter nog niet zo vaak gebruikt. Deze methoden tonen echter al grote mogelijkheden voor het vermijden van fouten.

Een literatuuronderzoek is gedaan naar het falen bij massiefomvormen en naar de manieren om afwijkingen te vermijden. Eerst is gezocht naar de literatuur, die geschreven is in de laatste tien jaar, vervolgens naar andere relevante literatuur.

Eindstudieopdracht

Student: M.A.J. de Vries

Onderwerp: Falen bij massief omvormen (Defects in cold forging).

Toelichting: Bij het massief omvormen kunnen veel verschillende fouten in het produkt optreden. Voorbeelden hiervan zijn: breuk of scheurvorming, ongewenste oppervlakte ruwheid, onvlakheid, maatafwijkingen, enz.. Deze fouten maken het produkt waardeloos of maken een dure nabewerking noodzakelijk. Het is daarom zaak om de faalcriteria en hun achtergronden te doorgronden.

Net zoals er veel fouten zijn, zijn er veel oorzaken. Enkele voorbeelden hiervan zijn: gereedschapsslijtage, slechte smering, enz.. Ook de achtergronden hiervan zijn interessant.

Omschrijving: In drie fasen zal worden geprobeerd om inzicht te vergroten in de belangrijkste fouten en oorzaken bij massief omvormen.

1) Opstellen van een overzicht van de meest optredende fouten en hun oorzaken bij massief omvormen. Dit wordt gedaan aan de hand van een literatuuronderzoek en gesprekken met bedrijven. Een stage van drie maanden aan The University of Reading, zal een onderdeel van deze oriënterende fase zijn.

2) Analyse van een aantal van de belangrijkste faalcriteria door middel van procesanalyses. De analyses zullen worden uitgevoerd met de methodes die worden aangereikt bij technische plasticiteitsleer en beschikbare simulatie pakketten. Ook zal er gebruik worden gemaakt van de dissertaties van P.J. Bolt en W. Sillekens en de eindstudie van L. Joosten. Daarnaast kan een materiaalkundige analyse deel uitmaken van de analyse.

3) Afronding door middel van een verslag met daarin een overzicht van de mogelijke fouten en de oplossingen hiervoor.

Plaats en Datum: Eindhoven 27 februari 1992

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1 Introduction

Nowadays manufacturing has claimed the largest single share of the gross national product, a measure which can be taken as an indication of the material well-being of a country[1]. This makes it evident that manufacturing should be competitive, on a local as well as a global basis. Competitiveness can only be achieved by attaining a high level of productivity, which itself is the key issue for the economic development of a country. Nations falling behind in this respect will find their living standards gradually eroding. Cold forging processes are processes with a high productivity. These processes could help to maintain a high level or increase the level of productivity.

The competitiveness of cold forging processes in relation to other manufacturing processes is good. Cold forging processes can produce very accurate high duty components with complex shape. These products often do not need any subsequent machining or, if required, machining can be limited to finishing operations. The products are made with the so-called near net shape processes. This greatly reduces the waste of material and the cost involved with its removal. This is a reason for the increasing popularity of the cold forging processes, not only in the automobile industry where 80% of the cold forged products are used [2] but also in other industries.

The strong dependence of cold forging processes on the industry and especially the automobile industry determines the economic conditions for the cold forging technology as [3]:

1. a strong pressure towards minimization of costs;
2. increased quality control leading to the demand for zero-defect;
3. decreasing order volume (order quantity) per component, due to the increasing diversity of shapes;
4. shortening of the production life of the components due to rapid changing of types (shorter span of life);
5. strong reduction of time between order and delivery;
6. demand for complex components, instead of using several components, components are integrated into one product;
7. demand for products with high dimensional accuracy and a good surface quality;

The first, second and seventh condition make it necessary to produce defect free products. The third, fourth and sixth condition make it necessary to manufacture complex components in small quantities economically. This indirectly leads to a demand for first time right manufactured products, no defects are allowed in this case any more. Loss of products due to defects will in this case lead to extra costs, costs which decrease the competitiveness of a manufacturer.

There is another very important reason for defect free products: the E.C.-guidelines about product responsibility of July 25th 1985 and the subsequent laws in the different E.C.-countries. The forthcoming laws make the manufacturers responsible for possible damage caused by their products even when they are not to blame for it[4].

The importance of manufacturing and defect avoidance is evident. In this report the defects in cold forging processes, their causes and the ways to prevent them will be discussed.

2 Defects

2.1 Definitions

As has been mentioned by Dodd[5], there is some confusion in the use of various terms associated with ductility. The following definitions will be used in this paper[5,6]:

Ductility: the ability to deform plastically without fracture in a standard test, usually expressed by some measure of limiting strain.

Formability: the ability of a material to deform plastically without fracture in a forming process.

Workability: the ability of a material to deform without the occurrence of any defect in a forming process.

In sheet metal working the onset of localized necking is often referred to as the limit of formability of the sheet material, generally presented in Goodwin and Keeler forming limit diagrams. However, in this paper the attention is confined to forging and when we are aware of the variations in usage of the above terms from country to country, industry to industry as well as between individuals, we will not become confused.

In the definition of workability, given above, the term defect is used. This term also needs definition.

Defect[5,6]: the properties of a product that do not conform to the design specifications, which make the product less suitable or unsuitable for the purpose for which it has been designed.

This definition is very wide in scope because a defect can have such occurrences as cracks in the component, dimensional and surface inaccuracies and buckling.

2.2 Classifications

Devedzić[7] has made a classification of the workability limits for all forming processes (figure 1).

It is evident that die resistance to fracture is also of importance and although die fracture is a defect in the cold forging tooling it is obviously not a defect in the product. Alternatively to the Devedzić classification, defects in cold forging processes can be classified as:

D1 Ductile fracture or cracking in the interior or on the surface of the product.

D2 Surface imperfections, other than cracking, such as roughening (e.g. the orange peel effect), scratching, scoring and laminations.

D3 Flow imperfections: shape and dimensional inaccuracies and positional errors such as folding, underfilling, non-concentric products, fins, flashes and buckling.

D4 Undesirable changes in the physical properties of the work materials during forming, including decarburization and the formation of martensite.

This is the classification that has been proposed by the ICFG Subgroup Defects in Cold Forging[8]. This is a simplified Devedzić classification which excludes sheet metalworking limits and die failures.

Other classifications, e.g. the one by Okamoto et al.[9] can be used as well, but only as a classification of the type of cracks that can occur in cold forging products. This kind of classification can be very useful as a subdivision in a more complete classification. Other authors make lists of the defects that can occur in certain processes, e.g. Johnson[10] and Johnson and Mamalis[11].

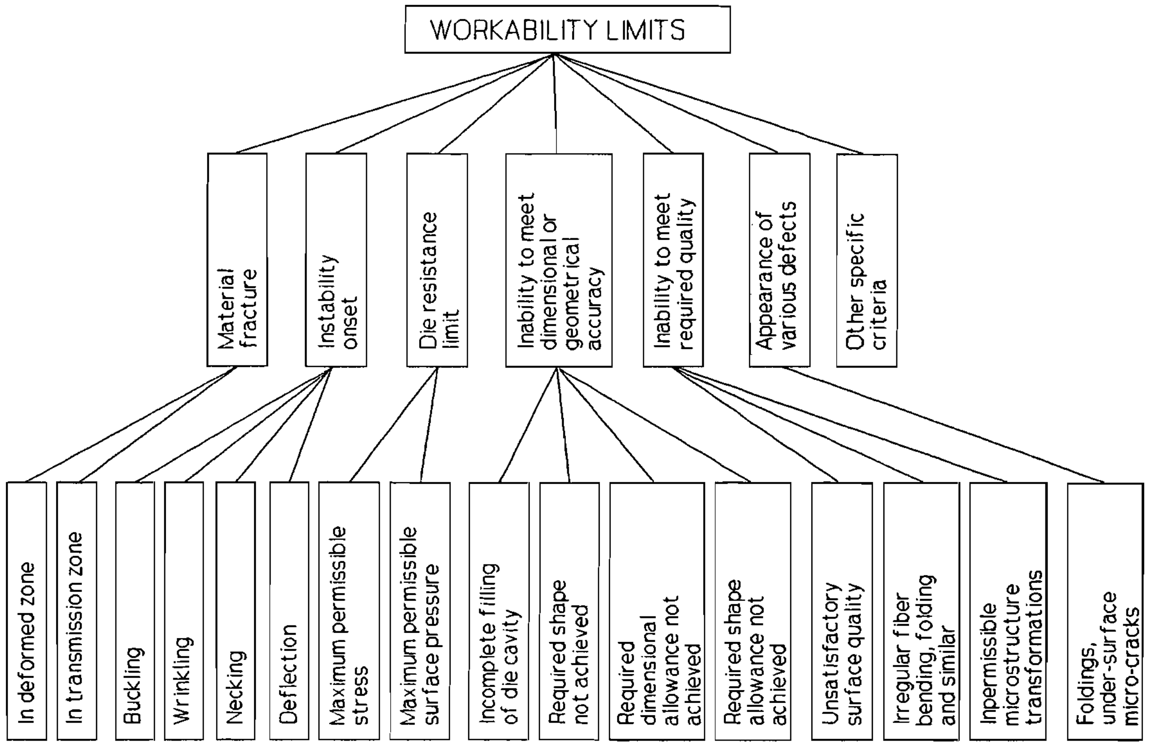

***Figure 1** Classification of workability limits according to Devedzić.*

The causes of defects can be complicated and often there may not be a unique cause of a defect or they may be interlinked, as we will see in the following sections. Despite these difficulties it is possible to make a classification of the possible causes of defects[8].

C1 The metallurgical nature of the start metal, including chemical composition, mechanical and physical properties, distribution, geometry and volume fraction of second phases or inclusions, grain size and heat treatment.

C2 Billet preparation, including billet cutting and concentricity of the billet with the container.

C3 Tool properties, including geometry, heat treatment, wear, tool stiffness and mechanical properties as well as tool surface coating (if any).

C4 Tribological variables, including die friction and lubrication and billet or workpiece lubrication.

C5 Forming machine variables, such as machine rigidity and speed of operation.

C6 Forming process variables or conditions, including sequence, number of steps in the sequence and the nature of each step as well as the transfer of material from step to step.

C7 Temperature rises in the workpiece and tooling, possibly resulting in shrinkage difficulties.

C8 Other causes.

In this report the proposed ICFG Subgroup Defects in Cold Forging-classifications will be used.

2.3 Fracture

Although fracture is not the only defect of importance, it certainly is in most cases the only one that is recognized as a defect. Cracking is also the defect that has been researched most extensively.

A classification of types of cracks which can occur in cold forging processes was suggested by Okamoto and his co-workers[9]. This is a valuable classification because it is probably one of the few classifications that go further than internal and external cracks and the only one that was found in the available literature.

The cracks, the causes and the manners to prevent them from happening will be looked at in the next paragraphs. The Okamoto classification will be used as a guideline although it will be slightly modified sometimes.

2.3.1 α-Crack

α-Cracks (see figure 2) are defined as external cracks which appear at the midheight of the specimen in upsetting. Depending on the friction at the die-workpiece interface and the initial geometry of the specimen, either longitudinal or oblique cracks can occur.

Open-die forging and heading, for example, are included in the - for industry important - process of upsetting[12]. Upsetting is defined as the axial compression of a workpiece in order to enlarge the cross-sectional area over either the whole or part of its length[13].

Figure 2 α-Crack, a crack which appears at the midheight of the specimen. Depending on the degree of end constraint and geometry of the specimen, either longitudinal or oblique cracks occur.

Clearly in upsetting operations, the apparent workability of the workpiece depends on the states of stress and strain on the expanding free surface. As soon as cracks appear at any position on the surface, the workability limit has been passed. In such processes it has long been recognized that the induced tensile stresses at the surface can lead to premature fracture[14]. The magnitude of these stresses is dependent on the severity of barrelling.

If these stresses are minimized by adjusting the process variables, then the workability can be improved. The most important variables that influence the workability, in literature also called the upsetability, are:

1. friction (interfacial).
2. specimen aspect ratio (=height-diameter ratio).
3. amount of pre-strain of the work material.
4. nature of the free surface of the material.

- *Effect of friction and specimen aspect ratio on upsetability*

The influence of friction and the specimen aspect ratio is shown in figure 3 [15-25].

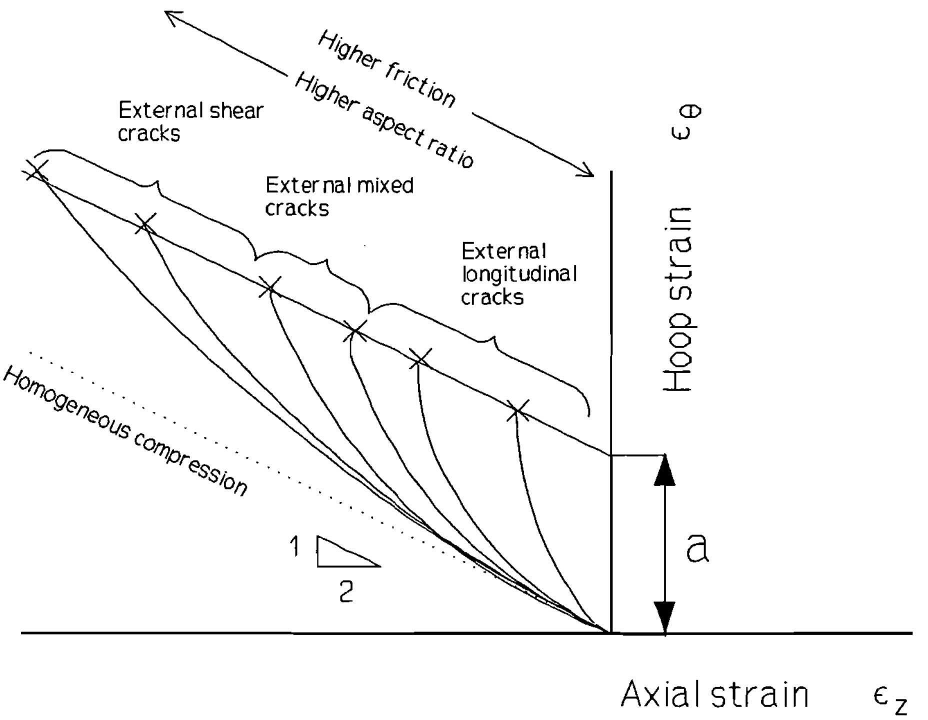

Figure 3 Influence of friction and aspect ratio on α-crack: the linear fracture condition.

It is clear from this figure that the locus of fracture strains is linear with a slope of -½. Therefore, the fracture condition can be written simply as[13, 24]:

$$\varepsilon_{\theta f} = a - \frac{\varepsilon_{zf}}{2} \tag{1}$$

where $\epsilon_{\theta f}$ and ϵ_{zf} are the hoop strain and axial strain at fracture and a is the plane-strain fracture strain. This fracture line is parallel to the line corresponding to homogeneous compression, for which $\epsilon_\theta = -\epsilon_z/2$. This fracture condition can be easily determined by doing a compression test. A discription of this test is given by Dieter[25].

Figures 2 and 3 illustrate the type of fracture observed by Kudo et al.[16], by Dodd et al.[24] and by Billigman and Feldmann[26]. Using the Lévy-Von Mises stress-strain increment relations, Kudo and Aoi[15] deduced that the fracture plane coincides with the maximum shear-stress plane. Kobayashi[27], Lee[VIII] and others[12, 28-32] have confirmed that this fracture condition is valid for a wide range of materials.

Lee[VIII] also shows that fracture points for bending, upsetting and edge cracking in rolling, all fall on the same straight line for a given material. Therefore the linear fracture condition is not confined to upsetting but is of wider generality.

- *Effect of pre-strain on upsetability*

It is well-known that the ductility of a material is strain-history dependent[33]. This has been confirmed in papers by Billigman[34], by Gill and Baldwinn[35] and by Luntz[36], who have shown that wire drawing after annealing can in some cases increase the workability in subsequent upsetting operations. Similar results were obtained by Tozawa and Kojima[37].

- *Effect of surface defects on upsetability*

In industrial upsetting and heading operations on wire and rod, the workability limit is often determined by the presence of longitudinal surface defects, such as grooves, scratches or cracks. These defects may originate from the ingot or, more often, from prior forming processes such as wire drawing[26]. In upsetting, such defects act as circumferential stress concentrators and they limit the workability of the material. Thomason[12] obtained similar results. He found that the greater the aspect ratio of the cylinder, the lower the effect of surface defects. It was also found that the upsetability decreased with increasing defect depth, and that variations in the defect root radius only had a secondary effect.

- *Prevention of α-cracks*

The linear fracture condition for α-cracking in upsetting and related processes can be seen as a guide to the workability limit of a material. In the development of a new part, care should be taken to remain within the range of permissible surface strains of a particular material. For crack-free upsetting of the material, the surface strain paths should always fall below the fracture line (see figure 3). In the forming of a new shape the surface strains should be determined. If the strain paths crosses the fracture line before the process is completed, fracture will occur. To avoid this, either a material with a higher "a-value" should be chosen, or the process variables should be altered. For example, if fracture is found to occur, the use of good lubrication will decrease the slope of the strain path and possibly avoid fracture. Kuhn et al. [38-40] show that this approach is a useful one. Kuhn[41] also finds that this condition is valid for other forming processes than upsetting and open-die forging e.g. bending. The other factors that influence the workability, cannot be forgotten. Although prevention of an α-crack by an extra annealing and subsequent drawing step or the examining of all the incoming material will always lead to extra costs, these actions can be just as effective.

2.3.2 β-crack

β-Cracks (see figure 4) are defined as longitudinal cracks which occur at the bottom of the inner part of the specimen in upsetting with a truncated conical punch. This type of crack is caused by the expansion of material under the cone punch in circumferential direction.

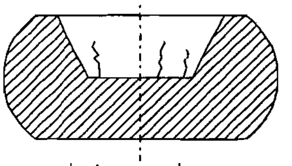

Figure 4 *β-Crack, a crack which occurs at the bottom of the inner part of the specimen in upsetting with a truncated conical punch.*

Prevention of these cracks can be achieved by selecting a suitable punch shape (diameter, height, taper). Figures 5 and 6 show the conditions under which β-cracks occur in upsetting with circular truncated cone punches. Okamoto et al.[9] demonstrate that other steels show the same distribution for the types of cracks as the S45C steel. The other crack types in these figures are discussed in other sections.

A more detailed description of this type of defect can be found in reference [9], [42] and [43].

2.3.3 γ-crack

A γ-crack (see figure 7) is defined as a shearing crack which appears at the corner of extruded material or as a surface crack in various processes[9]. The shear crack occurs at the boundary between a dead metal and plastic zone.

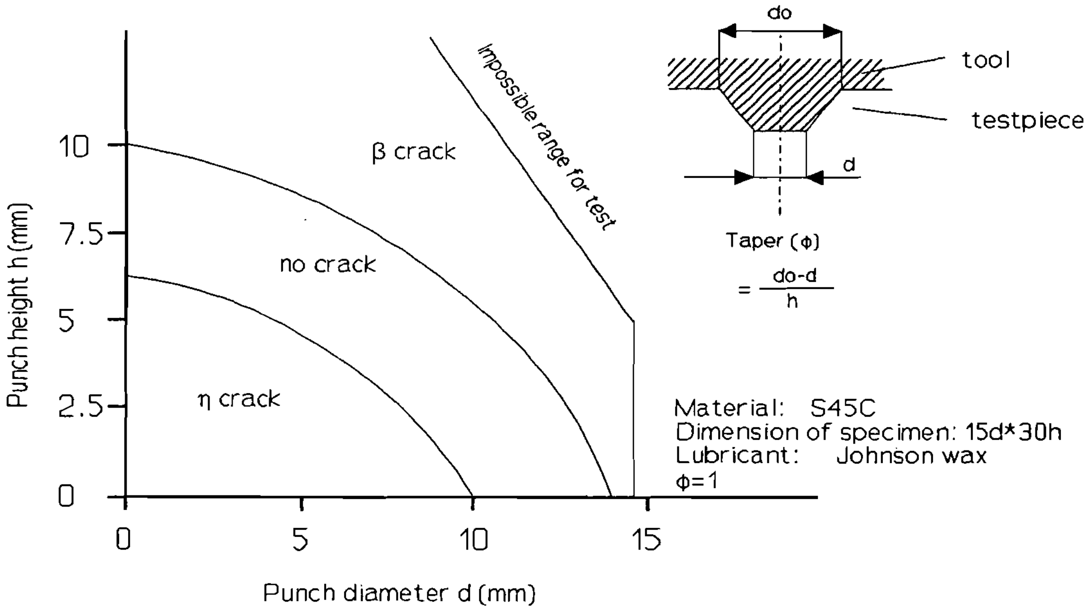

Figure 5 Distribution chart of cracking types [9].

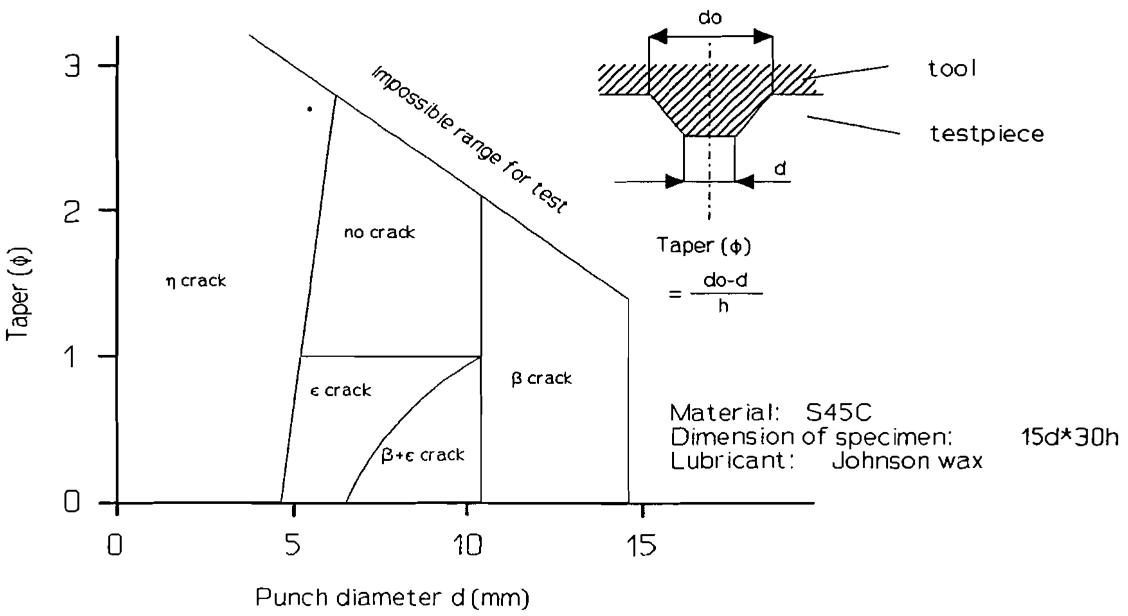

Figure 6 Distribution chart of cracking types [9].

A shear crack is a very common defect in upsetting and sometimes very difficult to detect. A possible cause can be a wrongly chosen previous heading step[26].

The surface crack has a wide range of causes:

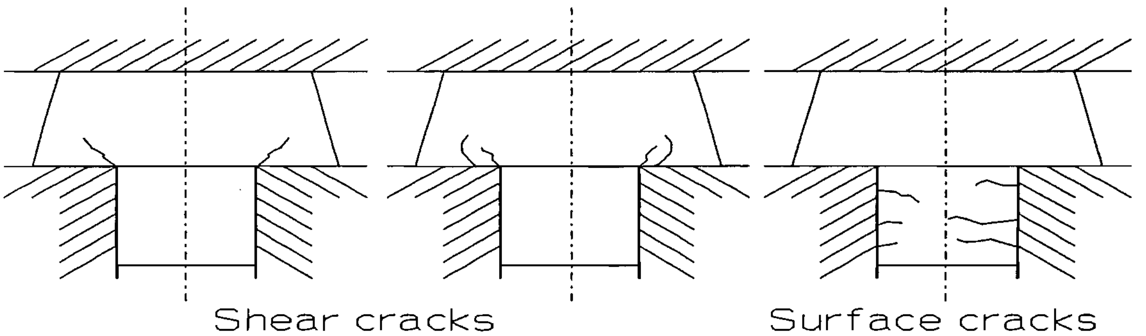

Figure 7 γ-Crack, a crack which appears at the corners of extruded material in free extrusion. Cracking occurs at the boundary between dead metal and plastic zone.

- γ-cracks, shear cracks, that occur at the corner[9]
- stresses induced by finishing processes[26]
- skin inclusions or non-metallic parts[26]
- previous process steps[26]
- lubrication explosion[26]
- expansion of the slug surface[42]
- feed marks that are produced when the slugs were machined[42].

These cracks can be prevented by selecting suitable die and workpiece dimensions and by a careful workpiece preparation. Figure 8 shows results from tests done by Okamoto et al.[9]. They conclude that no cracking occurs when the ratio of the initial diameter of the specimen, Do, to that of the die cavity, d, is kept below 2. The other crack type in this figure is discussed in and other section.

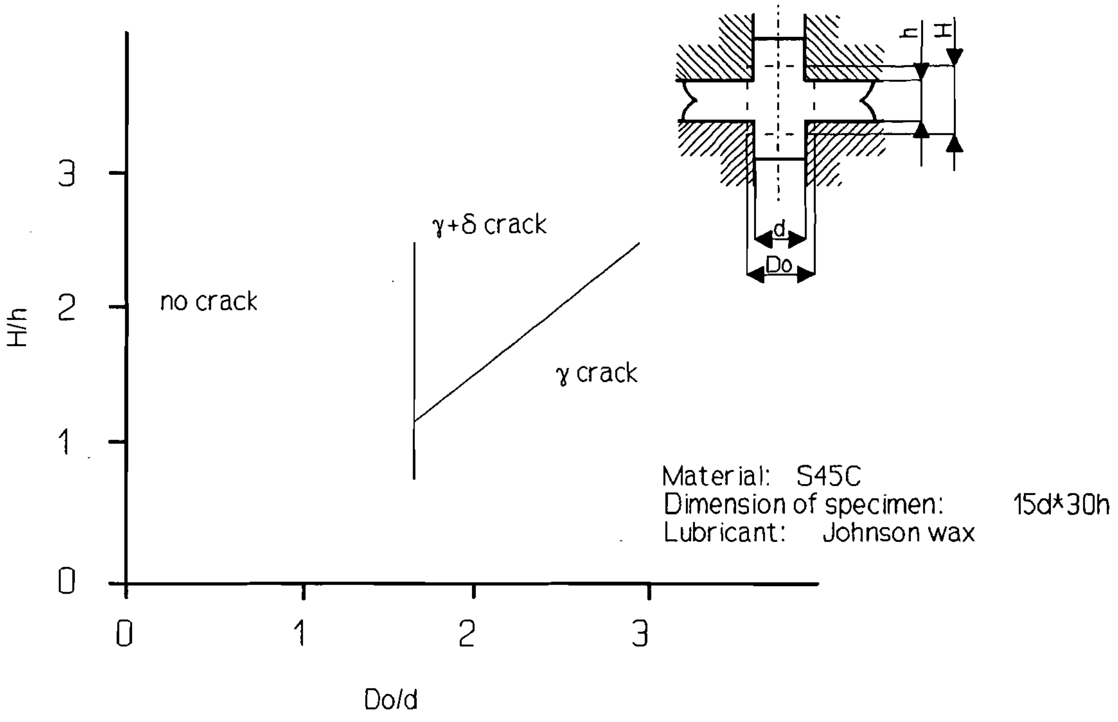

Figure 8 Distribution chart of γ- and δ-cracks in two direction free extrusion without side constraint [9].

2.3.4 δ-crack

A δ-crack (see figure 9) is defined as a crack which occurs at midheight of the material in the flange in two direction free extrusion without side constraint[9]. The material is extruded forward and backward; therefore, the cracking is caused by the depression of the material in the flange.

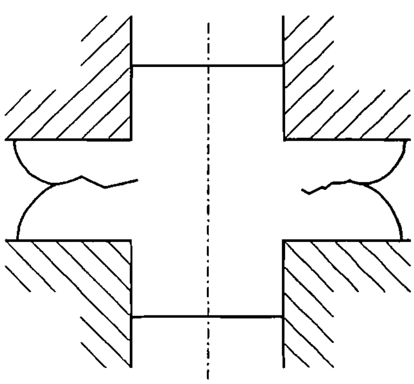

Figure 9 δ-Crack, a crack which occurs at midheight of material in the flange in two direction free extrusion without side constraint.

A prevention measure is to select a suitable diameter of the dies. Okamoto et al.[9] conclude from the chart in figure 8 that the ratio of the initial diameter of the specimen, Do, to that of the die cavity, d, has to be kept below 2.

This type of crack occurs according to Okamoto et al.[9] only in two direction free extrusion. A more detailed description of this defect can be found in references [9] and [45].

2.3.5 ϵ-crack

An ϵ-crack (see figure 10) is defined as a crack that occurs at midheight or just above the bottom radius of the inside surface and advances in the circumferential direction in upsetting[9].

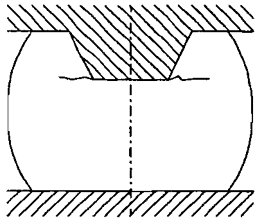

***Figure 10** ϵ-Crack, a crack which occurs at the midheight of the inside surface and advances in the circumferential direction.*

Causes for ϵ-cracks are the punch shape[9], and the rapid change of the velocity field in the corners of a backward extruded product[44]. The change of the velocity induces a high strain at the corners. This phenomenon is observed mainly if the wall thickness of the cup is relatively large in respect to the punch diameter.

Prevention of this type of cracks can be achieved by:

- an annealing operation[44]
- forward instead of backward extrusion[44]
- tapered slugs in the case of forward extrusion[44]
- an as high as possible hydrostatic pressure[44]
- changing the punch shape[9]. From the chart in figure 6 can be concluded that in case of S45C steel ϵ-cracks occur when the taper, ϕ, of the punch is smaller than 1 and the punch diameter is between 5 and

10 mm. Okamoto et al.[9] also conclude that in general ϵ-cracking is observed between η and β ranges in case of a small punch taper (<1).

2.3.6 ζ-crack

A ζ-crack (see figure 11) is defined as an internal crack which occurs in multiaxial extrusion processes. The crack occurs at the center of the material[46, 47].

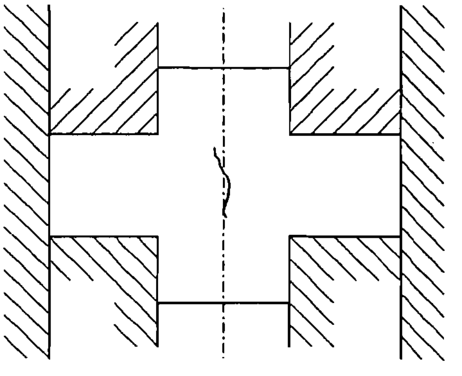

Figure 11 ζ-Crack, an internal crack which occurs in multiaxial extrusion processes.

A cause for this type of crack is a too low ductility of the workpiece material.

This defect can be prevented by:

- choosing a material with a better ductility.
- annealing the workpiece[47].
- raising the hydrostatic pressure with counter-acting pressures at the leading ends of the branches[47].
- modifying the design of the cross-section of the branches[47].

More information about the multiaxial extrusion process and ζ-cracks can be found in references [47] and [48].

Park et al.[46] try to predict the occurrence of these cracks by using several ductile fracture criteria. They find that the modified Cockroft and Latham criterion[I] predicts the occurrence of internal cracks fairly well. Only for the small extrusion ratio the difference between experiment and prediction is significant. This discrepancy can be attributed in part to the fact that the criterion is based on an approximate analysis.

2.3.7 η-crack

An η-crack (see figure 12) is defined as a crack which appears to grow from the upper and side surfaces of the concave portion of the upper surface of the specimen. In cross-sections the cracks are found to be radial.

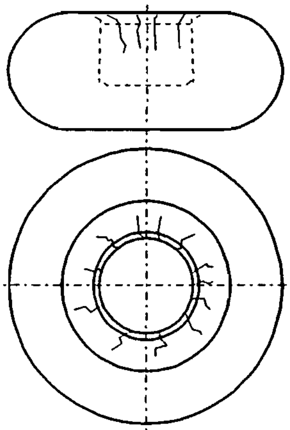

Figure 12 η-Crack, a crack on the upper and side surfaces of the concave portion of the upper surface of a specimen.

The cause for an η-crack can be an uneven deformation[26], the punch shape or a surface defect caused by a blunt cropping knife or saw[9].

This crack can be prevented by selecting a suitable punch shape[9] or by a careful workpiece preparation. Figures 5 and 6 show the conditions under which η-cracks occur in upsetting with circular truncated cone punches of different diameters height and taper. Other materials show according to Okamoto et al. [9] similar results.

More about this defect can be found in references [9], [26] and [42].

2.3.8 κ-crack

A κ-crack (see figure 13) is defined as a centre crack or centre burst which can occur in wire drawing or forward rod extrusion.

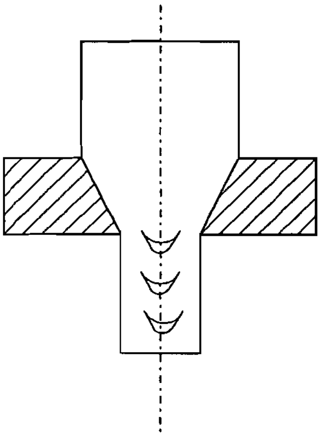

Figure 13 κ-Crack, a crack which is defined as a centre crack or centre burst. This crack can occur in wire drawing or forward rod extrusion.

Avitzur[49] has done extensive research on this type of defect. He determined that certain combinations of diameter reduction of the workpiece, friction and die angle can lead to tensile stresses in the core of the workpiece or to disturbances of the material flow which eventually can lead to central bursting. Other causes can be: a too low ductility of the workpiece material due to core segregation of inclusions; or excessive strain hardening.

Methods to prevent these cracks are: insertion of an intermediate annealing step in the extrusion sequence; selection of another die angle for a given reduction per pass; or selection of a different reduction per pass.

More references on this type of crack are given by Johnson and Mamalis[50].

Zavaliangos et al.[51] try to predict the formation of a κ-crack in rod drawing. Their numerical simulation qualitatively shows the major features of the problem. As expected, the material is deforming plastically primarily in the reduction region of the dies. They find that a high semicone angle and a small area reductions can induce a substantial negative pressure along the axis of the billet, and it is this negative pressure that promotes void growth which finally can lead to centre burst. They conclude that their procedures can be used to check approximately whether a particular die-design will lead to centre burst.

2.3.9 μ-crack

A μ-crack (see figure 14) is defined as a peripheral crack that occurs at the centre of a specimen in combined forward and backward piercing.

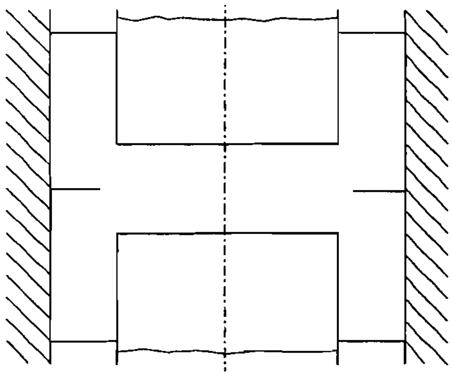

Figure 14 μ-Crack, a crack that occurs at the centre of a specimen in combined forward and backward piercing.

Okamoto et al.[9] are the only ones that mention this crack. They give one reference in their paper.

2.3.10 λ-crack

A λ-crack (see figure 15) is defined as a crack which occurs at the bottom of the inner surface in piercing.

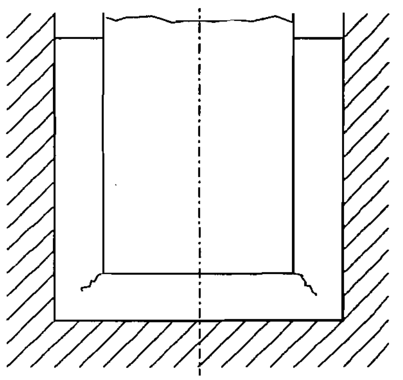

Figure 15 λ-Crack, a crack that is caused by a too small punch radius in piercing.

The cause for this crack is a too small punch radius. This crack can be prevented by using a larger punch radius.

Okamoto et al.[9] are the only ones that mention this crack.

2.3.11 θ-crack

A θ-crack (see figure 16) is defined as a microscopic crack which occurs at the boundary between the upper and lower dead metal zones and at a point where the metal flow changes during excessive plastic deformation in in upsetting.

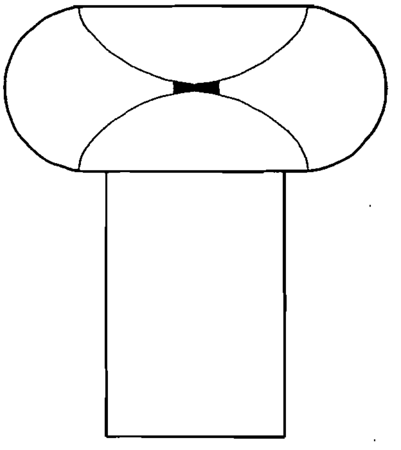

Figure 16 θ-Crack, a crack which occurs at the boundary between the upper and lower dead metal zones in upsetting.

Causes of this type of defect are:

- a too low ductility of the material[26, 50].
- buckling in a previous process step[26].

Some methods to prevent this type of defect are:

- annealing of the workpiece.
- preventing of buckling in a previous step.

More references about this crack are given by Johnson and Mamalis[50].

2.4 Surface imperfections

Not much interest is being displayed in literature about surface imperfections such as roughening, scratching and laminations. These defects are most times fairly easy to overcome by improving the lubrication. But the choice of the lubricant still is not quite well understood. The tribological system variables and their influences in forging processes have not been researched extensively yet, so that the choice of a lubricant and the kind of surface preparation still is a matter of experience.

Friction and wear (defects) may be explained through several related mechanisms: tearing of weldments, plowing, a thin surface layer of severe plastic deformations and galling. While these mechanisms can provide a fundamental understanding of the phenomena of friction and of wear, the total picture is much more complicated. Other factors like corrosion, fatigue, erosion, cavitation, and thermal effects, can also contribute.

In the following sections the surface defects that were found in literature will be explained. Only other ways to prevent these defects than improving the lubrication will be mentioned.

2.4.1 Plowing[52]

The localized high pressures cause the asperities of the hard tool to penetrate into the deforming workpiece. With the relative motion of each asperity over the workpiece, a deeply plowed groove is created (figure 17). These grooves expose fresh, uncontaminated surfaces, which produce a shiny appearance of the workpiece surface.

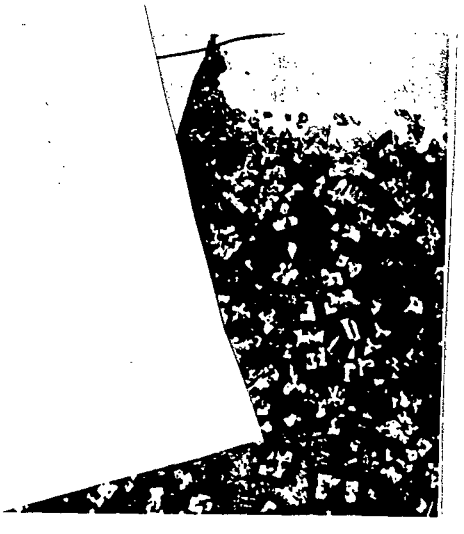

Figure 17 Plowed groove[53].

2.4.2 Tearing of weldments[52]

The high pressures over the relatively small areas of actual contact may cause localized welding. The weldments must shear off instantaneously because of the relative motion between the tool and the workpiece. As the weldments tear off, localized high temperatures are created. The metals at the weld interface may form hard intermetallic compounds. As the weldments break loose, they cause damage to both tool and workpiece. Intermetallic fragmented particles may now move between the two mating surfaces and cause further damage. The particles may be pressed into the workpiece, become imbedded, and present hard cutting edges plowing into the hard die. Thus, the die wears and roughens.

2.4.3 Galling[52]

When there is a strong chemical affinity between the tool material and the workpiece, layers of the workpiece material adhere to the tool surface and may become immobilized. The difference between tearing of weldments and galling is that the galling material contains only workpiece material, whereas the torn of weldments contain tool material as well.

2.4.4 Surface layer of severe plastic flow[52]

The description of plowing and tearing of weldments demonstrates that a thin layer in the surface of the workpiece is severely affected by friction between tool and workpiece. The amount of deformation is highest at the interface; and diminishes further from the surface. Within a very thin layer, one order of magnitude higher than the surface roughness, the deformation changes from severe on the surface to almost zero below it.

2.4.5 Surface roughening due to coarse grain size

The grain size is, as Dautzenberg and Kals[54] state, one of the main causes for surface roughening. For example when forging billets containing coarse grains are forged in closed dies, the wrinkles often fold in to cause a series of small laps. Although they are seldomly very deep, these laps produce a poor surface appearance that often necessitates considerable grinding and restrike forging. These wrinkles are commonly known as orange peel.

In agreement with the plasticity theory it can be assumed that the deformation takes place by shear in the planes of maximum shear stress. From a metallurgical point of view, this means that the nearest closed packed planes provide for shear by means of dislocation glide. In the Taylor theory these planes are chosen on the basis of an energy criterion. Inside the material this is necessary in order to maintain the continuity of the material. This condition is absent for the surface grains. Especially for material with a coarse grain size this can lead to extreme surface roughening during the deformation of the workpiece. Kudo[53] illustrates the effect of the grain size of the workpiece material on the rate of roughening of the free surface of a workpiece due to deformation.

Excessive lubrication of the tool-workpiece interface is another reason for surface roughening of the product[53]. The lubricant prevents the tool surface from making the workpiece surface smooth and, consequently, induces deterioration of the product's surface finish.

Extreme roughening can be overcome by choosing a workpiece material with a small grain size or a careful heat treatment of the billet, preform or interstage in order to refine the structure.

2.4.6 Remarks on surface imperfections and workpiece lubrication

Surface defects will become more important, especially in small quantity production and near net shape forging. In these techniques material waste and machining operations are to be kept at a minimum.

More about friction, surface treatment and some general guidelines concerning lubrication can be found in several handbooks, e.g. the handbooks by Avitzur[III] or by Lange[VI]. The ICFG has also published a report about lubrication aspects in cold forging [XI].

Mayrhofer[55] discusses the obtainable surface roughness and the process variables that affect this roughness for some extrusion processes.

More specific problems are discussed in journals such as Wear and Tribology Transactions.

2.5 Flow imperfections

The flow imperfections represent a wide range of defects, including such defects as buckling, non-concentricity, folding and the occurrence of fins and flashes.

Flow imperfections will be one of the most important defects in near net shape forging processes since in these processes as accurate as possible products and no material waste, subsequent machining or trimming are wanted.

Three kinds of flow imperfections can be distinguished[56]:

1. dimensional inaccuracies: the inability to achieve the designed dimensions.
2. shape inaccuracies: the inability to meet the designed product shape.
3. positional error: the inability to align the several design features.

The factors and sources that result in these three kinds of flow imprecisions are listed by Kudo[53] as:

1. heredity of bar quality (material stock).
2. heredity of billet quality (billet preparation).
3. improper lubrication.
4. poor precision, rigidity, strength and wear-resistance and thermal distortion of forming tools.
5. poor precision rigidity and wear-resistance of the forming machine.
6. undesirable deformation of workpiece due to improper product, process and tool design.
7. imprecision generated during and after ejection of the workpiece.
8. insufficient operational control resulting from improper planning, facilities and operator.

Mayrhofer[55], Leykamm[56] and Lange[57] use similar lists in their work.

In the following sections these factors will be briefly discussed.

2.5.1 Material stock

Heredity of the qualities of material stock and billet play an important role in determining product qualities in metal-forming processes[57, 58]. This is especially the case in net-shape forming in which preservation of the original surface is aimed for.

The mechanical properties of the material stock, i.e., bar, wire or plate are determined by their chemical composition and previous thermal and mechanical treatment[53, 55, 57, 58]. When there is scatter in the the work-hardening characteristic of the workpiece material the products will have dispersing thicknesses and other dimensions caused by fluctuation of the forming load and springback. Consequently, the deflections of the tool and machine will differ from one workpiece to another.

Kudo[53] gives some examples of the influence of the bar quality on the dimensional accuracy that can be achieved by a forging process.

Defects due to inadequate bar quality can be prevented by: a careful heat treatment of the billet, preform or interstage, favourable lubricant conditions and more rigid tooling.

2.5.2 Billet preparation

Billets are prepared by a separation process from bar, wire, plate or tube stocks. The volume is the property of the billet or blank that is transmitted to the product. In bulk-forming processes, over-volume billets may result in extra flashing and excessive tool and press load, while under-volume billets lead to incomplete products.

The inaccuracies in the preform or interstage, which subsequently lead to volume fluctuations, are a result of variations in the cross sections of the stock material. These variations are allowed to be according to DIN 1541 up to 16% and according to DIN 1013 about 5%. In addition, variations in the parted-off lengths, caused by the process, also affect the volume accuracy. The fluctuation in billet length when the billet is being sawed is 2 to 4% and in case of the billet being cropped 4 to 8%[55]. The excess volume of the material must be machined from the workpiece.

Kudo[53] gives some examples of dimensional inaccuracies that are caused by imprecisenesses of the billet.

Defects that can be caused by billet irregularities are amongst others: buckling, folds and burs, flashes and incomplete products.

2.5.3 Lubrication

High coefficients of friction due to poor lubrication generally cause non-uniform deformations, such as surface barrelling in upsetting and additional shear strains in extrusion and rolling, which lead to non-homogeneous properties within the material and, in some cases, to surface or interior cracking (see 2.3.1). Poor lubrication also induces high forming loads, workpiece-tool adhesion and tool wear. The high forming load and the tool wear directly influence the product dimensions.

Poor lubrication causes fluctuation in the coefficient of friction, which brings about variations in the shape dimensions, surface roughness (see chapter 2.4) and fracture of the products. A good example of the influence of imperfections in the lubrication on the material flow is given by Ramaekers and Kals[59]. In their paper instable material flow in an upsetting operation is connected with imperfections in the lubrication.

A too thick lubricant layer at the workpiece-tool interface, effects the surface finish of the product (see 2.4.6). Excessive lubricant deposited or trapped in tool recesses or fillet corners often prevents the material from completely filling the tool cavity. This defect can be prevented by designing lubricant drains in the die.

2.5.4 Tools

The accuracy of tools is very important for the accuracy of the products: forming is in a way copying. The tool can be considered an analog storage for dimensions and shape. Deviations from the desired values in the tools show up as systematic errors in the workpiece.

Factors that induce dimensional inaccuracies in the workpiece are:

- elastic distortion of the tool components[53, 57, 58].
  This effect can be decreased by using tool components with a high Young's modulus, e.g. tungsten carbide. Rigid tooling has a higher spring constant, with smaller elastic deformations, for a given loading condition. Kudo[53] gives an example of the influence of the insert's material on the distortion of a tool.
- temperature distortion of the tool components[53]. Changes in tool dimensions due to a steady temperature rise cannot be avoided. With the use of controls and regulations, a computer aided correction, e.g. software correction, in the closing area of the tool is practicable. A prototype of such a system has been realized at IFUM in Hannover[59].
- wear of the tool components[53, 57, 58]. In production the dimensions of the tool change because of wear and deformation. If sliding cannot be avoided, the wear can be reduced by using wear-resistant tools and good lubrication. When the wear behaviour under production conditions

is known, techniques such as statistical process control and sample control can be used[57, 58].

Kudo[53] and Lange[57, 58] give various examples of the effects of the tool precision on the final dimensions and shape of the workpiece. In general, dimensional and shape defects can be prevented by: a high tool accuracy and small dimensional changes during manufacturing through wear.

2.5.5 Forming machine

A considerable amount of distortion takes place in the press construction and in driving elements that are subjected to the working load and torque. Lange[57, 58] distinguishes three factors that affect the production accuracy:

1. ram or hammer guidances.
2. stiffness behaviour of the machines.
3. fluctuations in the work capacity of the machines.

Since the forming tool is generally made of two parts, a proper guidance of the ram in the frame is important for good positional accuracy. The positional error of a tool is the sum of the positional error during contact (without load) and the positional error due to drifting (under central and eccentric loading). The latter results in ram tilt. Ram tilt can lead to such defects as buckling[61] and fracture of the workpiece.

Special interest has been displayed in the layout of adjustable guide forms of metalworking machines and of the resulting flux of force[60]. Doege[60] gives some examples of, and alternatives to the in industry used layout of guides.

The stiffness behaviour of the machines is influenced by several elements of the machines used: guidance of the ram, cross-head, press drive and frame, for example[60]. In general, the elastic deflections will be smaller in a more rigid press. It is therefore necessary to use more rigid presses such as die forging and coining presses, in order to obtain close dimensional tolerances on thickness in the force direction. Closed-frame presses are to be preferred to C-frame presses for such processes [53, 57].

Fluctuations in the work capacity affect the thickness of the product. The available work capacity should therefore be maintained constant for increased requirements on accuracy. Lange[57] gives some examples of how this should be done: the use of relays in the control of drop hammers, and the control of the screw speed in the case of screw presses.

2.5.6 Process and tool design

When the product, process or tool design is inadequate, extremely high working loads may be required to attain satisfactory filling of the tool cavity. This may cause distortion or failure of the tool or machine.

Kudo[53] gives three examples of dimensional inaccuracies that are caused by improper process design.

2.5.7 Product handling

Imprecision of the product generated during and after ejection can have many reasons, for example:

- improper ejection of the formed product.
- elastic shrinkage of a die having no draft angle.
- shrinkage of the product due to cooling.

An improper ejection method may distort the product shape[53]. The ejection method should therefore be carefully chosen.

The elastic shrinkage of a die having no draft angle can cause a slight plastic deformation of the product. This is easily overcome by designing a die with a slight draft angle. In this way a product is pushed out of the die by the elastic shrinkage.

Although shrinkage of the product due to cooling after (hot) forming is said to be a reason for product inaccuracies[53], for example in fast cold extrusion, Leykamm[55] states that a temperature rise of the workpiece does not influence the accuracy of the product. Leykamm explains this by saying that an expansion of the die due to the temperature rise of the workpiece compensates the expansion of the workpiece. Dimensional inaccuracies can, according to Kudo[53], be overcome by adjusting the die, e.g. by designing a die which is slightly oversized.

2.5.8 Operational control

For the reasons stated in the preceding sections, imprecision in formed parts results from changes or fluctuations in the current workpiece temperature due to non-uniform heating in the furnace, varying cycle time due to manual operation, etc. Omission of occasional scouring to remove pick-up from tool surfaces or of controlling deterioration and concentration of lubricant may cause changes in the operational conditions and, consequently, changes in the quality of the product.

3 Defect avoidance

In the previous chapter the emphasis was on defects, their causes and the ways to prevent them. These are the basic things that are needed for the avoidance of defects.

In literature several manners to avoid defects in products are mentioned:

- statistical process control (SPC)
- physical modelling
- mathematical modelling (FEM, UBET)
- database
- knowledge based system, expert system
- neural network

In the following sections the techniques involved and a knowledge based system which was proposed by the author will be discussed.

3.1 Statistical process control

Statistical process control is in cold forging used to avoid dimensional and shape inaccuracies. In view of the fact that cold forging processes are still primarily used for the mass production of components, statistical process control has become engineering standard practice in the effort to assure production quality. Here, the word "control" means closed loop control. During production, a check is kept on the way certain quality determinant parameters are changing. This enables corrective action to be taken while parts are still being produced within tolerance limits.

SPC requires information on[62, 63]:

1. systematic errors: errors caused by such factors as tool wear, elastic and thermal deformation.
2. random errors: errors caused by uncontrolled factors.
3. quality of the production process: tolerances that can be achieved with a certain process (process capability) and specific machine (machine capability).

Figure 18 shows what is meant by capable and non-capable processes. In words: the process capability is the process quality in relation to the tolerance described for a part.

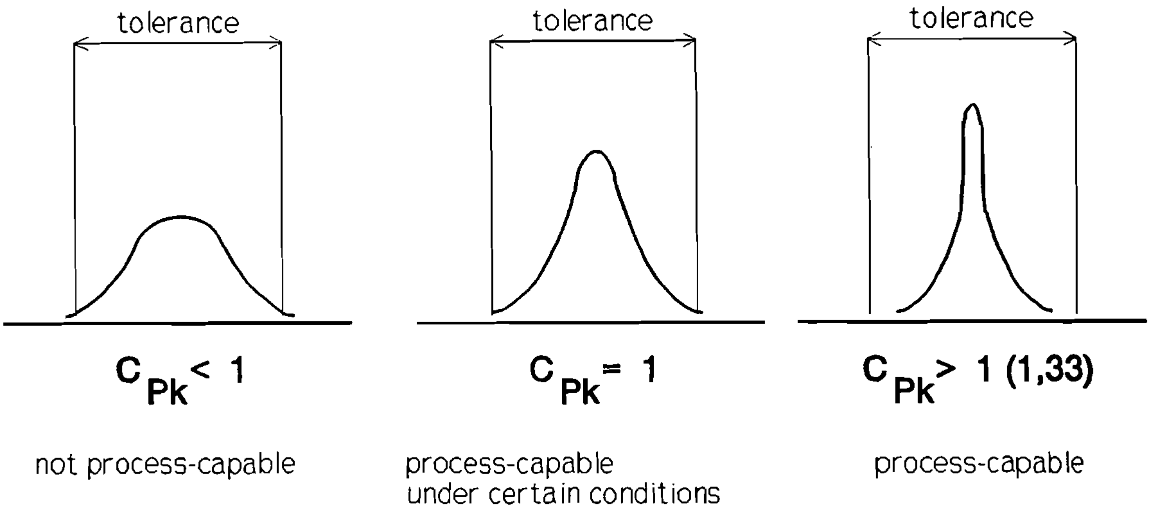

***Figure 18** Capable and non-capable processes. The frequency distribution of a process usually resembles a Gaussian curve. The process capability index, C_{Pk}, is an indication of the process capability.*

It is a matter of checking whether the scatter of a dimension is sufficiently tight compared with the tolerance, and whether the dimension changes result from systematic factors such as tool wear. The total of such comparisons for all of the part's characteristics determines whether the process is capable or not. Geiger and Perlhefter[62, 63] use the C_{Pk} index (process capability index) as an indication for the process capability. The C_{Pk} index expresses the position of a dimension's mean value in relation to the specified tolerance limits. Kirstein[64] and Lange[65] give an exact view of the process capability of several processes. The basic precondition for SPC is that both machine and process are capable. If not, there is no point in trying to apply this technique. This method therefore requires testing of machine and process capability besides the permanent statistical monitoring of the critical product dimensions.

Advantages of SPC are:

- knowledge of the manufactured product quality, due to the immediate assessment of the quality at any instant during a production run. The quality of a run can be documented with defined quality indicators and inspection results.
- possibility of early intervention in the production before out-of-tolerance parts are produced.
- possibility to demarcate the out-of-tolerance parts. As a result only a small portion of the production run would have to be scrapped or

subjected to 100% inspection.

An effect that according to Geiger and Perlhefter[63] should not be underestimated, is the strengthening of employee interest in quality matters when SPC is introduced. This can lead to improved quality of the products.

Disadvantages of SPC are:

- SPC cannot guarantee "zero defect" since it is based on random sampling. The forthcoming standard deviation is only a calculated estimation, which itself is subject to confidence limits. The SPC technique only tells how many products are likely to be defective.
- SPC cannot guarantee the detection of random defects in the order of p.p.m, (parts per million), e.g. defects in the original blanks or swarf. Only 100% inspection can eliminate such defects, and, because of faulty inspection even this cannot guarantee a zero defect result.
- the size of random samples has to be chosen large enough as to eliminate the influence of an individual measurement. Extreme figures would otherwise throw off the results.

More details and examples are given by Geiger and Perlhefter in their papers on SPC[62, 63].

3.2 Physical modelling

Development work cannot be conducted with production equipment, since it will disrupt the work done in the plant and will cause very high expenses. It is common practice to establish separate development laboratories with highly instrumented equipment. In this way it is possible to record all the data needed without interruption of the production process.

Because the use of production-scale equipment is expensive, normally all the tests are scaled down. Scaling down is a straightforward process when the workpiece is deformed at room temperature, and film lubrication and heat transfer are not factors that must be considered[66].

Flow patterns, including defect formation and forming forces can be studied on a small-scale workpiece with smaller dies, smaller equipment, and smaller forces.

Another simulation technique, the model material technique, has been developed by Wanheim et al.[67-70]. This technique uses model materials like wax, lead or plasticine to replace the workpiece material.

The model material technique is a 3-D technique and is very useful for determining flow, geometry, thrust magnitudes, pressure distributions and the effects of friction. This makes the technique suitable for the prediction of a workability limit of a material in a forging process. A good example is given by Yoshida and Wanheim[68] in their prediction of surface cracking.

3.3 Mathematical modelling

A reliable analytical model provides a determination of the dependent process parameters such as forces and flow patterns (fracture and failure) as functions of the independent parameters. Process design can be achieved with a high degree of success, and trial and error with the actual production equipment or physical models is minimized. This makes that mathematical modelling is one of the least expensive modelling techniques.

Due to the increasing capability and availability of computers, numerical simulation methods such as the finite element method (FEM) and the upper bound elemental technique (UBET) have been developed to a sophisticated degree. These techniques make it possible to determine the influence of the process parameters, e.g. lubrication, tool geometry, punch speed.

As mentioned in the previous section, there are several modelling methods: slab method, upper bound method, finite element method, for example. In comparison with the experimental procedures like material modelling, it is noted that the development of a mathematical model is more time-consuming. Whereas it sometimes takes months to derive a mathematical criterion, the problem may be solved in days or weeks by a trial-and-error experimental procedure. With an experimental solution though, only the solution of a specific case is obtained while an analytical model can give a general solution.

A complete review of these techniques is quite impossible, since it would be incomplete or outdated. Many papers about numerical simulation of forging processes can be found in the Journal of Materials Processing Technology[A]. There are several other journals[B-F] though, in which a considerable part of their articles involve numerical simulation techniques.

A good example of the application of a 2-D FEM programme for the simulation of cold forging processes is given by Oh et al.[71]. Mielnik[72] gives a comprehensive explanation of mathematical simulation of forging processes; the FEM is one of them.

3.4 Database

A database is a collection of data maintained by a database management system. The database management system is a file management system that assists in the operations of entry and storage of data and in linking related records of different types together.

Johnson[10] and Al-Mousawi et al.[92] emphasize the necessity for the design of a database with data on defects. Such a database should, once completed, provide a valuable source of information for academic researchers and process engineers. The database has to be flexible and updated to include new information.

With a database it would be possible to anticipate or avoid defects in a product. It would also be possible to couple such a database to an expert system as will be introduced in section 3.5.

3.5 Expert system

Expert systems are computer programmes which model human expertise and apply logic (inference) to the knowledge base in solving problems. The knowledge base itself is an organized set of information, i.e. a database, in the computer memory, obtained from people who are experts in a particular field, e.g. experts in metalworking processes[73].

The benefits of an expert system are: reduced time to market, capturing of the engineering knowledge and the ability of concurrent engineering. All these benefits are induced by the capturing of all the needed engineering knowledge into one integrated product model.

However, to make such a system operable for cold forging processes, highly specialized knowledge must be supplied in the following three areas[73]:

1. *Design for production.* Very specific cold forging rules must be provided, relating to such aspects as dimensions, shapes, surface finish, mechanical properties, in order to determine whether or not cold forging might be used to produce the particular shape. Even just to realize that a component might be suitable for cold forging needs specialist knowledge, which most product designers could not possibly possess.

2. *Process planning.* An optimizing system must be provided to select the best sequence of operations from those given, that will produce the part in the quantity desired at the lowest costs.

3. *Production equipment centre layout.* The proper selection, design and development and layout of the production equipment involving such equipment as presses, tooling, annealing furnaces, lubrication systems, that are essential for successful operation.

These three engineering activities are closely related, as has been shown by Lange[74, 75]. A fully competent component design for cold forging cannot be evolved, unless alternative process sequences and their effects on production equipment design, costs and the properties of the product are considered first.

As a result of the variety of cold forging processes, the products that can be produced, the defects that can occur and the causes of the defects, the development of an expert system must be based on several classifications. Appropriate processing sequences, design rules, process conditions, etc. can only then be formulated for each class of part and/or processes when these classifications are made.

The answers that are wanted from a cold forging expert system are:

- the forming stages.
- forming load (in each stage and total).
- requirements as to forging machine; i.e., maximum load, stroke.
- maximum strain and degree of work hardening in the final product and preforms.
- dimensional accuracy of the product.
- shape and size of the starting workpiece.

- requirements as to intermediate heat treatment and lubrication.
- total costs, including tool costs.

Some of these answers can be derived out of already existing expert systems, but most of these systems only give an answer to certain questions.

Expert systems have proven to be able to increase the consultation speed in the three mentioned areas[73, 76-90] and to provide reliable results. Most of these systems have been developed for process planning[73, 76, 78-86]. More about expert systems can be found in reference [6] or in the other given references.

3.5.1 Evaluation of defects and causes of defects

A classification of defects and their causes is not used in any expert system so far. But such classifications may provide the possibility of solving numerous problems in this field more efficiently, not only for the computation of the workability limit, but also its optimization, the varying of some parameters, and so forth. These classifications make it possible to answer questions about required intermediate heat treatment and lubrication; answers that are not given by the existing expert systems. When such an expert system has a design environment, it could adjust the product design so as to prevent some of the defects from occurring.

A possible programme structure for an expert system which includes the evaluation of defects is shown in figure 19. In this figure, i-1, i and i+1 correspond to stages in a generalized multi-stage process.

A programme for computer-aided evaluation of the workability limit requires definition of the following data:

1. Process.
2. Workpiece type.
3. Workability limit.
4. Characteristics of the forming material for example, degree of prestrain and mechanical properties.
5. Dimensional and geometrical characteristics of the initial shape of the workpiece.
6. Dimensional and geometrical characteristics of the final shape of the workpiece.
7. Working conditions.

8. Die characteristics.
9. Miscellaneous data.

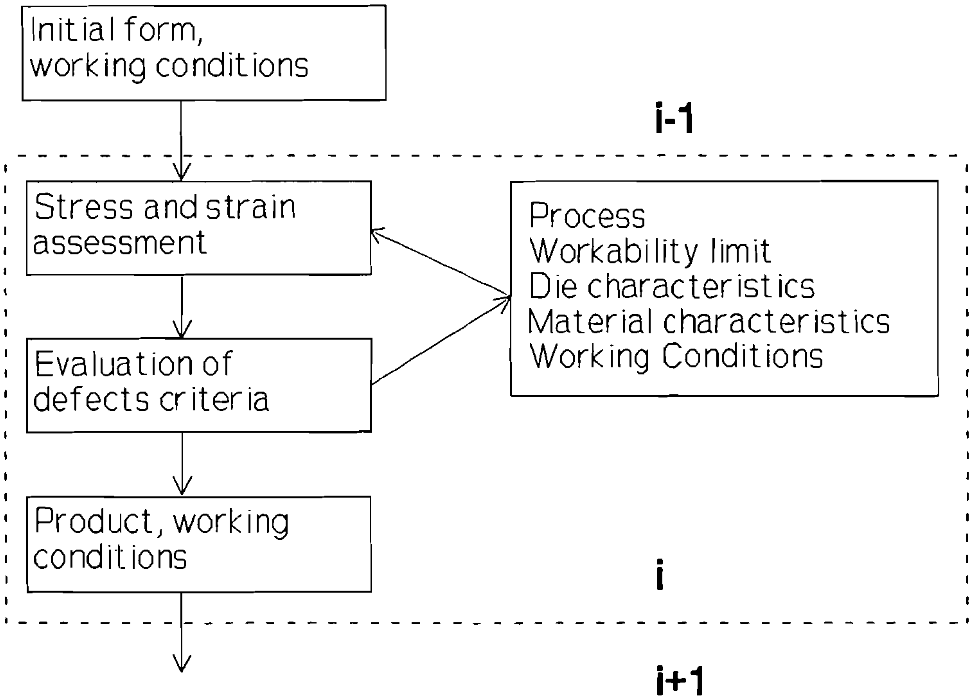

Figure 19 Possible program structure for an expert system.

The assessment of the stresses and strains (see figure 19) is a very important part. In expert systems[83, 87, 87] this is usually carried out by a FEM programme. This part calculates the strains in the product and then transfers this data to the evaluation of defects and overall process-evaluation. Finally, if it is found possible to carry out this stage without defect occurrence, all of the data is transferred to the next stage and the expert system evaluates the next stage in the same way.

FEM simulation is effective in getting the correct answers, but has the disadvantage of a long running time. Because of this, it would be better to make a good approximation of the critical strains in the product to limit the time needed.

One of the problems associated with the evaluation of defect criteria is the classification of defects and their causes. Although the ICFG Defects in Cold Forging sub-group[8] has made such classifications, realistically (see section 2.2) these may only be a beginning.

When a combination of a defect and process classification is used, it means for the expert system, that only rules related to a certain combination of defect and process have to be consulted. This has two main advantages:

1. since the number of clauses the interpreter has to search through is decreased, the execution time is decreased.
2. since the number of clauses in the knowledge base is decreased, the possibility of conflicting rules is also decreased.

In figures 20-23, the global relations between the defect and its possible causes are given in terms of the classifications used by the ICFG Defects in Cold Forging sub-group. The major causes for a defect are highlighted.

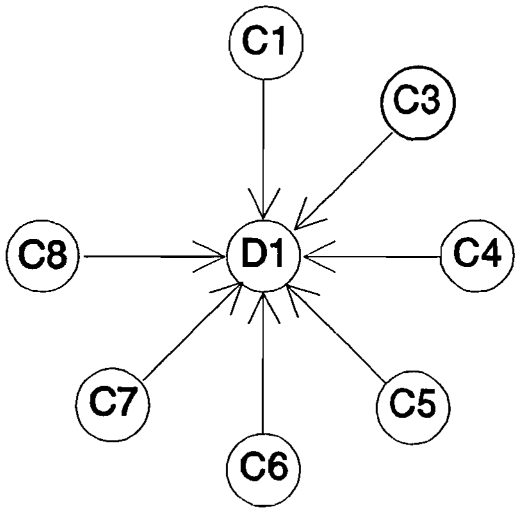

Figure 20 Possible causes for fracture or cracking (D1). The main cause for this defect is the tool properties (C3).

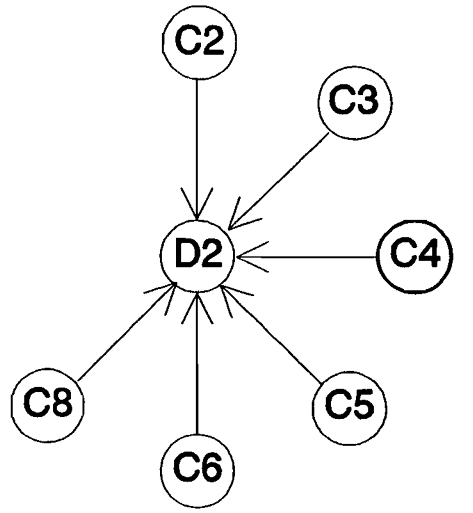

Figure 21 Possible causes for surface imperfections (D2). The main cause for this type of defects is the tribological variables (C4).

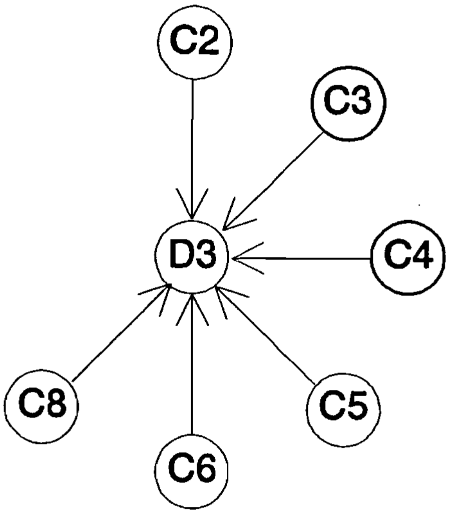

Figure 22 *Possible causes for dimensional inaccuracies (D3), the main causes are the tool properties (C3) and the tribological variables (C4).*

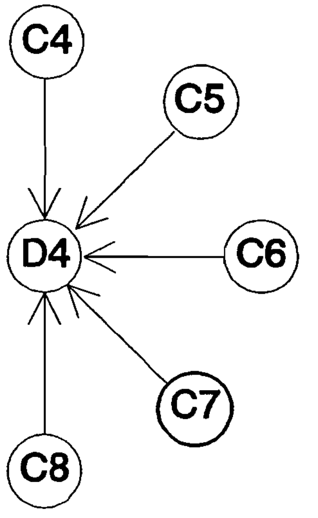

Figure 23 *Possible causes for undesirable properties of the product (D4), the main cause is the temperature rise in the workpiece and tooling (C7).*

3.5.2 Advantages and disadvantages

Advantages of expert systems are:

- They have proven to be able to increase the consultation speed and to provide reliable results in various applications[73, 76-90].
- They make high level expertise available and accessible to many users in a consistent quality, unlike the human expert who cannot always provide the same advice in the same situation and is often not available when needed.

Disadvantages of expert systems are:

- They are not able to replace human experts.
- For the development, very high efforts of time and money have to be made. All the knowledge which is scattered throughout the company has to be gathered; this will take a lot of time and highly educated people.
- Some of the knowledge that a human expert uses to solve a problem cannot be made consciously accessible to him or to others without a great deal of effort.

- It is hard to predict the break-even point for knowledge-based systems. You cannot point exactly where the benefits will be. In this way it is hard to convince managers of the need for these systems.
- Lack of software tools for implementing expert computer systems[91].

3.6 Neural networks

Neural networks can be seen as expert systems since they have the same functions. Besides, they add some human reasoning and decision making.

A good example of a neural network for cold forging is the one that has been developed by Osakada et al.[91]. This neural network decides which process sequence is the best one for a new product. This decision is being made after a training of the neural network with example products of which the process sequences have already been determined. A problem which is caused by this need for training is the acquisition and selflearning of reliable knowledge. When this training has been successful, most of the process sequences of new products can be correctly determined by the neural network.

4 Conclusions and remarks

1. There is a wide range of defects which occur during metal forming processes. A method of dealing with these defects is of considerable interest, because loss of products due to defects will lead to extra costs, costs which will decrease the competitiveness of a manufacturer.

2. There is some confusion in literature in the use of various terms associated with defects and ductility. The term defect is by most people only related to fracture. However, when noticed that the term defect is only used in relation to the term workability and not in relation to ductility or formability, terms which are related to fracture, confusion in terms will be overcome.

3. Defects can be peculiar to some materials or associated with some forming processes. It is a topic that, despite its importance, seems to attract little attention from academic researchers, who deal mostly with "ideal" materials and processes.

4. There are several possibilities to prevent defects: databases, expert systems and statistical process control, for example. Only statistical process control and the modelling techniques are common practice in industry; the other possibilities have still to be developed.

5. With an ad hoc solution for a defect, only a specific case is solved. Therefore analytical models of defects should be preferred since they give a general solution of a problem.

6. Solutions to defects, either ad hoc or analytical, are very seldom published. This makes it very difficult to find solutions in literature. Not publishing is probably caused by the "We have no problems, have we?" or "Our problems are only our concern" attitude.

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Journals with analytical models (of defects) or modelling techniques

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[B] Engineering Computations, Pineridge Press, Swansea U.K.

[C] Engineering Fracture Mechanics, Pergamon Press, Oxford-New York-Seoul-Tokyo

[D] Engineering with Computers, Springer International, Germany

[E] International Journal of Plasticity, Pergamon Press, Oxford-New York-Seoul-Tokyo

[F] The International Journal of Finite Elements in Analysis and Design

Recommended journals (general)

[G] Journal of Materials Processing Technology

[H] International Journal of Machines and Tools Manufacturing

[I] IEEE Computer

[K] CAE Journal

[L] Journal of Mechanical Working Technology

[M] Advanced Technology of Plasticity

[N] Werkstattstechnik

[O] Wire

[P] Stahl und Eisen

[Q] Maschinenmarkt

[R] Wear

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