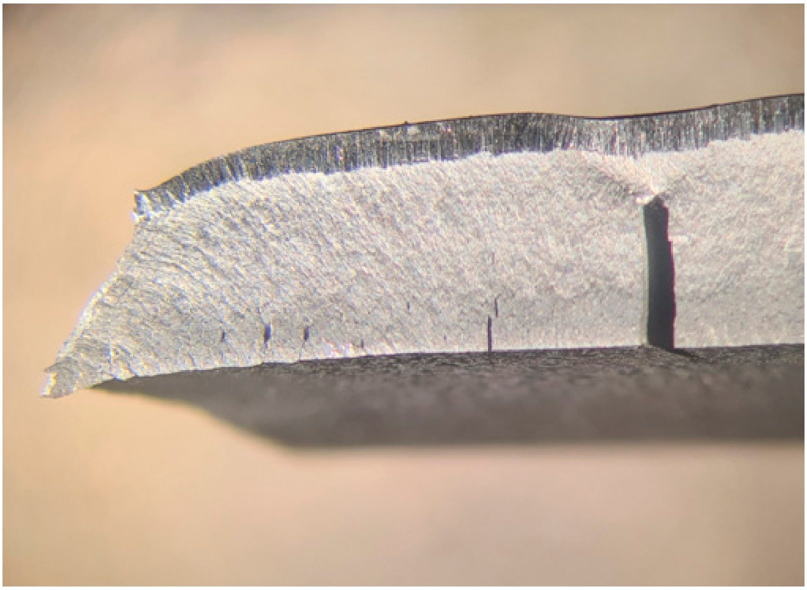
DOCTORAL THESIS

Influence of Sheet Metal Forming on High-Cycle Fatigue Life

A Predictive Framework



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Solid Mechanics

LULEÅ UNIVERSITY OF TECHNOLOGY

Influence of Sheet Metal Forming on High-Cycle Fatigue Life

A Predictive Framework

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Doctoral Thesis in Solid Mechanics

Preface

The work presented in this thesis was carried out at the Division of Solid Mechanics, Department of Engineering Sciences and Mathematics, Luleå University of Technology (LTU), Sweden. The European Union provided funding through the projects Fatigue4Light (Horizon 2020, LC-GV-06-2020 project no. 101006844) and Steel4Fatigue (RFCS, project no: 101157245). I would like to acknowledge my main supervisor Assoc. Prof. Erik Olsson for his clear communication and for sharing his experience. I am also grateful to my co-supervisors, Assoc. Prof. Jörgen Kajberg and Prof. Pär Jonsén for providing knowledge, guidance, and advice, as well as for identifying and designing suitable projects. Many other colleagues have also been valuable sources of support and company. I also want to express my deepest gratitude towards my wife and best friend, Marjukka. It's a privilege to share all aspects of life with you. You see and understand the needs of our children in such a beautiful way. Thank you, and thanks to the giver of all good gifts.

David Gustafsson
Luleå, October 2025

Abstract

Reducing weight of chassis components is an important task that does not need any further motivation or background. It can be read in a large part of the technical papers in the field. A tempting approach to achieving lighter designs is to increase the material stress bearing capacity, allowing for higher in-service stresses and thus enabling material thickness reduction and shape modifications. However, when cut edges from manufacturing processes are present, or when formed radii are found in critical locations, this design approach could be associated with high risks. The main aim of this thesis is to provide a framework for quantitative and qualitative estimation of the effect of sheet metal forming on high cycle fatigue strength on specimen level.

Increased steel grades often mean increased sensitivity for notches and surface properties, having implications both on formability and fatigue strength. Hence, the product developer might design for higher nominal in-service stresses, while selecting an alloy that is less suited to handle this increase. One solution is to increase the safety factors, decreasing the weight saving potential. Another alternative is to account for forming and post processing effect on fatigue life to find the most efficient solution. If sufficient and understandable estimation methods are lacking, the engineer has to rely on fatigue testing which is expensive.

In the synopsis an overview of metal fatigue in the context of sheet metal formed components is presented. Important aspects regarding fatigue modeling, common forming processes and post-forming operations are outlined along with a description of relevant numerical and experimental methods and considerations. Details of the conducted research are then presented in the appended papers, where the first introduces a simplified approach for numerical simulation of shear cutting to obtain residual stresses. The simplification mainly lies in the failure model calibration. The second paper studies the possibility of using the obtained residual stresses together with measured values of surface roughness to quantify fatigue life reduction of uniaxially loaded shear cut specimens. In the third paper the approach is extended to handle bending load cases and compressive residual stresses, while in the fourth paper the applicability to other forming processes and post-processes is studied.

For shear cutting it is shown that a simplified failure model calibration is sufficient for estimating the cut edge characteristics to be used in fatigue life estimations. The life estimations can, under certain circumstances, be done for various load cases and load ratios using only residual stress results from finite element simulations, surface roughness measurements, uniaxial tensile test results and a base material *S-N* curve. The method could also be used to estimate the effect from stamping and shot peening on fatigue. It

is suggested that engineers can use the proposed framework as a complementary tool to testing for assessment of the fatigue life implications of different alloys, grades, design choices and manufacturing processes. This could reduce the cost and time of product development and ultimately contribute to lighter and safer chassis designs.

Thesis

This is a compilation thesis consisting of a synopsis and the following scientific articles:

Paper A:
David Gustafsson, Sergi Parareda, Laia Ortiz-Membrado, Antonio Mateo, Emilio Jiménez-Piqué, Erik Olsson. Simulation of metal punching and trimming using minimal experimental characterization. *Journal of Materials Processing Technology*, Volume 321 (2023), 118148.

Paper B:
David Gustafsson, Sergi Parareda, Rémi Munier, Erik Olsson. High cycle fatigue life estimation of punched and trimmed specimens considering residual stresses and surface roughness. *International Journal of Fatigue*, Volume 186 (2024), 108384.

Paper C:
David Gustafsson, Sergi Parareda, Henrik Sieurin, Erik Olsson. Estimating the effect of punching on out-of-plane bending fatigue of steel sheet specimens. *Engineering Failure Analysis*, Volume 173 (2025), 109415.

Paper D:
David Gustafsson, Davide Ronco, Giorgio Gallio, Erik Olsson. Estimating the effect of cold forming and post processing on fatigue of high strength steels under component-related loading conditions. *Submitted to Engineering Failure Analysis.*

Contents

Synopsis

Chapter 1

Introduction

1.1 Background and motivation

The continuing request for lower environmental impact has forced researchers and developers to deepen their investigations of all sub-systems of passenger cars and Heavy-Duty Vehicles (HDVs). Two sub-systems stand out as particularly important in the context of sheet metal component lightweighting, accounting for approximately half of the total weight of passenger cars. These are the so-called Body-in-White (BiW) and the chassis each responsible for around one quarter of the weight according to Rowe (2012) and Lutsey (2010). For HDVs the chassis can account for a much larger part than the BiW (Hill et al., 2015).

BiW components are often designed to absorb energy in the event of a crash to protect the passengers and other components. Under such circumstances lower weight can be obtained by opting for stronger metals. Assuming constant density and ductility, components made by stronger metals can be made thinner and still absorb the same amount of energy as components made by lower strength metals. The main design challenges of BiW components are hence linked to rare events and not to cyclic loading. Chassis components, on the other hand, usually must bear significantly higher static and dynamic loads, making them susceptible to fatigue. The dynamic loads causing fluctuating stresses are coming from for example twisting and bending of the vehicle body due to road irregularities, acceleration, braking and turning, as well as vibrations (Zhang et al., 2025). In addition, the chassis partly consists of unsprung weight which means that, for example, the wheels do not benefit from the damping system but are in direct contact with the ground.

It is tempting to follow the same design strategy for chassis components as for BiW components, i.e. selecting a higher-grade alloy to save weight. At least for High Strength Steels (HSS), an increased steel grade also generally leads to a higher tolerance for fluctuating stresses (Tong et al., 2021). However, in the presence of edge defects and residual stresses the correlation between base material yield strength and High Cycle Fatigue

(HCF) strength could vanish. If the higher stress tolerance in fatigue is removed, the strongest argument to select a higher strength steel or aluminum alloy is removed.

In the automotive industry trimming, punching and stamping are common processes in the production of chassis components. In addition, post-forming processes, such as shot peening, are used to modify the surface properties. These processes can affect both the surface roughness and the surface residual stress state, meaning that engineers can't rely on base or smooth material S-N curves in the fatigue life assessment. As a consequence excessive testing, which is time-consuming and costly, or usage of high safety factors, which lead to higher component weight, is used.

Hence, knowledge about how the forming processes affect the high cycle fatigue performance, and convenient tools to quantify these effects could be of great importance in the pursuit of shorter development times and lower component weight.

1.2 Aim and objective

Considering the challenges described earlier, the ultimate aim of this research is to provide a simulation model where all initial conditions can be stated and where the outcome is an accurate prediction of the fatigue life of a component or structure at a given confidence level. To pursue this aim, the objective of this thesis is to establish a framework for estimating the fatigue life of shear-cut and stamped specimens. A second objective is to develop a methodology for simplified punching and trimming simulations that provides useful information to fatigue life estimations. Based on these objectives, the following research questions are identified:

(i) *How can the residual stresses from forming processes be estimated with sufficient accuracy for fatigue analysis, using simulation and experimental methods that are feasible for industrial users?*

(ii) *How can manufacturing process effects such as residual stresses and surface roughness be incorporated into estimations of fatigue life?*

1.3 Scope and delimitations

This study is limited to high cycle fatigue above approximately 10^4 cycles, where macroscopic plastic deformations are minimal, and below approximately 10^6 cycles, where cracks are assumed to initiate at the surface. The so-called fatigue limit is not considered, instead all cracks that initiate are assumed to propagate to failure. Very high cycle fatigue and fatigue with sub-surface crack initiation are not considered, instead the surface condition is regarded as the deciding factor for fatigue life. It is assumed that classic mean stress correction factors are applicable within this cycle range. Due to the intended application, chassis components, the materials used in this study are limited to high strength steels and aluminum alloys, with major focus on the steels. A phenomenological approach is taken, both to the manufacturing process modeling and the fatigue modeling to minimize the need for advanced experimental characterization and advanced modeling. This is believed to increase the usability and interpretability of the results to a wider audience of engineers. In the same spirit, no in-house finite element codes are developed, instead commercially available solvers and material models are used. The fatigue experiments are limited to lab-scale specimens where nominal stress can be calculated.

Chapter 2

Fatigue of Metals

This chapter serves as a general introduction to fatigue of metals. The definition used for the term *fatigue* is presented as well as a short historical review of the work that has led to the current state-of-the-art. Finally, the physical mechanisms behind the phenomenon of fatigue are discussed along with different factors that affect fatigue performance. Emphasis is placed on mechanical fatigue.

2.1 Fatigue definition and different types of fatigue

Many different formulations of fatigue definitions exist. According to Ribeiro et al. (2011), one of the oldest was formulated in 1964 by the International Organization for Standardization in Geneva and reads:

> 'Fatigue is a process of progressive localized permanent structural changes occurring in a material subjected to conditions that produce fluctuating stresses at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuation'

A much shorter and probably more intuitively understandable description of material fatigue is *failure due to fluctuating stresses*. The word fatigue in this sense has been used since the 1840s or 1850s (Stephens et al., 2000, Schütz, 1996).

Fatigue failure of metals are often divided into different sub-categories due to the difference in failure mechanism for each category. These are monotonic fracture, Ultra Low Cycle Fatigue (ULCF), Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF) and Ultra High Cycle Fatigue (UHCF). A rule of thumb to distinguish these different regimes in a Stress-Number of cycles (S-N) diagram could be to say that ULCF occurs when the number of cycles to failure is below 100. Correspondingly LCF is below 10 000 and HCF below 10 000 000 cycles, see Fig. 2.1. In this thesis, the focus is on HCF.

The monotonic fracture is usually characterized by void nucleation, growth, coalescence and finally macroscopic crack initiation. This mechanism is present in the ULCF region as well together with the traditional fatigue mechanisms that govern LCF and HCF, namely surface crack initiation, crack growth and finally catastrophic rupture when the remaining area is too small to bear the maximum stress in a load cycle. The difference between LCF and HCF is sometimes described as a significantly smaller amount of macroscopic plastic strains in HCF (Santecchia et al., 2016).

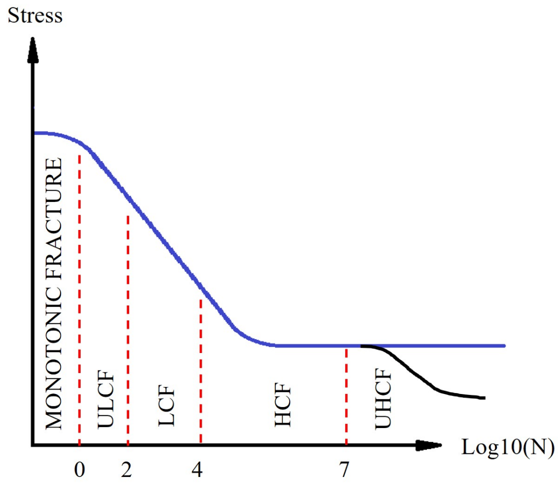


Fig. 2.1. Approximate division of the different types of fatigue.

Traditionally, for steels as opposed to aluminum alloys, the S-N curve in the HCF region is assumed to reach a plateau, i.e. the presence of a fatigue limit is assumed. It is assumed that the structure can withstand stresses below this limit for an infinite number of cycles. However, as presented in the review by Li (2012), the S-N curve starts to drop after a very high number of cycles even for materials that seem to exhibit a fatigue limit. In this region the cracks tend to initiate from sub-surface inclusions. If surface initiation could be avoided a complete shift of the S-N curve to the right could be observed for low stresses (Li, 2012), see Fig. 2.2.

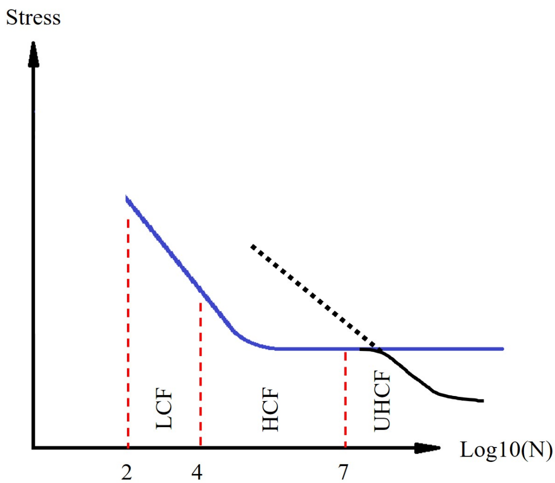


Fig. 2.2. The shift from surface (blue line) to sub-surface (black dashed line) initiation (Li, 2012).

2.2 Historical review

The study of material fatigue is relatively young. The pioneering research of this field, at least speaking of metal fatigue, can be traced back to Germany in the 1830s, where the first documented fatigue experiments were conducted. The results were published by Albert (1837). His research was driven by observations of conveyor chain failures in the mines of Clausthal. These chains were subject to stresses below the static strength, raising questions regarding the failure causes. (Suresh, 1998, Schütz, 1996)

The study of fatigue sadly continued to be fueled by accidents in the following years. One of the most famous examples is the railway accident in Versailles 1842 where an axle of one of the two locomotives broke, causing a disaster where over 50 people lost their lives according to Adams (1879). In fact, the number of railway accidents, of which many were related to fatigue, was so large during the 19^{th} century so that, still in the end of the century, an English newspaper had a column describing the *"most serious railway accident of the week"* (Schütz, 1996).

Many researchers and engineers were assigned the task to improve the safety of railway associated components and railway bridges but the next major contribution to the study of fatigue came in the 1860s and 1870s by another German engineer named August Wöhler (Schütz, 1996). His experiments and calculations led to what is called the "Wöhler laws". Reformulated using the common terminology of today they could read as follows (Schütz, 1996 and Pook, 2007):

1. Materials can fail if subject to many repetitions of stresses lower than the static

strength
2. The stress range, or amplitude, is decisive for fatigue failure of the material
3. A higher mean, or static, stress will make the material fail earlier for a given stress range/amplitude

Wöhler also discussed finite versus infinite life design, and the necessity of safety factors due to the scatter, or stochastic nature, of the fatigue test results and in-service loads. The famous Wöhler curves, in the form known today, were not introduced by Wöhler. He worked with tables rather than curves. According to Schütz (1996), whose work on the fatigue history contains 554 references, the modern form was presented by Basquin (1910).

The study of metal fatigue can be divided into mechanical and metallurgical description (Pook, 2007). Before 1903 the study of fatigue was limited to the mechanical part, but by that year the first metallurgical observations of the process were published in England by Ewing and Humfrey (1903) who discussed slip bands in relation to fatigue (Schütz, 1996).

From the end of World War One until the end of the Second World War a lot of research effort was invested in the subject of material fatigue. Most of the contributors were from the USA, United Kingdom or Germany. Examples of the investigations of this period are (Schütz, 1996):

(a) the effect of variable stress amplitude,
(b) the fatigue limitations of high strength alloys in components due to increased notch sensitivity,
(c) the pioneering work on what later became the linear elastic fracture mechanics,
(d) the influence of surface roughness,
(e) the influence of shot peening,
(f) the division of fatigue into different phases,
(g) the independence of static material strength in fatigue of riveted and welded steel joints,
(h) the importance of component design in relation to material selection,
(i) the fatigue stress concentration factor,
(j) fast fatigue testing methods, and much more.

Apart from these contributions by the leading nations of that time, the important work by Palmgren (1924) on the damage accumulation hypothesis, and by Weibull (1939) on the statistical variations in material strength, could be mentioned. (NBS, 1961, Schütz, 1996)

In the time after World War Two the main focus of fatigue researchers was to prevent accidents in the automotive and aircraft industries. An interesting note in relation to the research work presented in this thesis, is that already around 1950 a major part of the German automotive and truck manufacturers started to investigate the phenomena of fatigue, lead by an engineer called Ernst Gassner. The main objective was cost reduction by weight saving. This is still one of the main driving factors for the study of fatigue in chassis components, with the important addition of the environmental benefits associated with lower weight. By that time, this was going to be achieved, as described by Schütz, *"through service-load measurements and variable amplitude testing"*. During this period of time a new branch of the fatigue studies arose, namely the low-cycle fatigue. The main contributors to this were Coffin and Manson in 1954. (Schütz, 1996)

After or around 1960 many important contributions were presented. Examples of these are Paris' law, Endo's and Matsuishi's rainflow counting method, Elber's crack closure, the Damage Tolerance (D.T.) design concept and the servo-hydraulic fatigue testing machine. This machine enabled fatigue testing using much more freely designed load spectra than before. (Schütz, 1996)

The research proceedings of the time between around 1995 until today are covered in more detail in the following sections, where the author's interpretation of the current state-of-the-art is described. Naturally with emphasis on topics closely related to the research work presented in the appended papers.

2.3 Fatigue damage mechanisms and phases

Fatigue damage, and especially HCF damage, is usually divided into different phases. The reason for this is that the damage mechanisms are not equal throughout the damage evolution. The simplest distinction is to say that fatigue damage consists of crack initiation and crack growth. To further break down the process a subdivision of crack initiation into cyclic slip, crack nucleation and micro-crack growth could be made (Schijve, 2014). With this division the total fatigue life in terms of cycles N_{total} would become:

$$N_{total} = N_{cyclic\,slip} + N_{crack\,nucleation} + N_{micro\,crack\,growth} + N_{crack\,growth} \tag{2.1}$$

To scientists the scale of the first three phases in Eq. (2.1) is usually in the order of a grain size while engineers might consider the initiation as a larger scale phenomenon (Chan, 2010, Santecchia et al., 2016).

Other descriptions of the total fatigue life could also be found in the literature such as for example McDowell et al. (2003) who state:

$$N_{total} = N_{incubation} + N_{microstructurally/physically\,small\,crack} + N_{long\,crack} \tag{2.2}$$

and Makkonen (2009) who describes the total life as crack initiation, stable crack growth and unstable crack growth. For high cycle fatigue the earlier phases, which typically are surface phenomena (Schijve, 2014), are the most important in terms of fatigue life, around 40-90% (Makkonen, 2009). Sometimes even higher numbers are reported, making the crack growth phase negligible (Hachim et al., 2012).

2.3.1 Crack initiation

According to Deng et al. (2015) a major part of the often observed scatter in fatigue testing under equivalent conditions originates from the crack initiation phase while the number of cycles for the subsequent crack growth are more consistent between different tests.

As mentioned earlier, the fatigue damage process is commonly described as initiating with cyclic slip. Sangid (2013) provides a description of this complex phenomenon. He divides it into a number of steps or ingredients which could be described as:

(i) Existence and/or nucleation of dislocations. This is a prerequisite for the fatigue damage process to start if the fluctuating stresses are below the global yield stress of the material.
(ii) Dislocations gliding on slip systems. This starts when the resolved shear stress reaches a critical value. This critical resolved shear stress (CRSS) is dependent on the crystal structure. As an example, Mlikota and Schmauder (2018) states that the CRSS for body centered cubic (BCC) structures could be several times higher than for face centered cubic (FCC) structures.
(iii) The dislocations reach obstacles, for example grain boundaries, which lead to increased local stress.
(iv) New dislocations are formed, or the dislocations overcome the obstacles.
(v) Repetition of the former steps along the same low energy path.
(vi) Formation of persistent slip bands (PSB). Lukáš and Kunz (2004) use the following definition of a PSB: *"(i) There is a cyclic strain localization in this zone. (ii) Its dislocation structure differs from that in the surrounding matrix. (iii) In single crystals and surface grains of polycrystals the zone ends on the specimen surface in intrusions and extrusions."*. They also show that PSB formation is possible only for intermediate stress amplitudes and low magnitudes of mean stresses, and that PSB does not form in high temperatures but have been observed at around one half of the melting temperature for copper (Boehme et al., 1990).
(vii) Formation of positive and negative dislocations.
(viii) Nearby positive and negative dislocations cancel out each other (annihilation).
(ix) Ladder structures and/or parallel slip bands are formed.
(x) Ledges and/or intrusions/extrusions are formed between grains and at free surfaces.
(xi) Stress concentrations at the grain boundaries lead to slip in the adjacent grains.
(xii) Accumulation and localization of plastic strains leads to locally hard and soft material.

Step (xii) is followed by crack nucleation at the interface between the hard and soft material, i.e. the interface between the slip bands and the matrix (Sangid, 2013).

Tu and Zhang (2016) claim, in accordance with the description by Sangid (2013), that these damage mechanisms are especially dominant with increasing grain size. They claim that smaller grain specimens tend to experience another type of crack initiation originating from second-phase particles and that the difference in fatigue life might be an order of magnitude depending on the crack initiation location, namely on surface or sub-surface. This means that two separate groups of observations might be obtained for the same fatigue test setup (Tu and Zhang, 2016), which is in line with the previously mentioned work by Li (2012). Crack initiation due to persistent slip bands could look like illustrated in Fig. 2.3.

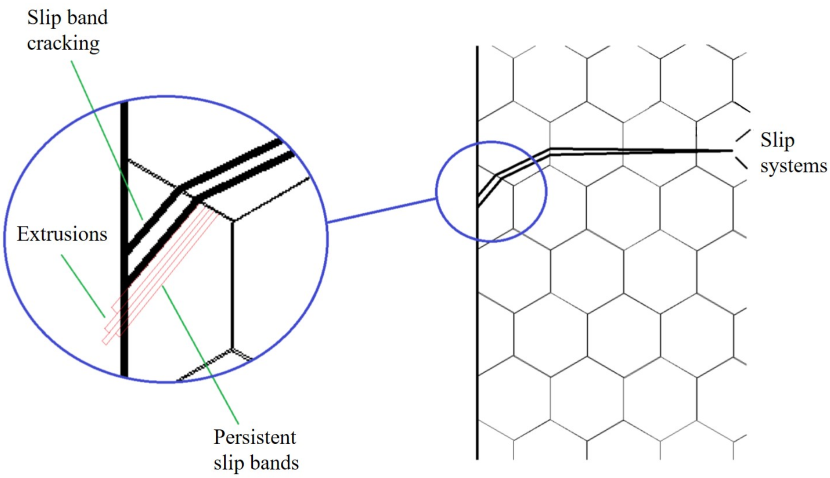


Fig. 2.3. Illustration of crack initiation due to persistent slip bands.

2.3.2 Crack growth

At the moment there is no easily defined, distinct border between crack initiation and crack growth even though the mechanisms of the phases are considered to differ (Schijve, 2014). This division is, however, useful sometimes. For example, it could enable usage of linear elastic fracture mechanics for predictions of the latter phase. Usually the crack growth phase is considered to start either when the size of the crack is in the order of 1 mm, or in the order of a grain size (Tu and Zhang, 2016, Chan, 2010, Schijve, 2014). The mechanisms of crack growth will not be further described here for two reasons. Firstly, because fatigue failures in automotive components, which is the focus of the author's research work, mainly are HCF failures, and in HCF the initiation phase is dominating (Ottersböck et al., 2019, Makkonen, 2009, Hachim et al., 2012). Secondly, because sheet metal forming processes mainly affect the initiation phase and not macroscopic crack propagation.

2.4 Fatigue design philosophies

There are different ways to approach fatigue design, and these approaches are here divided into three main categories. The first is when a component is designed to never fail, the infinite life design. The second is when a component is designed to manage a certain life and then be replaced, the safe life design. The last category is when a certain amount of damage is accepted, and the component is inspected regularly. When the damage increases above a certain criterion, the component is repaired or replaced.

2.4.1 Infinite life design

Infinite life design was the first approach to handle fatigue problems. It assumes a definitive fatigue limit. The component is then designed so that this limit, in terms of stress, never is exceeded. For high cycle fatigue components subject to a relatively homogeneous load spectrum, for example train axles, this approach could be sufficient. However, due to the statistical nature of fatigue safety factors must be employed which results in heavier and more expensive components. In aviation where weight is crucial, this is not feasible. (Stephens et al., 2000)

2.4.2 Safe life design

Many products, for example cars, are designed for a limited time of usage. This means that many components of the car could be designed for a finite life. One way of doing this is to measure the load spectrum during usage to get an idea about how often severe loading, i.e loads above the normal cyclic loads, occur. These could, even though appearing much more seldom than the regular loads, still be crucial for the life of the component. With this information a design criterion could be to withstand the occasionally higher loads for a limited time and assume that the smaller loads will be safe as well. This approach could be used for components where inspections for different reasons are cumbersome or impossible. Even if the car was assumed to be used forever this approach could be used by introducing service intervals where the component is replaced. Similarly to infinite life design, the safe life design requires usage of safety factors. (Stephens et al., 2000)

2.4.3 Damage tolerant design

To reduce the need for safety factors another approach to fatigue design was developed called damage tolerant design where damage and crack propagation are accepted to a certain degree. This design philosophy can be implemented in different ways.

Fail safe

In fail safe design components might fail or suffer from severe crack propagation but the structural integrity or the function of the product remains intact to an extent that it is safe to use until repairs can take place. The design concept of damage tolerant design and fail safe could include redundancy, load transferring or crack stopping features. (Stephens et al., 2000)

Slow crack propagation

A key ingredient in this approach is that damage or failure is detected in time. Hence the inspection interval must be set so that a crack smaller than the cracks detected during the last inspection did not have time to propagate in an unsafe manner before the next inspection.

2.5 Fatigue fracture surfaces

Often it can be concluded if a structure has suffered from fatigue simply by looking on the fracture surface. The two most clearly distinguishable features are the area where the crack has propagated, and the area of final rupture where the remaining cross section could no longer bear the applied load and complete separation had occurred. In real life components so called beach marks, see Fig. 2.4, are often visible without any use of microscope. These marks could be said to represent, not a single load cycle, but a block of cycles. The different appearance of each block has multiple explanations. One is environmental and comes from the fact that each part of the fracture surface has been exposed to the surrounding environment differently, depending on when the crack surface was formed. The load history of each block could also affect the appearance of the surface due to different crack growth rates, and the loading itself can also influence the impact from the environment. Often in controlled fatigue tests without interruptions or changes in loading, no beach marks are visible. (Milella, 2024)

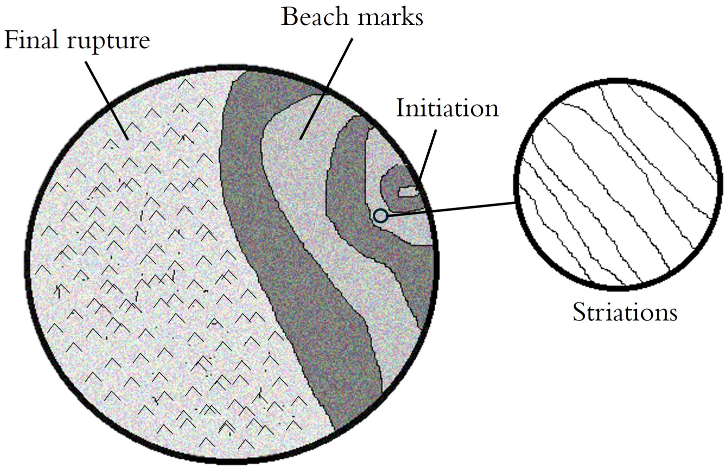


Fig. 2.4. Sketch of fatigue fracture surface (Milella, 2024).

On microscopic level striations could often, but not always, be found on the fatigue fracture surface. These represent the crack growth of a single load cycle. (Milella, 2024)

The investigated fracture surfaces in the research presented in this thesis did not exhibit any beach marks.

2.6 Effect of load ratio and mean stress

The load ratio R in fatigue is the ratio between the minimum and maximum load in a load cycle. The most common R values for fatigue testing are R = -1, i.e. a fully reversed load cycle and R = 0.1, i.e. a load cycle completely located on the positive load side. The fact that the load never shifts between tension and compression for R = 0.1, and that the load range usually is smaller, makes testing at that ratio gentler to the servo-hydraulic testing machine and the test frequency can be increased. The risk of buckling of the specimen is also eliminated.

It is important to notice the difference between load ratio and stress ratio even though they are sometimes used interchangeably. In fact, most of the time the correct phrasing would be load ratio in high cycle fatigue because it is the load that is controlled during testing. The actual local stress state at the point of fatigue initiation is often unknown, and hence the stress ratio is also unknown. However, speaking about stress ratio in nominal terms, as calculated from the loading, is often appropriate. Stresses could be easier to comprehend as they can be related to static material properties. Regarding this, an interesting side note is that the mean stress during fatigue testing often is slightly higher than the nominal calculations suggest, simply because of the smaller cross-sectional area at maximum tensile load as compared to the area at the minimum load (Ahlström and Karlsson, 2005). This effect was not considered in this thesis.

As stated by the Wöhler laws, two nominally identical stress cycles with different mean stresses will yield different fatigue lives. A positive mean stress will typically lower the fatigue life and negative mean stresses will extend it. This is important to consider when residual stresses from forming are present. The residual stresses can sometimes be treated as mean stresses (Hamada et al., 2018; Hariharan and Prakash, 2012) as further discussed later.

Nominal load ratios in the range of -1 to 0.69 were considered in this thesis.

2.7 Effect of manufacturing processes

There is an endless list of manufacturing processes used to produce components for different applications. The surface characteristics in cut edges and formed areas, which are a result of manufacturing processes, often have a great impact on the fatigue life of a component (Brinksmeier et al., 1982). The effect of the surface properties on fatigue life is a complex, material, and fatigue regime dependent phenomenon. Fatigue tests of various steel grades (Meurling et al., 2001) demonstrate, for example, an increased sensitivity to different cutting methods as the number of cycles increases (Thomas, 2017).

One approach to understand the effect of forming is to examine the surface, or edge, properties, given that the fatigue crack initiates from the surface (Thomas, 2017). Four surface properties that influence fatigue life, some of which may be interrelated, are (Murakami, 2019; Thomas, 2017):

(i) residual stresses
(ii) surface roughness and defects

(iii) microstructure
(iv) hardness and plastic strain

For cutting processes these characteristics depend on three factors according to the premises used in the review by Thomas (2017). These factors, extrapolated to include other manufacturing processes, can be formulated as:

(a) material and material grade
(b) manufacturing method
(c) process parameters

2.8 Effect of residual stresses

Forming induced residual stresses could have a significant effect on the fatigue life of components as reported by Hariharan and Prakash (2012). They state that these stresses are essential to include in fatigue life estimation models. Morrow et al. (1960) stated that not only shall these stresses be accounted for, but the possible change of these during cyclic loading should also, under certain circumstances, be handled. Brinksmeier et al. (1982) claim that residual stresses are often introduced to a component during manufacturing due to plastic deformation or material phase transformations. When these phenomena are inhomogeneous through the component it creates local volume changes that force the material to respond to accommodate the change. This response, in the form of elastic strains, introduce stresses that prevail within the component without external forces acting on it (Brinksmeier et al., 1982).

In the work by Yang and Liu (2002) the main reason for the fatigue life scatter observed experimentally, was variations in residual stresses, and this had a significantly higher impact on the scatter than the variance in material properties. In contrast, Murakami et al. (2021) argues that the main factors for fatigue scatter are variations in defect size scatter, microstructure variability and alignment variations in testing.

Shiozaki et al. (2015) found that heat treatment could reduce the residual stresses significantly, which improved the fatigue performance, at least in terms of an increased fatigue limit. One explanation for this could be that the tensile residual stresses in the cut edge act as tensile mean stresses, and lowers the fatigue performance in the HCF regime, given that the fracture zone is the initiation site (Hamada et al., 2018). For punched aluminium alloy sheets (with a yield strength of 112 MPa) the residual stress in the cut edge was considered to be of minor importance in the work by Winter et al. (2025). It should be mentioned, however, that the authors pointed out challenges in measuring residual stresses in the cut edge using XRD. The fatigue tests were conducted using a load ratio of $R = 0.2$, which might suggest that part of the residual stresses relaxed due to the high maximum stresses. The mean stress sensitivity of the studied grade could also be an influencing factor.

One example, showing that compressive residual stresses could have a positive effect, especially in the HCF regime where macroscopic plasticity is of less importance, is provided by Dehmani et al. (2018), see conceptual illustration in Fig. 2.5.

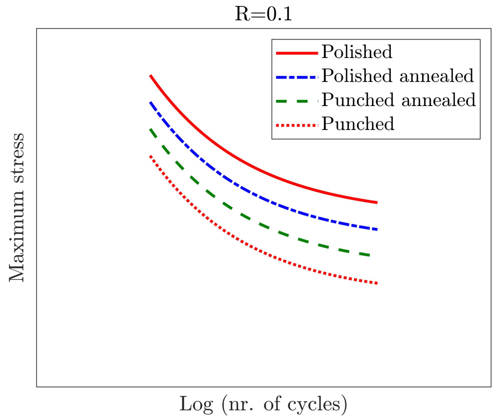


Fig. 2.5. Conceptual illustration of HCF test results presented by Dehmani et al. (2018).

In their comparison the fatigue performance was better for a polished cut edge as compared to polishing with subsequent annealing. Both, in turn, performed better than annealing without polishing and the worst performance was obtained for specimens in the as cut condition. The reason seems to be that tensile residual stresses in combination with high surface roughness, see Section 2.9, exist in the fracture zone of the punched edge. After annealing those stresses are removed and the fatigue performance is increased. If polishing is used without annealing the residual stresses on the surface changes from tensile to compressive and the surface roughness is decreased. With both polishing and annealing the positive effect of refined surface roughness is obtained, but the beneficial compressive stresses are reduced. (Dehmani et al., 2018)

McKelvey and Fatemi (2012) found that induced compressive residual stresses increased the fatigue life of forged steel in the HCF regime. The fatigue life increase was more pronounced at longer lives and for materials with higher hardness.

In the LCF regime the compressive residual stresses created by tensile prestraining have been reported to shorten fatigue life (Hariharan and Prakash, 2012).

Schubnell et al. (2020) showed that ignoring compressive residual stresses can result in over-conservative life estimations. For high magnitude of compressive stresses the estimations including residual stresses instead became non-conservative. This could imply that compressive stress relaxation should be accounted for.

2.9 Effect of surface roughness and defects

On a micro-level most surfaces exhibit significant geometrical irregularities, known as surface roughness. Various measurement parameters have been developed to quantify the, often highly stochastic, roughness of surfaces. Some measurement parameters focus on the average height of the peaks and valleys, while some are more focused on capturing the extremities. The geometrical peaks and valleys act as local stress raisers at, and close to, the surface. Increased local stresses mean increased risk for fatigue crack initiation, which often lead to a shorter fatigue life (Bayoumi and Abdellatif, 1995; Jiménez-Alfaro and Martínez-Pañeda, 2025).

Just like for the effect of residual stresses, a reversed effect from surface roughness in the LCF regime as compared to the HCF regime has been observed by some authors. Arola and Williams (2002) found a decrease of HCF life of AISI 4130 as the surface roughness increased, while the LCF life increased. One explanation for this could be local plastic deformation at the surface in LCF, introducing compressive residual stresses close to critical notches.

Itoga et al. (2003) studied fatigue of ultra high strength steel and found that increased surface roughness resulted in decreased fatigue life in the regime around 10^5 cycles. In that regime the crack initiated from the surface. For fatigue lives of 10^7 cycles and above the crack initiated from sub-surface inclusions. In those cases, the surface roughness did not influence fatigue life.

Winter et al. (2025) studied punching of AA-5754 using different punching speeds and found that the difference in roughness of the produced cut edges was the main reason for the difference in fatigue performance.

HCF under reversed loading of 4130 steel specimens with different surface roughness was studied by Singh et al. (2019). Their experimental results show that around 10^4 cycles the difference between the different S-N curves is small, but increases until around 10^6 cycles.

2.10 Effect of microstructure

Smaller grain size generally reduces the risk of persistent slip band formation (Sangid, 2013) and hence, a longer initiation phase can be expected while the subsequent crack growth could become faster. However, in HCF the overall gain from smaller grains in the initiation phase is, at least for some materials, proven to be larger than the loss in the crack growth phase (Hanlon et al., 2003, Chan, 2010, Tu and Zhang, 2016).

A reduced number of twin boundaries could elongate the fatigue life even though there is a lack of consensus about the mechanisms behind this (Sangid, 2013). In the studies by Hashimoto et al. (1999) and Miao et al. (2009) sub-surface initiations could be derived from large grains, twin boundaries and grain orientations resulting in low critical resolved shear stresses. One explanation for the negative effect of twin boundaries could be that pairs or clusters of grains with almost similar orientation could enable slip band formation along multiple grains (Chan, 2010).

Mlikota and Schmauder (2018) claims that the probability of a predominant slip band to form within a grain is smaller for some crystal structures than others, partly due to the different number of available slip systems. If multiple possible directions of slip within a grain are available slip bands will form in alternating directions to a larger extent enhancing fatigue life. The number of available slip systems varies significantly between crystal structures and is often 24 in a BCC structure and 12 in a FCC structure.

That said, Mlikota and Schmauder (2018) also conclude that the crystal structure is less important for fatigue than the critical resolved shear stress (CRSS), but a high CRSS is more often found in BCC structures as compared to FCC. The presence of a so-called knee in the S-N curve is also more associated with metals featuring a BCC structure and high CRSS (Mlikota and Schmauder, 2018).

The effect on fatigue performance due to microstructural changes during shear cutting is somewhat unclear. Lipiäinen et al. (2024) studied fatigue of advanced high strength steel specimens with a punched hole. They state that in terms of formability the post-forming microstructure is of great importance, but in terms of fatigue geometrical notches and crack like defects are of greater concern. On the other hand, Heshmati et al. (2025) claim that the post-forming microstructure has a contribution to the fatigue life of punched specimens. Due to the lack of consensus regarding the fatigue implications due to the punching process effect on the microstructure, the microstructure was not directly considered in this research work. The pre-punching microstructure was indirectly considered through the base material S-N-curve. Quantification and modeling of these effects are left for the future.

2.11 Effect of hardness and plastic strain

The local material properties can be affected by work hardening due to manufacturing processes. Yang and Liu (2002) showed that usage of the local material strength could increase the accuracy of fatigue life predictions for samples including notches as compared to using the base material strength, even though the change was small for the studied material (Ti-6Al-4V). The local material strength was evaluated by micro-hardness measurements.

Paetzold et al. (2017) investigated the maximum hardness in the shear affected zone and found that lower hardness seems to be beneficial for fatigue life of cut edges. However, the residual stresses were not evaluated and hence, it is unclear if the cut edges exhibiting higher work hardening also contains higher residual stresses. In line with Paetzold et al. (2017), Winter et al. (2025) also found that the cut edge with the smallest hardened zone performed best in fatigue tests. Shiozaki et al. (2015) found that heat treatment didn't have much effect on the hardness close to punched holes. On the other hand, the residual stresses were affected and so were the HCF lives. The materials in their study were HT540 and HT780 of thickness 2.6 mm. In some steels, annealing has been shown to influence the hardness of the cut edge (Dehmani et al., 2018).

Kantola et al. (2013) showed in their study on a high strength CrMn austenitic steel that even though plasma cutting resulted in lower surface roughness than laser and water-jet cutting, the fatigue life was lower. Their explanation for this, probably unexpected, result was the hardened burr, obtained with plasma cutting, where the crack always initiated.

Concerning mechanical surface treatments Schubnell et al. (2020) state, referring to two articles in German (Wohlfahrt et al., 1985; Wohlfahrt, 2000), that work hardening effects on fatigue are more pronounced for metals with a hardness around 200 HV, while for higher grades (approx. 450 HV) the residual stresses are more important. For grades around 700 HV the effect of work hardening is negligible, and the fatigue life improvement can be derived from compressive residual stresses solely (Schubnell et al., 2020).

The possible contribution from plastic work on fatigue properties of punched holes was neglected in the works presented in this thesis. Considering local material strength after punching could possibly increase the accuracy of the fatigue life estimation method. A challenge in this regard is that a hardness increase is generally considered beneficial for fatigue, and the current models reflect that, but for cut edges the opposite has been observed as mentioned above.

2.12 Material considerations

It is important to mention the differences in proportions of time spent in the different phases of fatigue for different metal grades. According to Lara et al. (2013) materials with high ductility has a low propagation rate and high strength materials have faster crack propagation but slower initiation in the base condition. Hence, the initiation phase is relatively more important for high strength materials. Speaking of HCF and highly localized residual stresses, the reduction in fatigue life due to cut edges, as compared to the parent material, is almost entirely expected to origin from a reduction of crack initiation life, whereas the crack propagation life could remain relatively unaffected as illustrated by Hultgren (2024). Hence, the benefit of increased initiation associated with high strength steels could vanish under some circumstances which could contribute to the increased manufacturing process sensitivity of these grades as compared to low strength, high ductile steels. The crack propagation rate could, however, be affected by tensile overloads introducing compressive residual stresses around the crack tip (Manson, 1965).

It is not only the material grade per se that seems to influence the ability of handling stress gradients, such as notches, during fatigue loading. It was shown by Sperle (1985) that the notch sensitivity of different steel grades increases as the yield ratio, defined as the 0.2% yield strength to tensile strength ratio, increases. He states that the reason for this is that a high yield ratio of 0.83 and above (Smith et al., 1963) indicate that cyclic softening will occur, and cyclic hardening is expected for materials with a low yield ratio of 0.71 and below (Smith et al., 1963).

High cycle fatigue testing is often load controlled. For this type of testing the local strains in the critical region can decrease if cyclic hardening occurs, and vice versa when it comes to cyclic softening as illustrated in Fig. 2.6 (Paul, 2025; Zhang, 2013). Cyclic hardening can have a positive effect on HCF life due to, as stated in the review by Paul (2025), an increase of material strength. They also state that the effect on LCF might be the opposite due to a reduction in ductility.

In terms of steel, coatings could provide an additional weakness in terms of fatigue, namely the interface between the coating and the base material. Lara et al. (2013) showed that for polished specimens this interface was the weakest point for fatigue crack initiation.

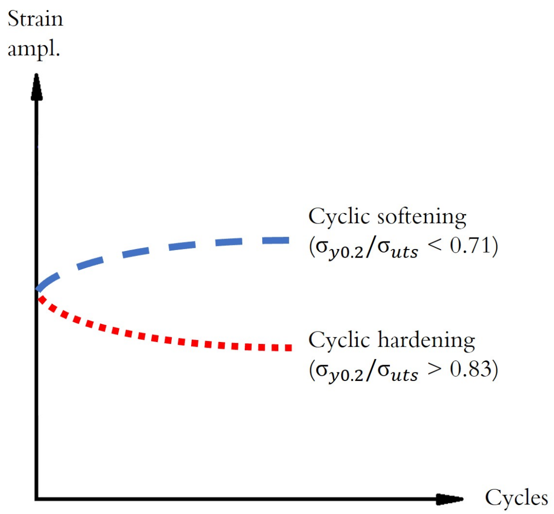


Fig. 2.6. Illustration of cyclic hardening/softening effect on local strain amplitude during load-controlled testing.

2.13 Effect of geometry and elastic stress concentration

Various expressions to estimate elastic stress concentration K_t analytically exist in the literature. One convenient expression for specimens with a hole is (Heywood, 1962)

$$K_t = 2 + \left(1 - \frac{D}{W}\right)^3 \tag{2.3}$$

where D is the diameter of the hole and W is the specimen width. For more complex geometries FEM simulations could be used to calculate K_t. The maximum stress close to the geometrical feature causing the stress concentration is obtained by multiplying K_t to the nominal stress, as calculated by the applied load F divided by the cross-sectional area A as shown in Fig. 2.7. However, this does not mean that the fatigue limit of notched specimens always can be obtained by dividing the fatigue limit of unnotched specimens by K_t as could probably be expected. In fact, the situation is more favorable and the real reduction in fatigue life is often smaller. One explanation for this is that the increased stress is acting on a very limited volume of the specimen (Schijve, 2014). It has been shown that the stress to nucleate cracks in notches is relatively close to the endurance limit σ_e divided by K_t, but for high values of K_t the initiated cracks do not propagate to failure (Frost, 1959), see Fig. 2.8. For higher loads and lower number of cycles, cyclic hardening could probably be a contributing factor to the reduced impact of K_t.

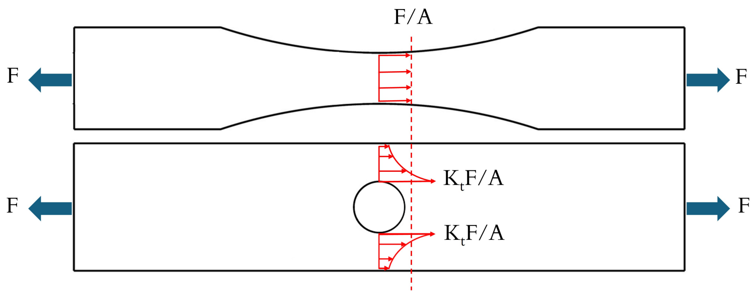


Fig. 2.7. Elastic stress concentration.

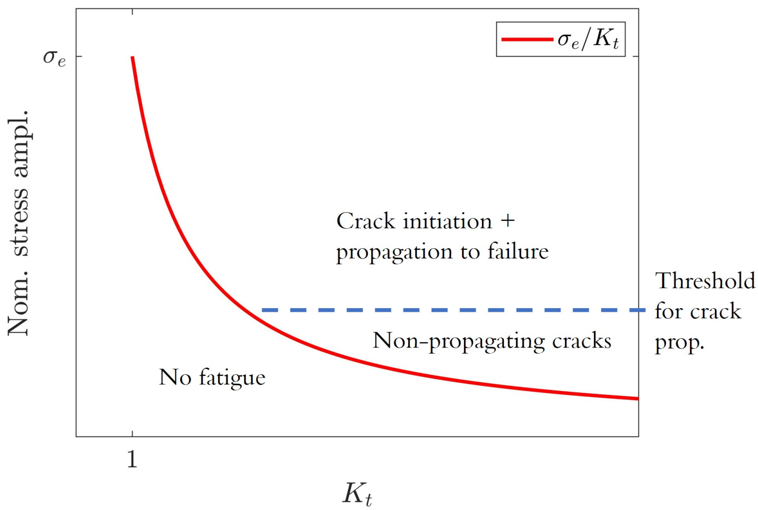


Fig. 2.8. The concept of non-propagating cracks (Frost, 1959).

The reduction in fatigue life due to a notch increases with material strength (Schijve, 2014). One explanation could be that, as mentioned above, the initiation phase gains importance with increased material grade, and that the high peak stress from a notch mainly acts on the surface, where the initiation occurs.

On a more local scale the geometry could play an important role in terms of fatigue performance as well. Not only in terms of surface roughness but also due to small geometrical features, such as for example burr formation in cut edges. Lipiäinen et al. (2021) studied fatigue of high and ultra-high strength steel specimens with cut edges produced by CO_2 laser, fiber laser and plasma cutting. They found that sharp burr formation could decrease fatigue performance drastically. They also found that if crack-like defects were present in the cut edge, these served as the weakest link in terms as fatigue performance when the burr was removed (Lipiäinen et al., 2021).

2.14 Effect of loading condition

A specimen subject to bending could sometimes withstand a higher number of load cycles compared to a specimen in uniaxial loading even if the nominal maximum stresses at the surfaces are equal. This can, at least partly, be explained by concepts of stressed volume and stress gradient (Milella, 2024). The difference is expected to be more pronounced for cylindrical specimens than for flat specimens for geometrical reasons. In flat specimens the difference in fatigue life can be derived almost entirely from the stress gradient produced by the bending load case, which is steeper and produces a smaller stressed volume the thinner the sheet is (Milella, 2024). Given that the fatigue crack initiates at the surface and that the surface stresses and surface area experiencing these stresses are equal, the differences in endurance limit at high cycles should be small. However, for higher loads cyclic plasticity might have an effect which could increase the differences with a clearly higher S-N curve for specimens in bending.

2.15 Overload effects

An overload is a load history irregularity with higher stress than the stresses in an otherwise homogeneous load spectrum. A summary of general statements concerning overload effects on fatigue life is presented in twelve points by Sadananda et al. (1999). The probably most important of these could be summarized as:

(i) Tensile overloads generally extend fatigue life due to an occasionally lower crack growth rate. The opposite applies to compressive overloads.
(ii) The effect depends not only on the magnitude of the overload but also the ”background” load amplitude and mean.
(iii) The effect has only been observed for overloads with peaks around 50% higher than background peaks.
(iv) Since the crack growth rate is affected numerous cycles after the overload, it is complicated to account for multiple over/underloads with overlapping effects.
(v) The effect is dependent on stress state with generally larger effect under plane stress than plane strain. Hence it also depends on specimen thickness with higher expected impact in for example thin sheets.

There is a lack of consensus regarding the mechanisms behind overload effects. The main theories rely on plasticity induced closure or residual compressive stresses ahead of the crack tip, according to Sadananda et al. (1999).

Chapter 3

Modeling of fatigue

Fatigue life prediction of real components and in-service conditions is a complex task. Material properties and constant amplitude fatigue results obtained from specimen testing under controlled conditions is not always applicable to in-service conditions. As described earlier, grain size, grain orientation, crystal structure, environment, defects, load history, geometry, surface conditions and probably much more seems to influence the results. Tu and Zhang (2016) claimed that there is *"no generally accepted quantitative description of the initiation process and consequently it is not possible to perform numerical analysis of the initiation"*. Furthermore, according to Thomas (2017), there is currently no generally accepted method to accurately incorporate the effect of edge defects in fatigue life estimations. Even for a given combination of material, cutting method and process parameters, the relationship between a cut edge *S-N* curve and a smooth edge *S-N* curve could be complicated and using a constant scale factor or offset between the two curves might be inappropriate (Thomas, 2017). The number of different models for fatigue life predictions is huge, see for examples the reviews by Santecchia et al. (2016) and Hectors and Waele (2021), and new models are emerging every year. The lack of consensus is confusing, and this could also be a reason why simple methods like, for example, the Linear Damage Rule (LDR) remain the number one choice for many engineers to handle, in that case, variable load amplitudes. According to Hectors and Waele (2021) an independent comparison of a larger number of the already available models with respect to performance and ease of use is lacking in the literature, making it difficult for product developers to select the most suitable method for their application. This chapter serves as a brief introduction to some of the types of methods available for modeling and prediction of fatigue life. It also presents some of the most established fatigue models derived from the stress-based approach.

3.1 General approaches to fatigue modeling

3.1.1 Stress-based approach

Stress-based empirical approaches to estimate fatigue life and fatigue strength were the first to be developed according to McKelvey et al. (2012), and have undergone continuous improvement over the years. They state that *"the major strengths of this approach include the ability to give both quantitative and qualitative estimates of fatigue life with minimal estimates on stress levels and material properties"*. The use of this methodology is often based around applying reduction factors to a "nominal" or "base" material S-N curve, accounting for notches, surface roughness etc. Practical guidelines have been developed based on this approach, to assist product developers in accounting for fatigue. One example is the FKM-guideline (Haibach, 2003; Rennert et al., 2020). These methods are particularly suitable for HCF where macroscopic plastic strains are missing (Suresh, 1998).

Due to the focus on HCF and the general ease of use, this type of assessment was utilized in the works presented in this thesis.

3.1.2 Strain-based approach

Strain-based fatigue life models could be suitable to assess LCF where macroscopic plastic strains are of importance. They are commonly used industrially (Suresh, 1998). The basis for this approach is found in the works by Coffin (1954) and Manson (1954).

3.1.3 Fracture mechanics-based approach

Fracture mechanics-based approaches could be useful to predict fatigue life in components, conditions or materials where crack propagation is expected to dominate the total fatigue life. This is often the case when initial cracks are present (McKelvey et al., 2012). With increased material grade and decreased stress levels, crack propagation is expected to be of marginal importance. Even for damaged edges, such as cut edges from punching operations, the initiation phase dominates the HCF life. Dehmani et al., 2016 showed that the initiation, before a crack of length 174 µm (smallest detectable crack size) was observed, occupied more than 99 % of the total fatigue life of punched specimens in the HCF region. The studied specimens were thin, about 350 µm, and the estimated average grain size was 100 µm.

3.1.4 Stochastic-based approach

To account for the typical fatigue life scatter, of macroscopically identical samples, a family of life prediction methods that are stochastic and probability-based have been developed (Santecchia et al., 2016). These models make it possible to explore the impact of material discontinuities type and size on fatigue life, and to predict the probability of failure for certain cases.

3.1.5 Energy-based approach

The energy-based approach was developed to handle the different natures of low and high cycle fatigue in one theory. The foundation is that the total strain energy per cycle is divided into an elastic and a plastic part governing crack growth and damage, respectively (Santecchia et al., 2016).

3.1.6 Continuum damage mechanics approach

The continuum damage mechanics (CDM) approach is a phenomenological treatment of fatigue. It rests on the assumption that fatigue damage will be manifested through changes at macroscopic level. These macroscopic properties, for example stiffness, are measurable and hence the models could be calibrated against experimental data. The CDM enables damage accumulation before macroscopic crack formation and coupled with a plasticity model it can account for plastic strain effects which are necessary in low cycle fatigue. The scientific justification of the approach is derived from thermodynamics. (Santecchia et al., 2016)

According to Hectors and Waele (2021) the first to use this approach in a fatigue life context was Chaboche (1974, 1987), who calls CDM *"a complementary tool between Continuum Mechanics and Fracture Mechanics"*. Later the CDM framework, originally developed for creep by Kachanov (1958) and Rabotnov (1970), was extended by Chaboche and Lesne (1988) (Hectors and Waele, 2021).

Oller et al. (2005) extended the work by Chaboche and others described above to enable the consideration of fatigue phenomena within a classical constitutive damage framework (Hectors and Waele, 2021).

3.1.7 Machine learning-based approach

To handle the complexity of in-service fatigue behavior various machine learning-based works have been presented. A review of the current state of the art in this regard is presented by Hamada et al. (2025).

3.2 Stress-based fatigue models

3.2.1 Models to account for mean stresses and residual stresses

During the last century and a half various models have been proposed to translate fatigue test results from one nominal mean stress to another. One of the first models was proposed by Gerber (1874) 37 years after the first study on metal fatigue was published by Albert (1837). It states that for a given stress amplitude σ_{aR} and load ratio R (or mean stress σ_{mR}), the stress amplitude at R = -1, denoted as (σ_{a-1}), yielding the same fatigue life can be estimated by (Gerber, 1874)

$$\sigma_{a-1} = \frac{1}{1 - \left(\frac{\sigma_{mR}}{\sigma_{uts}}\right)^2} \sigma_{aR}, \tag{3.1}$$

where σ_{uts} is the ultimate tensile strength of the material. A more conservative expression was suggested some years later by Goodman (1899), featuring a linear relationship instead of a parabolic such that

$$\sigma_{a-1} = \frac{1}{1 - \left(\frac{\sigma_{mR}}{\sigma_{uts}}\right)} \sigma_{aR}. \tag{3.2}$$

Other commonly used linear relationships are proposed by Soderberg (1930), using the yield stress σ_y instead of σ_{uts}

$$\sigma_{a-1} = \frac{1}{1 - \left(\frac{\sigma_{mR}}{\sigma_y}\right)} \sigma_{aR}, \tag{3.3}$$

and Morrow (1968), where the true fracture strength σ_f is used (Gaia da Silva et al., 2021)

$$\sigma_{a-1} = \frac{1}{1 - \left(\frac{\sigma_{mR}}{\sigma_f}\right)} \sigma_{aR}. \tag{3.4}$$

An elliptical version of the Soderberg criterion is the ASME Elliptic Line, that reads (Barata et al., 2017)

$$\sigma_{a-1} = \frac{1}{\sqrt{1 - \left(\frac{\sigma_{mR}}{\sigma_y}\right)^2}} \sigma_{aR}. \tag{3.5}$$

Around 100 years after the first mean stress correction model was presented, the SWT (Smith et al., 1970) model was presented, which, for positive (tensile) maximum stresses can be written as (Gaia da Silva et al., 2021)

$$\sigma_{a-1} = \left(\frac{2}{1-R}\right)^{0.5} \sigma_{aR}. \tag{3.6}$$

A similar expression was proposed by Walker (1970), featuring a calibration parameter γ instead of a fixed exponent of 0.5, that reads (Gaia da Silva et al., 2021)

$$\sigma_{a-1} = \left(\frac{2}{1-R}\right)^{1-\gamma} \sigma_{aR}, \tag{3.7}$$

where the exponent γ tends to be in the range of 0.4-0.8. Normally the value is increasing for decreased tensile strength, which means a decreased mean stress sensitivity (Dowling et al., 2009).

One benefit with the Gerber, Goodman, SWT and Soderberg expressions is that if the uniaxial tensile properties are known, no further parameter calibration is needed. Of these criteria the oldest, Gerber mean stress correction, is the least conservative and for positive mean stresses, moderate load ratios, and smooth specimens, often the most accurate for various steels. Oh (2022) showed that Gerber performed better than the SWT model, but even better predicting performance could be obtained by calibrating a Walker expression. It was concluded by Nabaki et al. (2023) that the Gerber method had closer experimental correlation than the Goodman and the ASME-elliptical criterion. In the work by Giri and Bhattacharjee (2012) fatigue of DP590 was studied and the Gerber criterion was found to yield better estimations as compared to Goodman for smooth specimens. Drawbacks with the Gerber criterion are that it can yield non-conservative results and is unable to handle compressive mean stresses (Dowling et al., 2009; Ince, 2017).

A slightly more advanced mean stress correction model for normal stresses is presented in the FKM-guideline (McKelvey et al., 2012; Rennert et al., 2020). In this method the (non-welded) component fatigue limit should be scaled by a correction factor $K_{m\sigma}$ that is dependent on the load ratio, material and a so-called overloading case. For one of the overload cases, where the load ratio is assumed to remain constant in the event of an overload, the correction factor is calculated by (Rennert et al., 2020)

$$K_{m\sigma} = \begin{cases} \frac{1}{1-M_\sigma}, & \text{if } \sigma_{mR}/\sigma_{aR} < -1 \\ \frac{1}{1+M_\sigma \sigma_{mR}/\sigma_{aR}}, & \text{if } -1 \leq \sigma_{mR}/\sigma_{aR} \leq 1 \\ \frac{3+M_\sigma}{(1+M_\sigma)(3+M_\sigma \sigma_{mR}/\sigma_{aR})}, & \text{if } 1 < \sigma_{mR}/\sigma_{aR} < 3 \\ \frac{3+M_\sigma}{3(1+M_\sigma)^2}, & \text{if } \sigma_{mR}/\sigma_{aR} \geq 3 \end{cases} \tag{3.8}$$

The described mean stress correction models above are illustrated in Fig. 3.1

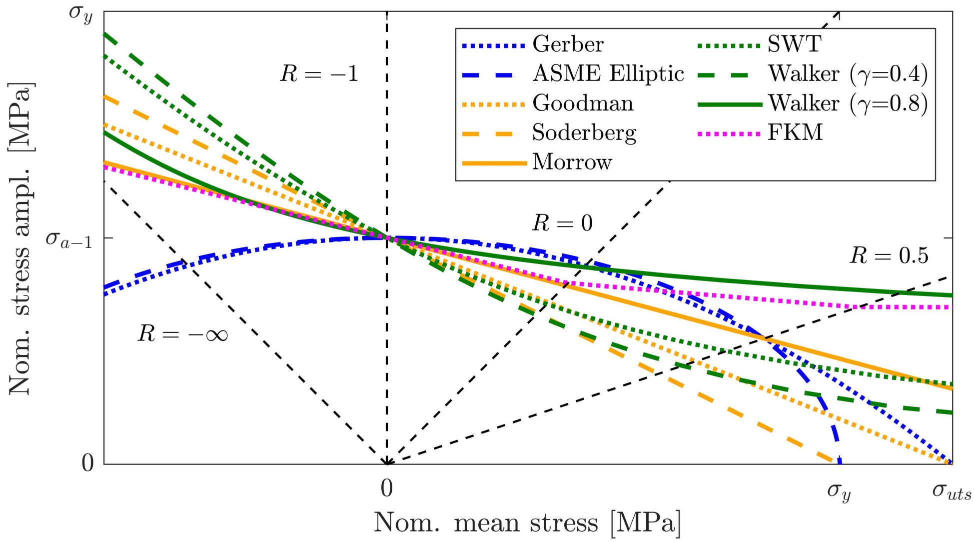


Fig. 3.1. Conceptual illustration of different mean stress correction models.

3.2.2 Models to account for surface roughness and defects

One of the simplest and most established approaches to account for surface roughness effects on fatigue is to apply a scale factor K_r on the fatigue strength of a base material *S*-*N* curve. This factor can be calculated in different ways. Hultgren et al. (2021) proposed an empirical expression, based on fatigue experiments of machined steels from the literature, in the form of

$$K_r = \frac{3}{4} - \frac{1}{4}\tanh\left(2.7\frac{\sigma_{uts}}{\sigma_{uts0}} + \frac{1}{2}\ln\left(\frac{R_a}{R_{a0}}\right) - 0.644\right), \tag{3.9}$$

where two normalizing parameters σ_{uts0} and R_{a0} are used with values of 1500 MPa and 50 µm, respectively, and R_a is the arithmetical mean deviation of the roughness profile.

Novovic et al. (2004) states, based on the work by Taylor and Clancy (1991), that the average maximum surface height R_z could be more suitable for fatigue life predictions than R_a as it has a closer correlation to the worst surface defects. These often serve as initiation sites for fatigue. R_z, as specified in the standard DIN 4768, is calculated by dividing the total measurement length into a number of sampling lengths. Within each sampling length the maximum peak to valley height is identified and the average of these values is calculated giving the R_z value. One expression to calculate a correction factor based on R_z is presented in the FKM-guideline and reads (Rennert et al., 2020)

$$K_r = 1 - a_R \log_{10}(R_z) \log_{10}\left(\frac{2\sigma_{uts}}{\sigma_{uts,min}}\right), \tag{3.10}$$

where a_R and $\sigma_{uts,min}$ are material group dependent parameters that are given for many types of materials in the guideline.

According to Grzesik (2022) a rule of thumb in engineering design is that if R_z has a value below approximately 2 µm the fatigue strength remains unaffected.

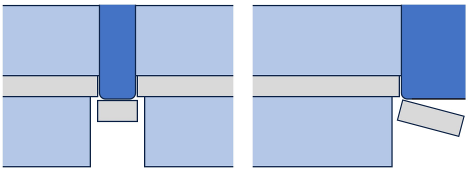
Chapter 4

Forming processes

The focus of this thesis is to evaluate the fatigue life implications from punching, trimming, cold stamping and shot peening. These processes are further described in this chapter. Other important processes for sheet metal forming and manufacturing include laser cutting, water jet cutting, hot stamping and welding, assembly and paint baking. These processes are not discussed in this thesis.

4.1 Punching and trimming

Shear cutting could be divided into punching (closed cut), see Fig. 4.1(a) and trimming (open cut), Fig. 4.1 (b).



(a) (b)

Fig. 4.1. Schematic sketches of (a) punching; (b) trimming.

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Three process parameters, among others, with impact on fatigue life are cutting speed, punch edge radius and cutting clearance. The cutting clearance is defined as the distance between the punch and the die, see Fig. 4.2(a), expressed in percentage of the sheet thickness. It affects both fatigue strength reduction and crack initiation site (Thomas, 2017). To understand how the process parameters are linked to fatigue performance, it is useful to examine their effect on the cut edge in terms of for example surface roughness and residual stresses. These are properties that could affect fatigue life as previously discussed. Hence, the relationship between process parameters and cut edge properties, is briefly discussed in this chapter.

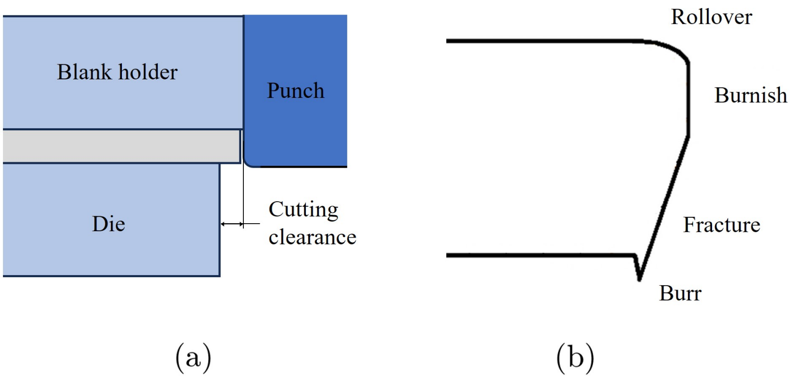

Fig. 4.2. Schematic sketch of (a) cutting clearance; (b) Cut edge zones from punching/trimming (Gustafsson et al., 2023).

Shiozaki et al. (2015) explored the residual stresses at four surfaces of the cut edge profile and found compressive stresses in the shear/burnish zone, see Fig. 4.2(b), and at the lower surface, and tensile stresses at the upper surface and in the fracture zone, as presented in Fig. 4.3.

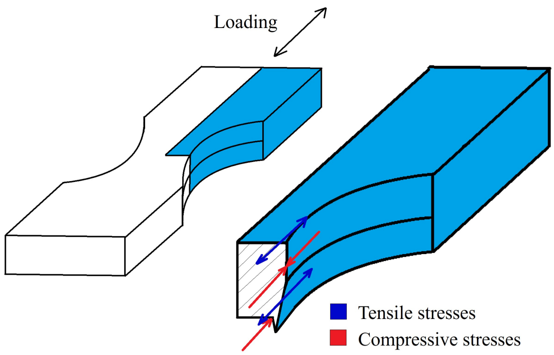

Fig. 4.3. Residual stresses in a cut edge profile (Shiozaki et al., 2015).

Many studies have found that fatigue cracks mostly initiate in the fracture zone, see for example Paetzold et al. (2017), Shiozaki et al. (2015) and Hamada et al. (2018). One contributing factor to this could be the surface roughness. Thum et al. (2021) showed that the surface roughness in the fracture zone was an order of magnitude higher than in the shear zone in a cut edge profile of aluminum. An example of a cut edge profilometry of CP800, see Fig. 4.4, clearly illustrates the difference in surface appearance between the shear and fracture zone.

Fig. 4.4. Profilometry of a trimmed cut edge of CP800. The upper part of the surface represents the shear zone and the lower part the fracture zone.

Only considering the surface roughness is not enough to qualitatively judge about the process effect on fatigue performance. Stahl et al. (2020) found that two stage cutting with higher surface roughness than one-stage still outperformed the one-stage in terms of fatigue life. The cut edge profile was different between the two methods with a significantly larger (around 2.7 times) fracture zone for one stage cutting.

4.1.1 Effect of cutting clearance

The cutting clearance highly affects the resulting cut edge. In turn, these effects on the cut edge will affect the fatigue properties of the component.

Gustafsson et al. (2016) showed that both the maximum shear force in shear cutting, and the shear zone height tend to increase with decreased cutting clearance. The study was conducted on thick steel sheets (around 5-6 mm thickness) of three different grades with yield stresses ranging from 210-1080 MPa. These trends have also been observed for thinner aluminum sheets (Tekiner et al., 2006), and for DP980 of thicknesses 1.2-2 mm (Choi et al., 2014), but concerning the height of the burnish zone, the study of Choi et al. (2014) found an increase with increased cutting clearance. Their explanation for this was that the strength of the material was of a significantly higher level than the hydrostatic pressure during forming. Hence, they claim, the occurrence of higher hydro-static pressure associated with small cutting clearances was insufficient to provide increased ductility, which would have resulted in larger burnish zone.

Maronne et al. (2003b) showed that the fatigue strength reduction for a certain steel sheet was constant below a cutting clearance of 10%. Above 10% the reduction increased drastically. They also showed that the fatigue crack initiation site depends on the clearance. For clearances between 5% and 10% the crack initiated in the fracture zone while for higher clearances it could still be said to initiate in the fracture zone but closer to the burr (Thomas, 2017). In no case did the crack initiate in the rollover or shear zone.

In another study Maronne et al. (2003a) showed that a critical cutting clearance could be defined for steel sheets of different grades and that this critical value decreased with increased ultimate tensile strength. In their work the reduction of critical clearance seems to flatten out at a level between 15% and 20% for steels with ultimate strength around 600 MPa. However, the study did not include grades higher than that. Below the critical clearance the fatigue strength reduction was approximately constant. In the same study they also showed that for a certain configuration the relative fatigue strength reduction increased almost linearly with material grade, from around 4% for a steel with a yield stress of 200 MPa up to 10% for a steel with a yield stress of 400 MPa.

Stahl et al. (2020) studied shear cutting of 8 mm S500MC steel sheets and found that for one stage cutting, cutting clearances of 10% or below was necessary to avoid delamination in the cut edge. The punch in their study had a roof-top shape.

In the study by Shiozaki et al. (2015), higher tensile residual stresses were found in the fracture zone using a clearance of 10% as compared to 25%. The residual stress measurement technique used was X-ray diffraction, with a measurement area of 1 mm in diameter, meaning that a major part of the fracture zone height, especially using 25% clearance, was included in the measurement and local variations in the zone could not be resolved.

In the study by Kaijalainen et al. (2017) the surface roughness in the fracture zone of shear cut high strength steels was studied for four different cutting clearances. It was found that the roughness increased when the cutting clearance was changed from 3.3% to 10% cutting clearance. Then the roughness decreased as the clearance was further increased to 13.3%. The highest roughness was found for 20% cutting clearance. The measurements presented by Thomas et al. (2011) indicate a decreasing trend in surface roughness as the cutting clearance is increased from 6.6% to 13.2%. Interestingly, the higher-grade steel in the study (DP600) had higher roughness at low cutting clearance as compared to the lower-grade steel (S355MC), but at high cutting clearance the opposite applied (Thomas et al., 2011).

4.1.2 Effect of tool edge radius and tool wear

Müller et al. (2021) studied fine-blanking of 6 mm thick S355MC steel sheets. They found that, with a cutting clearance of 0.5%, a decreased die edge radius led to lower surface roughness. Important to note is that cutting clearances of this magnitude results in a shear zone height of around 99% of the total cut edge height. The studied radius was between 50 µm and 200 µm and the measured roughness spanned from R_a = 1.36 µm, for the smallest radius, to 1.77 µm, for the largest.

Paetzold et al. (2017) compared a number of different cutting parameters for trimming of a dual phase steel (DP800). They found that for a given cutting clearance, in this case 15%, the effect of tool wear (tool radius 300 µm as compared to 10 µm) on the fatigue strength at 10^5 cycles, was a reduction of around 4-5%. The fatigue tests were conducted at R = -1. The corresponding R_z roughness in the fracture zone was increased from 11 µm to 15 µm when the tool radius was increased.

4.1.3 Effect of cutting speed

In a study of the shear surface obtained from punching of mild steel, Kanca et al. (2016) found that in both the fracture zone and the burnish zone, the surface roughness decreased with increased cutting speed. The studied cutting clearance interval was limited to 4.5-6%. The same trend was observed by Winter et al. (2025) for 5754 aluminum. The influence of different cutting speeds was not studied in the work presented in this thesis.

4.1.4 Effect of steel grade

The results by Shiozaki et al. (2015) shows that the magnitude of the residual stresses from cutting seems to increase with the material grade, see Fig. 4.5.

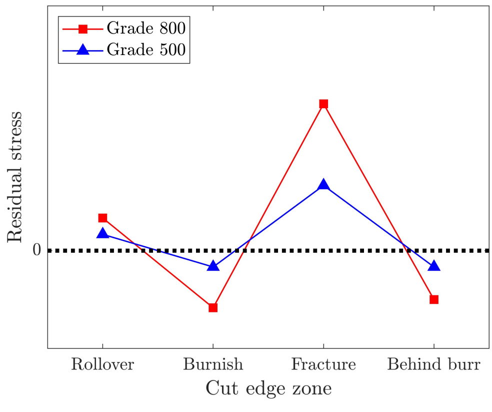

Fig. 4.5. Residual stresses from punching in cut edges of two different high strength steel grades. Conceptual illustration based on the results presented by Shiozaki et al. (2015).

The negative effect on fatigue life from shear cut edges, as compared to for example laser cut edges, is especially highlighted in high-strength steels as shown by Meurling et al. (2001).

In the review by (Thomas, 2017) it is stated that high strength steels produce rougher edges than low strength steels. However, recent studies only including high strength steels show a decreasing trend in surface roughness in the fracture zone as the yield stress increases (Gustafsson et al., 2024, 2025; Heshmati et al., 2025). Even though a higher-grade steel might result in a lower roughness it is important to note that the sensitivity to the roughness increases as the material grade increases according to Eq. 3.10.

4.2 Cold stamping

Analogous to punching and trimming, other forming operations could impact on the fatigue life of a component. Cold stamping is a common process used to produce, for example, chassis components for the automotive industry. With this process sheet metal is pressed to a new shape inside a die. In contrast to hot stamping the sheet is not heated before forming. This forming process induces thickness variations, plastic deformation and residual stresses to the component (Facchinetti et al., 2009; Kašpar et al., 2023; Meng et al., 2013; Shang et al., 2016).

4.3 Shot peening and blasting

One reason for the possible positive effect of surface treatments on fatigue life could be a transition from surface to sub-surface crack initiation according to Tu and Zhang (2016). They claim that the underlying reason for this is not fully understood but that the residual compressive stresses on the surface after, for example, shot peening have an effect. According to González et al. (2017) the shot peening process could also have a large effect on the micro-structure, especially in the surface layer. This modification consists mainly of a grain size reduction. As mentioned earlier smaller grains could shift the crack initiation from the surface to sub-surface inclusions. Apart from this, surface work hardening and modified surface roughness are mentioned as effects from shot peening that could influence the fatigue life (González et al., 2017). As discussed in Section 2.11 the hardening could also contribute negatively.

In the case of shot peening two important process parameters are surface coverage and Almen intensity. Depending on how these are selected conventional (CSP) or severe shot peening (SSP) could be obtained. The idea behind using SSP to improve fatigue properties is that it leads to refinement of grains and a thicker surface layer with compressive residual stresses. The backside is that SSP could result in higher surface roughness which in some cases could cancel out the benefits so that no improvement for SSP as compared to CSP can be observed. The negative effect could be larger in softer, high ductility materials such as aluminum as compared to steel. (González et al., 2017, Bagherifard and Guagliano, 2012)

The effect of shot blasting on trimmed edges seems to be largest for low stresses and high number of cycles (Parareda et al., 2018). One explanation to this could be that in high cycle fatigue the initiation phase dominates the fatigue life and that it is mainly the initiation that is affected by abrasive processes such as shot blasting. Another explanation could be that higher cyclic loads results in more relaxation of residual stresses. Parareda et al. (2018) also show that the positive effect seems to increase with increased material grade.

Chapter 5

Modeling of punching and trimming

Modeling of shear cutting operations and cold forming are obviously research fields of its own and a lot could be written about it. The focus of the author's research work is metal fatigue and the effect of manufacturing on fatigue properties, but this also includes estimation of manufacturing effects on the cut edge properties, which in turn requires a basic understanding of cutting simulations. This chapter briefly describes the main approaches for simulation of punching and trimming, i.e. finite element-based methods and particle-based methods.

5.1 Finite element-based methods

In his master's thesis, Söderberg (2006) showed that the punching process of a wide range of metals could be simulated using explicit time integration and 2D axisymmetric models with "acceptable accuracy". He showed that a slightly higher failure strain of 3.5 was adequate for softer materials (DC04 and DC350YP) as compared to 3 for high strength steels (DC800DP and DC1400M). The mesh density he found adequate was 128 elements through the thickness. The studied steel sheets had thicknesses of around 1 mm. For most of the materials he used an isotropic von Mises material model. He found that a balanced penalty contact was necessary between the outer surface of the blank and the punch/die to avoid penetrations. The clamping force he used was 10 kN and a friction coefficient of 0.2 was used in the contacts (Coulomb friction model). The punch velocity was 70 mm/s.

A similar approach was used by Soares et al. (2013) but with a slightly lower friction coefficient of 0.1. They used a power law to extrapolate the tensile test data for the isotropic hardening von Mises material model. A ductile damage initiation criterion was utilized for the onset of damage using a monotonically increasing parameter ω_D. The incremental growth of ω_D is given by

$$\Delta\omega_D = \frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}} \geq 0 \tag{5.1}$$

where $\Delta\bar{\varepsilon}^{pl}$ is the incremental equivalent plastic strain and $\bar{\varepsilon}_D^{pl}$ is the equivalent plastic strain for onset of damage. This parameter is dependent on the stress triaxiality and the strain rate. When ω_D reaches 1 the damage is initiated.

Gutknecht et al. (2015) simulated punching of 1 mm DP600 sheets using an enhanced Lemaitre damage model considering the effects of low triaxiality. They used axisymmetric elements with a mesh density of 100-200 elements over the thickness in the zone of interest. The contact was of penalty type with a friction coefficient of 0.1. The punch, die and blankholder were modeled as rigid bodies. An Arbitrary-Lagrange-Euler (ALE) mesh formulation was used for the blank. In another paper Gutknecht et al. (2016) extended the approach to open cuts, i. e. trimming. In this case they used 2D plain strain elements instead of axisymmetric. A kinematic node-to-surface contact was used with a friction coefficient of 0.3. They also presented a method for separation of the different cut edge phases (roll over, shear, fracture and burr) based on the stress triaxiality ahead of the crack. Even though, as briefly mentioned earlier, they found that the simulated triaxiality ahead of the crack was more constant for open cuts than for closed cuts with values between 0 and 0.33, they still saw that the material model had to account for negative values of triaxiality differently than the positive values in order to reproduce the experimentally obtained crack path.

5.2 Particle-based methods

Particle methods, such as Smoothed Particle Galerkin (SPG), has successfully been used to simulate the punching process in 3D, see for example Jonsén et al. (2019). Another particle based method that has been implemented to simulate cutting in 2D, is the Particle Finite Element Method (PFEM) (Cremonesi et al., 2020; Oñate et al., 2014; Rodríguez et al., 2017). Recent studies using PFEM for simulation of punching and trimming shows promising results, overcoming the challenges of element distortion or loss of accuracy during remeshing associated with FEM simulations of this kind of processes. It has been shown that PFEM could provide a stable and robust simulation solution with good possibilities to predict the crack path (Sandin et al., 2025a,b, 2024).

Chapter 6

Experimental methods

In this chapter follows a summary of the most relevant experimental methods for this thesis.

6.1 Fatigue testing methods

6.1.1 Testing to obtain *S-N* curves

The traditional method to obtain the finite life part of an *S-N* curve for a material/configuration is to test five different stress levels, usually using around 3 specimens at each level (Gope, 2002). Sometimes more accurate results can be obtained by using a larger part of the available samples at lower stress levels where failures not always occur and the scatter of the results is larger (Pinto et al., 2002).

Traditional fatigue testing is usually conducted according to standards, for example DIN50100, ASTM E466-15, ISO1099 and DIN EN 6072. The finite life part of the *S-N* curve can be expressed mathematically by for example the Basquin model (Murakami et al., 2021)

$$\sigma = C_1 N^{C_2} \tag{6.1}$$

where C_1 and C_2 are fitting parameters.

6.1.2 The staircase method to estimate fatigue limit

The staircase method is used to find the stress tolerance at a given fatigue life, for example the endurance limit at 2 million cycles, and to evaluate the statistical properties of the obtained tolerance following a simple procedure (Lin et al., 2001). The method evolves from an initial assumption/guess of the endurance stress for any given fatigue life of interest. The first test is then performed at this stress level. If the sample fails, the stress is decreased for the next test and if it withstands the test the stress is increased.

Usually at least 15 specimens are used. The test results might look like presented in Fig. 6.1.

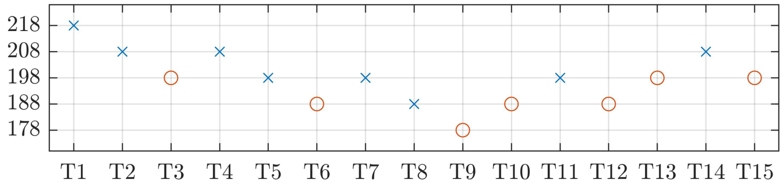

Fig. 6.1. Example of staircase test results. The circles represent runouts.

According to Lin et al. (2001), two methods that could be used to utilize the statistical evaluation are the Dixon and Mood (DM) method and the Zhang and Kececiogluy (ZK) method. They also state that the ZK method, as opposed to DM, does not require:

(i) Normal distribution of the fatigue limit
(ii) Fixed stress increments
(iii) Increments smaller than two standard deviations

The DM method, on the other hand requires no estimations of the statistical parameters and everything is calculated from formulas using the test data, see procedure described in for example Dixon and Mood (1948) or Lin et al. (2001). In the study of Lin et al. (2001), a comparison between different methods was made based on a proposed simulation method. They concluded that, for that configuration, DM performed better than ZK. The DM procedure is as follows:

1. Determine if failures or runouts is the least frequent event considering the whole testing series. For each stress level S_i, find the number of occurrences of this event n_i. The index i is 0 for the lowest stress level and increasing up to the highest stress level.
2. Calculate the parameter A according to

$$A = \sum in_i \tag{6.2}$$

3. Estimate the mean fatigue limit stress $\overline{\sigma}_e$ by using Eq. 6.3, where $\triangle S$ is the fixed stress increment. The plus sign is used in the expression if runout tests occur less frequently than failure tests.

$$\overline{\sigma}_e = S_0 + \triangle S \left(\frac{A}{\sum n_i} \pm \frac{1}{2} \right) \tag{6.3}$$

For calculation of the standard deviation, see Dixon and Mood (1948) or Lin et al. (2001).

6.2 Measurement of residual stresses

Measurement of residual stresses can be divided into indirect and direct methods. Both types are utilized in the papers presented in this thesis. In direct methods deformations are measured after a disturbance of the equilibrium in the component to be measured (Brinksmeier et al., 1982). This can be done by for example micro milling of the surface. The direct measurements can be done without disturbing the stress equilibrium. Even speaking of direct measurements, the stress is obviously not measured directly. Instead, for example strain or deflection can be measured and recalculated to stress.

6.2.1 X-ray diffraction

X-ray diffraction is a direct measurement method and one of the most commonly utilized residual stress measurement techniques. It is based on the fact that there is a relation between the wave length of the x-rays, the distance between the atoms in the surface to be measured, and the diffraction angle.

One factor influencing the measurements at surfaces of polycrystalline materials, such as the materials studied in this work, is the grain orientation relative to the surface (Brinksmeier et al., 1982). This could provide challenges in the measurement of a punched cut edge where the grains exhibit a severe deformation, so that the grains become more aligned with the punching direction (Sandin et al., 2025b; Winter et al., 2025). Another challenge is the measurement volume, especially for thin sheets, which might be insufficient for capturing the local variations due to the high stress gradients, both in radial direction and in the punching direction.

In this thesis, X-ray diffraction was used to measure the surface residual stresses in the cold stamped specimens in Paper D.

6.2.2 Neutron diffraction

Another method that has been used for measurement of residual stresses in cut edges, for example by Heshmati et al. (2025), is neutron diffraction. It is based on the same principles as X-ray diffraction. However, the nature of neutrons enables a considerably deeper measurement depth as compared to X-rays (Schajer et al., 2022). The neutrons have to be produced within minutes before the measurements due to the short half-life of free neutrons, using a nuclear reactor or a spallation source (Vogel et al., 2013). Hence, neutron diffraction is a method with limited accessibility.

6.2.3 Focused Ion-Beam Digital Image Correlation

An indirect residual stress measurement method with high potential in measuring local residual stresses in cut edges is Focused Ion-Beam Digital Image Correlation (FIB-DIC). The measurement volume can be measured in micrometers. With this method a groove is milled into the material in steps using a focused ion beam. Between each step the displacements on the surface are measured using DIC and recalculated through strains to stresses. A detailed description of the method can be found in Lord et al. (2018).

This measurement method was used on small scale in Paper A to validate the residual stresses obtained from cutting simulations. A more comprehensive study using the method on cut edges has been published recently (Ortiz-Membrado et al., 2025). This study confirms to a large extent the simulation results presented for moderate cutting clearances in Paper B, even if it seems like the magnitude of the compressive residual stresses in the burnish zone are somewhat underestimated by the simulation. However, in the simulations, the residual stress pattern obtained using 17% cutting clearance was qualitatively similar to that with 8.6%, whereas the measurements presented in (Ortiz-Membrado et al., 2025) showed a clear difference between the two clearances. The magnitudes of the standard deviations reveal, however, that there is still challenges of using this method for validation of the residual stress in the cut edge, meaning that the punching simulation results cannot yet be fully evaluated.

Chapter 7

Summary of appended papers

7.1 Paper A

Summary: Usage of residual stresses in a fatigue life estimation model requires that these stresses can be obtained in a convenient manner. Measuring local residual stresses is sometimes a complex task and so is also simulation of metal shear cutting. This work presents a simplified methodology for simulation of shear cutting where it is possible to calibrate all parameters using only two types of experiments for each material. One for calibration of the plastic flow model and one for calibration of the failure model. For the failure model there is only one calibration parameter. It is shown that this is possible because of the Lode angle parameter being close to zero in the failure region for a wide range of different cutting setups. The effect of mesh regularization in this context, and remeshing compared to non-remeshing, are also discussed. The method is verified by simulation of different setups showing that it is possible to reproduce force-displacement response obtained experimentally after calibration of the failure model. Validation is made by comparing residual stress measurement, nano-indentation measurements and measured cut edge morphology to simulation results.
Relation to thesis: In this work research question (i) is answered. It is shown that using a methodology, requiring a small amount of experimental effort as compared to, for example, classic failure model calibration, it is possible to reproduce complex forming results. This is done using commercially available software and does not require in-house FEM coding. The usability of the results in a fatigue context is explored in the following papers.
Author contribution: D. Gustafsson conceptualized the research idea and developed the methodology together with E. Olsson. D. Gustafsson conducted the numerical investigation and used the experimental results for verification and validation. D. Gustafsson was the principal author of the paper while Laia Ortiz-Membrado was responsible for the experimental part concerning FIB-DIC and nanoindentation, and Sergi Parareda for the specimen production and cut edge morphology measurements.

7.2 Paper B

Summary: In Paper B an empirical stress-based methodology for how residual stresses could be used, together with consideration of geometrical notch effects and surface roughness effects, to estimate HCF life of high strength metal specimens is presented. The residual stresses are obtained from shear cutting simulations according to the methodology provided in Paper A. These residual stresses are treated as mean stresses using the Gerber parabola correction factor. The difference as compared to conventional mean stress correction is that the stresses are allowed to relax according to a stress relaxation criterion, meaning that the effect of tensile residual stresses decreases as the nominal stress increases. Surface roughness is accounted for by applying the reduction factor proposed in the FKM-guideline and the elastic stress concentration factor is taken directly as a fatigue reduction factor. Exponents are added to both these latter factors to decrease their impact as the nominal stress amplitude increases. It is shown that for most of the tests in the regime above 10^4 cycles, the fatigue lives could be estimated within an error factor of three for two different steels and one aluminum alloy.
Relation to thesis: This work contributes to answering research question (ii) in this thesis. A phenomenological engineering approach is presented for how manufacturing effects, estimated from simulations of punching and trimming, can be used for fatigue life estimations of uniaxially loaded specimens.
Author contribution: D. Gustafsson conceptualized the research idea together with E. Olsson. D. Gustafsson developed the methodology, conducted the fatigue tests of the shear cut specimens and used them for validation of the results. D. Gustafsson was the principal author of the paper. Sergi Parareda was responsible for specimen production of shear cut specimens and cut edge morphology measurements. Rémi Munier was responsible for fatigue testing of the polished edge specimens.

7.3 Paper C

Summary: The results presented in Paper B assumed that the fatigue initiation site always is in the region of the fracture zone where the tensile residual stresses and the surface roughness are the highest and where the elastic stress concentration from for example the hole reaches its maximum. For uniaxially loaded specimens such an assumption is likely valid if no significant irregularities such as burr or secondary burnish formations are present. However, for chassis components, out-of-plane bending is often a more critical in-service load case. In such conditions the assumptions do not apply. In Paper C the methodology from Paper B was extended to handle out-of-plane bending which requires, inter alia, the implementation of a compressive residual stress relaxation criterion and to study the expected fatigue life at all possible initiation sites along the cut edge.
Relation to thesis: This work contributes to answering research question (ii) in this thesis. The applicability of the reduced fatigue life estimation approach is extended to a load case that is more relevant for chassis components.

Author contribution: D. Gustafsson conceptualized the research idea, developed the methodology and used experimental results for validation of the procedure. D. Gustafsson was the principal author of the paper. Sergi Parareda was responsible for fatigue testing, microstructure imaging, and SEM crack stage imaging.

7.4 Paper D

Summary: Paper A-C explores simulation of shear cutting, the effect of shear cutting on fatigue life, and how to estimate it. But other forming processes are of equal importance in manufacturing of chassis components such as wheels and cross members. One of these processes is cold stamping which can introduce tensile residual stresses to some of the formed regions. In Paper D a lab-scale steel specimen specifically designed to reproduce a component-like load condition in a steel wheel is studied. It is explored whether the proposed methodology from A and B is applicable also for this forming process. In addition, the effect of a common post-forming operation, shot peening, is studied and estimated. It is also shown that relatively simple stamping simulations are sufficient to obtain the information needed for fatigue life estimations of stamped specimens.
Relation to thesis: This work contributes to answering research question (i) and (ii) in this thesis. The applicability of the reduced fatigue life estimation approach is extended to include other forming processes introducing tensile residual stresses, which can be obtained by forming simulations.
Author contribution: D. Gustafsson conceptualized the research idea together with E. Olsson. D. Gustafsson developed the methodology and used experimental results for validation of the procedure. D. Gustafsson was the principal author of the paper. Davide Ronco and Giorgio Gallio provided fatigue test results and ordered residual stress measurements.

Chapter 8

Discussion and conclusions

The main dilemma in product weight optimization considering fatigue can be summarized by Gassner's conclusions stated in the review by Schütz (1996):

"If the higher static strength of the new alloy is taken advantage of, a shorter fatigue life will result, because it only makes sense to use the higher-strength and more expensive material if higher allowable stresses are employed, and that results in a shorter fatigue life."

This is particularly true when manufacturing effects are present. Hence, it is of crucial importance to learn how to predict these effects on fatigue. By knowing that, improvements based on the simulation results could be made which would provide the possibility to reduce weight, cost and emissions in the automotive industry. A prerequisite for an accurate prediction of these effects is, according to the author, to have a basic knowledge of how manufacturing process parameters affect the cut edge, and how the cut edge properties, in turn, affect fatigue performance. Paper A and B in conjunction, presents a contribution towards adequate quantification of these effects.

The phenomenon of fatigue is complex. Modeling this on a physical basis for a full automotive component would be extremely challenging. Micro-structure, grain orientation, dislocations, slip, surface roughness etc. would be necessary to incorporate in such a model. However, simplicity, in the sense that a model is easy to implement and understand, seems to be one of the key ingredients for successful methods. An example of this is that the Palmgren-Miner method for damage accumulation, originating from 1924, still seems to be popular among engineers despite its well-known limitations and the fact that it often results in non-conservative predictions (Hectors and Waele, 2021). Considering this, a simplified approach to obtain residual stresses, see paper A, and use them to estimate fatigue life, see paper B, requiring a minimum of experimental effort, was developed and evaluated. In paper C and D it was demonstrated that the method could be extended to another load case and for processes and conditions where compressive residual stresses influence the results.

Depending on the intended use of the results higher accuracy and more stable simulations might be necessary. The failure modeling used in Paper A is not a crack propagation model and the crack path is dependent on mesh size and orientation to some extent, and sometimes unstable. This means that for brittle materials, where the crack path is more unpredictable such as the studied aluminum alloy, it might be hard to reproduce the experimental results. However, in a fatigue life estimation context, the obtained results from FEM simulations with remeshing seem to be sufficient for many conditions.

Chapter 9

Outlook

A natural step forward to increase the accuracy of and reliability of the shear cutting simulations, would, according to the author, be to use the developed calibration approach in conjunction with PFEM simulations which are more stable and robust. This could be necessary to enable a more detailed study of, for example, the effect of different process parameters.

So far, the research has been focused on relatively small specimens and limited to constant amplitude loading. An upscale of the approach to real automotive and HDV components, and a possibility to handle more service-like load spectra, would enhance the usefulness for the industry. One of the challenges to face in this regard is how to determine the nominal stresses. It might turn out that on component level more advanced methods, such as for example the 4R method, are more relevant to consider. However, such methods require additional work, as stated by Lipiäinen et al. (2022). The local material properties and cyclic hardening must, for example, be considered. If the theory of critical distances is used for obtaining local stresses, a suitable stress averaging distance must be determined (Lipiäinen et al., 2024).

Focus material-wise in this thesis has been hot-rolled steel even if a cold rolled aluminum alloy was included in Paper B. Further studies of aluminum alloys and cold rolled steels with higher anisotropy are necessary to confirm the estimation framework applicability.

In terms of fatigue life enhancement, it would be valuable to study other processes than shot peening, for example pre-straining and annealing, and how the effect of these can be estimated.

To increase the usability and robustness of the fatigue life estimation method approach, a clear definition of what can be considered a "base material S-N" curve is needed. The surface condition in as-rolled sheets can presumably vary a lot depending on the processes involved in production, such as pickling. It would be desirable to specify for example a surface roughness and residual stress level range in the as rolled surface that is acceptable for usage of the estimation approach.

The post-punching microstructural effect on fatigue of cut edges is still somewhat unclear. In the near future a study together with partners to examine this will be initiated. The idea is to use punching simulations to provide a residual stress field that can be used as boundary condition in crystal plasticity modeling where the microstructure during cyclic loading is studied.

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