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Development of a systematic evaluation of failures in wrought material in deep drawing processes as well as the prevention of them in final products

Masterthesis

for acquirement of the academic title

M.Sc./ Dipl-.Ing.

Technische Universität Graz

Mechanical Engineering and Economy

Field: Production Science and Management

Institute of Materials Science, Joining and Forming

Research Group Tools & Forming

Member of [FSI]

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Graz, 17.10.2017

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Abstract

The automotive supplier Magna Fuel Systems GmbH specializes in producing fuel pipes, filler sockets, filler caps and fuel tanks. The subsidiary in Weiz produces among other things, high-precision filler sockets, which are deep drawn in a fifteen step forming process via a multi station press. The sheet metal used in this process is bought from a supplier and already includes faults. These faults cause several issues that include an average scrap of around 3% and increased labor costs due to the sorting of defective parts. The aim of this thesis is to specify the fault in the raw material, find an accurate non-destructive measurement system and implement the chosen system for detecting faults in the raw material before the formative process. To reach these goals, an investigation of state of the art, regarding sheet metal production and established non-destructive testing methods, is done. Afterwards all fault causing factors are examined and all detected fault types visualized. The results of the executed tests, evaluating the found non-destructive testing applications, are presented. Conclusive a recommendation for the best testing assemble as well as a possible implementation strategy is given.

Kurzfassung

Der Automobilzulieferer Magna Fuel Systems GmbH ist auf die Produktion von Tankstutzen, Tankdeckel und Tanksysteme spezialisiert. Die Zweigstelle in Weiz produziert unter anderem hoch präzise Einfüllstutzen, welche in einem 15 schrittigen Tiefziehprozess hergestellt werden. Das verwendete Blech wird bereits fehlerhaft angeliefert. Die enthaltenen Fehler führen zu hohem Ausschuss und das aussortieren fehlerhafter Teile zu erhöhten Personalkosten. Das Ziel dieser Arbeit ist die Spezifikation der Fehler im Rohmaterial, die Findung eines adäquaten, zerstörungsfreien Prüfsystems sowie die Konzeptionierung einer möglichen Implementierung dieses Prüfsystems in den bestehen Prozess. Um dieses Ziel umzusetzen bedarf es einer Literaturrecherche, sowohl über die Blechherstellung als auch über bestehende zerstörungsfreie Prüfverfahren. Anschließend werden alle Fehlerquellen, die mögliche Ursachen für Ausfälle sind, aufgetan und visualisiert. Weiter werden die Ergebnisse der durchgeführten Tests, betreffend der Evaluierung der in Frage kommenden Testverfahren, aufgezeigt. Abschließend wird eine Empfehlung des besten Verfahrens, sowie dessen Implementierung vorgestellt.

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List of abbreviations

α	thermal diffusivity	$m^2/_s$
δ	standard penetration depth	m
λ	wavelength	m
μ	permeability	$H/_m$
ρ	density	$kg/_{m^3}$
σ	conductivity	Ωm
τ	limit of observation time	s
ϕ	magnetic flux	Wb
ω	frequency	Hz
c	speed of light	$2{,}998 * 10^8\ m/_s$
c_p	specific heat capacity	$J/_{kg\ K}$
k	thermal conductivity	$W/_{m\ K}$
ASIS	Automation Surface Inspection System	
DDQ	Deep Drawing Quality	
TOF	Time Of Flight	

1. Introduction

The automotive supplier Magna Fuel Systems GmbH specializes in producing fuel pipes, filler sockets, filler caps and fuel tanks. The filler caps have an extraordinary accuracy of fit and the tanks captivate through a high grade of innovation. The company profits from more than 75 years of experience.

The subsidiary in Weiz produces among other things high-precision filler sockets. These sockets are deep drawn in a fifteen step forming process via a multi station press. The sheet metal used, is bought from a supplier and already includes faults such as doublings, pipes, scratches and impurities. These faults cause several issues and have to be fixed to increase production efficiency and reduce labor costs.

The most common occurring fault in the final filler socket is formed as a u-curve which often bursts along its contours (see Figure 1). This kind of fault causes around 3% scrap in average, but depending on the suppliers´ quality up to 10% over a shorter period of time which is attributable to a higher percentage of recycled material at the sheet metal production.

Figure 1: u-curve fault pattern

1.1. Aim of the thesis

Currently the fault is recognized after the deep drawing process by optical inspection of the final socket by employees. This leads to high labor costs and an increased potential for defective end products, which is unacceptable due to the company´s zero defect philosophy for its customers.
Changing the supplier respectively increasing the quality of the raw material is not possible due to the fact that the supplied amount is too low for a good position in negotiating.
The only possibility to fix the issue and reach the goals is to specify the fault in the raw material, find an accurate non-destructive measurement system and implement the chosen system for detecting faults in the raw material before the formative process. This system must work in-line, ideally without disturbing the established process in terms of throughput time.
The objective of the master thesis is the investigation and evaluation of a measurement system, which can also be a combination of different non-destructive testing methods, to detect defective sections of the sheet metal. Furthermore the found system should be implemented in the established process.

1.2. Structure of the thesis

To understand the issues and the development of the outage causing faults, an investigation of the production of sheet metals is essential. The production process is the origin of all faults in the raw material, so a detailed study on the theoretical background will help to determine the underlying cause. After casting a glance on the sheet metal production, it has to be observed which technologies are suitable in finding faults in the produced sheet. For this reason a short overview on the common used non-destructive testing methods is given. This overview includes eddy current testing, industrial radiography, thermographic inspection, ultrasonic testing and optical inspection. Additionally a short prospect on future applications of steel producers on quality tracking is given. At the end of chapter 2 the used material is introduced.
Towards looking on the theoretical background of sheet metal production and common non-destructive testing methods, a short overview of failure causing factors on the final part is given and visualized in an Ishikawa diagram. Possible

error sources could be the forming process, the staff, transportation and stocking and the raw material. Additional to that, the process chain is introduced which includes an overview about the material flow from the raw material to the formed part and a more detailed view on the forming process itself. At the end of chapter 3, a brief overview on the caused costs is given.

Detected faults can occur on the materials´ surface like scratches, deformations, discolorations and contaminations, as well as in the material like inclusions, segregations and doublings. In chapter 4 these faults are presented and discussed

To specify the actual outage causing fault which leads to the burst u-curve fault pattern and with that to the greatest portion of scrap, a systematic for determining this specific fault is given in chapter 5. This goes from discussing the theoretical background, observing the final part, conducting several tests and finally observing the raw material.

In chapter 6 all potential non-destructive testing methods are discussed regarding the advantages and disadvantages in order to compare them. Afterwards there are two executed tests presented to get an overview of the practical use of two measurement principles and to give an insight regarding the specific experience of the provider of them.

In chapter 7 all results are presented showing conclusively what was done in finding a solution for the given issue. This chapter contains the results of the executed tests, the outcome of consulting with a steel producer, as well as a detailed use-value analysis about the appropriate non-destructive testing methods.

The presented results are analyzed and discussed in chapter 8 and in the end, a short prospect on future approaches is given.

2. State of the art

This chapter gives an overview on the production of sheet metal to see potential sources for faults in the raw material. There is then an introduction of non-destructive testing methods to determine the capabilities of investigating sheet metal without destroying the sheets, and in the end the used material is discussed in detail.

2.1. Sheet metal production

Metals are all around us. Metallic materials have versatile properties like good formability or reusability, making them very attractive for industrial applications. Sheet metal is particularly popular in the automotive industry. Naturally metals are formless and occur bound with oxygen as oxides. There are different types of ferric oxides with different iron content, magnetite (Fe_3O_4), hematite (Fe_2O_3), limonite ($Fe_2O_3H_2O$) and siderite ($FeCO_3$). To detach them from the bound oxygen, an elaborative procedure known as the furnace process is necessary. Metals are rarely used pure, only mixtures of different metals make them a usable material. This mixture is called an alloy and it can be differentiated so that the metal properties meet the customer´s need. After the mixture of the right alloy, the liquid material is brought into an unwrought, called slap. This process is done by casting. Sometimes ingot casting but more often continuous casting in sheet metal production. The slap is rolled into its final thickness. In which rolling machines use pairs of heavy rollers to make the traversing metal thinner and thinner. The former slap length of a few meters increases after the rolling process to several kilometers and is rolled to a coil to enable transportation and storage. The process of getting the raw material ferric oxid to coil is visualized in Figure 2. [1] [2]

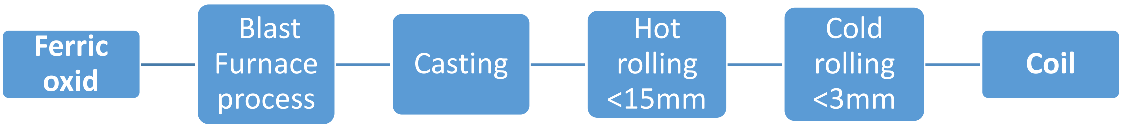

Figure 2: Sheet metal production

2.1.1. Blast furnace process

A blast furnace is a technical setup in which iron ore (ferric oxid) is processed to raw iron through a continuous reduction process (Figure 3). Due to the fact that iron does not occur in a pure form in nature, but is bound to other substances like oxygen and minerals, other ingredients are needed for the furnace process to bind unwanted elements. These ingredients are called burden and consist of for example silicon oxide and calcium oxide. Coke is used as a reductant and an energy source. Hot wind is blown through nozzles into the furnace to provide oxygen for the combustion of the coke. The exothermic reaction of the combustion of the carbon contained in the coke is shown in (1). [2]

$$C + O_2 \rightarrow CO_2 \tag{1}$$

This reaction brings the temperature of the furnace up to 2200°C. This energy is needed to build the reducible gases carbon monoxide and hydrogen (2), (3) needed for the reduction of ferric oxid.

$$CO_2 + C \rightarrow 2CO \tag{2}$$

$$H_2O + C \rightarrow H_2 + CO \tag{3}$$

These gases ascend from the bottom of the furnace to the top, and reduce the ferric oxid to iron (4). [3]

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \tag{4}$$

The furnace is continuously filled from the top with iron ore, coke and burden. Hot air containing the needed oxygen is blown from the bottom into the furnace. Iron melted by the heat of the combusting coke falls to the bottom of the furnace. Impurities on the liquid iron rise up. These impurities are called slag and are separated from the iron through different outlets.

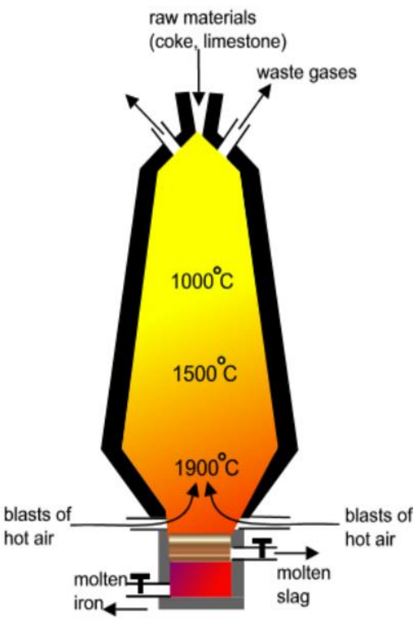

Figure 3: Blast furnace [1]

The carbon content of the molten iron is about 4%, which is too high for formable steel. Carbon content above 2% doesn't allow formability because there is too much brittle cementite in it. Due to this, a further process is needed to reduce the carbon content, refining. Refining is done by oxidation with pure oxygen or with the oxygen contained in fresh air (Figure 4). Within this process the carbon and other accompanying materials are oxidized. The oxygen bound to the iron is reduced in a further step, deoxidation.

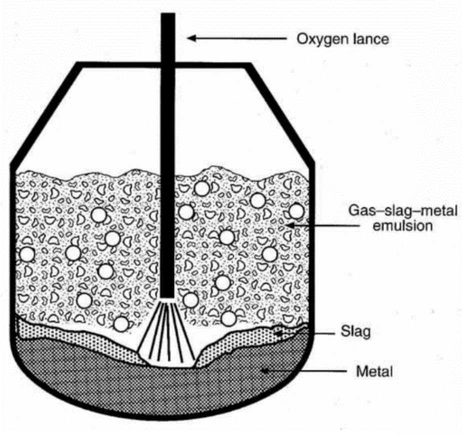

Figure 4: Steel refining [4]

Deoxidation is done by adding deoxidizing agents such as aluminum, manganese, calcium and silicon to the molten iron which binds the included oxygen. [5]

2.1.2. Casting

There is a distinction between ingot casting and continuous casting. While ingot casting is rarely used nowadays, continuous casting is widely used. Ingot casting is used for smaller batches. The big disadvantage of this process is the resulting pipes out of the slow solidification of the casted slap. A more economical way of casting is continuous casting (see Figure 5). Within this process the molten steel goes through a tundish leading to a continuous stream of steel. The small opening (mold) and the intensive cooling lead to a fast solidification of the steel. After a defined length the solidified metal gets cut off. The resulting part is called slab.

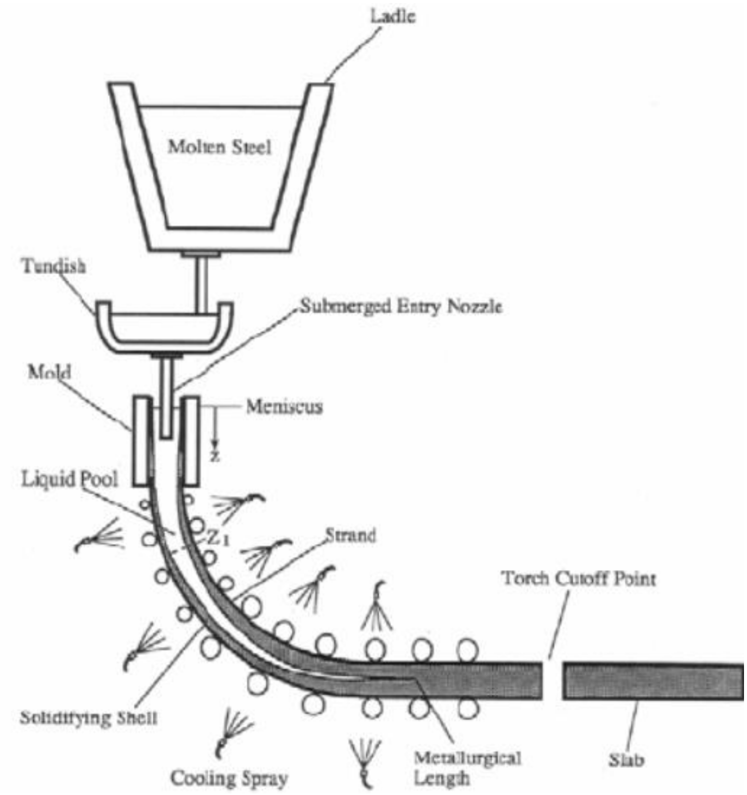

Figure 5: Continuous casting [6]

Structure faults due to solidification

During the solidification of the molten metal some faults may occur, segregation, gas porous, pipes and coarse grain. The formation of these faults is dependent on the solidification velocity.

Segregations are inhomogeneities in the material. They change the material behavior locally or over the whole cast. Differences between micro- and macro-segregations have to be distinguished. Segregations come from concentration differences during the formation of a solid solution. Homogenization processes can remove these inhomogeneities. Gas pores are formed through gases that are dissolved in the molt. These gases are excreted during the solidification process. They can be avoided through moderation of the molt.

Pipes occur during casting out of a shrinkage effect during the cooling process. There are several causes of volume shrinkage, but crucial for the formation of a pipe is the solidification shrinkage while transition from liquid to solid.

Slow solidification and a low number of nuclei lead to coarse grain. With additional nuclei remedies the formation of coarse grain can be avoided even with a slow solidification velocity. [5]

2.1.3. Rolling

The rolling process brings the slab, produced by casting, into its final geometry. It has to be distinguished between hot- and cold rolling, where the principle is the same except of the working temperature. The slab traverses through pairs of rolls. Since the volume of the material remains the same, each roller-sting reduces the thickness and increases the length of the material.

Hot rolling

The slab is either directly fed to the hot rolling machine or if it is temporarily stored the slab has to be reheated again. The cooled slab is reheated for example by induction or a fired soaking pit to a temperature of around 1200°C (above recrystallization temperature). At this temperature the steel is rolled to its semi-final thickness.
The rolling changes the structure of the material, but if the temperature is high enough, recrystallization starts immediately. The repeated rolling refines the rough structure of the casting. Through hot rolling a final thickness of around 3 mm is possible, for a thinner sheet cold rolling is necessary.
After hot rolling the surface of the sheet metal is covered with oxides (mill scale), which have to be removed before further processing. This is done by a metal surface treatment called pickling. A pickling liquid, which consists of strong acids is used to remove impurities on the surface. [7]

Cold rolling

Deformation of material below the recrystallization temperature is called cold forming. Cold rolling is mostly done at room temperature. Because of the missing recrystallization process, cold forming changes the materials' properties such as increasing the strength and decreasing the ductility.

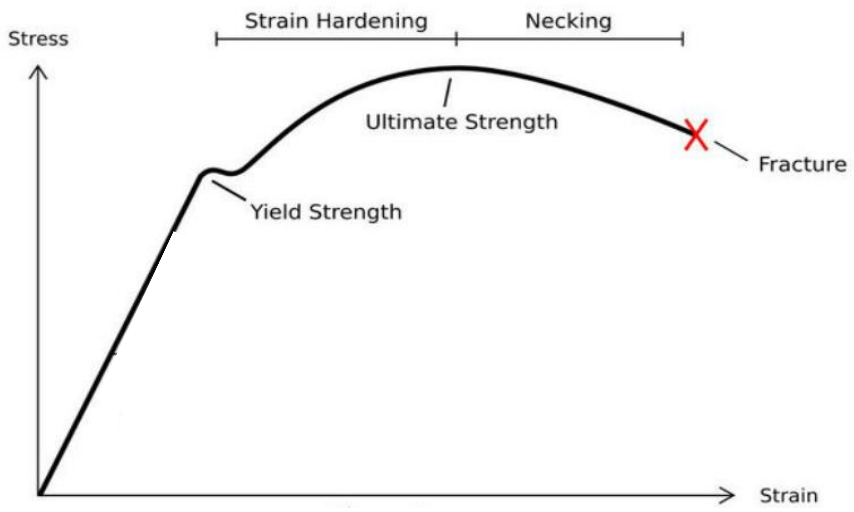

Figure 6: Stress strain curve [8]

The effect that increases the strength is called strain hardening (see Figure 6). Strain hardening occurs after reaching the border from elastic to plastic deformation. While elastic deformation leads to a reversible deformation, during plastic deformation the material is deformed permanently.

After releasing the force below the elastic limit, which leads to an elastic deformation, the shape of the material returns to its original shape.

Once the deforming force is higher than the elastic limit (yield stress), an amount of the deformation is permanent.

In the interstitial consideration the applied force forces the atoms away from their original position. During elastic deformation the force is not high enough to break the inter-atomic bonds, meaning that the atoms are able to return to an equilibrium. During plastic deformation the force is high enough to break the inter-atomic bonds and leads to a rearrangement of the atoms in the material.

A further effect of cold rolling is a better surface finish like reducing the waviness and the roughness of the sheet metal. [7]

Surface faults due to rolling

The rolling process also contains a potential for faults that mostly occur on the surface. Six types of surface defects can be determined from literature, laps, mill-shearing, rolled-in scales, scabs, seams and slivers. [9]

- Laps are defects formed through folded corners or fins which are rolled but not welded with the metal.
- Mill-shearing are defects which occur as light laps. According to A.I.S.I. (American Iron and Steel Institute) committee: "*Shearing occurs when a longitudinal strip of base metal is torn off a bar during rolling. This strip often reattaches as rolling continues, not necessarily to the same bar. Shearing can refer either to the discontinuity resulting from the detachment or to the subsequent reattachment. There are usually several occurrences of shearing with a single orientation along the bar.*"[10]
- If mill scale (iron oxides) is rolled into the material, rolled-in scale occurs.
- Scabs are patches of loose material rolled into the material´s surface.
- Seams are caused by scale and occur as decamped lines along the material.
- According to A.I.S.I. committee:" *Slivers are elongated pieces of metal attached to the base metal at one end only. They normally have been hot worked into the surface and are common to low strength grades which are easily torn, especially grades with high sulfur, lead and copper.*"[10]

2.2. Nondestructive testing methods

To get an in-depth view into different material behavior, some kind of testing is necessary. This can be done by taking the material to its limits and making measurements using destructive or nondestructive testing methods. Since the procedure of destroying the material is not the target aim in terms of an in-line measurement system, this chapter focuses on nondestructive testing methods. These methods are able to collect data on the material´s behavior without destroying it using different physical effects. The testing methods for the purpose of testing sheet metals in-line can be divided into its basic physical functionalities, electrical-, ionizing-, thermographic-, acoustic- and visual- testing methods. Each physical effect underlies a testing method, which is explained in detail afterwards.

- Electrical -> Eddy current testing
- Ionizing -> Industrial radiography
- Thermographic -> Thermographic inspection
- Acoustic -> Ultrasonic testing
- Visual -> Optical inspection

2.2.1. Eddy current testing

Eddy current testing is one example of a non-destructive testing procedure. It works on electrical conductive and/or ferromagnetic materials and due to physical effects it is only for detecting surface and surface near faults. The principle of eddy current testing underlies electromagnetic induction.

Electromagnetic Induction

If a magnetic field, which alters over time, interacts with an electrical conductor, an electromotive force (voltage) occurs. Michael Faraday first discovered this effect and so Faradays law describes and predicts this interaction. The electromotive force correlates with the time rate change of the magnetic flux. The magnetic flux (Φ_B) is calculated as follows (5).

$$\Phi_B = \iint_{\Sigma(t)} B(r,t) dA \quad (5)$$

$\Sigma(t)$ describes a hypothetical moving surface through which the magnetic flux occur, dA is an infinitesimal element of the moving surface and B describes the magnetic field dependent on space and time coordinate (r,t). If B changes or the surface moves, it leads to a change of the magnetic flux Φ_B and this leads to an acquisition of an electromotive force through the surface. To generalize Faraday´s law, the Maxwell equations are introduced. The Maxwell equations reveal that a magnetic field that varies in time, always comes with a spatial varying, non-conservative electric field and the other way around. [11]

Functional Principle of eddy current testing

Time varying magnetic fields leads to eddy currents in metallic and electric conducting materials. The size and the allocation of these eddy currents are dependent on the electric conductivity, the electric permeability and the geometry of the material. Eddy current testing methods uses this fact. An alternating current is incorporated in the testing object by induction. This means that there don´t have to be direct contact between the magnetic field producing coil and the testing object (see Figure 7).

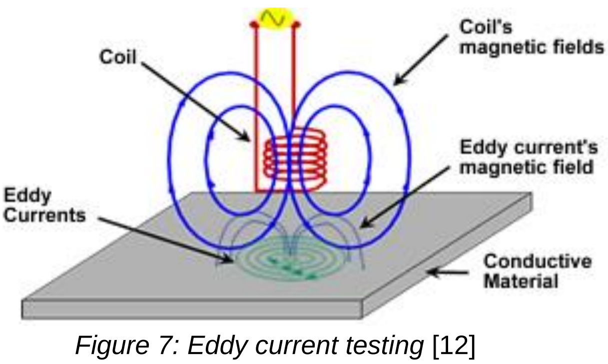

Figure 7: Eddy current testing [12]

The alternate current leads to an alternating magnetic field (primary field). As a reaction eddy currents occur in the material, which also leads to a magnetic field (secondary field) and an electromotive force. The secondary field works against the magnetic field of the coil and weakens it. Due to this effect the inductive resistance of the coil decreases. The bigger the eddy currents the smaller the inductive resistance of the coil and the bigger the electric voltage. If there is an inhomogeneity or an inclusion in the material, there is a disruption in the development of the eddy currents, which leads to an alteration of the occurring magnetic field. Through the weaker secondary field, the inductive resistance increases. This effect can be used to determine failures in the material. There exist different methods to measure the impact of material faults. Either the electric voltage is measured on the inducting coil (Figure 8b) or there is used a transmitter coil and a separate receiver coil (Figure 8a). The third method is to use a non-inductive magnetic field sensor, which measures the magnet field strength and converts it into the electric voltage (Figure 8c). [13] [14]

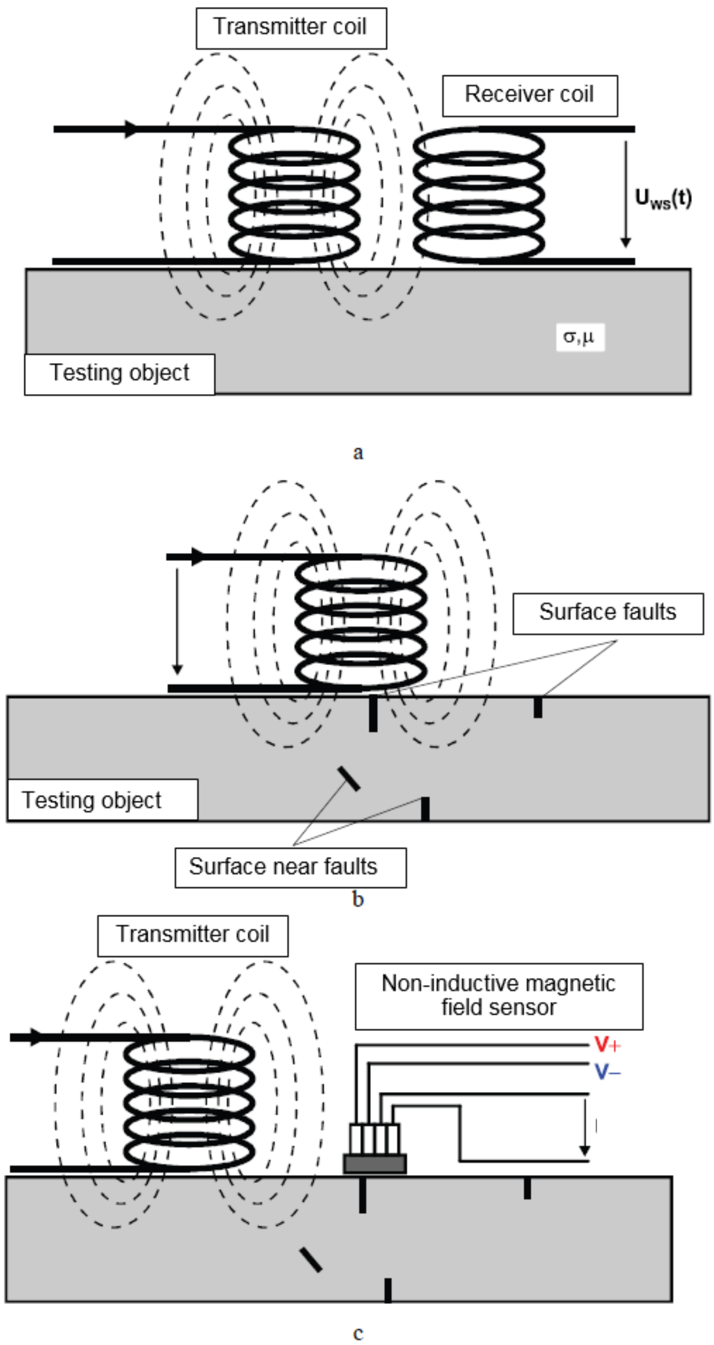

Figure 8: Eddy current measurement assemblies [14]

Penetration depth of eddy currents

The main restriction with eddy current tests is the penetration depth. Due to a physical effect, the amplitude of the alternating field (secondary field) and the eddy current density decreases with increasing depth. This effect is called “Skin Effect”. The standard penetration depth (skin depth) δ of an electromagnetic wave is calculated as seen in (6).

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{6}$$

The standard penetration depth is dependent of the conductivity σ and the permeability μ of the testing object and also the testing frequency ω. The skin depth describes the depth in the testing object, in which the amplitude of the alternating field is decreased around $1/e$ (~36,8%) of the surface value. However, this approach calculating the penetration depth is a theoretical one. The effective penetration depth could be a multiple of the standard penetration depth. It is also dependent of the test probe dimensions. If the testing object is accessible from both sides, the usage of a transmission assembly (Figure 9) brings a consistent measurement over the whole testing object thickness.

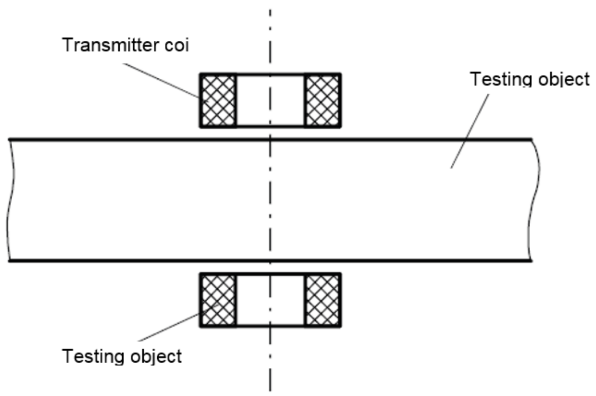

Figure 9: Transmission assembly [14]

2.2.2. Industrial Radiography

One further part of the family of nondestructive testing is industrial radiography. This method uses electromagnetic radiation with a short wavelength ($5 - 250 * 10^{-12} m$), which is able to penetrate diverse materials.

Radiation rays

In general there exists two different types of valuable radiation, x-rays and gamma rays. Both are quite similar but the difference lies in the source of the rays. The x-rays are generated in an x-ray tube where high voltage accelerated electrons (from a cathode) in an evacuated and fully capsuled tube are shot onto an anode. In order, the anode consists of tungsten, copper or molybdenum. Around 1% of the collision energy is emitted as x-rays, the rest (99%) is heat. A beryllium window lets these electrons pass only if high voltage is applied. (Figure 10)

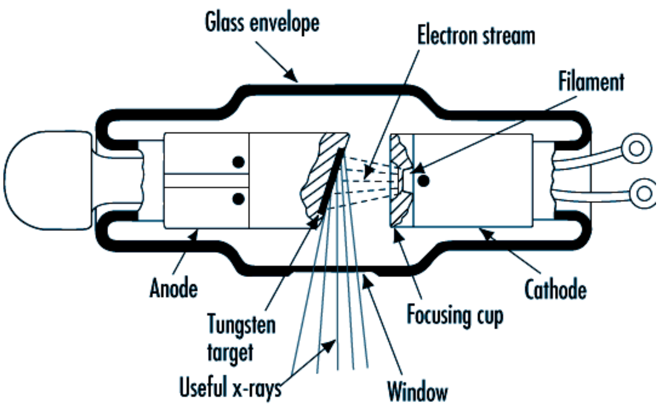

Figure 10: Schemata of an x-ray tube [15]

Gamma rays occur with the decay of radioactive isotopes, mostly Cobalt (Co60) or Iridium (Ir192). These materials are embed in a radiation proofed case. The decay persists all time and cannot be switched on or off. The gamma rays are released through an opening controlled remotely. [16]

Functional principle of industrial radiography

At the classical radiation film exposure a film is installed on the other side of the probe. This film sensitive to radiation, is irradiated with a specific intensity and over a specific time. Afterwards the film is developed and evaluated (Figure 11). During the transition of the radiation through a testing object, the radiation intensity decreases. If there is for example a pore or a pipe, the transition of the rays is easier than in the normal material, which leads to dark dots on the film. If there is a nonmetallic inclusion for instance, the transition could also be harder which leads to weaker radiation and a brighter area on the film. [16]

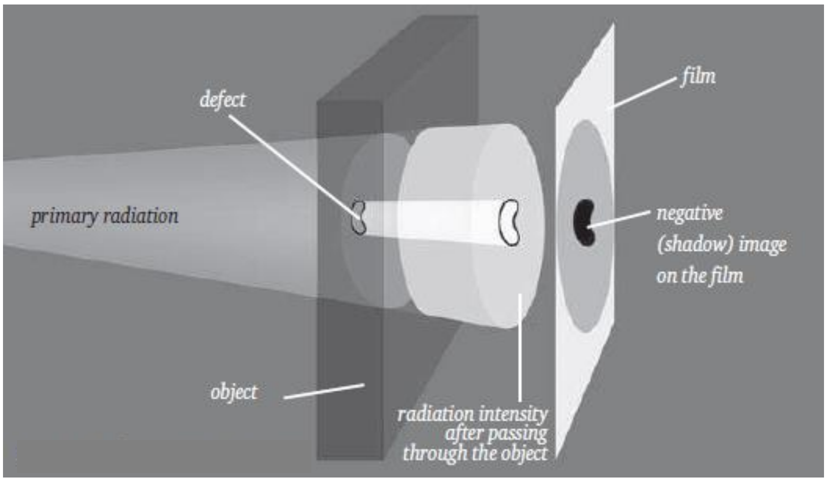

Figure 11: Functional principle of industrial Radiography [17]

A more modern approach instead of using radiation sensitive films, is to use electro-optical devices (image intensifyer) to make the invisible radiation shadow visible and capture the picture with a digital camera. An alternative to image intensifyers are digital flat plate detectors. This technology uses a scintillator foil which converts the x-ray shadow image into visible light. This image is directly detected by a photo diode array and visualized via a computer on a display. For an accurate arrangement of radiation source, testing object and film or digital device, a good education and a lot of experience is needed. To drive such a system in industry, special trained personal is obligatory.

<u>Debilitation of the radiation</u>

The intensity of the generated radiation decreases during the transition through different materials. The reduction ratio depends on the material composition of the testing material and is described through (7).

$$I = I_0 * e^{(-\mu_s * T)} \tag{7}$$

I_0 describes the intensity of the generated radiation before the transition of the testing object. *I* describes the intensity after the transition of the testing object with the material thickness *T*. μ_s stands for the debilitation value which is calculated as described in (8). [18]

$$\mu_s = \mu_a + \mu_{st} + \mu_p \tag{8}$$

$\mu_a = C_1 z^4 \lambda^3$ …Absorption coefficient

$\mu_{st} = C_2 z$ …Strew coefficient

$\mu_{st} = C_3$ …Pairing coefficient

z …Ordinal number of testing material

C_n …Constants

λ …Wavelength

Failure perceptibility

Due to a limited irradiation ability of gamma- and x- rays, the failure perceptibility decreases with increasing testing object thickness. Maximum testing object thicknesses are 100mm for steel and 300mm for light metals respectively. To test the failure perceptibility of industrial radiography, "image quality indicators" (Figure 12) are used (DIN EN 462-2). These image quality indicators are built out of different wires with different diameters, which are mounted on the testing object. After the radiation, the wires appear as bright lines on the film. The number of the thinnest yet cognizable wire on the film, stands for the image quality value. Recognizable is defined as the even area of blackness over a distance of minimum 10 mm. [17]

Figure 12: Image quality indicator [18]

Radioprotection

Radiation has a carcinogenic effect and is very harmful for organic tissue as well as genetic material. Both can suffer irreversible damage or even be destroyed. The radiation exposure sums up over lifetime and cannot be removed. Due to this fact some provisions have to be made to avoid harmful damages.

- The detachment to the radiation source should be as big as possible
- An appropriate shield against the radiation is obligatory
- The detention time in the radiation area should be as short as possible

The personal have to be equipped with special measurement systems (dosimeter), which measure the exposed radiation. [19]

2.2.3. Thermographic Inspection

Thermography is a non-destructive testing technique, which measures radiative heat emissions from object surfaces to predict and determine eventual failures in the testing object. In the past years thermography has become very important in science.

Physical Background

As a result of the oscillation of thermal excited electrons in a material, radiation is emitted of all kind of materials with a temperature above $0K$. As it is still not exactly known how thermal radiation leaves an object´s surface, there exists two theories. One theory states that radiation is a propagation of electromagnetic waves and another theory declares that it is a propagation of particles (photons or quanta). However, radiation can be expressed in standard terms of wave properties, wavelength λ and frequency f. The propagation of waves is described through (9).

$$\lambda = {}^{c}/_{f} \tag{9}$$

c stands for the speed of light ($2{,}998 * 10^{8}\, {}^{m}/_{s}$ in vacuum). Radiation, which is pertinent for thermographic inspection, has a wavelength of 0,1 to 100 μm.

Functional Principle of thermographic inspection

In general it is distinguished between active and passive infrared thermography. At passive thermography an infrared camera measures the thermal radiation, which is emitted by the testing object´s surface. This method is mainly used in civil engineering for example inspection of the thermal insulation of buildings or predictive maintenance for different devices. As opposed to this, active thermography is mainly used as a non-destructive testing method. By active thermography the testing object is thermally innervated. This can be done by an infrared radiation source or inductive innervation. Some amount of this excited radiation is absorbed while the rest is reflected. The absorbed part is transformed into thermal energy, which then distributes from the surface into the object by thermal diffusion. The thermal propagation within the material can be ideally described by Fourier´s equation.

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{10}$$

In the Fourier equation (10) *T* is the temperature in Kelvin, t is the time in seconds and α is the thermal diffusivity in m^2/s and calculated as shown in (11).

$$\alpha = \frac{k}{\rho \, C_p} \tag{11}$$

ρ is the density of the material in kg/m^3, k is the thermal conductivity in $W/m\,K$ and C_p is the specific heat capacity of the material at constant pressure in $J/kg\,K$.

A thermographic camera can then measure the time evolution of the different temperatures on the surface of the object, which result out of inhomogeneities in the material. These inhomogeneities could be inclusions, material inhomogeneities or other faults in the material. These material defects on or under the surface change the thermal diffusion rate through different material properties (density, conductivity, heat capacity). Infrared detectors are used to measure the amount of radiated energy of an object. The higher the temperature of a local area on the surface, the higher the amount of radiated energy. The amount of radiated energy is then converted into electrical signals, amplified and visualized. (Figure 13) The produced image is called thermogram. This thermogram shows a picture with different intensities or colors to visualize the different temperatures on different areas of the observed object. [20] Due to the fact that the thermal diffusion in the material needs some time (not stationary), there exists a limit of observation time τ (12).

$$\tau \approx \frac{z^2}{\alpha} \tag{12}$$

z is the distance from the surface to the depth of the fault in the material. The limit observation time is approximately the same than the thermal propagation time from the surface to the fault. [22]

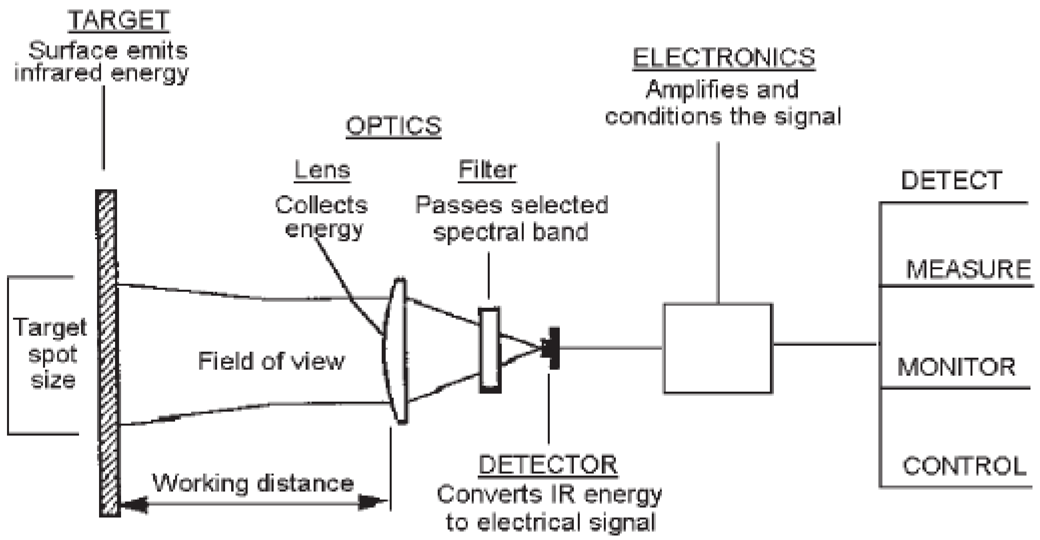

Figure 13: Working principle of thermography [21]

2.2.4. Ultrasonic testing

Ultrasonic testing methods also belong to the family of non-destructive testing. Within this testing method, ultrasonic waves initiated in the testing object are used to determine failures, testing object thickness, inclusions and doublings. It is often used to observe pipelines, used in metallurgy applications, aerospace and many more.

Ultrasonic waves

In general, waves are oscillations that spread in a surrounding medium. These oscillations occur through displacements of particles in this medium (solid, liquid or gas). There exist two kinds of waves, the transverse wave and the longitudinal wave. The difference between these two waves lies in the motion way of the oscillation. (Figure 14)

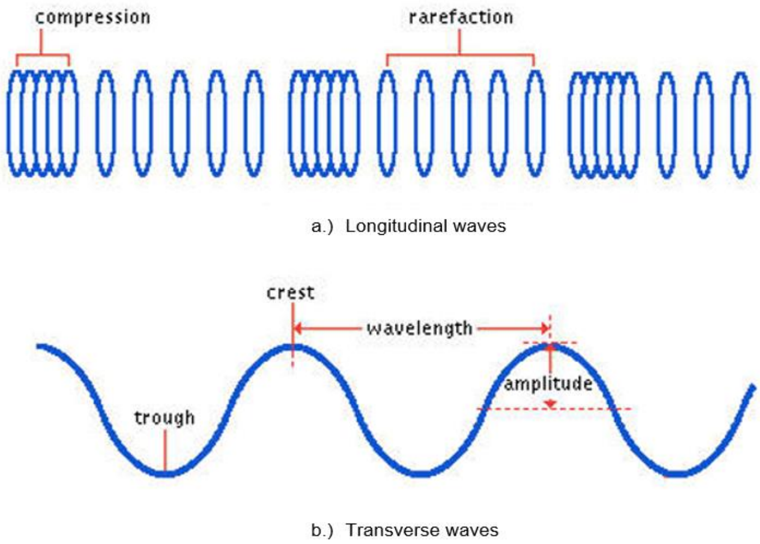

Figure 14: a.)Longitudinal waves b.) Transverse waves [23]

The direction of oscillation of longitudinal waves is in propagation direction of the wave. As seen in Figure 14a, it comes to compressions and rarefaction of the particles of the propagation medium. Transverse waves (Figure 14b.)) spread vertically to the propagation direction of the wave. Sheer forces and torsion forces occur. The wavelength is the distance between two wave crests. The amplitude describes the vertical deflection. The frequency is described by the amount of oscillations of a particle per second, or in terms of transverse waves, amount of crests per second. In reality waves are combinations of these two kinds of oscillation. The typical frequency of an ultrasonic wave is over 20 kHz but in ultrasonic testing equipment between 0,5 and 25 MHz (1MHz=10^6oscillations per second). [23]

Functional principle of ultrasonic testing

Ultrasonic testing methods are based either on reflecting waves or transmitting waves depending on the used application. Pulse echo ultrasonic testing uses reflecting waves and is the more commonly used system. Such a system consists of several units (Figure 15). A pulse produces high voltage electrical pulses with which the transducer generates ultrasonic waves. These waves are initiated into the testing object and reflected on discontinuities (for example inclusions or cracks) or on the back surface of the testing object. The reflected waves are caught by the transducer, which transforms it into an electrical signal. This signal is displayed on an external device (oscilloscope or screen).

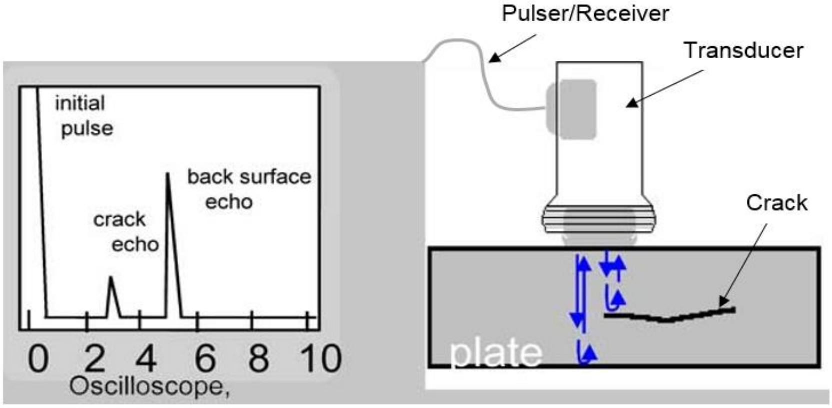

Figure 15: Ultrasonic testing device (pulse-echo) [24]

In the through transmission method (Figure 16) there is a transmitter mounted on one side and a receiver mounted on the other side of the testing object. The intensity of the receiving waves gives some indication about potential faults and discontinuities in the material. [25]

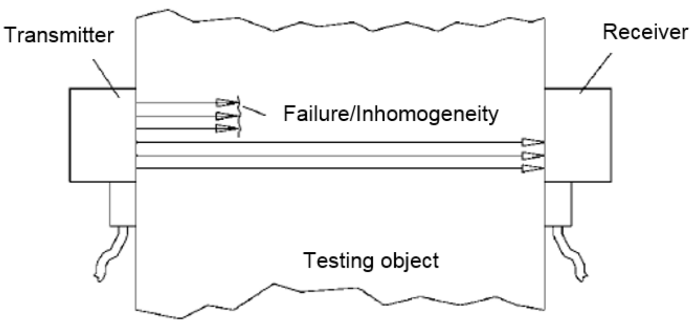

Figure 16: Through transmission method [25]

Ultrasonic waves are reflecting on zones where the acoustic impedance changes. On boundary zones where one material or substance end and another begins there exists a difference in acoustic impendence called “impedance mismatch”. The bigger this impedance mismatch, the bigger the percentage of energy or waves reflected in the boundary zone. To keep this effect as small as possible, coupling devices are used between the transducer and the testing object. The used coupling device is usually water or oil, which has a higher density than air and so coupled with the testing object (steel) a smaller impedance mismatch, which means that more energy (waves) can be initiated into the testing object. [26]

Excitation principles

There exists several forms and methods of how ultrasonic waves can be created. Following up the most important and most common methods are described briefly.

Piezo electric excitation

Piezo electric excitation is the most common method to create ultrasonic waves. This method makes use of the piezoelectric effect. If mechanical stress is applied to a piezoelectric crystal (e.g quartz $SiO2$), electric charge is accumulated and vice versa. To create ultrasonic waves an electric charge is applied to the piezoelectric crystal and as a result the crystal releases taction and compression force in an ultrasonic frequency. These created waves are initiated into the testing object. The big advantage of this excitation method is that only one test probe is needed. Due to the fact that the piezoelectric effect is bidirectional, the test probe can act as a transmitter and a receiver. [27]

Electromagnetic excitation

Electromagnetic excitation makes use of several different electromagnetic interactions in conductive materials and creates ultrasonic waves. The main principle is visualized in Figure 17. A quasistatic magnetic field is created by a permanent magnet and a high frequency magnetic field is created using a coil. The high frequency magnetic field interferes` with the quasistatic field which leads to diverse forces in the testing material depending on the geometric setup. Occurring forces can be: Lorentz force, magnetic force and magneto-strictive force. Due to the fact that that the ultrasonic waves are not created in the test probe, but in the testing material itself, there are a lot of advantages along with this testing method. For example there is no coupling device, and no direct contact with the testing material needed, which leads to the possibility of testing objects with high material temperature.

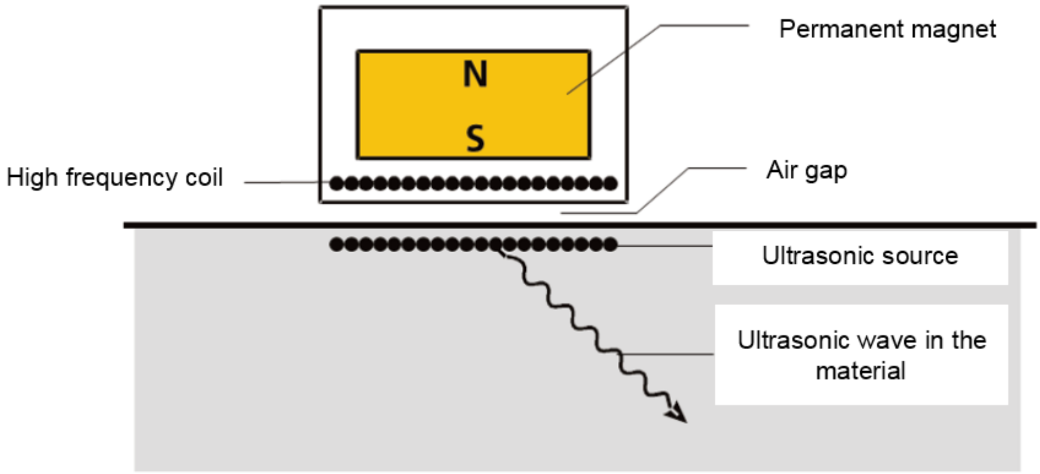

Figure 17: Electromagnetic excitation [28]

Lorentz force

A high frequent alternating current flows through a coil initiating eddy currents of the same frequency in the surface of the testing object. If these eddy currents interfere with a 90° displaced magnetic field, a force effects the free electrons, called “Lorentz force”. These oscillations are transferred to the atomic lattice.

The big advantage of this method is that it can be used for both ferromagnetic materials and non-ferromagnetic materials.

Magnetic and magnetostrictive force

In ferromagnetic materials appear magnetic forces. They occur due to the gradient of magnetic flux density. In a perpendicular magnetic field the forces appear left and right beside the high frequent coil. If the magnetic flux density is parallel to the alternating magnetic field, dynamic forces occur inside the testing material. They lead to local shape changes, which appear as local ultrasonic waves in the material. [29]

Laser excitation

The excitation is done by a short-pulse laser, which irradiates the surface of the probe. This irradiation leads to a thermo-elastic excitation in the material. Again the material itself produces the ultrasonic waves, which means that no direct contact with the material is needed. The irradiation direction of the laser on the material is not important, helping to the possibility of excitation of difficult accessible zones on the material.

In contrast to other excitation methods that are mostly limited at a frequency of about 20 MHz, laser excitation makes an ultrasonic frequency spectrum of around 1000 MHz possible. This leads to a much higher resolution.

Time of flight (TOF) measurement

To characterize the material of the testing object via ultrasonic waves, the time of flight (TOF) of the waves is essential. The TOF in a material is dependent on the material structure (homogeneous or inhomogeneous), the temperature and the sonic speed in the material. The higher the density of the material, the higher the sonic speed. Due to the slight damping of homogeneous materials, nearly random material thicknesses (e.g. several meters in steel) are possible. Inhomogeneous materials (e.g. cast iron) only allow small thicknesses. Once these parameters are known, it is possible to measure the time from transmitting to receiving the ultrasonic wave. At known material thickness, the back surface echo can be calculated, and if the measured time is shorter, a fault is detected. [25]

2.2.5. Optical inspection

Optical inspection or surface inspection can be done manually by staff or automated by cameras. Due to the fact that staff are very expensive and during monotonous work a high potential for failures exist, automated surface inspection is often the better choice.

Functional Principle of optical inspection

The automated surface detection is done by a line scan camera, which are cameras with just one photosensitive line. In industrial applications, the camera stands still and the testing object is moved. The objective of the camera is individually adapted depending on the task. To get a proper picture of object, the testing zone has to be illuminated (Figure 18).

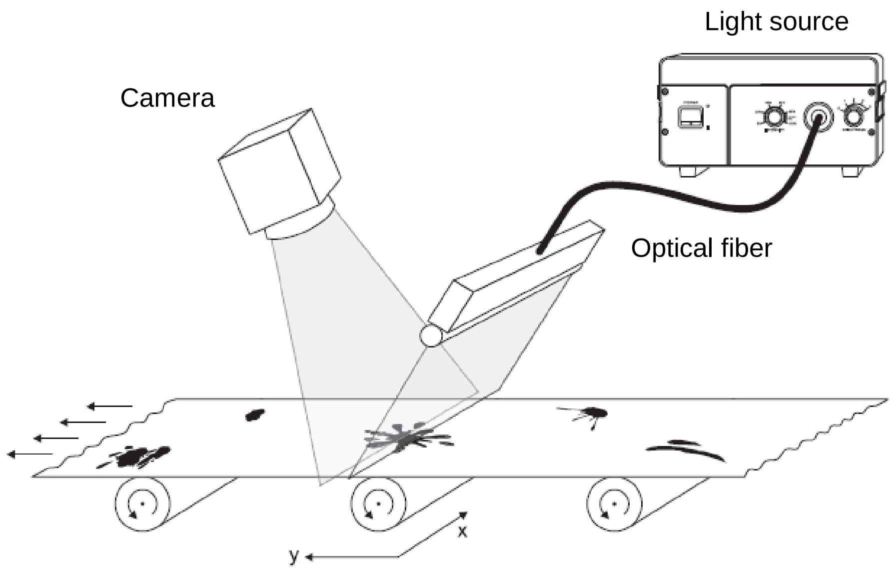

Figure 18: Optical inspection principle [30]

During operation the charge of each pixel is elected in a parallel register and converted into a digital signal. This digital signal can be saved and processed by a computer. To get an accurate image ratio the scanning rate has to be adjusted to the motion speed of the testing object, otherwise the fixed scanning rate of the camera and the variable motion speed of the testing object lead to stretching or compression of the image. This means that the scanning rate has to be coupled with the motion speed, often done by an incremental position encoder. This module has to be mounted on a position with low slippage of the testing object (sheet metal) to avoid inaccuracies. The adjustment of the exposure time is also very important to avoid brightness differences of the pictures. The exposure time is estimated using the reciprocal scanning rate of the camera. To detect faults on the material, there are two different approaches. Either the image is compared with a fault free reference picture or the software in the background recognizes faults on the basis of a detailed fault description. [30]

2.2.6. Quality Tracking

Sheet metal production is a very complex process that goes along with a high potential for imperfections in and on the material. These failures are very hard to reduce and nearly impossible to avoid completely. Customers of sheet metal, especially in automotive industry often have a zero defect philosophy which does not allow any defective products. Failures in the raw material could cause disruption in the customer´s fabrication process. Due to this, some steel customers expressed interest in tracking information on potential failures of the material from the producer to the customer. In 2011 the world´s biggest steel producers cooperated on creating and implementing a quality tracking system to provide more information of the material for the customers. The quality tracking project functions as a big working group between steel producers, device producers and blanking line builders. The idea behind is to increase the global resource efficiency of the steel supply chain by implementing industry 4.0.

Functional principle of quality tracking

The produced coil is observed for failures directly at the producer. Since this project is still not fully developed, nowadays the only inspection method is ASIS (Automatic Surface Inspection System) which only detects imperfections at the coil´s surface. However, the quality tracking can be coupled with any other non-destructive testing method depending on the customers need. It is planned in the future to convey information about the surface roughness, the mechanical properties as well as the actual thickness of the sheet metal to provide more information for the customer. The information of the position of the failures on the material are saved on a central server and assigned a unique bar code printed directly on the material. This printed bar code is over the whole length of the coil with gaps of around 50 centimeters. The idea is that the customer reads out the bar code at the production line and is able to adapt to failures on the material without generating a defective product. Already completed tests have an impressive positive result of about 99.5% accuracy in reading out the bar codes. [31]

2.3. Used material

The used material in the process corresponds to continuously cold rolled stainless steel (1.4301). Depending on the produced part it is differed between a material thickness of 0,8 mm and 1mm. The width differs between 380, 430 and 465mm. However, independent of the materials´ geometry, the chemical composition and the mechanical properties are the same. The material quality complies X5 CrNi18-10+2B DDQ. This austenitic stainless steel is with 33% the commercial stainless steel with the highest production proportion. It was cold rolled, heat treated, pickled and cold post-rolled to get a final thickness of 0,8 to 1mm.

Table 1: Chemical composition (wt %) of 1.4301

Material	C	Si	Mn	P	S	N	Cr	Ni
1.4301	<0,05	<1	<2	<0,045	<0,015	<0,11	17-18,5	>9

This steel is admitted for temperatures up to 600°C and shows good formability for low temperatures. The high corrosion resistance is based on the development of a homogeneous, passive layer on the surface, which is built from chromium oxide. This passive layer is corrosions resistant and also resistant against acids. However the development of this layer leads to chromium impoverished areas around the oxide precipitation, which makes the steel susceptible for intergranular corrosion at high temperatures. It inclines to work hardening and due to that is does not have good machining properties, though the formability for deep drawing is very good. The materials´ properties are shown in Table 2.

The optimum regarding mechanical properties is achieved through solution annealing in a temperature range between 1000°C and 1100°C and a following quick cooling with air or water. Due to the low carbon content, the hardness, strength and the yield strength are of low value which stands for good cold formability.

Table 2: Mechanical properties of 1.4301

Material	Thickness in mm	Density in kg/dm^3	Yield strength ($Rp_{0,2}$) in N/mm^2	Tensile strength (Rm) in N/mm^2	Strain(A 80) in %
1.4301	0,8-1	$7,9$	230	$540 - 750$	45

3. Fault causing factors

Within each process there are many different factors that influences the process and lead to an effect. The type of influence determines whether it is a positive effect or a fault. To determine which factors could influence the final part, the process chain needs to be introduced for a better overview. The main influencing factors that could lead to a fault are then discussed. The resulting costs are also introduced briefly.

3.1. Process Chain

The raw material is produced at an european steel manufacturer. This manufacturer produces steel in conventional way which means that the slap is produced via continouse casting with an thickness of about 100 – 200mm. Afterwards the slap is warm rolled and finally cold rolled to a sheet thickness of 0,8 – 1,0mm.

After the production, the sheet metal in deep drawing quality is rolled to a coil and shipped to the external stock of Magna Fuel Systems. The whole process chain is visualized in Figure 19.

One day before the material is needed, it is transported from the external stock (1) to the shop floor to aclimatisate to room temperature (2). This is neccesarry, because the material behavior is strongly dependent on the temperature. If the material is too cold, cracks appear due to a decreased plastic flowability of the material, in other words the material behaviour becomes more brittle.

Later the coil is clamped on the reel and added to the deep drawing process (3). The sheet metal is treated by a straightener to reduce the waveines of the sheet and to flatten it. Afterwards the sheet metal is prepared with lubricants (drawing oil) by a stock oiler to increase the deep drawing behavior and cut to round plates with a diameter of 170 mm. This is done by an intergrated mechanical blank cutter. These plates go through a 15 step deep drawing process in a mechanical multi station press. After this process, the finished parts are ejected from the machine and collected on a sorting table. Depending on the test results of a random sample, picked by a worker, the parts are put into a green box or a red box (4). The green box stands for good and the red box for defective parts (scrap).

The green boxes are emptied afterwards into a lattice box (5). This lattice box collects the parts to an amount of approximately 2500 pieces. The detailed process chain is visualized in Figure 20.

In this lattice box the parts are transported to a temporary stock (6), which is emptied once a week where the goods are further transported to an external cleaning company (7). This company cleans the parts from the lubricants and transport the goods back to Magna where the parts go to the distribution departement. The transportation is done by another external company.

Back in the company the parts are either dispatched to the customer or distributed internally for further worksteps (8).

The sorting of good parts and defect parts is done if required. This requirenment may be requested by the customer if they recieved some defective parts but want zero defects. Or some, later in the vehicle visible parts, are always sorted to prevent dissatisfaction of the customer.

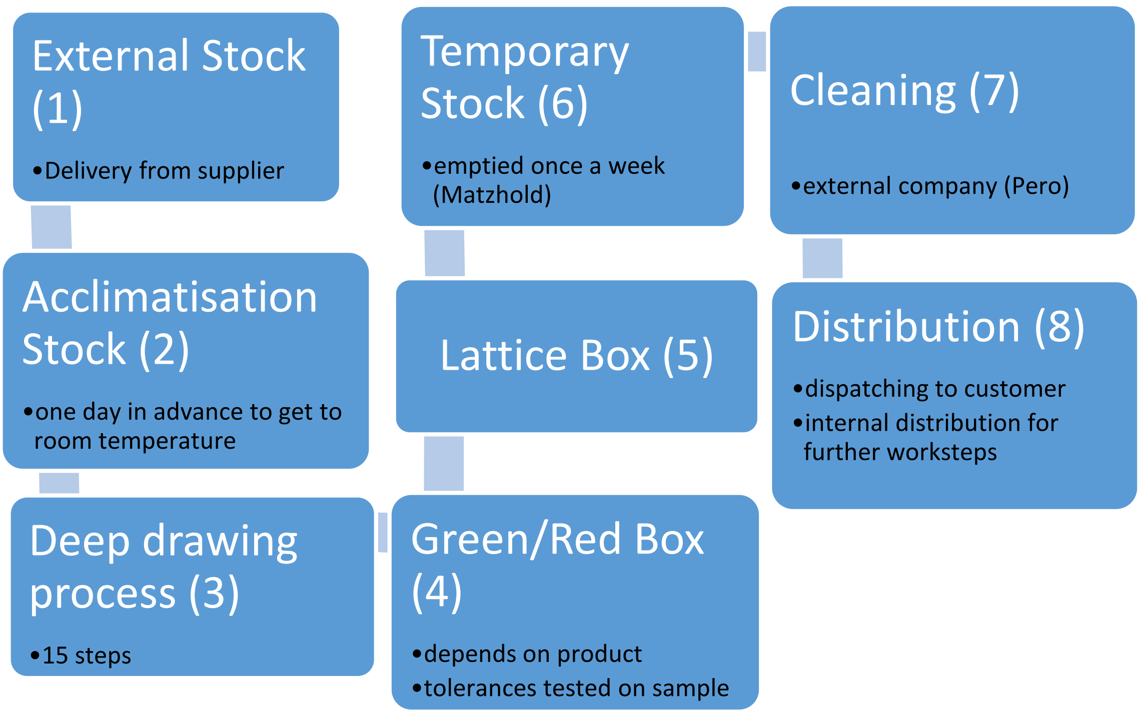

Figure 19: Process chain of the material flow

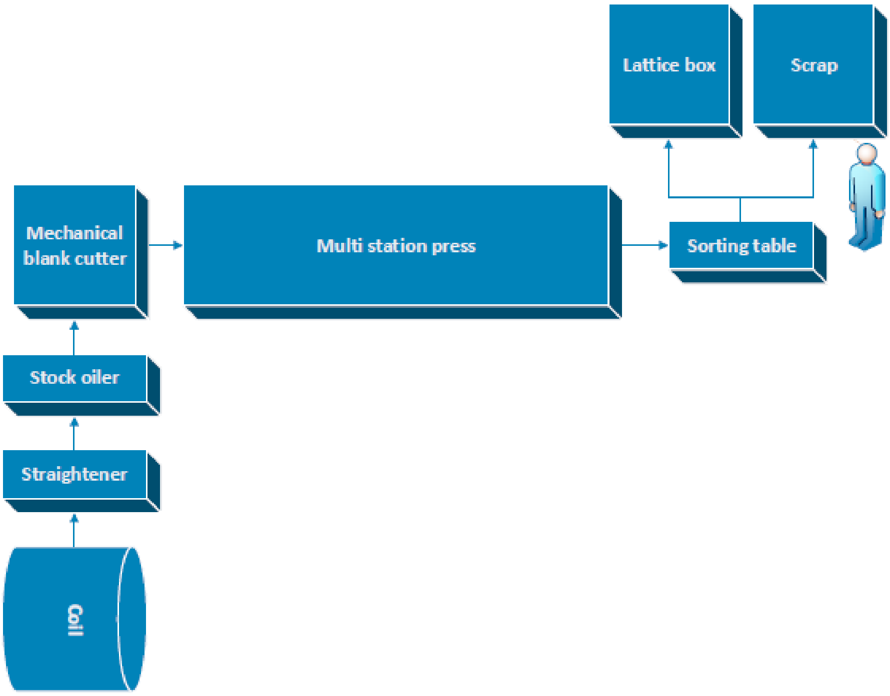

Figure 20: Detailed Process Chain

3.2. Main error sources

For a better overview of all influencing factors, visualization such as an Ishikawa diagram is helpful (see Figure 21). Applied to this work, the Ishikawa diagram shows the causes for faults in the final product. The main influencing factors are the forming process itself, the quality of the raw material, the workers, the transportation and the stock.

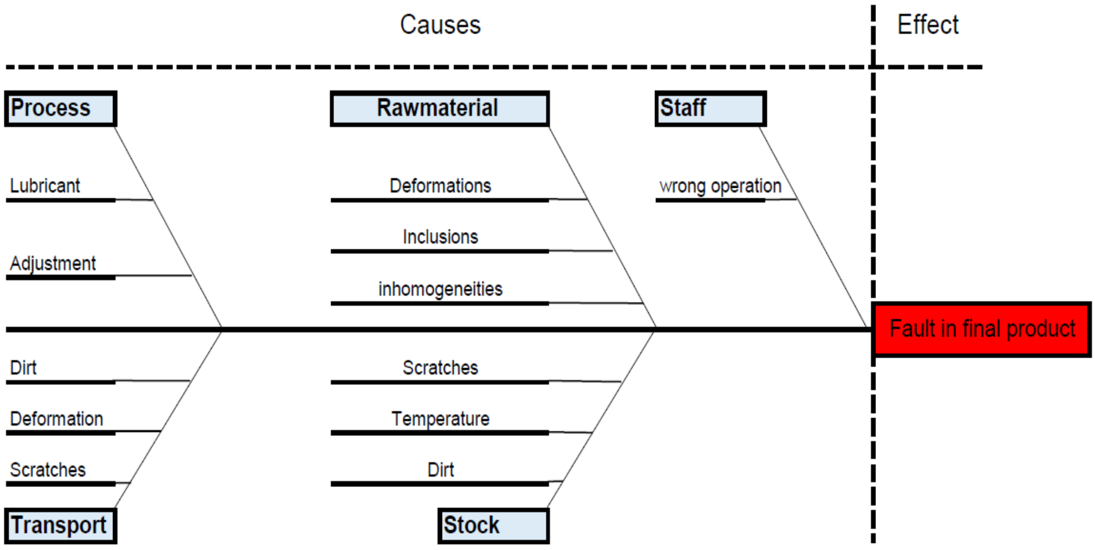

Figure 21: Ishikawa diagram of influencing factors on the process

3.2.1. Process

The process could contain many potentials for faults, as there are many mistakes in adjustment of the forming parameters, such as deep drawing ratio, plank holder force, drawing depth, damaged used tools or wrong lubricants.

The coiled sheet metal is unrolled from the coil and aligned with rolls to reduce the waviness. This is done by a separate working step inline before the material is introduced to the press. Afterwards the sheet metal is wet with drawing oil, and introduced into the deep drawing press.

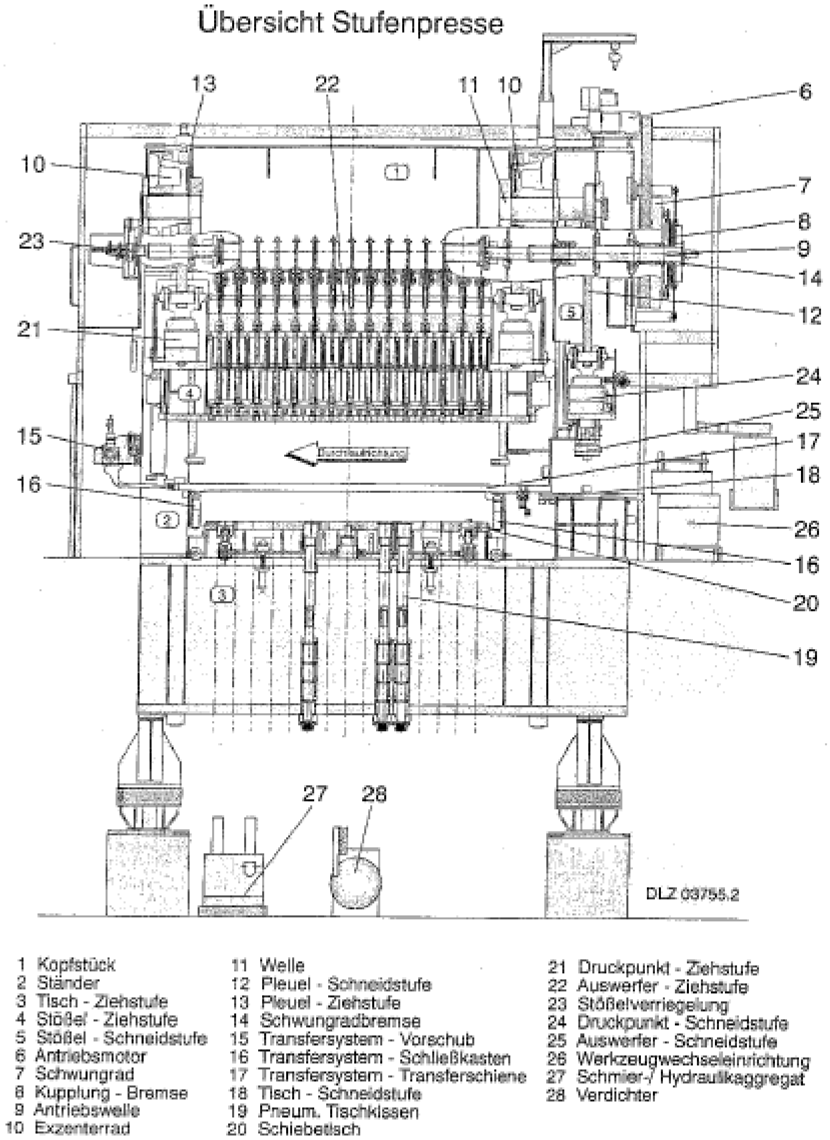

Figure 22: Multi station press [32]

The used presses are mechanical multi station presses with 15 work steps (see Figure 23) These presses have an overall pressing force of 7900 kN, a maximum lifting rate of 50 lifts per minute and an integrated mechanical blank cutter (see number 24 in Figure 22)). This cutter cuts the blanks out of the coiled sheet metal in a zigzag pattern to get as much blanks out of the raw material as possible. Each working station adjustment can be individualized which leads to a high portfolio of different products which can be produced on a single press. Currently there are produced about 5 different filler sockets with different drawing geometries. The conversion from one socket to another requires the change of the used tools and, depending on the socket, the change of the used raw material. This conversion should not need more than 4 hours in time.

Figure 23: 15 steps of drawing process

Accurate adjustment within deep drawing processes is very complex and key to produce proper products. Finding the wright adjustment is more a process of experience than theoretical calculations. This statement is supported by the fact that simulations in the past leaded to the outcome that some of the parts are theoretical not producible with the used material and the desired geometry. Since the company has long-term experience in deep drawing these parts, it could be barred that these parameters are causing the high number of scrap and are chosen correctly. One other outage-influencing factor is the used tool. It is possible that the tools are wrong in geometry or defective which could lead to faults in the final product. Since these tools are changed at the conversion from one to the other product but the faults stay the same, it can also be barred that the tools are the reason for defective parts. Lastly, the drawing oil has a big influence on the friction of the process. In previous years experiments with different drawing oils were conducted, to discover the influence on the product. Experience showed that the currently used oil (“Leko Z-250-CHL-1”) is the only one that leads to desired quality. Other oils lead to an increased attrition of the tools and scratches on the part.

3.2.2. Staff

Also the staff could cause damages either at the deep drawing sheet or at the final product. The workers could operate the machines in a wrong way or just handle the materials carelessly. Actually there are some faults made by the staff that leads to some scrap, but the main part of the scrap arise from another source.

This perception comes from the fact that the observed fault exists for long time and it’s unlikely that different workers all do the same fault.

3.2.3. Transportation

Transportation could also be an error source. Dirt could come on the material´s surface, which leads to problems during the drawing process. Also damaging of the surface or the geometry could occur through inappropriate handling.

3.2.4. Stock

The stock has also an influence on the final product. If it is too cold, the formability of the sheet metal decreases. But also damaging of the coils or the final product can be possible during storing. Of course there are some cases were scratches were in the surface of the coils, but this damage is mostly in the first view meters of the coil, which is more or less the outer layer of the coil before processed. The influence of the temperature is futile because there is a place for the coils to acclimatize before they get processed, which means they reach room temperature before production.

3.2.5. Raw material

Finally, the raw material can also contain some faults occurring from the production of the sheet metal. These faults could be both on the materials´ surface and in the material. On the material could be scratches, deformations, discolorations and contamination with dirt, and in the material itself there could be metallic and non-metallic inclusions, doublings and segregations. Since the other sources, mentioned before, are not the main problems determining the overall scrap, the source “raw material” will be discussed more detailed in chapter 4.

3.3. Costs

The overall costs c_O that comes from defective parts with the raw material as the origin, are the sum of material costs c_M of the scrap and the labor costs c_L for sorting the produced parts and detect defective parts (13).

$$c_O = c_M + c_L \tag{13}$$

These costs were evaluated from the past years. The material costs are very small due to the fact that the raw material price for such small parts is very low. For the sake of convenience the production costs of the filler sockets (machining costs and labor costs for the duration of production of the sockets) are included in the material costs. Calculated with an average scrap of around 4%, an average production price per piece of around 0,50€ (there are produced several different sockets with different production costs) and a production volume of around 2.500.000 pieces per year, the material costs are as shown as in (14).

$$c_M = 2.500.000\ {}^{\#}/_{year} * 4\% * 0{,}5€ \tag{14}$$

$$c_M = 50.000\ {}^{€}/_{\text{year}}$$

The labor costs includes the costs of sorting the produced parts in house, the costs for the administration effort of complaints of the customer as well as the costs for sorting of the delivered parts at the customer. These costs are recorded over the last years and are as shown in (15).

$$c_L = 100.000\ {}^{€}/_{year} \tag{15}$$

This means that the amount of overall costs, resulting from faults in the material are around 150.000 € each year. It can be seen that the costs for sorting are double the costs of the material itself. If the scrap is more than 3%, which are ordinary rejects from the supplier, the supplier assumes costs of the scrap for the material. The labor costs for sorting are so high because the optical inspection of the staff is very inaccurate which means that even if all parts are sorted and inspected, there is a high possibility that a few defective parts are overlooked and are delivered to the customer. Once the customer spots a defective part, all further delivered parts have to be sorted and inspected again to guarantee zero defects. An automated inspection in the process line, which is able to detect 100% of defective parts, would lead to a dramatic decrease of the labor costs, up to a complete elimination. The benefit for the material costs must not be ignored. The position for price negotiation would be improved.

4. Fault types

There exist different types of faults with different origins. In general it has to be distinguished between faults on the surface of the sheet metal and in the material. The following chapter will show all possible faults on the coil.

4.1. Faults on the surface

Faults on the surface are mostly scratches, deformations, discoloration or contamination with any kind of dirt. In contrast to faults in the material, faults on the surface can often be detected very easy by optical inspection through for example a camera or by staff.

4.1.1. Scratches

In general scratches can occur in different geometries, from a few millimeters to several centimeters in length and different widths and depths (see Figure 24). Depending on the depth of the scratches they could cause harmful outage of the final product or just a visible mark on the formed part. The origins of the scratches are due to the incorrect handling of the coil or roll marks. This could come from improper transportation, storage or wrong adjusted of the process set up. Roll marks come from the sheet metal production process, where a slab with a length of a few meters could end up as a length of several kilometers. The used reduction rolls in the process rotate at a very high speed. If particles come to these rolls and the coil runs through, a roll mark is created.

Figure 24: Collection of detected scratches on the raw material

4.1.2. Deformations

Deformations can occur on small local zones or over huge zones along the sheet metals´ surface. The origin of such deformations can be wrong handling or stress within the material coming from the sheet metal production process. Besides outage of the part, deformations of the material could cause some serious impact on the machinery. If the part gets jammed and the deep drawing process does not stop, the tools could be destroyed, leading to high restoration costs. Such harmful deformation of the sheet metal is shown in Figure 25.

Figure 25: Deformation on the coil

4.1.3. Discolorations

Discoloration is not harmful in terms of outage of the product, but inacceptable in terms of appearance of the part. The origin of the discoloration is still not clear. It could come from an inappropriate curing with corrosions during pickling, which have to be done between hot and cold rolling to remove the built scale on the surface (Figure 26).

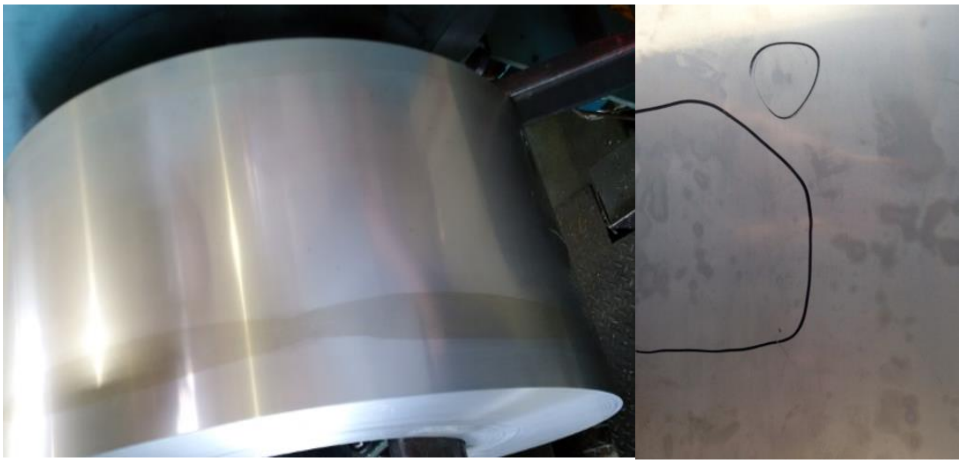

Figure 26: Discoloration on the coil

4.1.4. Contamination

The contamination with dirt could cause some problems within the forming process. Dirt could come from the producer, from the stock or from the facility. An Example includes rest magnetization that could lead to attraction of metallic particles or some glue residues, from affixed reprimands of the steel producer, could contaminate the sheet metal´s surface.

4.2. Faults in the material

Faults in the material are much graver in terms of outage than faults on the surface. Detected faults are inclusions, segregations and doublings.

4.2.1. Inclusions

Inclusions are distinguished between exogenous and endogenous inclusions. Their origin is the steel production process.

Exogenous inclusions are usually particles of fire resistant materials such as ceramic. Ceramic is used for protecting containers, staff protection, casting powder as a layer between the molten metal and the mold or as a protective coat between the molten metal and the surrounding atmosphere. Casting powder consists mostly of calcium oxide (CaO), silicon oxide (SiO_2), sodium oxide (Na_2O), aluminum oxide (Al_2O_3), manganese oxide (MnO) and fluoric (F). These particles come into the molten bath and become exogenous inclusions during the cooling process of the metal. Scrap iron is used as a deoxidizer to bind the oxygen in the material to avoid the formation of pipes during the cooling process. Recycled metal which is fed to the molten bath reacts with the including oxygen and becomes an oxide. The oxide´s density is lower than from the molten metal and because of this it usually swims up as a slag. However, some particles remains in the molten metal and become endogenous inclusions during the cooling process. [5]

4.2.2. Segregations

Segregations are inhomogeneities in the material that also have their origin in the steel production. They change the material behavior locally or over the whole cast. It has to be distinguished between micro- and macro- segregations. Micro segregations are on the scale of crystal plane and come from concentration differences during the formation of a solid solution. If the cooling process is too fast, concentration differences cannot be compensated through diffusion processes and micro segregations develop. However, there is a method to revert micro segregation, homogenization or diffusion glowing. At this process the metal is heated nearly to solidus temperature (for steel 1100-1300°C) for a long time (up to 50 hours). This enables the diffusion processes to homogenate the solid solution. The principle of macro segregation is the same as for micro segregations, but over a bigger scale. It has to be distinguished between ingot segregation and gravity segregation. Due to the fact that gravity segregation occur at alloys with different density of the alloying elements like lead and tungsten, ingot segregation are more important for steel alloys. The solubility of the elements or of impurities in the rest melt is lower than in the solid. Therefore the last solidified region is supersaturated with elements like carbon, phosphor or sulfur and their oxides, sulfides, etc. Because the cooling process takes place from the outside to the inside, the supersaturated areas are in the middle of the cast. [33]

4.2.3. Doublings/Pipes

Doublings also have their origin in the steel production process. Doublings are pipes that are pressed flat in a later point of the production chain. Pipes occur during casting out of a shrinkage effect during the cooling process. The volume decrease during cooling consists of a volume decrease in the liquid state between the casting temperature and the solidification temperature, a volatile volume shrinkage when achieving the solidification temperature (solidification shrinkage), and a steady shrinkage at the solid state from solidification temperature to room temperature. Crucial for the formation of a pipe is the solidification shrinkage while transition from liquid to solid. If it comes to the inclusion of already solidified material, no further melting can flow back for compensating the solidification shrinkage and a pipe is formed. After forging or milling the castings to for example, sheet metal, the pipes become doublings by pressing them flat. Doublings occur as split up material in the middle of the thickness. [33]

5. Fault determination

The process to spot which faults are included in the raw material is very complicated and needs several steps. The approach to find results is top down, which means that the first step is an investigation of the theoretical background to get some background knowledge, then an observation of the final part to see the formation of the material fault after deep drawing, afterwards the execution of some tests on the influence of some parameters (anisotropy, scratches) and in the end an observation of the raw material for a final determination of the shape of the outage causing fault.

5.1. Theoretical background

The investigation of the theory helps to make assumption on the types of faults that are realistic and which are unlikely. However there are several causes which lead to a final product which is not usable but there is one error pattern which occurs most frequent and leads to the most scrap.

Figure 27: Failure pattern u-curve

This failure occurs as a lacerated u-curve (Figure 27). It seems like that the basically homogenous material has some kind of coating that has burst. The shown picture is just an example, but this failure pattern occurs in several different sizes and positions on the final part. To simplify the process of failure determination, it was focused on this failure pattern at the first step. Literature and consulting from experts helped as a first assumption the type of failure that could lead to such an outage. However, in the first step it was not totally clear the exact fault in the raw material.

Possible faults could be:

- Inclusions
- Segregations
- Doublings

Endogenous or exogenous inclusions in the raw material could affect the material during the forming process. Possible endogenous inclusions could be oxides and exogenous inclusions could be particles of casting powder. A zone of inclusions could obstruct the flow of the material during deep drawing and lead to failure pattern like the shown u- curve. The presumption is that this zone must be a line in the raw material, which is formed to an u-curve during deep drawing from a round plate.

Segregations in the raw material could also lead to outage of the final part. As previously mentioned, the fault looks like a burst coating of the part. Due to the fact that the material actually should be homogenous, segregations could be to blame. Local concentration differences could be accountable for burst cracks on the surface like seen in Figure 27. Segregations that lead to brittle material behavior on the surface, however, the possibility that segregations occur as thin lines in the raw material in such a high frequency is not very high.

The possibility for doublings as the outage-causing fault is higher than for segregations. Pipes in the cast, which are rolled afterwards, occur as long lines of doublings in the sheet metal. Once the round plate is drawn deep, the lines appear as u-curves in the final part. Doublings mostly occur in the middle of the sheet metal which arising from the production process.

5.2. Observation of the final part

However, assumptions are not accurate enough to determine the outage-causing fault. To get a more significant view on the issue, in the next step the final part is observed more accurately. Looking “into” the part does this. An outage during the forming process led to a cracked part that shows the split material along the u-curve fault (see Figure 28). In this part it seems like that the material is split in the middle of the wall thickness, which would be typical for doublings.

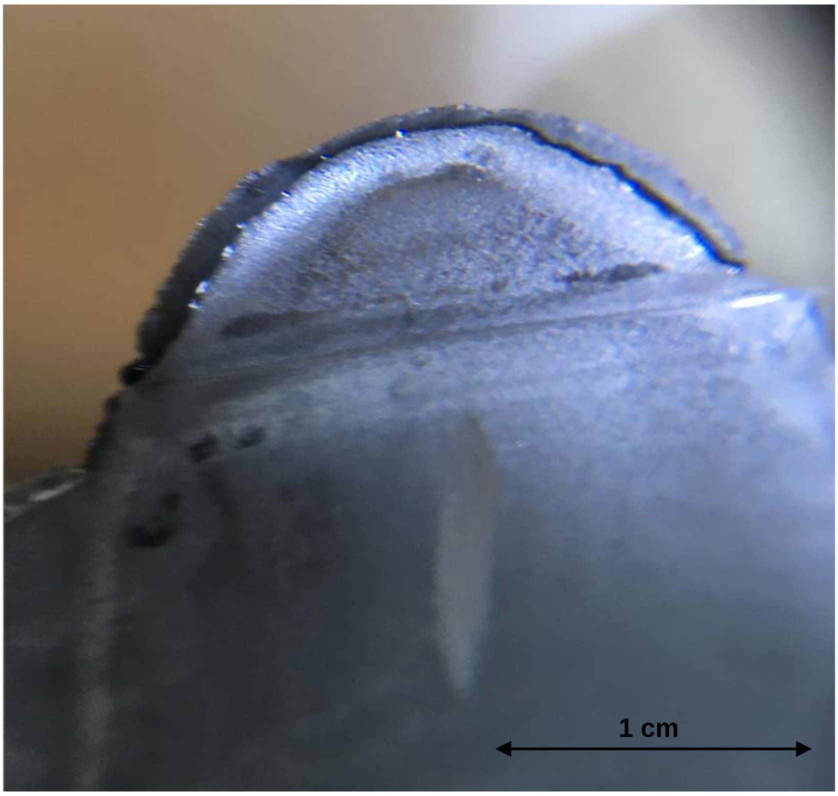

Figure 28: Cracked u-curve fault

To get a better view, the idea was to cut one part directly through the fault to visualize the geometry and the formation of the fault (Figure 29).

Figure 29: Cut part

The first attempt was to cut the part with an ordinary hacksaw. This was not target- aimed because the cross section was cold-welded and so the fault invisible.

Figure 30: 4 Cut parts

The second attempt was much better in terms of visibility. The part was cut via wire cut EDM (Electrical Discharge Machining). To get a better view, the part was cut into 4 pieces (Figure 29 and Figure 30). This part exhibited two u-curve faults. The cuts are done through different positions of the fault.

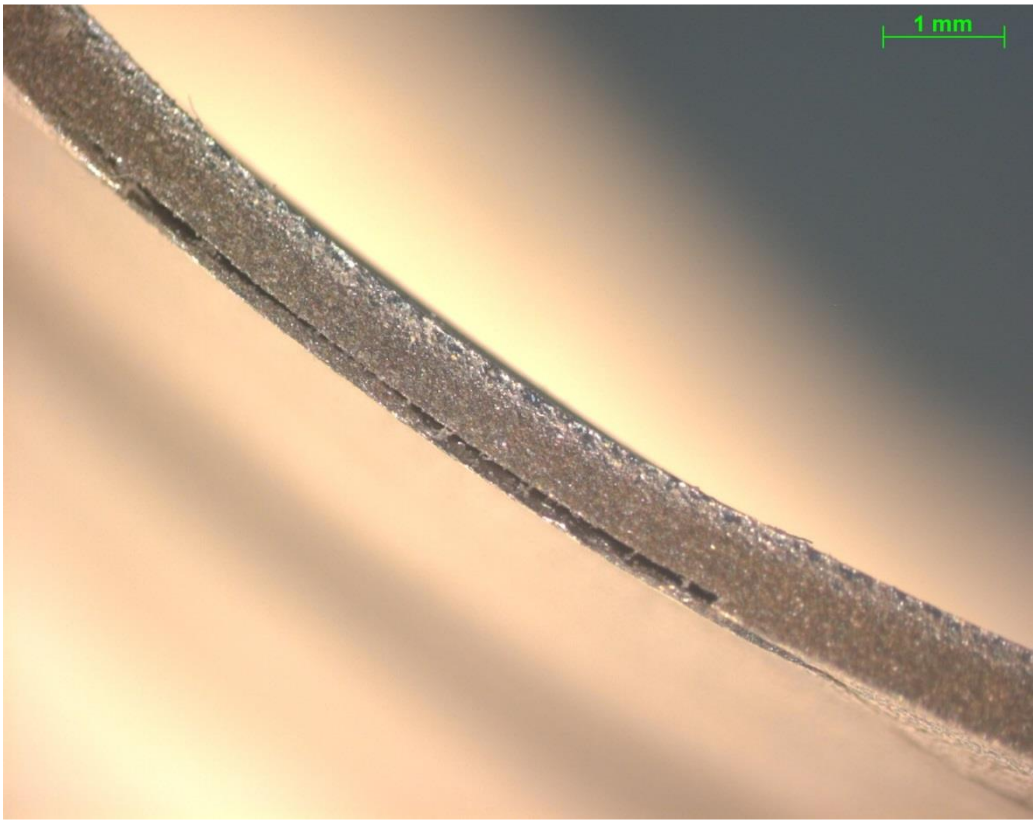

Figure 32: Detail horizontal cut

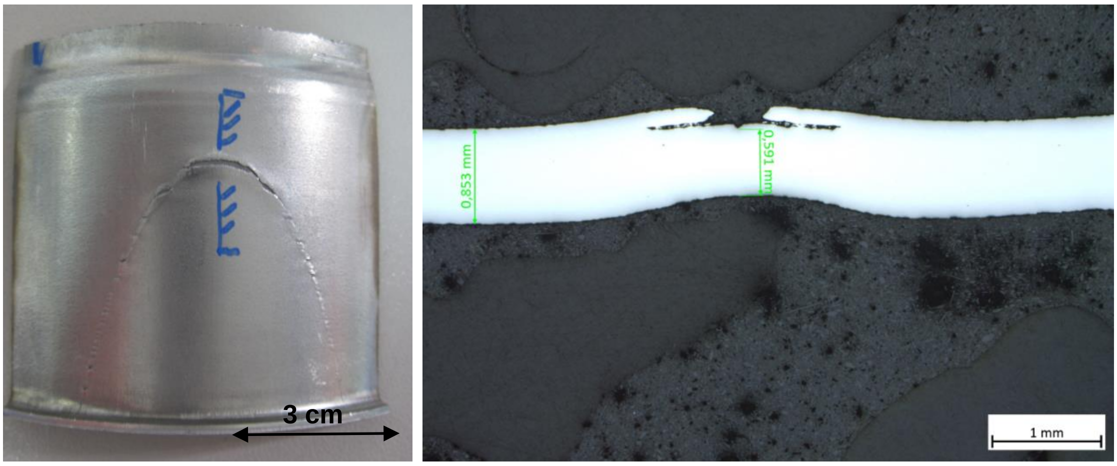

Figure 31: Detail vertical cut

Figure 32 is representative for all the other cuts. The fault in this part does not appear in the middle of the wall thickness, but close to the outer surface. It again looks like a separation of a coating on the part, but in fact there is no coating. These facts again leads to the assumption that the faults in the raw material are doublings or inclusions. One other part was cut vertically to see the formation of the fault more exactly (Figure 31). The position of the cut is marked with a blue line. Again this fault is surface near and looks like a burst bladder. Under the microscope the cross section of the fault was made visible.

Figure 33: Inner surface near fault

As seen in Figure 33 the fault also occur on inner surface near areas. Here the surface along the u-curve looks like a bladder that is not yet broken up. This leads to the conclusions that the fault is arbitrarily distributed on the thickness of the raw material which leads more into the direction of inclusions rather than doublings. To get a more detail view, another part was cut through its fault and a micro section was customized. In Figure 34 the material fault again looks like a bladder and the whole surface is flaky.

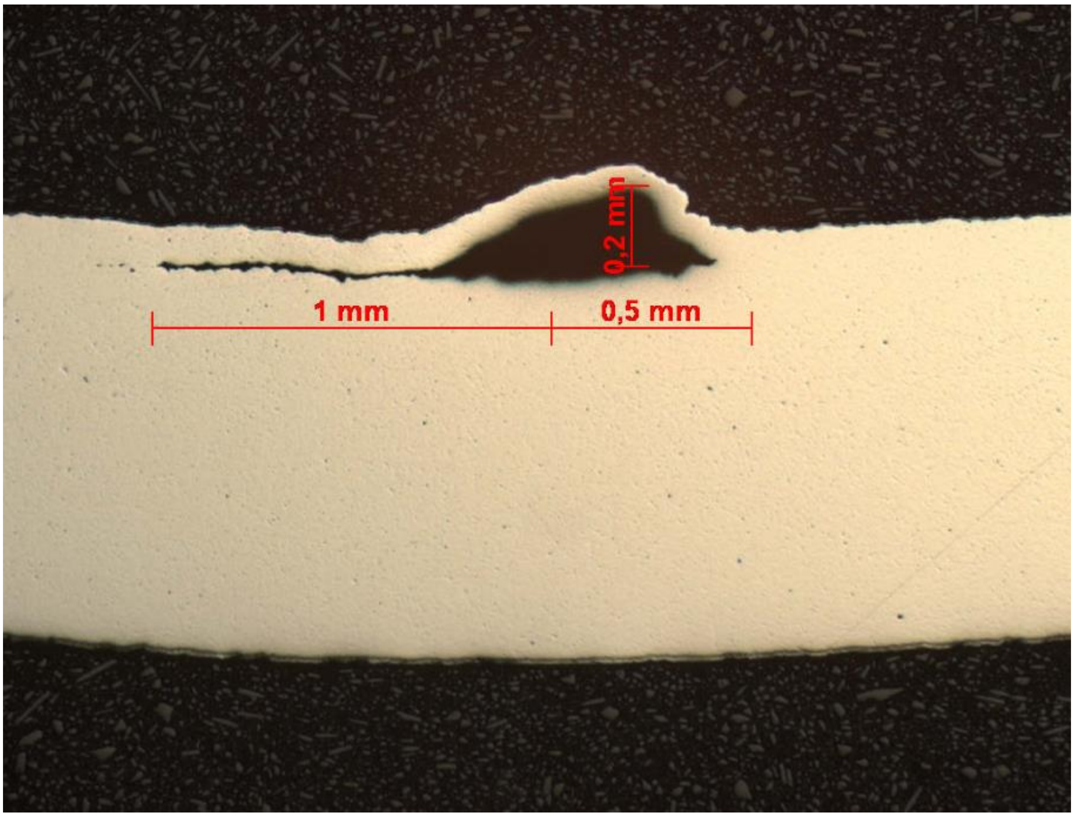

Figure 35: Micro section (25X)

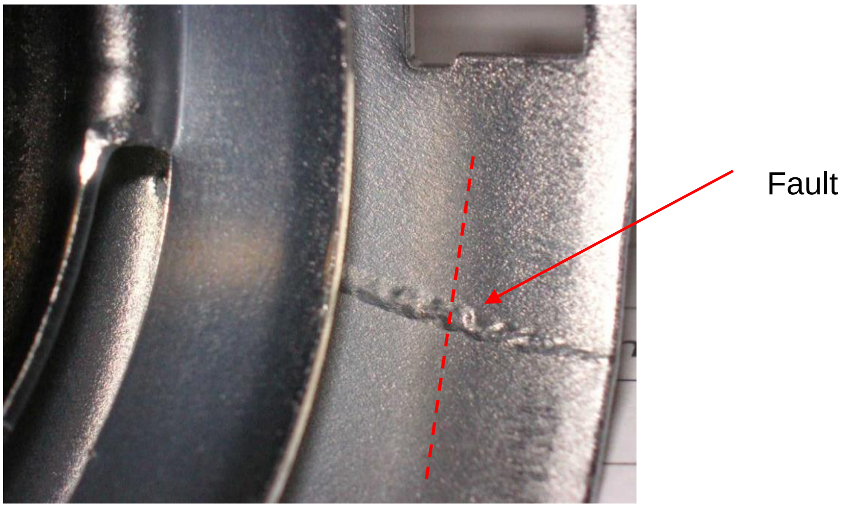

Figure 34: Flaky material fault

The position of the cut is marked through a dashed red line. After the cut the section of interest of the probe was polished with diamond suspension and later etched with a “V2A”-pickle to make the structure more visible. The micro section of the fault shows a lift of the material of about 0,2mm (see Figure 35). The whole width of the fault is about 1,5mm. Out of this visualization it is hard to say if the crack in the material happened during deep drawing or was already in the raw material before the forming process. Another part on which the characteristic of the u-curve fault was not that distinctive than the former ones, was also cut open, polished, etched and observed under the microscope.

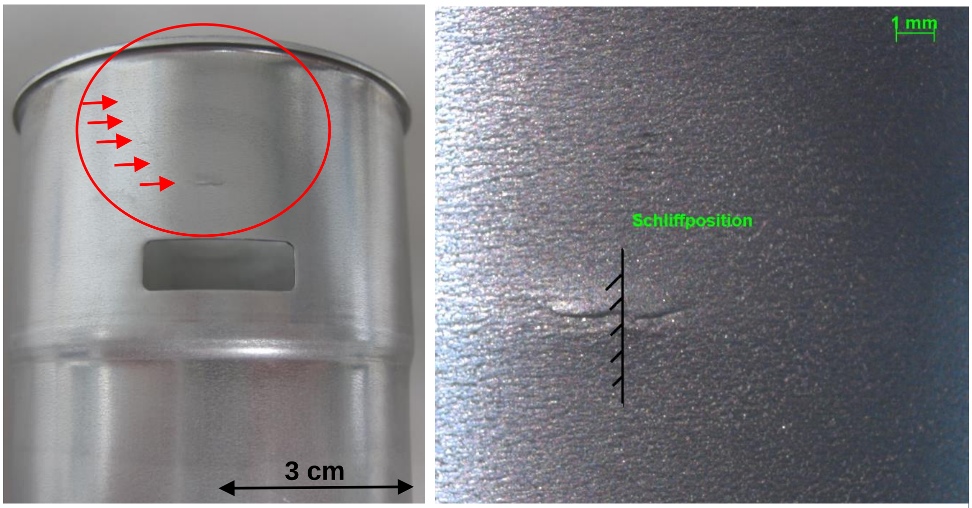

Figure 36: Weak pronounced u-curve fault

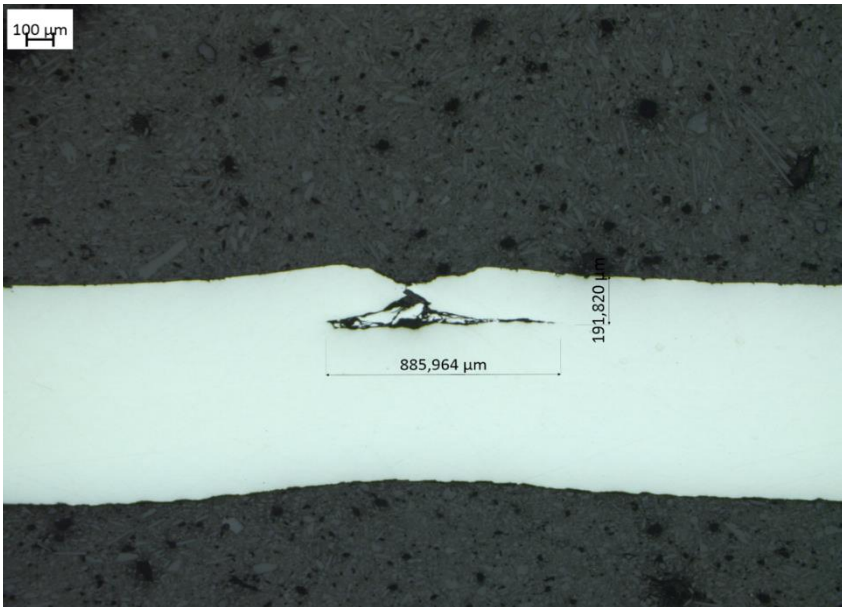

Figure 37: Micro section of weak pronounced u-curve fault

The position of the cut is marked by the black line in Figure 36. It can be seen that the u-curve below the crack (marked by the red arrows) is almost invisible. The micro section of the crack shows some kind of inclusion in the material (Figure 37), which again is near the surface. In Figure 38 an additional inclusion is found near the main crack.

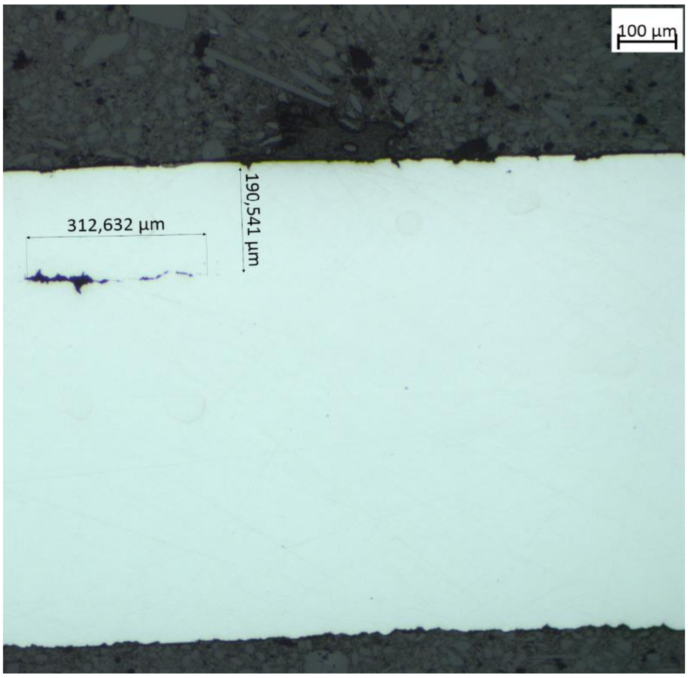

Figure 38: Additional inclusion near the crack

5.3. Executed tests

To see what could affect the final product in terms of outage and to find which fault in the raw material could lead to the typical u-curve shape in the final part, some general tests were executed.

5.3.1. Anisotropy

Due to the production of sheet metal, the behavior of the material depends on the stressed direction. This phenomenon is called anisotropy. To eliminate the possibility that failures in the final product occur during the deep drawing process out of direction dependency, there were some tests implemented. The raw plates, which are stamped out of the sheet metal, were twisted for 45˚ and 90˚and then fed into the deep drawing process. The twisting was done automatically by a twisting mechanism in the machine. For each variation of the direction one lattice box was filled (approximately 2500 pieces) and sorted afterwards. The sorting did not show any trends of higher or lower failure rate than the average, which shows that the anisotropy does not influence the total outcome of deficient products. However, it still influences the deep drawing behavior in terms of tolerances. The outcome of proper products depends on the rolling direction but not the amount of defective products.

5.3.2. Surface scratch observation

As mentioned in chapter 4 some kind of material failures are surface damages like scratches. These scratches can occur in different geometric forms. They reach from a few millimeters to a couple of meters in length and from a fraction of a millimeter to a few centimeter in width. The depth of the scratches could be from a fraction of a millimeter to a complete crack, which does not occur very often. To see the influence of the different scratches on the deep drawing process, the faults in the material were marked with a permanent marker and observed during the whole process. It was observed that scratches did not lead to proper cracks on the final product. They elongate in length or width depending on the relative direction of the scratch to the drawing direction. To observe the influence of scratches, depending on the rolling direction, deep scratches were made artificial. They were arranged in rolling direction, 90° to rolling direction and 45° to rolling direction (see Figure 39).

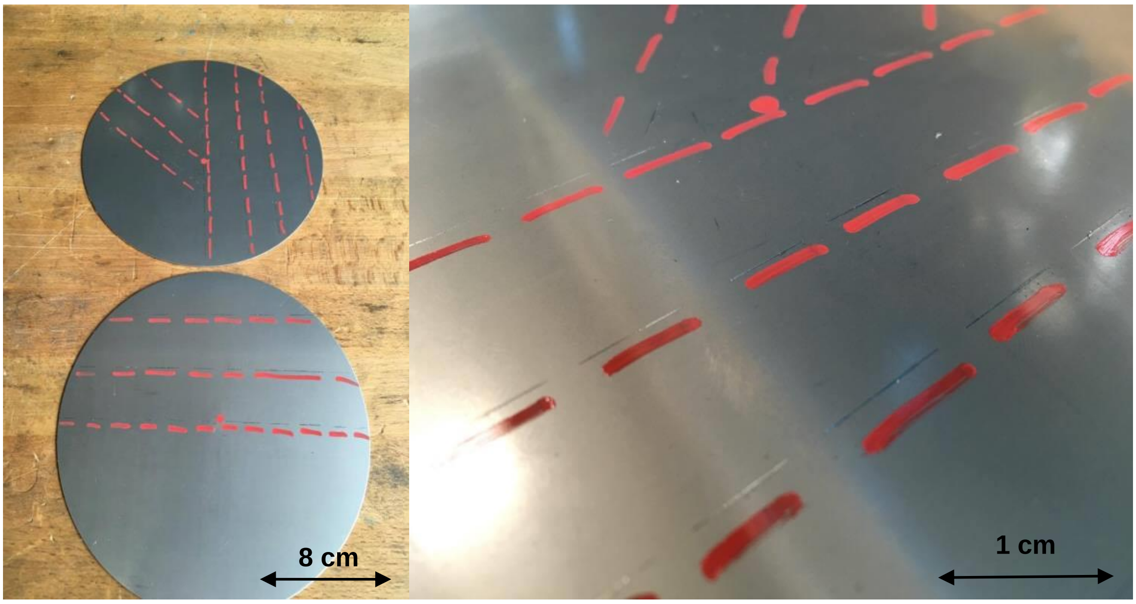

Figure 39: Artificial scratch observation

These scratches also lead to elongated scratches in the final part, but not to an outage of the part. The former straight scratches in rolling direction, 45° and 90° to rolling direction were shape into the typical u-curve form.

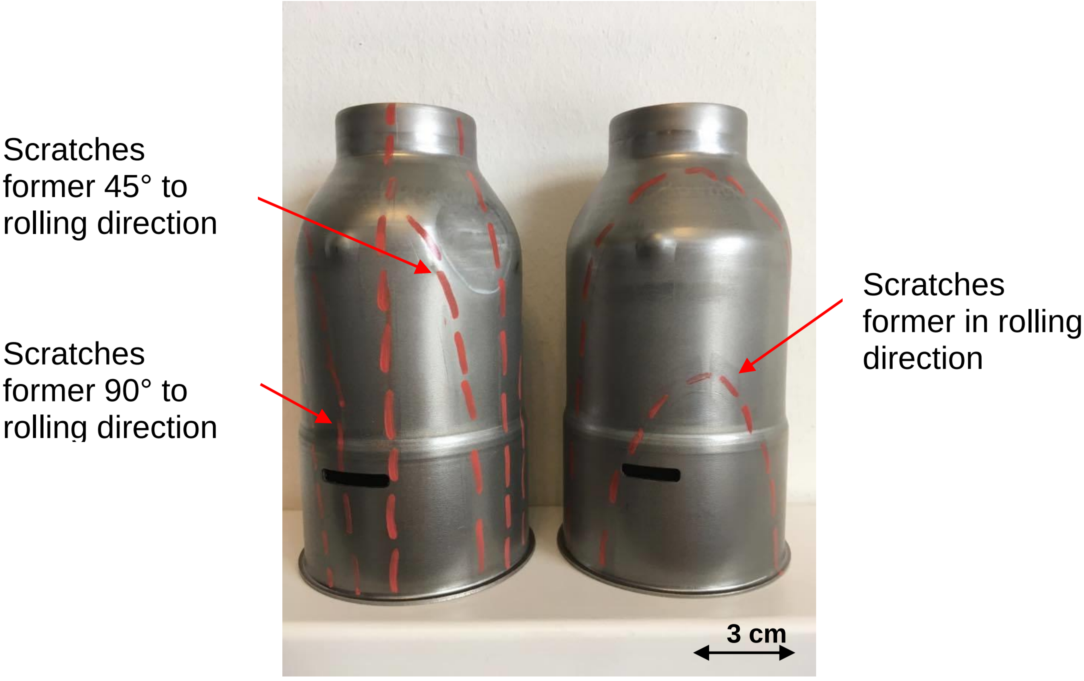

Figure 40: Artificial scratches after deep drawing

5.4. Observation of the raw material

In all previous investigated examples it is still impossible to say if the outage causing factors are either doublings or inclusions. According to the steel producers ("ThyssenKrupp") the issues that lead to such u-curve cracks are inclusions. However, to confirm this assertion, further investigation is necessary. Probably the outage causing fault is not detectable by surface investigation, but by looking into the material. Because of this reason the raw material is investigated under laboratory conditions with different non-destructive testing methods, ultrasonic testing, industrial radiography and eddy current testing.

5.4.1. Microsections of the raw material

An alternative to non-destructive testing is a destructive observation of the metal. With such method under laboratory conditions the main reason for outage can be observed and determined. For this purpose the raw material was cut open, polished and observed with a microscope with an enlargement of 200.

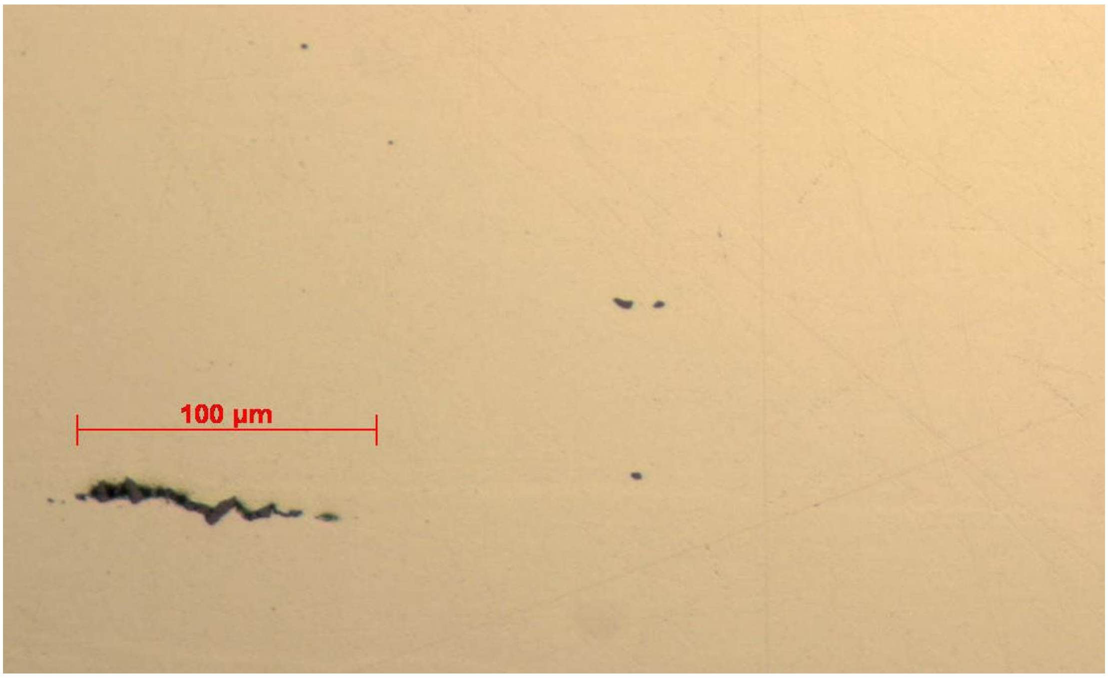

Figure 41: Microscopy (200X) section A

As seen in Figure 41, there is a linear constellation of inclusion with a size of around 100μm. Besides that, there can be seen some particularly smaller, dot shaped inclusions obvious smaller than the linear one.

In Figure 42 there can also be seen some smaller inclusions with sizes around 5μm.

Figure 42: Microscopy (200X) section B

While Figure 41 and Figure 42 are non-etched, the next microscopy are etched. Figure 43 as well shows some linear constellation of inclusions with sizes around $10\mu m$.

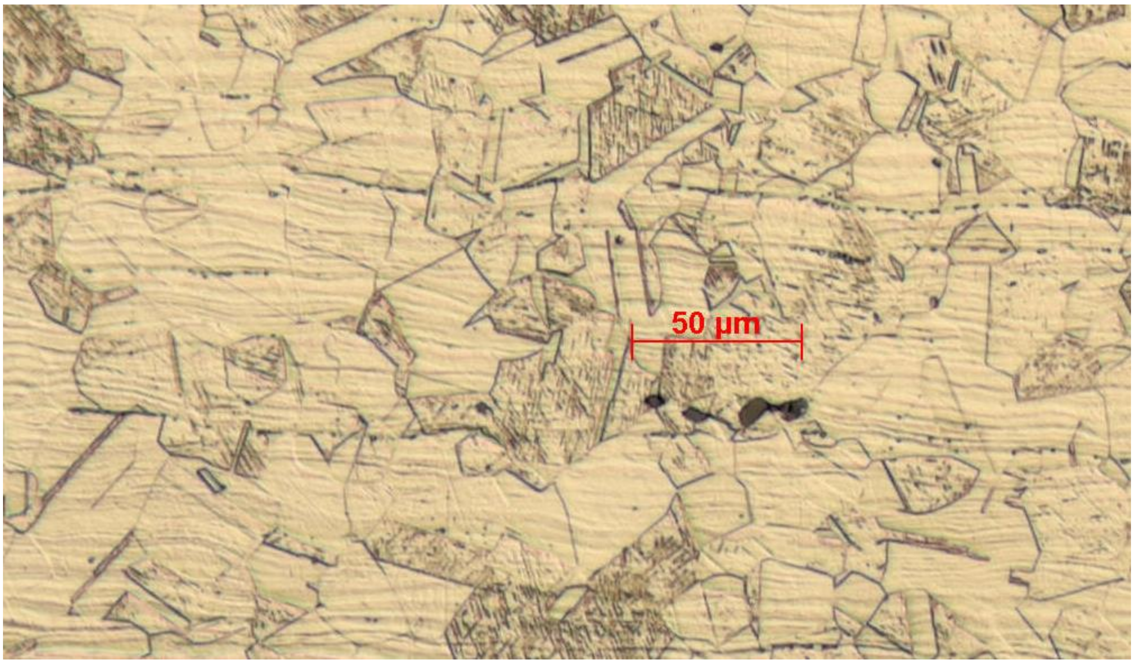

Figure 43: Microscopy (200X) etched

6. Assessment of the testing methods

Although all non-destructive testing method mentioned in chapter 2.2 are theoretical possible solutions, there are some boundary conditions which make some more suitable than others. In this chapter all testing methods are compared and discussed to get an insight if a method is suitable for the given issue or not. Afterwards the realization of some tests of found providers for different testing methods are presented. Concluding some possible implementation strategies in the established process are shown.

6.1. Discussion of the testing methods

All possible testing methods are discussed and evaluated regarding different parameters such as detectable fault spectrum, specific experiences, testing speed complexity, installation space and risk potential. The insights come from discussions with consultants and experts in their respective fields and self-knowledge after working through literature.

6.1.1. Industrial Radiography

Industrial Radiography brings the best resolution with it. Both surface faults and faults in the material are representable with good accuracy. One constraint in representable faults is doublings in sheet metals. Due to the fact that doublings take a bigger area in the horizontal axis than inclusions but are very small in the vertical axis compared to the overall thickness of the sheet metal, the attained contrast is not high enough to build an accurate picture of the fault. One other issue with this testing method is the slow measurement velocity, which would not fit to the forming speed of the used multi station press. The high costs and high potential risk in terms of carcinogenic effects on the human body mean that this system is not suitable for an industrial application.

6.1.2. Thermographic Inspection

Thermographic inspection systems are theoretical very good non-destructive testing methods. There exists some experience for specific applications. However, after consulting with experts in the topic thermographic inspection, there were many issues raised against this method as a suitable solution. It is possible to detect surface faults if the surface is free of contamination like oil or other dirt, but detecting faults within the material is almost impossible because of reflections of the high reflecting surface of the material. Additional outside influences like downlights or other applications in the shop floor could make the result more sophisticated. This issue can only be fixed through a very complex setup to seal the measurement from environmental influences. The risk potential of such a system, depending on the insertion principle, is manageable. Furthermore the heat insertion in the material is problematic. Inductive insertion would be possible, but the resolution would not be accurate enough to visualize small faults like inclusion. One other insertion method would be laser insertion. However, this method would be impossible for Magna’s industrial application because the energy insertion would require too much time. Because of these reasons thermographic inspection is more suitable for laboratory applications than for industrial applications.

6.1.3. Quality Tracking

Quality tracking is a futuristic approach of implementing industry 4.0 in steel production industry. Although this attempt is very good, the demand for such accurate testing of the sheet metal as needed by Magna is not yet given. Out of this reason EUROFER is not planning in detecting material faults in the wrought material. The only testing method is inspecting the surface via ASIS. For the future it is envisaged to convey information like mechanical properties or local thickness to the customer.

6.1.4. Optical Inspection

Optical inspection is a very basic approach to investigate faults in sheet metals. This type of non-destructive testing can be done manually and automated. Since manual optical inspection, done by staff, is very exhausting for the workers and difficult to hold a predefined quality, it is a high financial burden as well as an increased potential for defective products. In contrast to that, the automated optical inspection nowadays is very accurate and also works for high cycle times. It is possible to detect very small faults on the surface due to a very high contrast ratio. There exist lots of different providers for such systems, which means that there exists lots of experience. The optical applications are very compact in terms of installation space. However, the big constraint that goes along with optical inspection is that only faults on the surface can be detected. Furthermore the differentiation between faults on the material and dirt or oil on the material is very difficult which leads to a requirement of constant surface texture. The risk potential for such an application is equal zero. Optical inspection systems consists of cameras that are very good in terms of installation space.

6.1.5. Eddy current testing

Eddy current testing methods are usable for detecting faults in the material as the faults are on the surface or near the surface. Since the used material is very thin, this application is usable for the given issue. There exists experience in measuring sheet metals. The needed installation space is assessable and the measurement time is quite short. With enough reference data in the system, eddy current is capable of comparing the generated data from one measurement cycle with the stored data, which lead to measured result of more than 6 mechanical properties of the material (“3R-Technics” see Chapter 6.2.2). Since the mechanical properties are dependent on the homogeneity of the material, the change of mechanical properties can be directly converted to faults in the material. However, the algorithm behind the measurement application is quite complex and could cause some problems after implementing. This system needs some learning time to have enough comparable data. The installation space is manageable due to inspecting sheet metals with the given width, only requires one inducing test probe. The risk potential is also manageable but could be a problem for staff with heart pace maker.

6.1.6. Ultrasonic testing

Ultrasonic testing is widely used in inspecting oil pipelines for breakages and fractures, which means that there exists lots of experience for industrial applications. These systems run at very high inspection speed. The detectable fault spectrum is quite good since faults in the material as well as faults on the surface can be detected. Depending on the thickness of the tested material the test probe´s frequency has to be lower for thicker materials and higher for thinner materials. Since there are no applications available for sheet metals with thicknesses of around 1mm, the test probes have to be custom made which is very complex and expensive. One further point is that the range of one single test probe is quite small which leads to a requirement of many test probes in a row to inspect the whole width of the sheet metal which also dramatically increases the price and the installation space for such an application. The test probes have to have direct contact to the tested material via a coupling device (except laser excitation) making the installation space bigger and increases complexity. However, the risk potential for such applications is equal zero. One further excitation principle is laser excitation which has a higher possible resolution due to a higher achievable frequency. Since there is no coupling device necessary, the relatively free installation possibility of the device is a big advantage. However, according to specialists in this area, the measurement time is too long and the complexity is too high for testing the raw material in-line.

6.2. Executed tests

In the following passage some executed tests in cooperation with the companies Mittli (ultrasonic testing) and 3R-Technics (eddy current testing) are presented. This is done in order to evaluate the possibility of a practical use of application for each testing method as well as to evaluate the competences of each company.

6.2.1. Ultrasonic testing with Mittli

There was the possibility to evaluate the non-destructive testing method ultrasonic testing via a portable testing device. For this reason some probes of the raw material with a high possibility of containing faults were collected. These probes were cut out of coils with an outstanding percentage of defective parts.

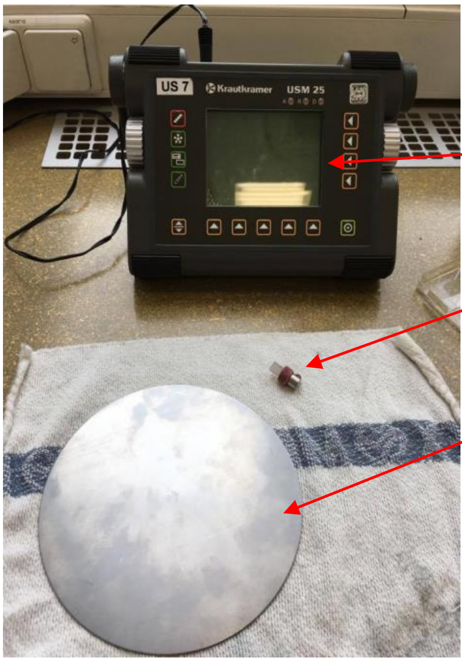

Figure 44: Ultrasonic testing setup

At the company Magna Steyr, there is a department for non-destructive testing. In this department they have a portable testing device (GE Krautkramer USM 25) which can be used to see the functional principle of ultrasonic testing under laboratory conditions with an expert in this field. In the beginning it was said that testing austenitic steels in general is very difficult for ultrasonic testing devices because of their big grain size and that the right testing probe is very important. The thinner the tested material, the higher the frequency of the testing probe should be. The used test probe was designed for 15 MHz, the used coupling device was ordinary machine oil and the tested material was stainless steel (1.4301) with a thickness of 0,8mm. (see Figure 44) The evaluation of the acoustic velocity was done automatically by the testing device. The only parameter that had to be rendered was the materials´ thickness. The outcome of this testing is that the solution of the zone between the entry echo and the backplane echo is too small to see accurate echoes from potential material faults like inclusions or doublings. The reason for this issue is the testing probe. The pulse length of the 15MHz testing probe is too big to see a proper reflection on potential faults in the material. A testing probe with a higher frequency is needed, according to the expert; such thin materials need a testing probe with more than

20MHz. Since this kind of testing probe was neither available nor affordable the test was concluded.

After research for further providers for non-destructive testing methods, a testing probe with a higher frequency (22MHz) was found and available. Since it was impossible in the first attempt to find faults in the raw material resulting from steel production, artificial faults were implemented in the material (see Figure 45) to generally evaluate the testing principle on such thin materials. For this purpose holes with a diameter of around 1mm, different depths (0.2, 0.4 and 0.6mm) and different distances were milled in a plate. This should represent imperfections in different areas of the material.

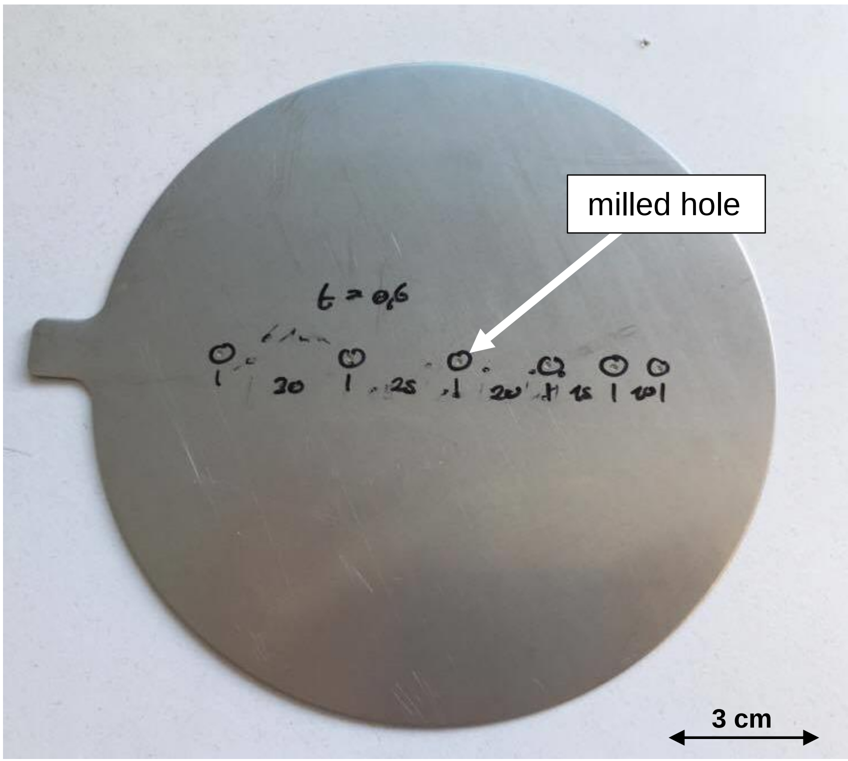

Figure 45: Artificial faults in a plate (0,8mm)

Afterwards, the testing device (GE Krautkramer USM 36) was adjusted and calibrated to the new test probe (22 MHz). After calibration the plate with the artificial faults was turned around and the discovery of possible milled holes from the other side was attempted. The coupling device was an exclusive one from General Electrics (ZG-F Ultrasonic Couplant).

The first test was done with the 0.2mm hole, as according to the theoretical background, this was the distance easiest to detect. First a reference measurement was done away from the artificial faults (see Figure 46). The peak of the entry echo is at around 0.8mm and the peak of the first backplane echo can be found at around 1.6mm, which is accurate for a plate with a thickness of 0.8mm. The range between the entry and the first backplane echo is the area to observe potential faults. In Figure 49 the echo of artificial fault in a depth of around 0.6mm can be seen. Because of the reflection on the fault that leads to a reduced amount of waves going to the backplane, the backplane echo is weakened.

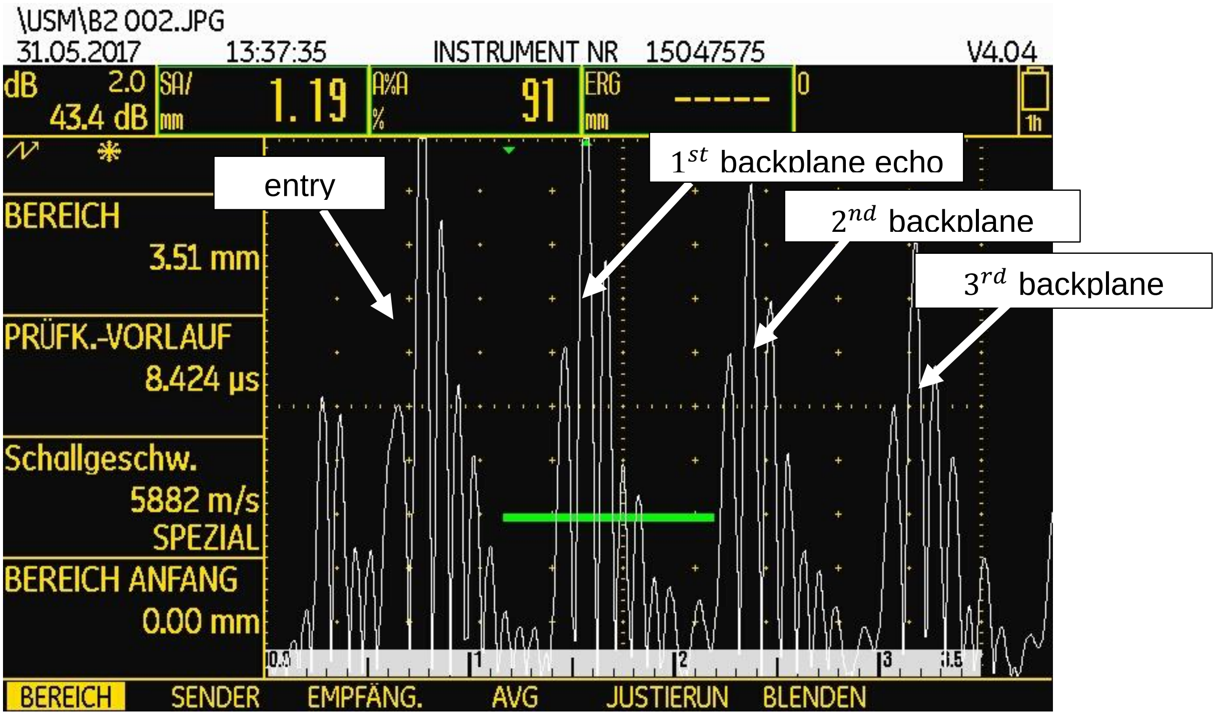

Figure 46: Reference testing of 0.2mm hole

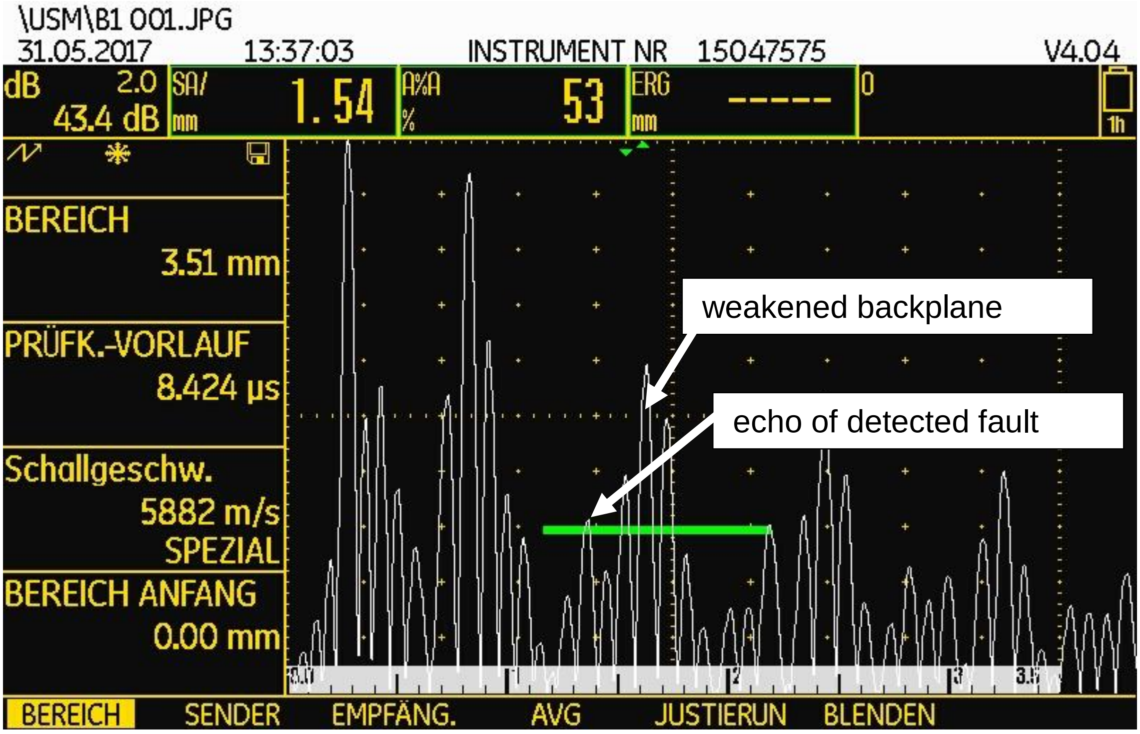

Figure 48: Found fault of 0.2mm hole

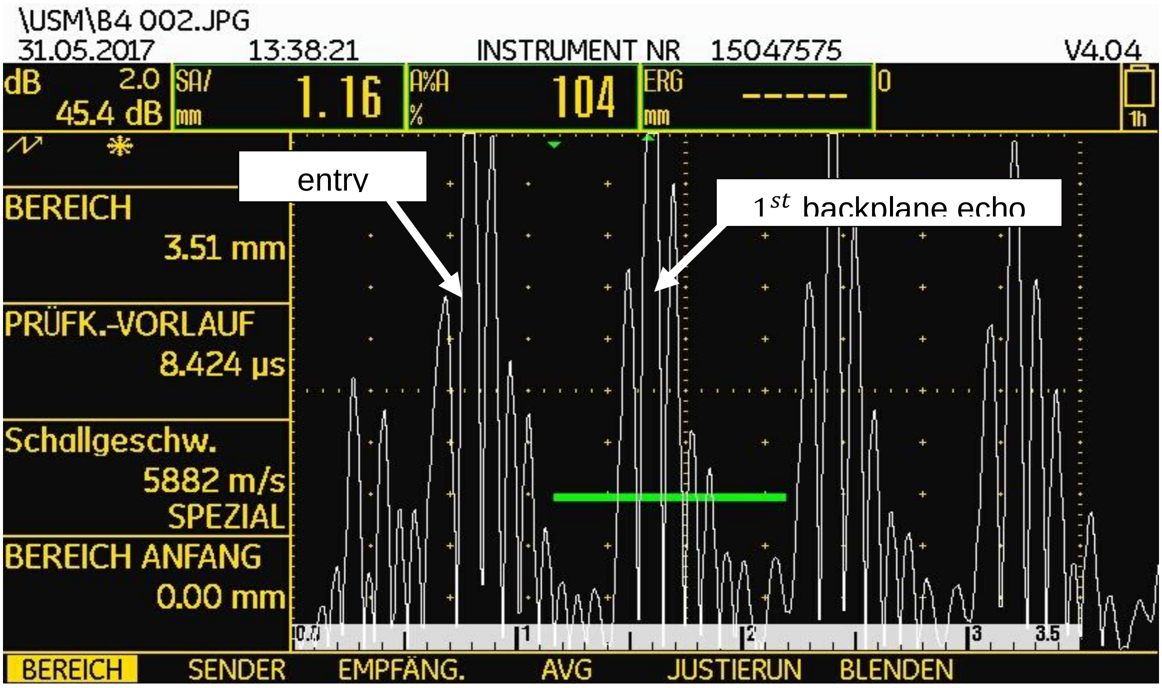

Figure 47: Reference testing of 0.4mm hole

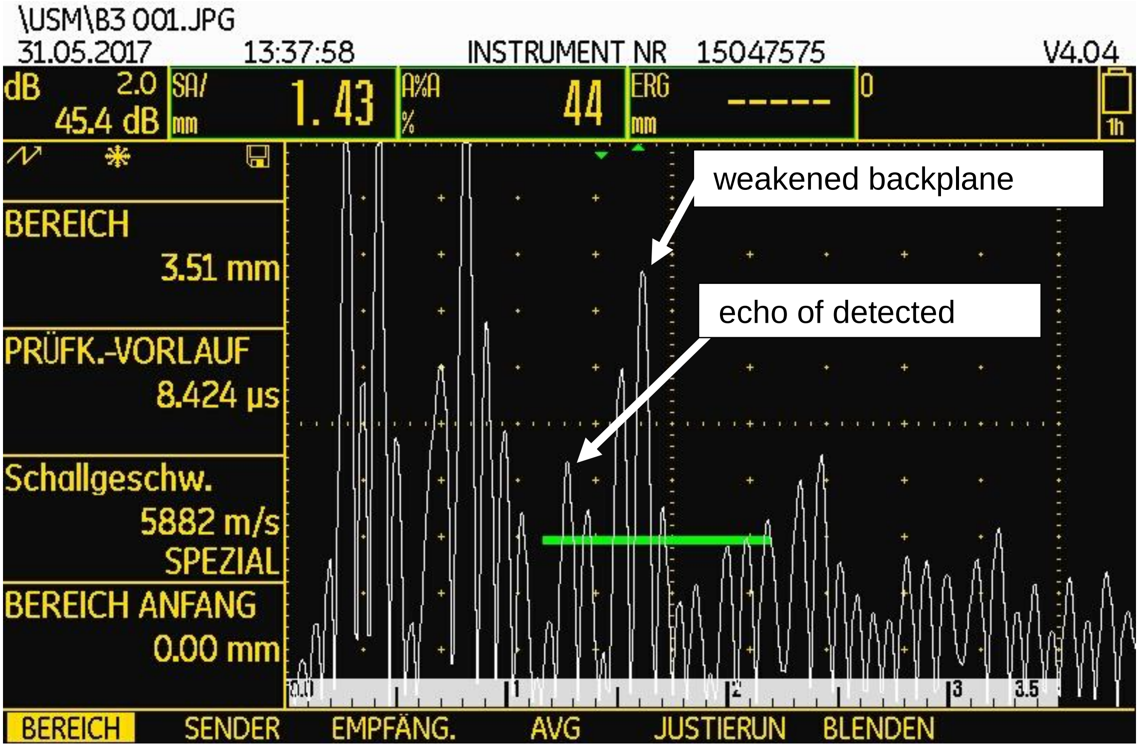

Figure 49: Found fault of 0.4mm hole

The same constellation of the echoes can be seen in Figure 47 as the reference testing of the 0.4mm whole plate and in Figure 49. There are no visualized test results of the 0.6mm hole plate because there were some issues. Due to the fact that the artificial fault was only 0.2mm under the surface, there was too much of the ultrasonic waves reflected to early. This means that the test probe was not able to catch the reflecting waves to get an appropriate deflection. This results in a so called “backplane echo mitigation” which could be seen as a collapse of the backplane echo. Since it was not possible to freeze the picture during that effect, there are no diagrams to show.

6.2.2. Eddy current testing with 3R-Technics

Since it is very important for the company to keep the investment risk as low as possible, it is key to find a company that has experiences in automated measurement applications. Through research in terms of non-destructive testing devices and companies which have experience in this topic, “3R-Technics” was found. 3R-Technics offers customer specific system solutions for material identification, material properties acquisition and in cooperation with a hardware company automated complete solutions for industry. They developed measurement concepts with high-performance algorithms as well as modern measurement methods. The possible measurement system for the solution of Magna´s issue was based on multi frequent eddy current measurement. This systems works with up to 48 different measurement data per measurement depending on the frequency. The higher the induced frequency, the nearer on the surface of the sheet metal is observed and the smaller the measured zone. Within one measurement cycle different frequencies are induced to generate a high range of different data from a preferably big measured area of the observed metal. The generated measurement data is automatically processed by integrated mathematical models and algorithms. The measurement systems works quantitatively, which means that a basic reference condition have to be learnt in advance. The mathematical models compare the actual state with the reference data. It is possible to evaluate more than 6 measurements, like yield strength or tensile strength simultaneously. The accuracy of the test, according to 3R-Technics, is in the order of the tensile test. To verify the company's promises, again some probes of the raw material with a high probability of defective sections (marked with a minus), as well as some reference probes (marked with a plus) were cut out of different coils and sent to 3R-Technics. The company has a testing device to test under laboratory conditions to see in a first attempt rather finding potential faults are possible or not. The geometry had to be adapted to the testing device in terms of dimensions (30cm x 30cm) and each probe had to be even. Since the cut out probes were prior rolled on a coil, each sheet was a little wavy. To counteract the waviness of the probes, each piece had to be plan set by another company. It is necessary to mention that it was important that all probes had to be plan set in the same direction due to the sensitiveness of the measurement device. If the probes were rolled in different directions, different internal stresses would occur which would lead to different parameters and distorted results. After setting all boundary conditions of the probes (in sum 21 pieces), the test could be conducted.

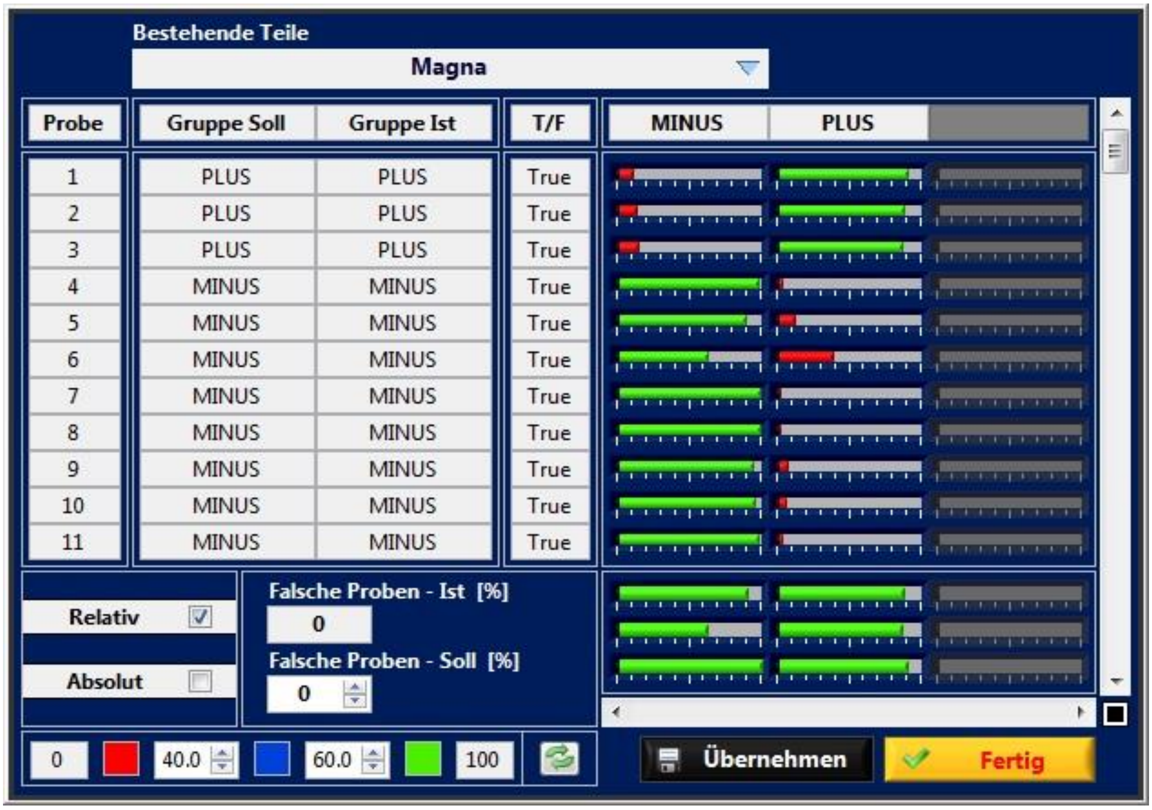

Figure 51: 3R-Technis results 1/2

Figure 50: 3R-Technics results 2/2

As seen in the print screens of the used 3R AMI software, represented by Figure 51 and Figure 50, all 21 probes could be exactly determined rather they are defective (minus) or not (plus).

6.3. Implementation of the testing application

The found testing application has to be implemented in the established process, ideally without any disruption in terms of material flow and without any additional working steps of the employees. Different implementation strategies have different impacts on the process. The aim is to improve the process in terms of outage without disturbing the process steps. In fact the topic of implementation spawns two issues, at which position the application could be installed and how to deal with a defective area in the raw material after detection. The possible positions for implementing the application are restricted through installation space and operating principle of the testing application. As seen in Figure 52 there are three possible positions, one between the straightener and the stock oiler (1.), one between the stock oiler and the mechanical blank cutter (2.) and one directly after the blank cutter (3.). Since the geometry of the formed part is too complex for an appropriate measurement, it would make no sense to

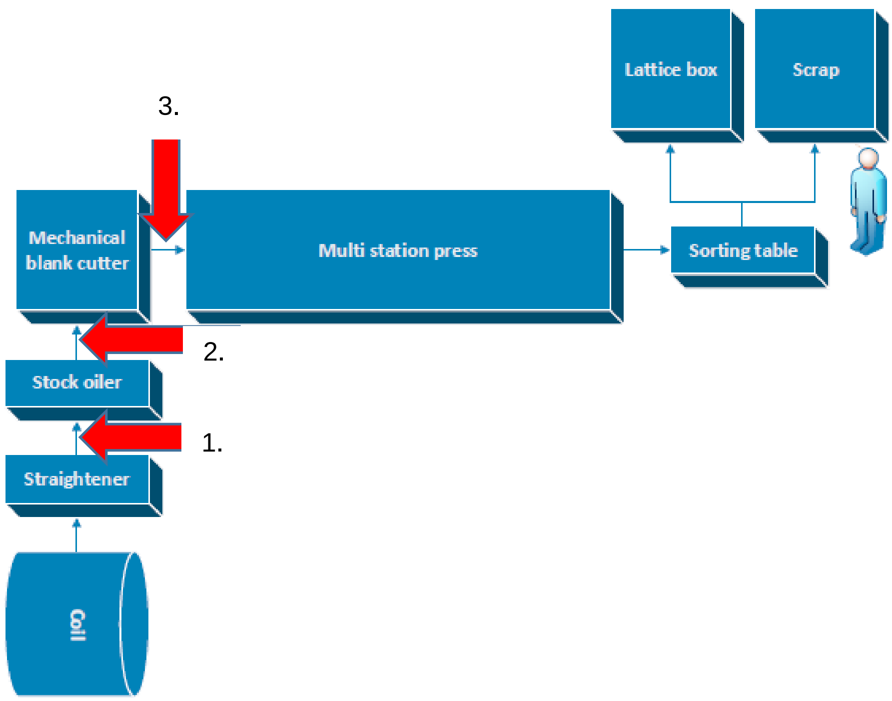

Figure 52: Possible implementation positions in the established process

implement the testing application after the formative process step. Also the position before the straightener is unsuitable because of the unequal conditions (e.g. internal stress, waviness, etc.) of the raw material. The position after the straightener (1.) is a good place for optical inspection, ultrasonic testing with laser excitation or eddy current testing because no disturbing layer of the drawing oil is yet added. Actually at this point the sheet metal is cleanest. However, dirt like dust, metal shavings or other loose particles have to be removed by a brush. The position after the stock oiler (2.) could be an appropriate solution for ultrasonic testing with conventional piezo electric excitation. This position would bring a large advantage that the deep drawing oil would also conduce as a coupling device. This means that no additional application to apply the coupling device on the sheet metal is necessary. The position after the mechanical blank cutter (3.) is difficult. At this point in time the plate has already been cut out of the raw material which leads to a redundant complicated observation of each plate separately. However the advantage of this position is that only the actual part is observed and not the material around it. One other possibility without influencing the process at all would be an external solution. Within this solution the coil gets unwound and wound up on another coil. In between the wrap round, the raw material gets observed. The found faults have to be marked by for example a spray can with easily removable paint. An exemplary application is visualized in Figure 53. The observed material goes through the process chain and is sorted out automatically after the formative process. This could be done by a combination with an optical inspection application, which focuses on the color indicating a defective part. However, beside this advantage, there is also a disadvantage to this solution. The wounding of the coil causes an additional setup and additional working steps, which needs labor force, which in turn causes additional costs.

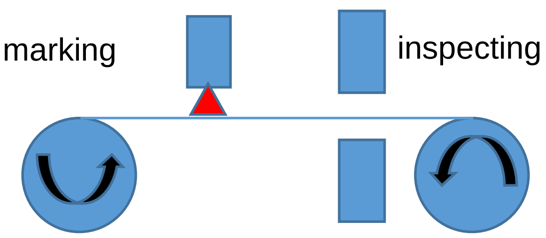

Figure 53: External inspection setup

A further solution is implementing the measurement application after the straightener (1.) or after the stock oiler (2.) at a clear defined distance to the mechanical blank cutter. Once the measurement application identifies a fault in the unrolled sheet metal and the distance to the blank cutter is known, the feed speed can be accelerated so that the fault is by passed by the cutter. On the one hand this would lead to an increased amount of scrap of the raw material, but on the other hand the process itself is not influenced that much and the implementation is rather simple. The biggest issue within this solution is faults over long distances in the sheet metal. If the fault is too long so that bypassing the fault within the given time of the machine stroke is not possible, the machine would have to drive an empty run which is not permissible due to different aspects. Another solution would be a direct overleaping of the defective area. In Figure 54 the established cut pattern is visualized. If there is a fault detected in advance (visualized as an x), the defective area simple gets overleaped. However, again there is the issue of the possibility of huge defective areas.

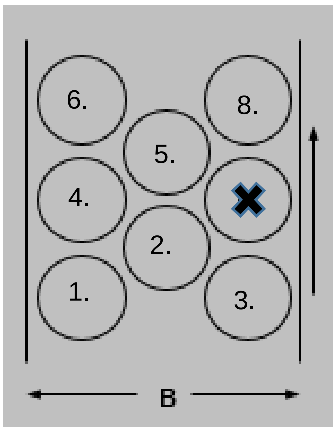

Figure 54: Cut pattern

To eradicate the issue of the previous solutions, the implementation of a deposit of pre-cut blanks could help. In the case of faults over long distances, the deposit would inject the pre-cut blanks in the formative part of the process to increase the time for feeding the defective raw material and to avoid empty runs. However, this solution also has a big issue. The blanks for the deposit have to be cut in advance, resulting in additional working steps and labor force, and therefore increased costs. Also the implementation of the deposit construction is really sophisticated and expensive.

7. Results

This chapter represents the results of the done work. In the beginning the outcome of the fault determination is shown, afterwards the outcome of the cooperation and consulting with different companies and employees, the results of the executed tests as well as the evaluation and ranking of the best non-destructive testing methods for the given issue is shown.

7.1. Fault determination

The outcome of the executed tests in chapter 5.3 lead to the conclusion that the anisotropy that comes from the rolling process during sheet metal production does not influence the amount of scrap regarding deficient products. However, it does influence the deep drawing behavior of the material.

The second result finds that scratches on the raw material´s surface does not lead to the harmful u-curve error pattern. But the executed test shows that former straight lines of scratches on the raw material lead to a u-curve shape after deep drawing on the final product. This leads to the implication that, whatever fault is in the raw material, the shape of it must be straight either in rolling direction, 45° or 90° to it.

Of course the forming process itself includes a high potential on the outcome of the final part. For the sake of completeness it has to be mentioned that the forming parameters could have been modified to see the influence on the final parts. Since the company has long-term experience in deep drawing these parts, it could be barred that these parameters are causing the high number of scrap and are chosen correctly.

The microscopies in chapter 5.4.1 clearly show some inclusions could lead to the harmful u-curve fault during deep drawing. After conducting the scratch observation in chapter 5.3.2, the insight was generated that the faults in the material must be linear to get a u-curve after forming the raw material. The microscopies also confirm this hypothesis since most of them are in a linear constellation.

After consulting with one of the biggest steel producers, ThyssenKrupp, it was clear that the searched fault causing the huge amount of outage is attributable to the steel production. During the production process (see chapter 2.1) inclusions are formed in the raw material. The sources for these inclusions are the recycling of scrap metal (endogenous inclusions) and residues of fire resistant materials like casting powder (exogenous inclusions). This assertion is supported by the fact that the amount of scrap increases during periods of high recycling at the steel producer (an increase from 3 to up to 10%). These inclusions prevent the material from properly flowing during the forming process, which leads to the material bursting along the area of inclusions.

7.2. Appropriate non-destructive testing method

This chapter represents the insights of consulting with different providers for non-destructive testing applications, as well as the results of the executed tests done in cooperation with them. Conclusive a use-value analysis is presented to see the outcome of the evaluation of the different testing methods.

7.2.1. 3R-Technics

The first insight of the conducted tests under laboratory conditions in cooperation with 3R-Technics was really promising due to the fact that all probes could be differed between defective and non-defective (see Chapter 6.2.2). One big advantage is that a similar system that would fit Magna´s issue has already been implemented in the automotive industry, which brings lots of experiences in this field. This application works with two measurement coils in the test probe to minimize the measurement time, approximately 0.22 seconds. This enables a clock cycle of the deep drawing press of around 80 lifts per minute. The multi station press of Magna has a maximal clock cycle of around 50 lifts per minute. Also the price is affordable compared to other systems. The application for one multi station press would be around 150.000 € for the software, the inducing testing probe as well as the electronic behind. However, there exists an issue, a learning curve is necessary so that the system has enough reference data to compare via an algorithm, whether a segment of the coil is defective or not. The determination of a tolerance samples is quite difficult since the sum of different fault patterns on a segment is really high. The retraction of this learning curve could cost a high amount of additional money without a guarantee that the system is continuously running satisfactorily. This issue leads to a very high investment risk.

7.2.2. Mittli

The company Mittli is a dealer for non-destructive testing applications like ultrasonic testing, industrial radiography and many other techniques. However the cooperation with this company focused on ultrasonic testing with conventional piezo electric excitation testing probes. As seen in chapter 6.2.1, it was not possible to detect any natural occurring faults. Because of this, artificial ones were made to get an insight in the working principle of such systems. Even though the milled wholes were too big, compared to inclusions how they occur in the material, the testing results were not satisfying. It was possible to detect the holes, but the adjustment and the search for them was very sophisticated. This system could work for laboratory applications but not for industrial ones. Furthermore, the expert concluded that inclusions with approximately 5-10μm of size, are not detectable with these testing devices due to the weak frequency and inferential of the weak solution of the testing probes. One further insight during these tests was that the interpretation of ultrasonic testing results needed in depth experience. Non-experienced workers could interpret for example interferences of pulses as reflection of inclusions. A long time is required to gain enough empirical knowledge to operate ultrasonic testing devices correctly, and in the case of industrial applications it would need a very long learning curve. Furthermore, the proposed price of such an in line system would be disproportionately high. The testing probes, which would be customized probes, since there are no standard testing probes for such an issue, would be over 1000€ each. As a single probe has a testing width of only a few centimeters, there would be a huge amount of probes needed. The estimated price for the electronic around the testing setup would be around 200.000€ and the price for the software is not yet appreciable. The resulting price would be too high to amortize within an assessable amount of time. The resulting price, the weak resolution of the measurement and the slight experience lead to the conclusion that a testing application using commercial ultrasonic testing probes is not suitable for the given issue.

7.2.3. Recendt

The company Recendt (Research Center for Non-Destructive Testing) offers a special kind of ultrasonic testing method. As briefly introduced in chapter 2.2.4 ultrasonic testing can be excited by different physical principles, one of them is laser excitation, which is actually the used technology of the company Recendt. While all other conventional excitation principles for example, piezo electrical excitation, use a separate device to produce the ultrasonic wave, with laser excitation the tested material itself produces the ultrasonic wave, which has many advantages. One big issue within the implementation of a conventional ultrasonic measurement system is the requirement of a coupling device like oil or water to conduct the ultrasonic wave from the excitation device into the testing material. This requirement is void while using laser excitation because no direct contact with the material is needed. Additionally, the direction of the produced waves are independent of the direction with which the laser is pointing on the material. This leads to the possibility of a more flexible implementation of the system in the established process. One concern was that the laser could damage the material or change the material´s properties within the excitation process. In fact, it does damage the material´s surface but in such a small range that it is negligible. The laser removes about 10 nm of the material´s surface, but it doesn´t change the material´s properties during the heat insertion. One further advantage of this system is the possibility to detect with a very high resolution, with a frequency of about 100 MHz Compared to other ultrasonic excitation systems the resolution is up to 4 times better. Due to the fact that exogenous inclusions have a size around 5 to 10μm, which is undetectable with conventional test probes with an average frequency of around 20 MHz, laser excitation would be a suitable technology. While during conventional excitation methods the requirement of a high number of testing probes is necessary because of a raw material width of 470 mm and a small testing width of the test probes, laser excitation can work with only one laser. This is possible because of the opportunity to fan out the light linear over the whole width. This results in a much smaller investment for the application. However, beside the advantages there is also one issue. The use of such a laser (Nd:Yag fiber laser) includes a high risk potential due to the fact that it is in the laser safety class 4. Lasers in this class are the most dangerous ones. They can damage eyes or even burn the skin with direct or even indirect irradiation. This fact requires an additional safety construction like capsulation of the detection area and safety goggles for employees, which adds to additional costs.

7.3. Use-value analysis of the testing methods

On the following page shows a use-value analysis of all potential non-destructive testing methods. The numbers are aligned with the discussion of the testing methods in chapter 6.1. This analysis focuses on some appraisal criteria that seems most important for the decision what testing method suits best. The given points reach from 0 to 10, where 0 is worst and 10 is best. This analysis uses loadings to weigh the different parameters regarding their importance for the needed application. The most important parameter is the specific experience (30%) as systems with less experience entail too much risk regarding impeccable working within the process. Followed by the detectable fault spectrum (20%). A provider (15%) who is capable of producing the needed application should be available because otherwise the risk and the cost are too high. Of course also the costs (10%) are very important. The system´s complexity is weighted with 7.5%, followed by the measurement velocity with 5%. The most unimportant loading is the installation size weighted with 2.5%. The committed points are multiplied with the loading to get a weighted number. These numbers are summed up in the end and compared with the others to get a ranking of the testing methods. The percentages in the yellow row are the proportions of the maximum reachable points (80 points for the unweighted and 10 points for the weighted categories) and the given points for each testing method. This number shows how much percentage each testing methods fits to the given issue. The more expressive value is the weighted one due to the fact that this shows the percentage of the prioritized categories. The outcome of the use-value analysis shows that there are two non-destructive testing methods which fits best for the given issue, eddy-current and ultrasonic testing. Both of them have an adequate range of detectable fault spectrum. The costs of both are quite high. Ultrasonic testing needs a high investment because of the high amount of testing probes that have to be custom made. With eddy-current testing there is a learning curve for collecting the reference data whereby the duration is not predictable resulting in high additional costs. The specific experience of both of them is given, even though it is not guaranteed that the applications work properly on the given boundary conditions in-line. The risk potential and the complexity of eddy current testing are higher than of ultrasonic testing. So both of them have potential for solving the given issue. Because of the high complexity resulting from the high sensibility against environmental influences, thermography has a quite low rating compared to the former mentioned testing principles. Industrial radiography has a high-risk potential and the investment costs are too high. Even though this measurement method has the highest detectable fault spectrum, it is not suitable for in-line applications because of the weak measurement velocity. Optical inspection has absolutely no risk potential, there exists lots of experience and the design of such a system is quite compact. The detectable fault spectrum constrains on faults on the materials surface, which makes this testing method ideal for a combination since all others are for detecting faults in the material.

Table 3: Use-value Analysis

Use-Value Analysis											
Appraisal Criteria	Loading	Eddy current		Ultrasonic		Industrial Radiography		Thermography		Optical Inspection	
		unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted	unweighted	weighted
Costs	10,0%	3	0,3	4	0,4	1	0,1	3	0,3	4	0,4
Fault spectrum	20,0%	8	1,6	6	1,2	10	2	4	0,8	2	0,4
Specific experience	30,0%	7	2,1	8	2,4	6	1,8	6	1,8	8	2,4
Risk potential	10,0%	8	0,8	10	1	0	0	8	0,8	10	1
Measurement velocity	5,0%	8	0,4	6	0,3	2	0,1	4	0,2	8	0,4
Compexity	7,5%	4	0,3	6	0,45	0	0	2	0,15	8	0,6
Provider	15,0%	10	1,5	8	1,2	2	0,3	6	0,9	8	1,2
Size	2,5%	4	0,1	6	0,15	2	0,05	8	0,2	10	0,25
Sum Σ		52	7,1	54	7,1	23	4,35	41	5,15	58	6,65
Value %		65,0%	71,0%	67,5%	71,0%	28,8%	43,5%	51,3%	51,5%	72,5%	66,5%

8. Summary and outlook

The aim of the thesis was the evaluation and specification of the outage causing faults, the investigation of adequate non-destructive testing methods and a conceptual design of an implementation of the found system to detect the faults before the formative process. This system must work inline ideally without disturbing the established process in terms of throughput time. In the end, the anticipated result would have been a reduction of defective final products as well as a reduction of labor costs.

To understand the issues and the development of the outage causing faults, an investigation of the production of sheet metals was essential. The production process is the origin of all faults in the raw material, so a detailed study on the theoretical background was done. After getting an overview on this topic, a literature research on established non-destructive testing methods was done.

Towards looking on the theoretical background of sheet metal production and common testing methods, a short overview of failure causing factors on the final part was given. Possible error sources are the formative process, the staff, transportation, stocking and the raw material.

Detected faults occur on the materials´ surface like scratches, deformations, discolorations and contaminations, as well as in the material, such as inclusions, segregations and doublings. To specify the actual reason for the scrap, an observation of the raw material and the final part as well as the execution of some tests were done. The outcome of the determination of the actual outage-causing fault leads to the insight that inclusions, arising from the sheet metal production, are responsible for the burst u-curve fault pattern.

Theoretically there are many testing methods that could fit the issue. However in the end there has to be a provider who is able to fit the issue leading to a reduction of the potential testing methods. After searching for providers, only ultrasonic testing and eddy current testing for detecting in the material and optical inspection for faults on the surface were possible applications. Since it is most important for companies to minimize the investment risk for such applications, the potential provider of the chosen non-destructive testing method should at least have an adequate amount of experience. To evaluate the pre-existing experience of different providers and to be able to appraise the risks, some tests in cooperation with different providers were done. The outcome of these tests was quite sobering. Even though each testing method have some advantages, the disadvantages predominate.

Ultrasonic testing is theoretical a very good approach to detect a variety of different faults, on the material´s surface as well as in the material. Depending on the excitation principle, there exist physical restrictions in terms of detectable size of the faults. There are two providers offering two different excitation principles, piezo-electric and laser excitation. Piezo-electric excitation is the most common used form of ultrasonic testing, which lead to a high amount of experience in this field. Since the outage causing faults are inclusions in a size range of 5 to 100μm, piezo electric excitation is not appropriate for the given issue. To detect such small particles, a higher frequency of the detecting ultrasonic wave is necessary. This condition leads to another excitation principle developed by the company Recendt. Although laser excitation provides the right technology to detect inclusions, the status of experience is currently too low to justify an investment risk.

The company 3R-Technics provides another non-destructive testing method, eddy current testing. The introduction of this measurement principle was quite promising in the beginning, since it is theoretical possible to generate data regarding mechanical properties and grain size, as well as to detect a great variety of faults. Additionally there already exists experience in the automotive industry. To evaluate the promises, some tests under laboratory conditions were made leading to the following assumption. The system works satisfactorily if a huge amount of data is collected in advance. This data conduces as reference data to compare measurements with stored data to decide if a measurement reveals a defective section on the material or not. The size of data that should be collected, or how long this learning curve would last, is not predictable, which leads to high additional cost, which again results in a really high investment risk.

In my perspective there exists adequate testing methods, which theoretical fit the given issue, but the execution of them in an established process is a topic of research and development and goes along with a high investment risk. The found eddy current method is theoretical really promising, but the extent of the learning curve is currently unable to be predicted. Regarding this technology it is

recommended to wait until the provider has gained some more experience so that they are able to expect the extent until the system works properly in-line. With this information it is possible to calculate the real investment cost, consisting of the actual investment and the running costs until the system works satisfying.
Within the extent of this thesis it was not possible to do further tests with laser excitation. For future approaches, it should be focused on testing this technology under in-line conditions to gain further insights to investigate if this technology can be utilized in these issues or not. As there is no clear decision for one testing method, the decision for a suitable implementation strategy also cannot be made. However, it can be said that a standalone solution of one single testing method is not sufficient since each testing principle can only detect a range of the whole fault spectrum. If assumed that either ultrasonic testing or eddy current testing is the solution to detect inclusions, optical inspection is the perfect combination technology to detect faults on the surface. Optical inspection systems are wide spread meaning that there exists lots of experience, which in turn, makes such systems economically priced.

List of figures

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