LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering

Santtu Kovasiipi

POTENTIAL OF MULTILAYER PUNCHING OF ELECTRICAL STEEL COMPONENTS

Updated 22.5.2021

Examiner(s): Professor Juha Varis
D. Sc. (Tech.) Mikael Ollikainen

TIIVISTELMÄ

LUT-Yliopisto
LUT School of Energy Systems
LUT Kone

Santtu Kovasiipi

Monilevylävistämisen potentiaali sähkölevytuotteissa

Diplomityö

2021

76 sivua, 39 kuvaa, 6 taulukkoa ja 0 liitettä

Tarkastajat: Professori Juha Varis
TkT Mikael Ollikainen

Hakusanat: monilevylävistäminen, sähkölevy, sähkömoottori, staattori, häviöt

Sähkömoottorien käyttö kasvaa nopeasti ja niiden suorituskyvyltä vaaditaan yhä enemmän. Moottorin hyötysuhteen parantamisen ja fyysisen koon pienentämisen vaatimukset ajavat sähkömoottoriteollisuutta kehittämään yhä tehokkaampia ja pienikokoisempia moottoreita alati matalammalla hinnalla.

Työssä käsitellään sähkölevyn monilävistämisen tuomia mahdollisuuksia sähkömoottorien valmistuksessa. Monilävistämisellä tarkoitetaan usean päällekkäisen sähkölevyn lävistämistä kerralla. Tutkimus toteutettiin laboratoriokokeiden, kirjallisuuskatsauksen sekä valmistajahaastatteluiden avulla. Lisäksi selvitettiin ohuiden ja vähemmän häviöitä tuottavien sähkölevyjen mahdollistamaa energian säästöä sähkömoottoreissa.

Kirjallisuuskatsauksen yhteydessä ei löydetty aiempia tutkimuksia tai tieteellisiä artikkeleita. Monilävistämistä ei myöskään mainittu alan kirjallisuudessa. Sen sijaan aiheeseen liittyviä patenttihakemuksia löytyi useita, joten katsaus keskittyi niihin. Laboratoriokokeissa havaittiin, että monilävistäminen on mahdollista, mutta prosessiparametrit eivät noudattaneet tavanomaisia yksittäisen levyn lävistämisen parametreja. Ennakkohaastatteluiden perusteella selvisi, että valmistajat eivät pitäneet menetelmää toteutuskelpoisena nykytekniikoita käyttäen. Ohuiden sähkölevyjen taloudellinen potentiaali perustuu energian säästymiseen. Sähkömoottorin elinkaaren aikana toteutuvien säästöjen arvo nykyhetkessä laskettiin nettonykyarvon kaavalla.

Työn tuloksena todettiin monilävistämisen olevan potentiaalinen valmistusmenetelmä sähkömoottorien valmistuksessa. Merkittävä määrä energiaa voidaan säästää käyttämällä sähkömoottorissa ohutta ja vähemmän häviöitä tuottavaa sähkölevyä. Monilävistäminen on toteutuskelpoinen valmistusmenetelmä, mutta vaatii jatkotutkimuksia.

ABSTRACT

LUT University
LUT School of Energy Systems
LUT Mechanical Engineering

Santtu Kovasiipi

Potential of multilayer punching of electrical steel components

Master’s thesis

2021

76 pages, 39 figures, 6 tables and 0 appendices

Examiners: Professor Juha Varis
D. Sc. (Tech.) Mikael Ollikainen

Keywords: multilayer, punching, electrical steel, electric motor, stator, losses

As the use of electric motors is rapidly growing and their performance is required to continuously improve, the electric motor industry is demanded to constantly develop more efficient motors with smaller size and lower costs.

This Master’s thesis studied the potential of multilayer punching of electrical steel sheets. Multilayer punching is a manufacturing method where a stack of metal sheets is punched with a single punch stroke. The research was done as a combination of laboratory tests, literature review and manufacturer interviews. In addition, the financial potential of using thin electrical steel sheets in electric motor iron core was examined.

In literature review no previous research reports or scientific articles were found on the subject. Multilayer punching was not mentioned in books either. Instead, multiple patent applications with short descriptions were discovered. Laboratory tests proved that multilayer punching is possible, but the process parameters are different than in single layer punching. Based on the interviews, manufacturers question the feasibility of multilayer punching in electric motor production. Financial potential of thin electrical sheets is based on energy savings. The equation of Net Present Value was used to determine the value of savings created during electric motor lifetime in present moment.

In conclusion, multilayer punching was found to have a great potential in electric motor manufacturing. Significant energy savings are possible if thin electrical steel is utilized in electric motors. The method is feasible but further research is recommended.

ACKNOWLEDGEMENTS

This Master’s thesis was carried out as a cooperation between LUT University and The Switch during spring 2021. I want to thank my thesis examiners Professor Juha Varis and D. Sc. (Tech.) Mikael Ollikainen for great support and guidance during the work. Special thanks go to Senior Laboratory Technicians Juha Turku for carrying out all the practicalities during the laboratory tests in the University’s sheet metal work laboratory and Antti Heikkinen who guided me with macroscope examinations. Toni Väkiparta, a Laboratory Technician, did outstanding job imaging my test pieces with scanning electron microscope.
With these great people we were able to safely conduct all the necessary work at the university even though the COVID-19 situation had almost shut down all face-to-face activities.

Huge help and support were also received from my mentor Mr. Panu Hava from The Switch. He helped me with good advice and gave perspective to the writing work to see things objectively. Whenever I became “blind” to the writing, Panu could always help me to get back on track, thank you Panu. Not enough gratitude can be expressed to my employer, The Switch, and the key people there for making all this possible by being flexible and supporting my studies.

Lastly, I want to thank my girlfriend and my family for supporting me during my studies and thesis work. It must be said that the whole two years of studying has not been easy, and COVID-19 did not certainly help. Social contacts have been rare and working remotely day-to-day from our small apartment has been mentally challenging. The closest ones gave me hope and positive thoughts to carry on.

Thank you all!

Santtu Kovasiipi

Santtu Kovasiipi

Lappeenranta 22.5.2021

TABLE OF CONTENTS

TIIVISTELMÄ

ABSTRACT

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

1 INTRODUCTION 8

1.1 Electrical steel 9

1.1.1 Manufacturing 9

1.1.2 Sheet types 11

1.1.3 Chemical composition 12

1.1.4 Mechanical properties 13

1.1.5 Coatings 13

1.1.6 Magnetic properties 15

1.2 Punching 16

1.2.1 Process and phenomena 17

1.2.2 Presses for punching 18

1.2.3 Tools 22

1.2.4 Additional costs of multilayer punching 28

1.3 Electric motor 29

1.3.1 Main components 30

1.3.2 Losses and efficiency 33

1.3.3 Financial potential 34

1.4 Multilayer punching 38

1.5 Research problem 39

1.6 Research questions 40

1.7 Objectives, scope, and hypotheses 40

2 MATERIALS AND METHODS 42

2.1 Laboratory tests and analysis 42

2.2 Manufacturer interviews 47

3 RESULTS **49**

3.1 Laboratory test results 49

3.2 Manufacturer comments 57

4 DISCUSSION **60**

5 CONCLUSION **67**

LIST OF REFERENCES **70**

LIST OF SYMBOLS AND ABBREVIATIONS

H_{Ci}	Intrinsic coercivity [A/m]
HV	Vickers hardness
Hz	Hertz
T	Tesla
W	Power
W/kg	Core loss
wt. %	Percentage by weight
μΩcm	Electrical resistivity
EIC	Electrical Insulation Coating
EMF	Electromotive Force
GO	Grain-oriented
NGO	Non-grain-oriented

1 INTRODUCTION

The use of electric motors is continuously growing. One reason for this is the concern about the environment. The requirements for reducing emissions and re-using and recycling products is pushing the technological development of electric motors. The transition from combustion engine cars to electric cars is ongoing. People are starting to take the responsibility of the change for better and are educated on the subject more than ever. Demand for high performance electric motors is increasing with the popularity of electric and hybrid cars.

Requirement for more compact, more efficient, and inexpensive motors is constantly growing and it is challenging the electric motor manufacturers. Competition is fierce and the pressure to lower the price of motors and devices is increasing. The situation pushes the companies to streamline their manufacturing chain and inventing new, innovative manufacturing methods as well. Lean manufacturing methods, use of automation and robots and reducing waste, improves the overall efficiency and profitability of production. New and better materials can be discovered through research and development as well.

The efficiency of electric motors is already quite high, more than 95 %. The higher it gets the less losses there are, and the ratio of input and output energy approaches value 1. Electric motor losses occur in various ways but one of the major factors are the core losses or “iron losses”. Iron losses refer to the losses occurring in the iron core of an electric motor, which is typically the rotor and the stator. The iron core consists of thin steel sheets, which are made of material called electrical steel. This material has a high content of silicon and it has very good magnetic properties. It has been discovered that the thinner the sheets are, the less losses occur. Though, the thinner the sheets are, the more time and energy is used to manufacture the sheets. This dilemma leads to the situation where a compromise between motor performance and manufacturing costs must be made. What if the described compromise could be avoided? What if going thinner with the electrical steel sheets would not increase the manufacturing costs so drastically? Manufacturing method that enables cutting multiple sheets at once could possibly solve the problem and release new potential in the field of sheet metal punching.

This thesis focuses on the idea of multilayer punching of electrical steel sheets. Included in the work are background information about electrical steel, electric motor, and punching. A literature review to previous research and work was carried out and is presented to the reader. On practical level, laboratory tests and manufacturer interviews were made to investigate the feasibility of the method and to hear professional opinions and thoughts around the subject. The economical point of view was kept in mind by calculating the financial potential of using thinner electrical steel. Finally, the results are presented and analysed, and a conclusion is made.

1.1 Electrical steel

There are two main types of electrical steel are: non-grain-oriented (NGO) and grain-oriented (GO). Similar phases exist in their manufacturing processes but GO steel production has some specific steps for controlling grain growth and orientation in the material. Both steels can be produced in many ways which are continuously developed.

Electrical steel's magnetic properties are improved by keeping the carbon content as low as possible. This is achieved by decarburization annealing. NGO steels have isotropic grain texture, and their silicon content is between 1 – 5 wt. %. They are commonly used in rotating electrical machines like electric motors and generators. GO steels silicon content is usually around 3 – 3.3 wt. %. Their grain orientation brings desirable magnetic properties in the rolling direction of the sheet. GO steels are commonly used in applications like transformers. (Jahangiri, et al., 2014)

1.1.1 Manufacturing

Production of electrical steel has the same general phases as sheet metal production. It starts from producing liquid steel in a blast furnace from iron ore or recycled scrap steel. No major differences exist between these two raw materials when producing electrical steel. The steps in the steelmaking process determine the chemical composition of the final product and have important role in determining the electrical steel magnetic properties but mechanical properties as well. Alongside with the composition, the temperature of the liquid steel during each phase is very important. (Moses, et al., 2019).

The process has small differences depending on the electrical steel type. Non-grain-oriented grades benefit from lower reheat temperature after slab casting than grain-oriented grades because it helps to reduce fine precipitates of sulphides and nitrides in the final coil. GO grades on the other hand require high reheat temperatures because the sulphides and nitrides must be taken into solid solution in the furnace so that during hot rolling process, they can be finely precipitated. Precipitates are between 50 – 100 nm in diameter and they control the grain growth during cold mill process. The higher price of GO grades over NGO grades comes partly from the higher reheat temperatures which increase energy costs and furnace wear. New methods are constantly being developed to overcome this problem. After reheating, the slabs are hot rolled to thickness between 2 – 6 mm. (Moses, et al., 2019).

The process phases after hot rolling depend on the type of the electrical steel. Figure 1 describes the process for non-grain-oriented electrical steel with options for full or semi processing. Semi processing does not include continuous annealing, coating, and slitting of the sheet. The hot rolled strip is first pickled before optional hot strip annealing and then it is cold rolled. Pickling is done to remove the oxide layer of the hot rolled steel (Cornu, et al., 2014). After pickling, the steel can be hot strip annealed which improves the steel's magnetic properties (Mehdi, et al., 2019). Next in the process is the cold rolling of the sheet to final thickness which is commonly less than 1 mm. After cold rolling there is an option to do recrystallization, which means nucleation and grain growth in the material which improves the magnetic properties (Pan, et al., 2016). If recrystallization is not needed, then the sheet proceeds to continuous annealing phase, where the sheet is exposed to temperature between 900 °C – 1,150 °C to improve the materials magnetic properties. The soak time depends on the desired material properties. (Moses, et al., 2019). The annealed sheet is then coated, slitted and rolled into coils. If continuous annealing and coating are not needed, then the sheet proceeds to skin pass rolling phase. Skin pass rolling straightens and flattens the steel sheet, but it also affects the texture of the sheet (Mehdi, et al., 2017).

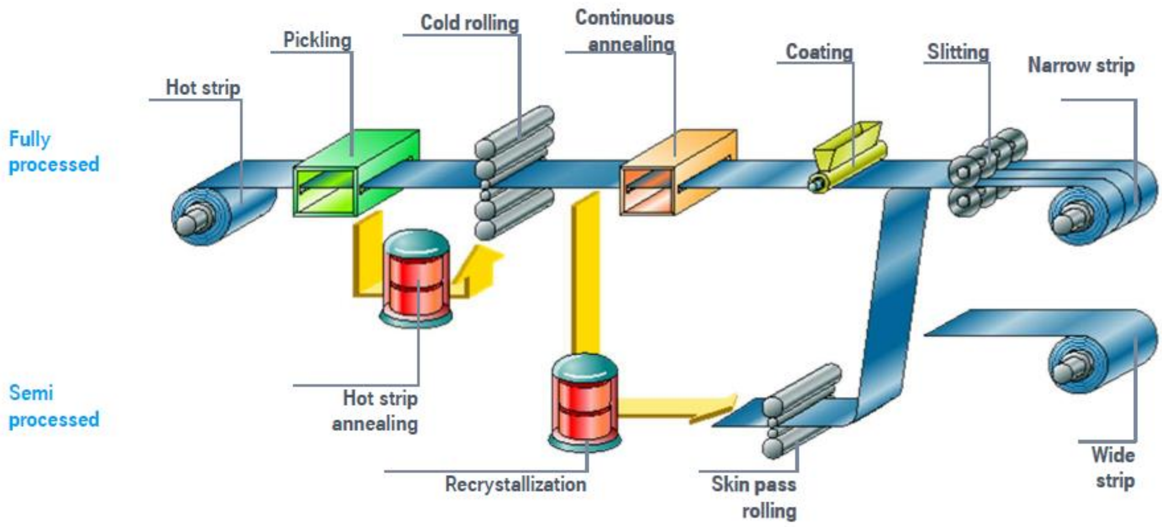

Figure 1. NGO electrical steel production process (Tietz, 2021).

The manufacturing of electrical steel is explained above, but it is worth mentioning that there are multiple variations to the process phases and methods. The industry is under continuous development and research and different process methods are carried out. (Moses, et al., 2019).

1.1.2 Sheet types

The two main types of electrical steel are grain-oriented and non-grain-oriented. As a soft magnetic material, GO steel is mainly used in transformers. Steel's magnetic properties are based on the texture of the material structure. Commonly the texture is referred as "Goss texture" according to the invention by Norman P. Goss in 1934. The texture is created during the manufacturing of the steel by secondary recrystallization which promotes grain growth and orientation. (Xie, et al., 2008).

Non-grain-oriented steel is commonly used in rotating electrical machines like electric motors and generators. As the name suggests, the texture of the material structure is not oriented like it is in GO steels. Nevertheless, they have good magnetic properties that are suitable for electrical devices. (Takeshi, et al., 2015).

Thickness of commercially available electrical steel sheets, NGO and GO, are usually in the range of 0.10 mm – 1.00 mm (Cogent Power, 2020). The trend in sheet thickness is heading to thinner sheets due to their lower iron losses. Even 0.075 mm GO steels have been studied with promising results (Menga, et al., 2021).

All electrical steels are not simple sheets with an insulating coating. There are also special products like composite sheet that has two sheets glued together with insulating adhesive. According to the manufacturer, structure-born and airborne sound levels can be lowered with this type of construction. (thyssenkrupp Materials Processing Europe GmbH, 2019).

NGO steels are graded for example as “M270-35A”. The capital letter “M” refers to electrical steel. The number “270” is hundred times the specified value of the maximum total loss at 50 Hz in watts per kilogram at 1.5 T (Tesla). Tesla refers to the density of magnetic flux at which the measurement has been done. Number “35” is hundred times the thickness of the material in millimetres. Letter “A” refers to non-grain-oriented electrical steel. (Finnish Standards Association, 2005). NO30-1600 is another example of a grade name. “NO30” refers to non-grain-oriented electrical steel with thickness of 0.30 mm. Number “1600” is hundred times the maximum core loss (W/kg) at 400 Hz at 1.0 T (Cogent Power, 2020).

1.1.3 Chemical composition

The chemical composition is defined during the steelmaking process when the liquid steel is produced. The original composition depends completely on the raw material which is either iron ore, scrap metal or both. Smelted iron ore from blast furnace has carbon content of about 4 % and various amounts of phosphorous, silicon, sulphur, manganese, and other elements. In the steelmaking process the non-ferrous elements are reduced and additives are used to achieve the desired composition. Much reduced element is carbon. Different elements bring various properties to the steel, some are desired, and some are not. Silicon helps to reduce oxygen. Grain orientation capability can be affected with the balance between sulphur and manganese but also with the amount of aluminium. The material’s resistivity is affected by the amount of manganese. Material’s final hardness is affected by the amount of phosphorous. The use of scrap metal in the steelmaking process can increase the amount of copper in the composition especially if electrical scrap steel has been used. There can be small titanium content as well because it is not practical to remove it. (Beckley, 2002)

1.1.4 Mechanical properties

Depending on the exact steel type, the mechanical properties for GO steels are usually within the range presented in Table 1. Material strength is usually provided in two testing directions. RD refers to ‘rolling direction’ and TD to ‘transverse to rolling direction’ of the sheet. TD values are usually about 5 % higher than RD values (Cogent Power, 2020).

Table 1. Typical range of mechanical properties for GO steel (Thyssenkrupp Electrical Steel GmbH, 2021)

Density [kg/dm³]	*Yield strength RD [N/mm²]*	*Tensile strength RD [N/mm²]*	*Young’s Modulus TD [N/mm²]*	*Hardness [HV]*
7.65	300 – 340	330 – 370	-	185 – 200

Typical range of mechanical properties for NGO steels are presented in Table 2.

Table 2. Typical range of mechanical properties for NGO steel (Cogent Power, 2020) (Thyssenkrupp Steel Europe, 2019).

Density [kg/dm³]	*Yield strength RD [N/mm²]*	*Tensile strength RD [N/mm²]*	*Young’s Modulus RD [N/mm²]*	*Hardness [HV]*
7.60 – 7.85	250 – 475	375 – 590	175,000 – 210,000	125 – 220

Density of GO and NGO steels are quite the same. Yield and tensile strength are higher on NGO steels.

1.1.5 Coatings

Electrical steels are always coated before production of the stator or rotor core. The purpose of electrical insulation coating (EIC) is to provide insulation between the electrical steel sheets in a stator core, improve their magnetic properties, provide heat resistance and to lower the core losses of the final product. (Ding, et al., 2014). Coating can also provide better performance for manufacturing of stator cores by improving the punchability and weldability of the electrical steel sheets. (Beckley, 2002). Corrosion, chemical, compression and scratch resistance can be achieved with coatings as well (Loisos, et al., 2003). Though, the manufacturing method of the stator core must be considered before making the decision of the coating to be used because some coating types are not suitable for welding, thus leading to generation of blowholes and gases in the weld seam (Beckley, 2002). In addition to beforementioned properties, coatings bring tensile stress to the electrical steel sheets. This is due to differences in thermal expansion coefficients between the chemical elements of the electrical steel and the coating. During the cooling from coating curing temperature there are differences in contraction between the elements of the material and the coating, which creates tensile stress. Tensile stress in the electrical steel sheets reduce the core losses. Especially in GO steels the tensile stress decreases the steel’s domain wall spacing which affects the core losses. The coating can help to decrease the core losses approximately 4 %. (Park, et al., 2020)

SFS-EN ISO 10342:2005 divides the surface insulations to oxide layers and applied coatings. Oxide layer can be either naturally formed during manufacturing or intentionally formed by the presence of oxidizing furnace. The standard does not require any specific insulation resistance to be specified for these. Applied coatings can either be organic, inorganic or “hybrid” with components both organic and inorganic. The type is defined by the content of the coating. Organic-based coating with inorganic fillers can be considered as “hybrid”. (SFS-EN 10342)

Commonly used coatings in electrical steels for rotating machines are classes EC-3, EC-4, EC-5, and EC-6. Some classes have sub-types with specific benefits and their detailed descriptions can be found from SFS-EN 10342. For example, organic coating EC-3 cannot handle the 800 °C temperature during stress relief annealing, whereas the inorganic EC-4 class is especially made to resist high temperatures. EC-5 and EC-6 have both organic and inorganic elements in them. Matters like improving certain manufacturing property or suitability for certain product application, are promoted depending on coating’s sub-type. (Lindenmo, et al., 2000) (Cogent Power, 2020).

Applying of coatings can be done in various ways. Methods include physical vapor deposition (PVD), solution-gel, chemical vapor deposition (CVD), printing, plasma spraying, electroless plating, wet coating, and electrochemical method. (Goel, et al., 2016). Coating thickness is typically between 0.5 – 6.0 µm (Cogent Power, 2020).

1.1.6 Magnetic properties

Electrical steel is soft magnetic material. Such material can switch its magnetic polarization rapidly under applied magnetic field. Due to this property, the material is very suitable for power generation applications, conversion and transfer in electric devices, sensors, and power electronics. Materials intrinsic coercivity (H_{Ci}) is characterized as less than 1000 A/m. (Ouyanga, et al., 2019). Intrinsic coercivity indicates the materials ability to resist an external reverse magnetic field or demagnetizing effect to preserve its original magnetization state (Ningbo Ketai Magnetic Material Co.,ltd, 2017).

Magnetic properties of electrical steel are determined by the steel's chemical composition, strain, grain size, purity level, surface oxidation and crystallographic texture. Major effect to iron loss is the grain size which is obtained during the final annealing phase of the steelmaking. (Jin, et al., 2011).

Magnetic properties like magnetostriction, magnetic permeability, low Eddy current and hysteresis loss are all important properties for electrical steel. (Cai, et al., 2017). Magnetostriction is described as the lattice deformation that accompanies magnetization. It is caused by the coupling of elastic and magnetic forces and thus has major importance when converting energy between elastic and magnetic degrees of freedom (Buschow, et al., 2001).

Internal circulating currents are called Eddy currents. These currents are created when a conductor or a part of a conductor moves across a magnetic field. This movement generates an electromotive force (EMF). Charges will follow unless this EMF is balanced by other EMFs. These currents can be quite large in low-resistance circuits. (Arfken, et al., 1984). Magnetic material's changing magnetization induces Eddy currents which result as a power loss, alias Eddy current loss. (Soshin, 1997).

Hysteresis loss is the loss of energy appearing as heat during magnetization of material. Part of magnetization work's energy is stored as potential energy and partly it is dissipated as heat generated in the material (Soshin, 1997).

Magnetic permeability describes the ease with which a material can be magnetized. Watt loss is also important magnetic property that is always mentioned in electrical steel sheet specifications. Watt loss describes the loss that merges as heat when a material is exposed to an alternating magnetic flux. (Chaudhury, et al., 2007)

Essential properties of electrical steel are resistivity, loss, and relative permeability. NGO steel's resistivity ranges typically between 18 – 59 μΩcm. The total loss at 50 Hz ranges between 0.92 – 4.05 (1.0 T) W/kg and 2.25 – 8.89 (1.5 T) W/kg. The anisotropy of loss is between 0 – 10 %. Relative permeability at 1.5 T ranges between 610 – 1,980. It has no unit as it is a proportion unit. (Cogent Power, 2020).

1.2 Punching

Punching is a manufacturing method for cutting sheet metal to produce desired shapes. To cut the sheet metal a punch and a die are used. Process variables are punching force and speed, the tool materials and their conditions, tool clearance and lubrication. Punching is strongly related to blanking which is virtually the same process with the difference of what is being used of the cut sheet. Figure 2 demonstrates this difference. Both sheets have the same shape but what is scrap for blanking, is the workpiece for punching. Scrap piece is commonly called a slug. (Boljanovic, 2014).

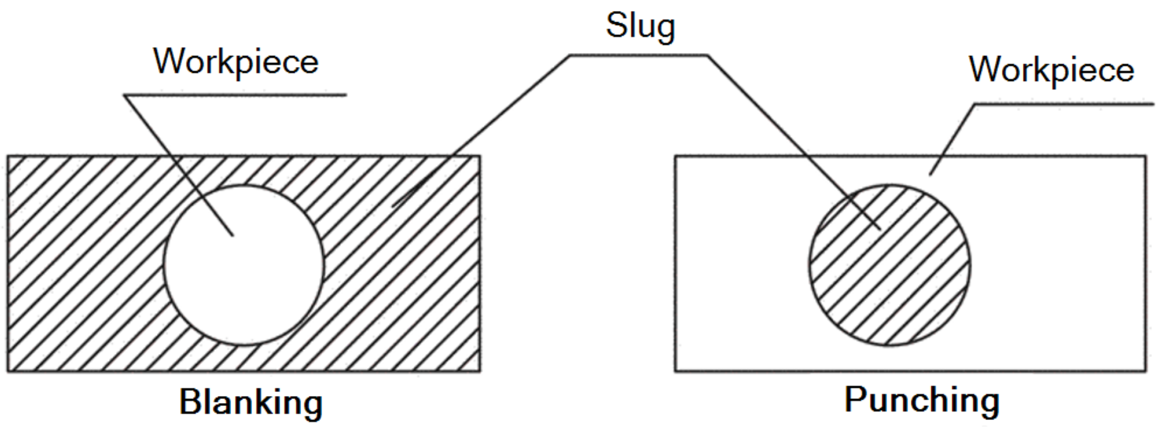

Figure 2. Difference between blanking and punching (Boljanovic, 2014) Edited by author.

Stamping, blanking, and punching are basically different names for the same main method. Shaving on the other hand is its own method of cutting and mainly used with thick plates. A punched hole or a blanked part usually has some fractures or burrs on their edges. Shaving process "shaves" these defects from the part and enables the meeting of required dimensional tolerances. (Hoffmann & Hörmann, 2007).

1.2.1 Process and phenomena

Punching process can be divided into three phases. These three phases are demonstrated in the Figure 3 below. In the first phase the deformation and stress of the material stay under the elastic limit when the work piece is pressed between the punch and the die. In the second phase the punch presses the work piece further inside the die. During this phase, the edges of the work piece exceed the elastic limit and are permanently deformed between the punch and the die. In the end of the second phase the stress in the edges of the work piece reach the material's shear strength but no fracture yet occurs, thus plastic phase is reached. In the third phase the fracture limit of the work piece is reached, and micro cracks begin to appear. These cracks expand to macro cracks until the slug eventually separates from the work piece. Cracking starts on the upper side of the work piece, on the punch tool's cutting edge and on the lower side of the work piece on the edge of the die. After materials separate, the slug is pushed inside the opening in the die, where its burnish zone expands which makes the slug to stay in the opening. (Boljanovic, 2014)

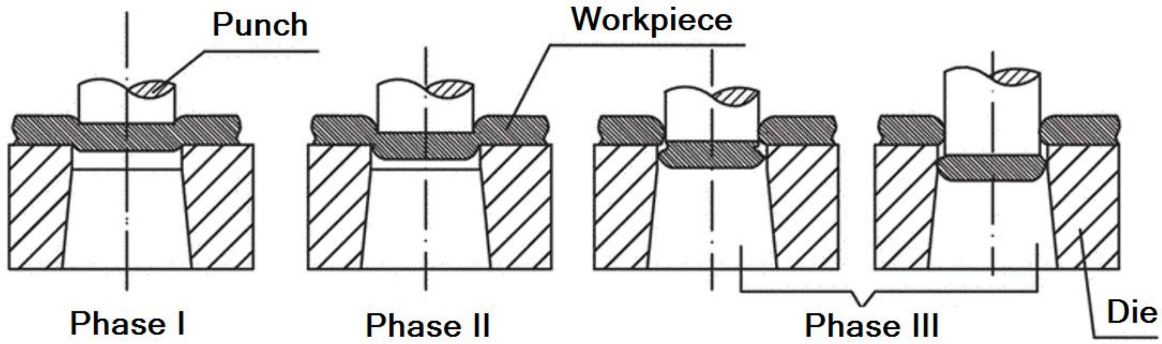

Figure 3. Three phases of punching (Boljanovic, 2014) Edited by author.

Generally, a burr is formed on the top rim of the slug and on the lower rim of the work piece. The burnish zone in the work piece contracts and sticks to the punch. The features of a punched work piece are shown in Figure 4. The punching direction in the Figure 4 is from top to bottom. The upper rim of the work piece is rounded for the length of the rollover depth. After the penetration depth, the fracture of material leaves the surface uneven. On the bottom rim a burr is generated. Commonly a minimal burr height is sought-after. Quality of punching and final product is usually considered from the perspective of the burr height. Acceptable burr height is typically around 10 % of the material thickness (Ulintz, 2013).

According to standard SFS-EN 10303, the maximum burr height for sheet thicknesses 0.20, 0.25, 0.27, 0.30 and 0.35 mm is 0.03 mm (Finnish Standards Association, 2015).

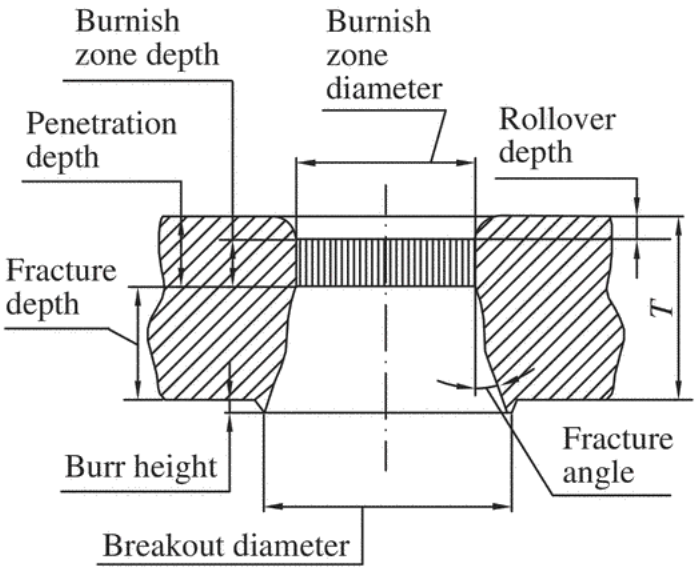

Figure 4. Features of a punched work piece (Boljanovic, 2014).

1.2.2 Presses for punching

The variety of punching machines is large. This chapter presents the main press types but there are other types as well. Three main categories of presses are divided by their drive systems: path-driven, force-driven, and energy-driven. In path-driven machine the path of the ram is defined by the drive system and the feedback from the forming process defines the force. Mechanically driven press is a good example of a path-driven press. In force-driven machines the force is defined at every position of the ram by the drive system. The ram path is defined by the feedback of the forming process. A hydraulic press is an example of a force-driven machine. In hydraulic press, the force is defined by the pressure and the cross-section of the piston. Both path-driven and force-driven systems suffer from energetic limitations due to their drive-systems, which affect acceleration and speed. In an energy-driven system, only the energy for the process is defined by the machine, nothing else. Typical machines are flywheel spindle presses and hammers. (Wegener, 2014).

Mechanical press drive system consists of flywheel which is driven by an electric motor. There is a gear system to control the speed, and a link drive that converts the rotation to translation of the slide of the piston, which has the punch tool. The drive system is coupled with a clutch and a brake to the flywheel, and it can be stopped by coupling to the frame. These presses are very energy efficient, because they can be run continuously while their workload consists of friction and the energy taken by the forming process, which is only shifting between kinetic and potential energy. Approximately only 1/12 of the forming power is required as the motor power, so the motor can operate in quite energy efficient mode all the time. (Wegener, 2014)

In hydraulic presses the drive system is substituted by a cylinder, which is fixed to the machine frame, and a piston which is fixed to the ram. Figure 5 shows the operation of a forming press, but the same principle applies for hydraulic punching presses. In step a) fast down stroke is made by opening the prefill valves which connect the cylinder to the oil tank that is positioned above the cylinder. The weight of the ram sucks the oil out from the tank. Meanwhile the oil around the piston in the cylinder is pushed to the tank or into the upper cylinder chamber. In step b) pump pressurizes the cylinder room and the punch stroke is made. In step c) fast upstroke pressurizers the cylinder ring chamber around the piston and pushes the oil above the piston back to the oil tank. (Wegener, 2014).

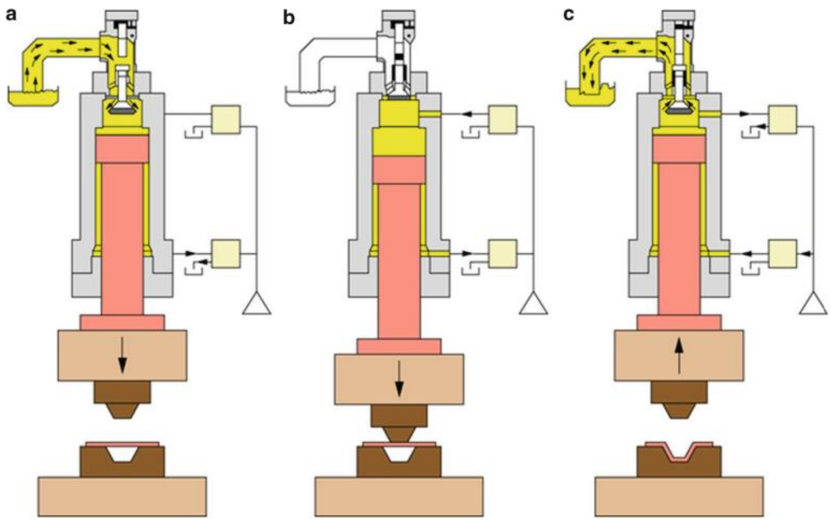

Figure 5. The operation of a hydraulic press (Wegener, 2014).

The hydraulic system enables efficient and fast downstroke and prefilling, with the capability of delivering full press force on any given position of the stroke. This on the other hand, means that the pump must deliver all required power for punching. Hydraulic presses are approximately 1.5 times slower than comparable mechanical presses. (Wegener, 2014).

The need for developing servo presses started from the limitations of ram path of mechanical presses. These presses enable the modification of the ram path by programming. Fully flexible servo presses have discarded the flywheel completely and the electric motor has become a servo motor. All power for punching comes from the servo motor. The system can contain several servo motors, depending on the torque and power requirements, thus servo presses are divided to three categories. These are depicted in Figure 6 with corresponding numbers. (Wegener, 2014):

1. Servo press with link drive system. Flywheel is replaced by one or more servo motors which drive the gear system by operating in parallel (Wegener, 2014).
2. Servo press with ball screw drive system. One or more servo motors operate ball screws for making the punching movement (Wegener, 2014).
3. Servo press with linear motor drive system. Mostly used for micro-forming, as the system is only capable to produce a force up to 100 kN (Wegener, 2014).

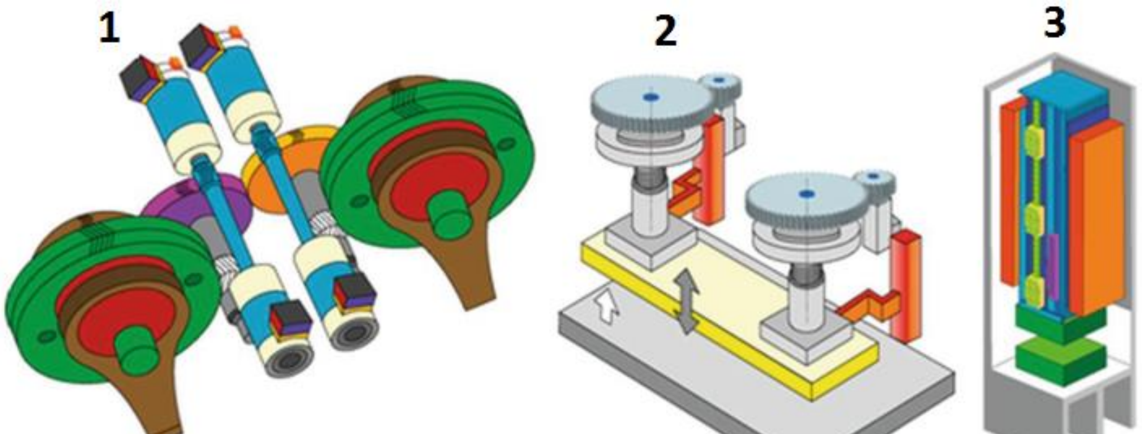

Figure 6. The three types of servo presses (Wegener, 2014) Edited by author.

Servo presses have been used to increase productivity. Adjusting the cycle between forming and transfer of parts from one phase to another is helped by their variability of speed. This enables faster idle movements with same forming and transfer speeds. (Wegener, 2014).

Servo presses combine the infinite ram speed and position control and the availability of pressing force at any ram position of a hydraulic press, and the reliability, accuracy, and speed of a mechanical press. (Osakada, et al., 2011)

Modern punch presses are controlled by computerized numerical control (CNC) system. The press is equipped with a computer. This computer is used for programming punch press tool and table movements (Evans, 2016). The computer can store various programs into its memory which can be uploaded in seconds (Smid, 2007).

Commonly the CNC punch presses have a table where the metal sheet is moved to correct position under the machine’s ram head for punching a hole based on the program (V&F Sheetmetal Co. Ltd, 2021). An example of a CNC punch press with its main components named, is shown in Figure 7. This machine is Prima Power Punch Genius which is a pure servo press.

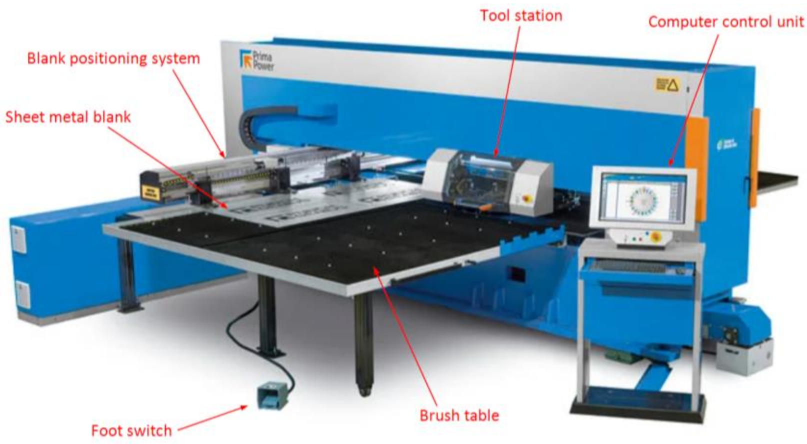

Figure 7. CNC punch press by Prima Power (PRIMA INDUSTRIE S.p.A., n.d.) Edited by author.

The programming is dependent on computer aided design (CAD) and computer aided manufacturing (CAM). CAD file has the desired shapes and patterns that is going to be cut. These shapes and patterns can be presented in 2D or 3D format. CAM software uses this file to create a flat sheet metal component and selects the most suitable tooling for production. Nesting helps to determine the most efficient layout for the patterns so that material waste is minimized. (AW Precision, 2019).

1.2.3 Tools

Punching tools consist of standard shapes and sizes, but they can also be custom made. Commonly used tool type in servo presses is shown in Figure 8. The structure of a press tool typically consists of a spring-loaded canister, punch, punch guide, stripper plate and a die.

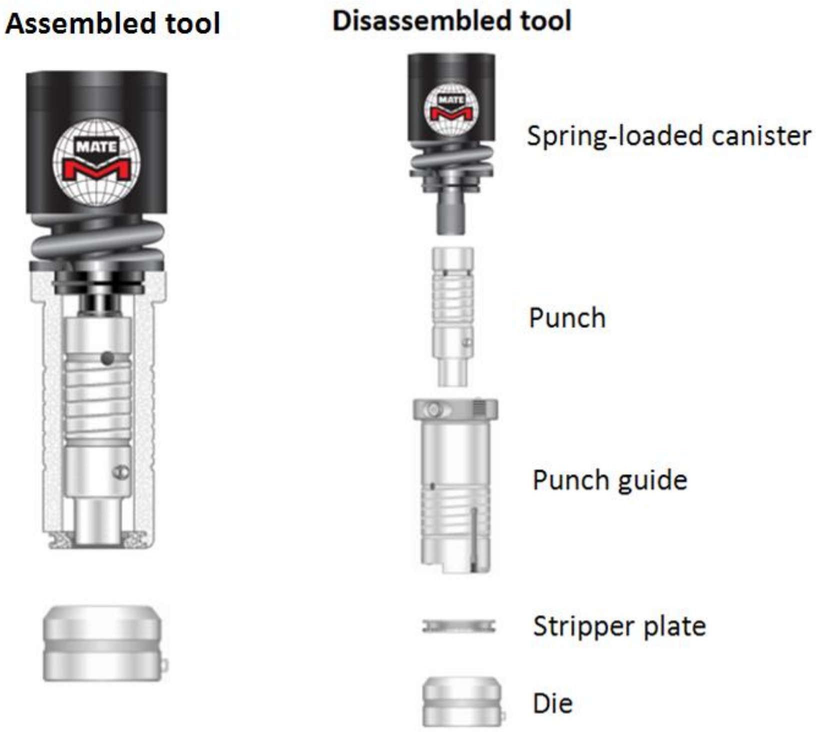

Figure 8. CNC turret press punch tool structure by Mate Precision Technologies (Pärmi, 2019) Edited by author.

Since CNC turret punch presses are mainly used to cut openings of various shapes to sheet metals for building machine frames and the like, the use of custom tools is generally not economical. Thus, most often standard tools are used. (Radhakrishnan, 2015). Though, for certain purposes the use of custom-made tools is more profitable. Series production of stator lamination sheets is one example. Since manufacturing punching tools is rather costly, custom tools are not commonly made for manufacturing prototype products. A custom-made tool is shown in Figure 9. One half works as the punch and the other as the die. With this tool, electrical steel sheet is cut progressively to its final shape in four steps, thus four different ring-shapes in the tool.

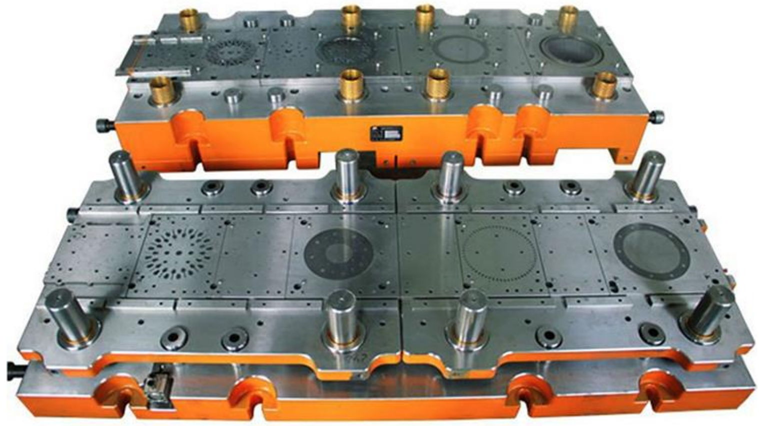

Figure 9. Custom tool for punching stator sections (Dongguan Hongkai Precision Technology Co., Ltd., 2019).

Variety of standard tools is vast in case using of custom-made tool is not profitable. Standard tools can be found in many shapes and sizes as shown in Figure 10. These shapes are rather basic, but they present the idea of various sizes and shapes well.

Figure 10. A set of different size punches and dies (Hason Precision Mould Fittings Co., Ltd., n.d.).

There are five main classes for tool holder sizes which are A (½” = 12.7 mm), B ($1\ {}^{1}/_{4}$” = 31.75 mm), C (2” = 50.8 mm), D (3 ½” = 88.9 mm) and E (4 ½” = 114.3 mm). The dimension refers to the maximum size of the punched shape (Mate Precision Technologies, 2021).

Tool variety is increased with cluster, indexing and multi-tools. Cluster tool has the same shape multiple times in a single tool; thus, one punch stroke creates several cuts with same shape. Indexing tool can be rotated around its vertical axis to punch the shape in multiple angles. Multi-tools can have more than 20 different tools in one tool frame.

Turret punching devices commonly use a rotating tools stations (turrets) capable of storing tens of punching tools. Rotating turret provides quick access to hundreds of tool shapes by utilizing indexing and multi-tools. An example of a turret is shown in Figure 11, which can store 16 tools which enables maximum of 384 tools or 128 indexable tools.

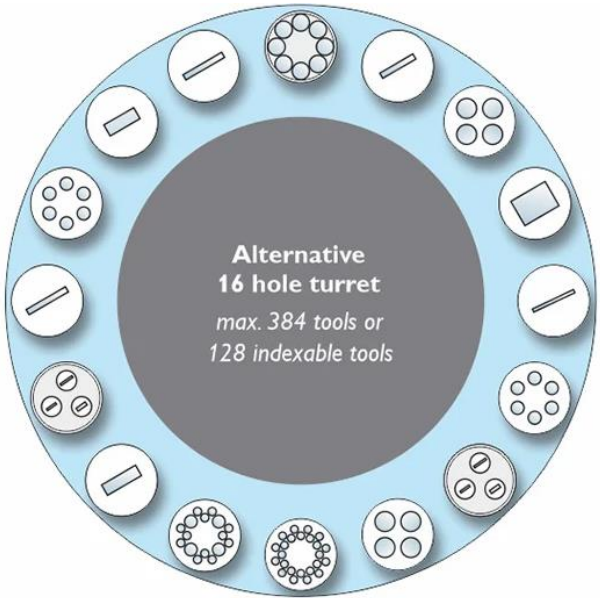

Figure 11. Prima Power turret with 16 tool holes (PRIMA INDUSTRIE S.p.A., n.d.).

Turret consists of an upper and a lower half that rotate in synchronous movement to the punching position. The upper half has the punch tool, and the lower half has the corresponding die tool. An example of a turret is shown in Figure 12. The turret rotates the desired tool defined by the CNC program under the press ram head for the punch phase.

Figure 12. The turret of Prima Power CG 1225.

Sometimes it is more profitable to use custom tools for punching. For instance, punching electrical steel sheets in series for stator core manufacturing, using the standard tooling can take more time and is not as efficient. Custom tools are produced by tool manufacturers and they can punch segments of a laminated stator core or even the complete cross-section of the core at once.

Very important parameter of tooling is the die clearance. Usually, it refers to the diametral clearance between the punch and die tool while cutting clearance is the radial clearance of the tools. Die clearance affects both the tool wear and quality of the punched work piece. Thus, optimal clearance will provide better tool life and product quality. Clearance is defined based on the thickness of the selected sheet metal. It is calculated as a percentage of the sheet thickness and it depends on the mechanical properties of the work piece material. In general, the clearance value is around 5 – 7 % of the work piece thickness. (Akyürek, et al., 2017). The cutting clearance for cylindrical tools is shown in Figure 13.

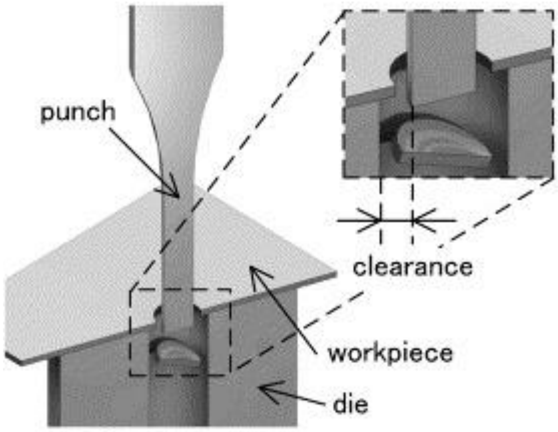

Figure 13. Cutting clearance of cylindrical punch and die (Kibe, et al., 2007).

Clearance is not necessarily always evenly distributed between the tools even with cylindrical tools. Ideally the punch and die are perfectly concentric, but it is virtually impossible. The term machining accuracy is used to describe the concentricity of the tools. When punching thin sheet metal, the misalignment can cause problems with the punching quality. The formation of burr is not spread evenly around the work piece and slug, but instead it locates to the area where there is more clearance. (Kibe, et al., 2007)

Figure 14 shows the die clearance as a function of material thickness. In addition to conventional blanking die clearance, the same is shown for a method called fineblanking. These processes are similar but there are some differences that make fineblanking more accurate than conventional blanking.

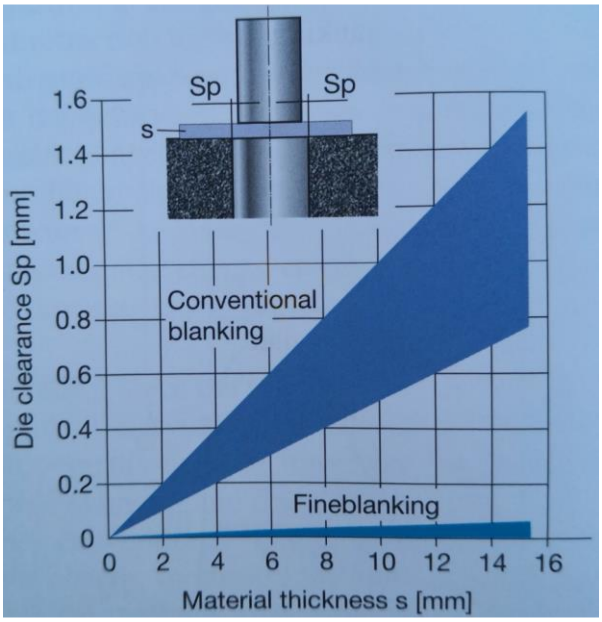

Figure 14. Die clearance (Sp) as a function of material thickness for conventional blanking and fineblanking (Süddeutscher Verlag onpact GmbH, 2014).

Tool wear is inevitable in punching, dull tools increase the plastic deformations and lead to increased burr height as well. (Harstick, et al., 2014). Tool is affected by adhesive and abrasive wear caused by friction between the tool and the work piece during punching. Tool material, work piece material, tool clearance, punch speed, lubrication and the work piece thickness define the rate of tool wear. In Figure 15 the wear profile of punching tool is described. The tool wear takes place on the side and the face surface that are in contact with the work piece.

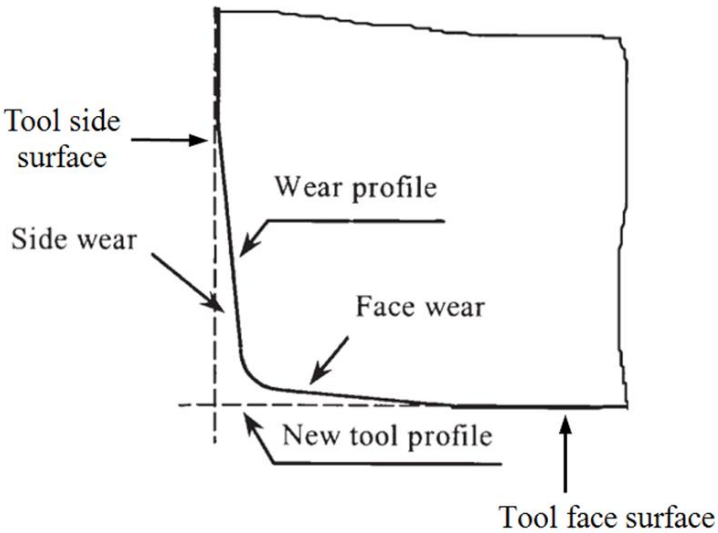

Figure 15. Tool wear profile (Hambli, et al., 2003) Edited by author.

Adhesive wear causes the tool edge to become rounded. The sharpness decreases which increases the deformation in the work piece. Formed burrs and punching noise level increases as well. (Hambli, et al., 2003).

The wear condition of tools and tool clearance have the most effect on the punching quality. Tool wear can be reduced with proper coefficient of friction and surface hardness of the tool's cutting edge. Coatings like physical vapour deposition titanium nitride (PVD TiN) reduces direct metal to metal contact between the tool and the work piece. They have been found to extend the tool life and reducing burr height and roll-over depth. Coating reduces friction between the tool and the work piece. (Mucha, 2010). Tool wear also increases the reach of plastic strain zone and in the case of electrical steel, it deteriorates the magnetic properties (Mucha, 2010).

To ensure consistent quality of punching, the tools need to be resharpened regularly. The need for resharpening can be estimated by measuring the burr height on punched work pieces. Punching devices also have a punch counter which shows how many punches the tool has made and how many are left before next maintenance is needed. Klingenberg et al. studied the possibility of detecting tool wear during the punching process and their suggestion was to monitor the force-displacement graph. According to them, the starting of tool wear causes major changes to the graph (Klingenberg, et al., 2008).

It is essential to use sharp tools during punching. More force is required when punching with dull tools. More force means more stress and distortion to the material, which equals lower quality. (Ripka, 2014).

1.2.4 Additional costs of multilayer punching

Multilayer punching means cutting a stack of sheets with one punch stroke. The method would require investments in addition to a punch press and tools. Depending on how many sheets at a time would be punched, the feeding system should have the same number of spools to house and unwind the coils. The system would also have to be able to handle multiple electrical steel sheet coils simultaneously. Sheets would have to be aligned for punching and after punching they should be handled as a complete stack. System like this is not integrated to current conventional punch presses. A simplified diagram of a punching production line with the main devices is shown in Figure 16. It clarifies the idea of potential increase in complexity in the case of multilayer punching.

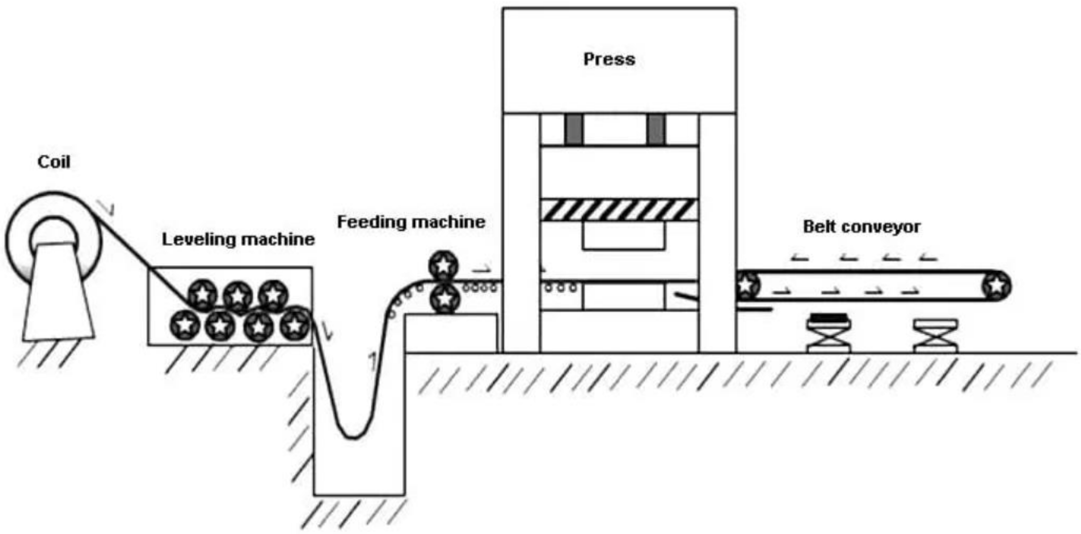

Figure 16. Electrical steel punching production line (Zhang, 2021) Edited by author.

There is also the question of the amount of consumed electricity. Would the consumption increase or decrease, or perhaps stay the same? It is known that the required punching force increases when the number of sheets increase, but at the same time the number of punch strokes decreases. Thus, less strokes but possibly more electricity used per stroke. The additional features of the feeding system would also consume electricity. One aspect is also the tool wear. It could be an issue, but it would require more research to make any statements. Possibly the stack of sheets should be held firmly together during punching so it would require some additional tools or adjustments.

1.3 Electric motor

Electric motor converts electricity to mechanical force. The main types are synchronous, asynchronous, and direct current (DC) motor. Synchronous and asynchronous motors are alternating current (AC) machines, of which operation is based on the rotating magnetic field inside the machine. There are various structure options for each motor type, and some special types as well. The working principle of all motor types is based on the forces produced when a current-carrying conductor is placed into a magnetic field. This force makes the rotor to rotate. Magnetic flux travels from the stator to the rotor and then back to the stator over the air gap between these two parts. The coil winding in the stator produces the magnetic field in the air gap. (Korpinen, 1998).

1.3.1 Main components

The main components of an electric motor are bearings, end shields, a rotor, and a stator, which are shown in Figure 17 with other components. Commonly used bearing types are ball-, roller- or slide bearings. Their purpose is to hold the rotor and enable it to spin inside the stator. The bearings are installed to the end shields, typically one on each end of the machine. The end shields are attached to the machine frame, which is often also the stator frame. End shields are typically made of steel. There are many types of rotors but in general a rotor is a steel shaft that rotates inside the stator. The air gap between the rotor and the stator ensures that the rotor can rotate freely. (Korpinen, 1998).

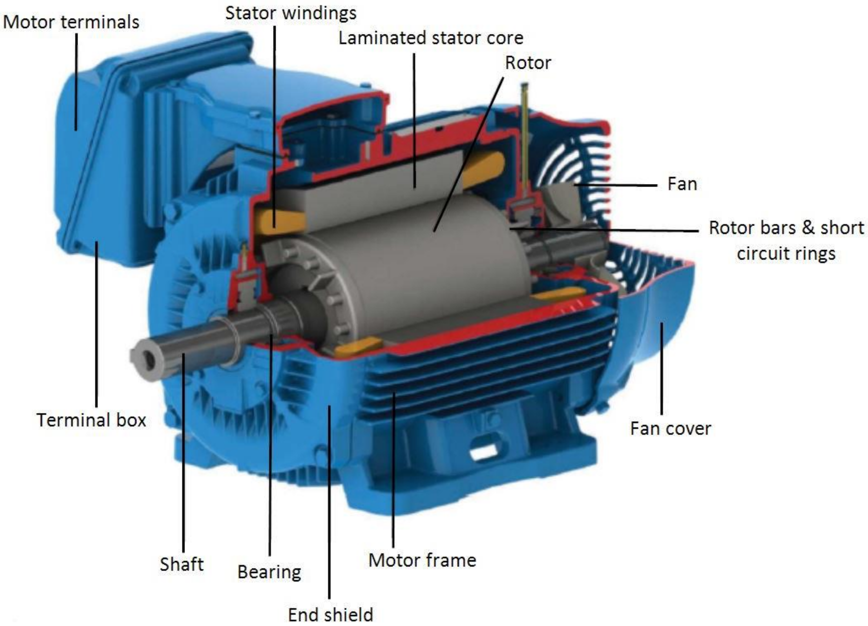

Figure 17. Three phase AC motor components (Electrical Engineering Tool Box, 2016) Edited by author.

The stator and the rotor, or either of them, is made of a stack of laminated and insulated electrical steel sheets. Often the stack is referred to as a “laminated core”. This core is installed to a motor frame which is usually made of cast aluminium or iron. The frame can also be made as a welded assembly. The electrical steel sheets are cut to shape so that the inner diameter of the sheets has certain number of slots. Copper wiring is housed inside the stator into these slots to create the stator winding. (Tong, 2014). An example of a stator installed to an aluminium frame is shown in Figure 18.

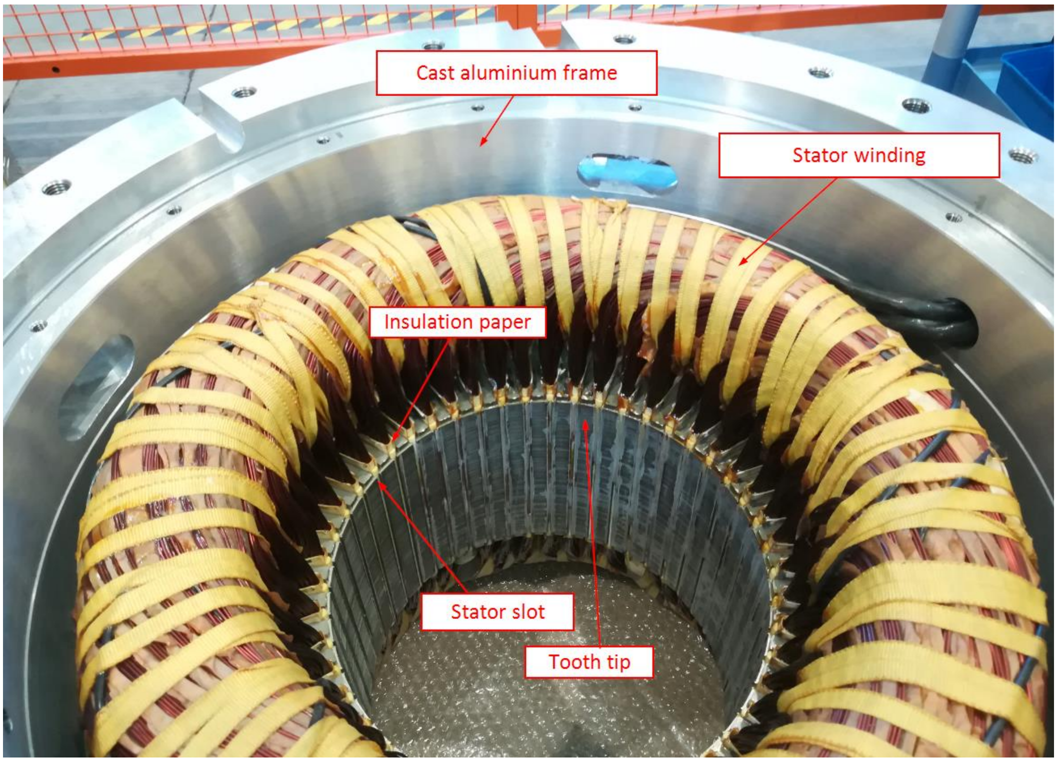

Figure 18. Stator inside a cast aluminium frame.

In the case of three phase motor, there are three individual windings inside the stator. Together, the laminated steel core and the winding will enable to create the rotating magnetic field in the air gap between the rotor and the stator. (Tong, 2014). An example of a complete stator cross-section sheet is shown in Figure 19 with its features named.

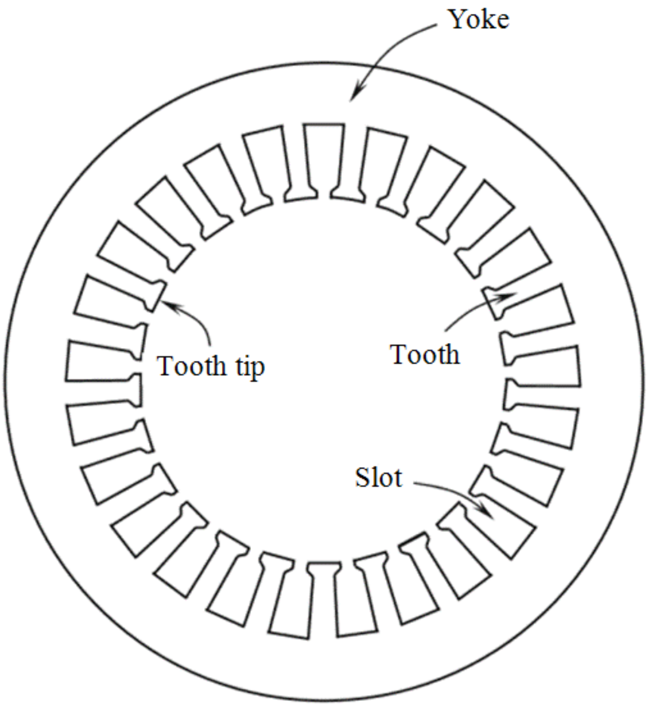

Figure 19. Complete stator cross-section sheet made of electrical steel (Tong, 2014).

The slots shown in Figure 19 are for housing the stator copper windings. The tooth tips hold the winding in the slots, but the tips have also electromagnetic purposes. Laminations for large motors are often manufactured from segments rather than complete cross-sections. The reasons are mainly the impracticality of handling such large sheets and the physical limitations of the electrical steel sheet coils and machines used for punching these sheets. The segmentation of the laminations has its own benefits as well, such as lower tool costs, less material waste, increased continuous motor torque and lower Eddy current due restricted Eddy current path. However, segmented laminations also have downsides like increased core losses due to increased length of punching line, which equals to more residual stresses in the material and degraded material conditions. It is known that punching electrical steel changes drastically the material's magnetic properties near the cut edges which in turn results in increased core losses. (Tong, 2014).

This happens in two different ways:

1) Residual stresses near the cut edges are created in the material due to punching, which can increase hysteresis loss and thus, the total core losses as well in these locations.

2) The magnetization profile of the material can change due to punching. Material's magnetic permeability may drop, and thus material's polarization decreases near the cut edges. This will require higher polarization in the bulk of lamination, if same total flux across the lamination is desired. Higher total loss is induced by the higher polarization.
(Tong, 2014)

1.3.2 Losses and efficiency

The main terms and definitions of losses have been explained in chapter *Magnetic properties.* Efficiency and losses are always present in electric motors. In European markets, the efficiency of an electric motor is commonly between 70 – 95 % (EUR-Lex, 2009). Losses are defined as the part of electrical energy that has not been converted into mechanical energy. Efficiency of an electric motor is the difference between power output and power input. Losses increase the temperature rise inside the motor and its windings. High temperature increases the degradation of insulation materials inside the motor. It is also a risk for permanent magnet motors since it can significantly reduce the properties of the magnets. (Tong, 2014). Losses are categorized based on their location of occurrence or electromagnetic origin. They can take place in windings, laminated core, and in other mechanical components like bearings (friction), cooling fan and rotor (air resistance). (Kärkkäinen, 2015).

Insulating coating on the electrical steel sheets reduces Eddy current losses in a motor. The thinner the sheets are, the less Eddy current losses there are. Magnetic properties of the sheets depend on the material, but they are affected by the manufacturing methods as well. Deformations caused in punching worsen the magnetic properties of electrical steel and thus increase losses. (Harstick, et al., 2014).

The stacking method of the stator core affects to the losses also. Stacking the electrical steel sheets can be done for example by mechanical interlocking or welding. Interlocking utilizes forming of the sheets to lock them together. Welding is another option, but both create electrical connections between the laminations thus creating Eddy current paths which increase losses. Typically, the laminated stator core is inserted to a motor frame which means that the outside diameter of the whole stack is touching the frame's metal surface, thus creating an electrical connection between the laminations. (Lamprecht, et al., 2012). Stator lamination in connection with a motor frame is demonstrated in Figure 20. It is worth noticing that losses are inevitable in an electric motor.

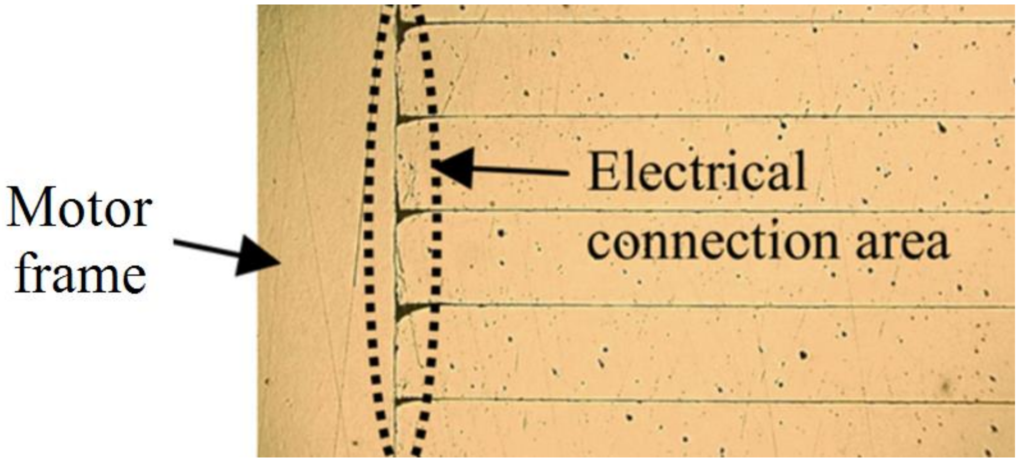

Figure 20. Cross-section view of a motor frame and a stator core (Lamprecht, et al., 2012) Edited by author.

1.3.3 Financial potential

General trend for improving the efficiency of electric motors requires the industry to develop. Using thinner electrical steel sheets is a straightforward solution to the problem. Thinner sheets on the other hand create a second problem, the thinner the sheets, the more time spent cutting them to create an equal size stator core. Thus, it is justified to study the idea of multilayer punching. Since multilayer punching would require some investments, it makes sense to calculate the savings created by using thinner electrical steel sheets to evaluate the potential.

Using electrical steel with less losses in an electric motor can save a substantial amount of money. Higher amount of electricity is converted to mechanical energy and less goes to waste. Even small improvement in the efficiency has a significant effect on reducing wasted energy during the motor's lifetime, which is generally assumed to be 20 years. Long lifetime creates long term savings. The equation of net present value (NPV) is rather suitable for evaluating the savings in today's monetary value. It enables to discount the savings to present moment. For calculating NPV three things are needed, amount of cash flow, discount rate and number of time periods. Amount of cash flow is the amount of annual savings. Discount rate or internal rate of return refers to the rate of return expected by investors or the interest rate of a loan. The value is commonly between 1 – 20 % (Gallo, 2014). In this case three different values are used, 3 %, 8 % and 13 %. Discount rate should reflect the uncertainty of future profits or saving in this case. The higher the estimated risk for future profit is, the higher must the discount rate be and thus the smaller the net present value is. Time period used in the calculation is one year. The discounted savings were calculated separately for each operation year of the motor. Finally, they are summed up and the result is the net present value of the future savings.

Machine nominal power was assumed to be 600 kW (Suuronen, 2020). The price of electricity used in the calculations was 0.1254 €/kWh. Price is based on average cost of industrial consumers in Europe with power consumption between 500 – 2,000 MWh per year. (Strom-Report, 2021). Machine life was chosen to be 20 years, which is commonly used in calculations. Operating hours were calculated as 24 hours a day and 365 days a year with 5 % reduction to take maintenance into consideration as well. This resulted in 8,322 hours per year which is 166,440 hours of operation for 20 years lifetime. In the calculations, year 0 is the first operation year. Electromagnetic calculations were made by Otto Suuronen from The Switch and they are presented in Table 3 below.

Table 3. *Calculation results of losses for M270-35A and NO20-1350A* (Suuronen, 2020).

Loss	*M270-35A*	*NO20-1350A*	*Unit*
Stator DC-copper losses	2,970	2,970	W
Stator fundamental iron losses	11,480	8,378	W
Rotor slip loss	1,330	1,330	W
Rotor slot loss	410	410	W
Rotor coil loss	340	340	W
Rotor permeance losses	340	340	W
Mechanical friction losses	890	890	W
Air-gap friction losses	960	960	W
Additional losses	6,950	6,950	W
Total losses	**25,670**	**22,568**	W
Efficiency	**95.8**	**96.3**	%

Suuronen compared materials M270-35A and NO20-1350A based on their magnetic properties and made calculations to investigate their losses. The calculations were made for a 2-pole high-speed induction motor. M270-35A was used in laboratory tests but NO20-1350A was not. Instead NO30-1600A was used because its thickness is closer to M270-35A and this made the comparing of the punching quality more rational. According to Table 3, electric motor with NO20-1350 would be roughly 0.52 % more efficient than with M270-35A. The difference does not seem significant, but it should be evaluated as amount of saved energy within the machine's lifetime.

Machine's total power consumption can be calculated with the following equation:

$$P = \frac{P_n}{\frac{\eta}{100}} \tag{1}$$

In equation 1, P is the machine's total power consumption, P_n is machine's nominal output power, η is efficiency percentage of electrical steel.

Based on equation 1 the saved energy per year when using NO20-1350 compared to M270-35A, can be calculated as a subtraction between the power consumptions with the following equation:

$$P_s = P_1 - P_2 \tag{2}$$

In equation 2, P_s is the amount of saved energy in kWh, P_1 is the machine's total power consumption with M270-35A and P_2 is the machine's total power consumption with NO20-1350.

Thus, yearly energy savings in EUR can be calculated with the following equation:

$$e_a = P_s * h * C \tag{3}$$

In equation 3, e_a is the amount of annual energy savings in EUR, P_s is the amount of saved energy in kWh, h is annual operating hours and C is the cost of energy per kWh in EUR.

Annual energy savings can be used to calculate the Net Present Value (NPV) of using NO20-1350 instead of M270-35A for machine's operating lifetime of 20 years. NPV also takes the discount rate into account. NPV can be calculated with the following equation:

$$NPV = \sum_{i=0}^{n} \frac{e_a}{(1+r)^i} \tag{4}$$

In the equation 4, *r* is the discount rate and *i* is the number of time periods. The equation was solved with three *r* values to see how it affects the result.

Net present value was calculated with three discount rates and the results are shown in Figure 21. All curves start from year 0 with annual saving of 3340 €. The higher the discount rate, the faster the annual savings drop. The faster the savings drop the smaller significance the future savings have in today's monetary value.

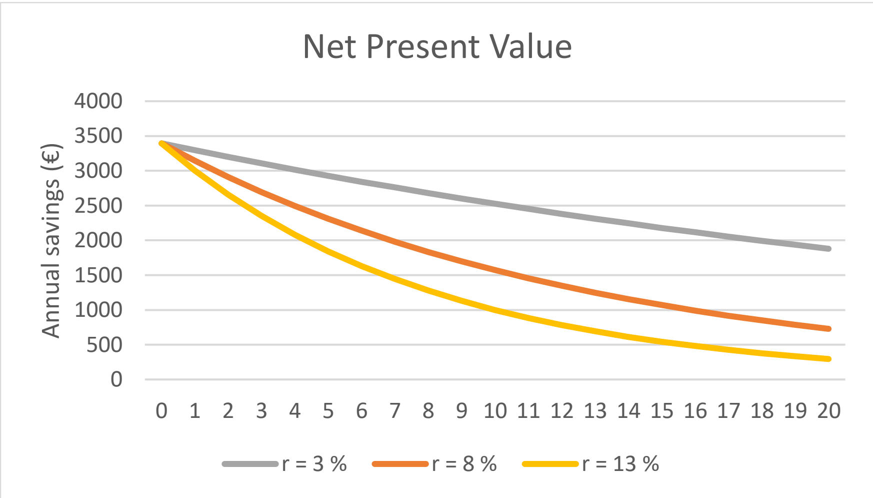

Figure 21. Net Present Value chart with three discount rates.

Total savings for each discount rate in today's money were:

- 53,880 € with discount rate of 3 %.
- 36,710 € with discount rate of 8 %.
- 27,230 € with discount rate of 13 %.

1.4 Multilayer punching

Already in 1979 Iwamoto et al. developed a method for punching two overlapped electrical steel sheets to reduce manufacturing working hours. Another pursuit was to reduce the damage to the die tool. (Iwamoto, et al., 1979).

In 1995 Toyota Motor Corporation with inventors Egawa & Totsuka filed a patent concerning punching of a plurality of laminated steel sheets. They found that with die clearance of 5 % or less of the total sheet stack thickness, the burr formation could be kept minimum. They also developed a method to punch the stack so that the first punched piece of sheet (slug) is moved away, to punch the second sheet with the punch tool's cutting edge and so on with the next layers as well. This enabled achieving very good punching quality because the slugs did not build up on the punch tool's head. (Egawa & Totsuka, 1995).

Matsuno et al. found that punching a plurality of stacked metal plates results in lot of sagging and burrs. Thus, they developed a punching method for plurality of metal plates by using a plurality of punches and dies. The system consists of a pile of punches and dies so that each plate in a stack is punched individually but the whole stack is punched at once. This was enabled by placing a punch and a die between each metal plate. The quality of the punched plates with this developed method was equal to the quality of punching plates individually in the conventional way. (Matsuno, et al., 2010).

Senda et al. developed a punching method, punching device and a manufacturing method for a laminated core that utilizes punching a stack of electrical steel sheets at once. Their study focused on material with thickness of 0.35 mm or less with hardness of 150 – 400 HV and with average grain size of 50 – 250 μm. They used die clearance of 7 % or more of the individual sheet thickness and 7 % or less for the thickness of the sheet stack. They found that punching a plurality of sheets at once increases the deterioration of the material's magnetic properties. It was also noticed that holding the sheets together during punching was very important. (Senda, et al., 2015).

In 2016 Senda et al. released another patent application for punching a plurality of electrical steel sheets. This time they found a way to suppress the increase in burrs when punching a stack of sheets at once. Thus, the deterioration of magnetic properties could be reduced. (Senda, et al., 2016).

Koopmans et al. generated a process for blanking multiple metal parts stacked on top of each other. The patent application was filed by the company Robert Bosch GmbH. The method considers metal parts in the shape of plate, sheet, or strip. The process described resembled more fineblanking than conventional blanking. (Koopmans, et al., 2017).

In 2018 Koopmans & Janssen as inventors, the company Robert Bosch GmbH filed another patent application for multilayer fineblanking process. This time they defined the sheets to be interlocked prior to punching. The interlocking was done without deteriorating the electrically insulating coating of the steel sheets. The thickness of a sheet was defined to be not more than 0.30 mm and the total thickness of the sheet stack was set to maximum of 1.20 mm. They discovered that the interlocking of the sheets improved the punching quality. (Koopmans & Janssen, 2018).

Szary et al. used electrical steel and came up with an idea of stamping and packing composite material that consists at least of two lamellas with a plastic layer in between. The patent was filed in 2018 by ThyssenKrupp Steel Europe AG. It was found that the material's magnetic and insulating properties were not negatively affected with the developed method. (Szary, et al., 2018). ThyssenKrupp Steel Europe AG filed another patent application during the year 2018. Inventors Szary et al. developed a method for punching multiple metal sheets at once so that the sheets were connected prior to punching. (Szary, et al., 2018).

1.5 Research problem

Keeping the manufacturing costs reasonable while improving electric motor performance is continuously sought after. One option for improving the performance is to decrease the thickness of the electrical sheets of the stator core. Currently the problem is that by decreasing the sheet thickness, the production time is increased because the sheets are punched one at a time. This equation has forced the electric motor designers and manufacturers to make a compromise between the manufacturing costs and the performance of electric motors. If electrical steel sheets could be punched at once as a stack, the manufacturing costs could be reduced or kept the same while the sheet thickness could be decreased.

1.6 Research questions

1) Why electrical steel sheets are commonly punched one at a time?
2) How does multilayer punching affect the punching force and tool parameters?
3) How will the cutting and fracture take place when punching a sheet stack?

1.7 Objectives, scope, and hypotheses

The aim of this research was to find out is it possible to punch multiple electrical steel sheets at once, how different punching parameters and material properties affect the quality of a punched sheet and how big investments could be justified for the method. The scope of the research focuses on punching multiple electrical steel sheets at once. The emphasis is on the viability of the method from technical and economical point of view.

Included in the scope:

- Literature study to electric motor, electrical steel, and punching
- Studying the effects of different coatings
  - How do coatings differ in punching quality?
- Punching test by varying the number of sheets and thicknesses
- Punching force
  - How does the required force change when thickness or number of sheets is increased, or does it?
- Effects of tool dimensions and tolerances
  - Can affect the punching quality and force
- Punching quality
  - Minimal burr height
  - Aim is to achieve equal quality as when punching one sheet at a time
  - Deformations in the material due punching

Excluded factors are:

- Reviewing the manufacturing of punching machines and tools
- Developing a feeding system for multilayer punching

- Nesting or optimizing the sheet usage
- Handling of the punched sheet stack
- Studying the tool life

Vast number of combinations can be constructed from the above-mentioned variables. All possible combinations will not be tested or studied. Punching force will be kept constant if possible. All possible tool tolerances will not be tested or studied. Limitations must be made due to the timetable and to achieve answers to the main questions. Excluded factors are important for the complete production chain of the stator core but are not considered in this research. They could be part of further research.

The hypotheses of the research are:

1) Multilayer punching is possible if the maximum sheet thickness of the punching machine and tool is not exceeded.
2) Multilayer punching creates perfectly cut sheets between the top and the bottom layer of a stack.

2 MATERIALS AND METHODS

The work was conducted as a combination of laboratory punching tests, literature review and manufacturer interviews. Laboratory tests were carried out in the sheet metal work laboratory of LUT University. The literature review was presented in chapter *Multilayer punching*. No scientific articles, books or conference proceedings were found. Thus, the review was based on patents found on the subject. Industrial opinions and views were surveyed with manufacturer interviews. Questions and thoughts were shared with manufacturers of electrical steel, punching devices and electric motor laminated cores.

2.1 Laboratory tests and analysis

The conducted laboratory tests included punching single and multiple layers of M270-35A and NO30-1600A non-grain-oriented electrical steel sheets but also DC01 steel. Since the potential of combinations of test samples was found very large it was decided to make punching “pre-tests”. These pre-tests were done to see how multiple sheets react when punched at once. From these results it was easier to decide how to continue the testing and which test parameters were important. Eventually 32 punches were made, and more than 90 sheets cut. From these tests a fundamental idea could be established how the sheet stack and individual sheets behave. It was decided that the reporting of the test results would focus on comparing the two electrical steels. They had different type of coating but unfortunately the material thickness was different as well. M270-35A had an EC-3 class organic coating and NO30-1600A had EC-4/EC-5 class inorganic coating. EC-3 has better punching characteristics according to the manufacturer. The coating works as a lubrication in punching.

The tested materials were from different manufacturers. Their mechanical properties are presented in Table 4. M270-35A values are based on data sheet by Cogent Power. For NO30-1600A the values are minimum values according to standard EN 10303. Standard EN 10303 did not include values for Young’s Modulus nor hardness.

Table 4. Mechanical properties of M270-35A and NO30-1600A (Cogent Power, 2020) (Finnish Standards Association, 2015).

Material	*Density [kg/dm^3]*	*Yield strength RD [N/mm^2]*	*Tensile strength RD [N/mm^2]*	*Young's Modulus RD [N/mm^2]*	*Hardness [HV]*
M270-35A	7.65	450	565	185,000	215
NO30-1600A	7.60	370	450	-	-

The sample sheets were cut with a Finn-Power JS 12-3000 guillotine shear to convenient size for handling and processing. The test material of M270-35A, shown in Figure 22, were waste slugs from a Finnish stator manufacturer.

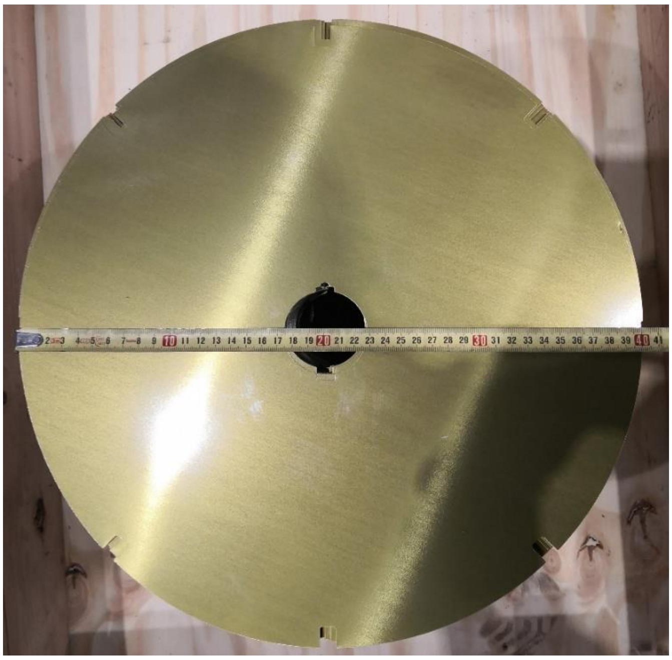

Figure 22. M270-35A electrical steel sheet blanks.

The blanks were cut to four pieces and designed so that only one punch was made to each sample stack. The punching machine set its demands for the test piece size due to a safety feature. The sheet had to be attached to at least two clamps on the brush table to enable punching. The test piece stacks were compiled of 3 and 6 sheets and held together with duct tape. A test piece stack clamped to the press's brush table is shown in Figure 23.

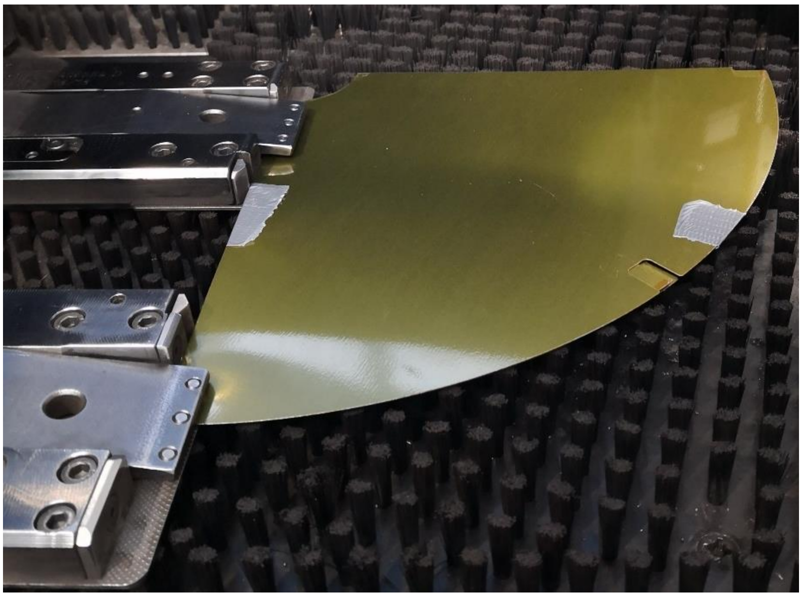

Figure 23. M270-35A test sample sheet stack ready for punching.

Before punching, the die tool was covered underneath with a piece of duct tape to ensure that the slugs do not fall through it. This enabled to keep the slug stack together and prevent mixing the sheet layers together. After punching, each test piece sheet and punched slugs were marked with a marker pen for identification and put inside a plastic bag with same identification information written on it. This way it was easy to keep record of the samples and identify each test piece afterwards. Two holes were cut to each slug. One in the centre of the slug and a smaller one off the centre line, to the same angular position as the die tool wedge slot. The hole in the centre was used to hold the stacks of slugs together with a bolt and a nut. Smaller hole was made to mark the angular position of which the cut edge would be examined. This way the examining of the cut area would be the same for all slugs. Example of a punched and marked slug stack is shown in Figure 24.

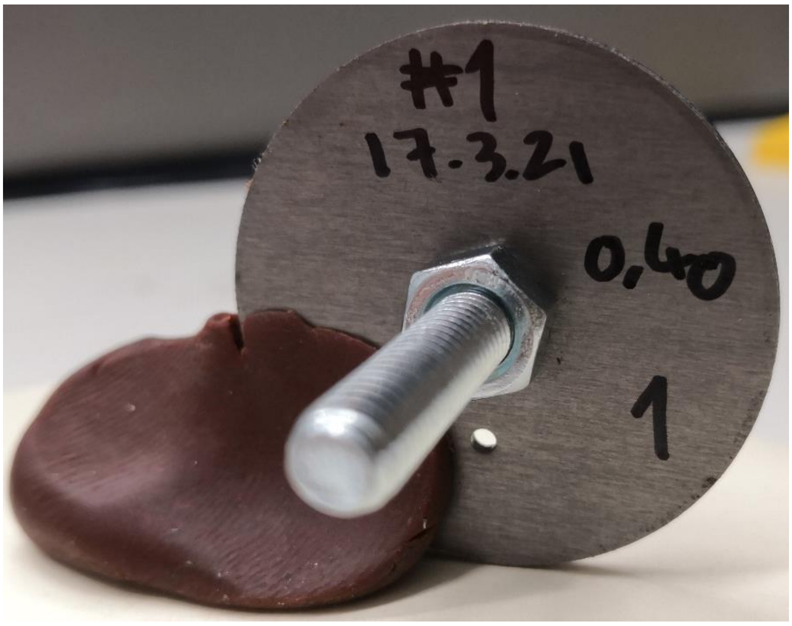

Figure 24. Marked NO30-1600A slug stack. First punch of the day on 17th of March 2021 with die clearance of 0.40 mm. First layer is visible, marked with number 1 on the lower right side of the slug.

The punching machine used in laboratory tests was Prima Power Combi Genius 1225. It is a combined servo press punching and fibre optic laser cutting device. The maximum sheet size is 2,500 x 1,250 mm with thickness of 8 mm. The power of fibre optic laser is maximum 4 kW. (Prima Power, n.d.). Notes were taken during punching to record detail level information about each punch. General observations were written but also punching force for each stroke. The punch tool used in all the tests was flat and round headed with diameter of 40 mm. The spring-loaded canister in all tests was from tool manufacturer Pass-Stanztechnik AG. All the other tool parts were from Mate Precision Technologies. Variables were die clearance, number of sheets and their materials. Three different die clearances were chosen to see how they affect to the behaviour of the sheets. First, the minimum die clearance was defined based on a single sheet thickness, thus 0.04 mm was chosen. Then the maximum clearance was defined based on the stack thickness. Depending on the number of sheets, the clearances 0.20 mm (3 sheets) and 0.40 mm (6 sheets) were chosen. To find out how the behaviour and punching quality changes from the smallest to the largest clearance, a middle clearance was chosen as well. For stacks with 3 sheets, it was 0.08 mm and with 6 sheets, it was 0.20 mm.

An interesting tool option, that was never used in tests due to schedule limitations, would have been a punch with a triangle shape with different radius in each corner. Since actual stator laminations have multiple shapes like straight lines and tight corners, this could be studied more. In the tests, the punch and die were from one manufacturer and the spring-loaded canister, punch guide and stripper plate were from another one. The tools were kept the same in all tests, only the die clearance was varied between 0.04 – 0.40 mm. Table 5 presents the test setup parameters and variables for each punch.

Table 5. Test setup parameters and variables.

Material	*Sheet thickness [mm]*	*Sheets [pcs]*	*Stack thickness [mm]*	*Die clearance [mm]*	*Clearance /sheet thickness [%]*	*Clearance /stack thickness [%]*	*Punching force [kN]*
M270-35A	0.35	3	1.05	0.04	11.4	3.8	56
M270-35A	0.35	3	1.05	0.08	22.9	7.6	56
M270-35A	0.35	3	1.05	0.20	57.1	19.0	56
M270-35A	0.35	6	2.10	0.04	11.4	1.9	106
M270-35A	0.35	6	2.10	0.20	57.1	9.5	102
M270-35A	0.35	6	2.10	0.40	114.3	19.0	100
NO30-1600A	0.30	3	0.90	0.04	13.3	4.4	63
NO30-1600A	0.30	3	0.90	0.20	66.6	22.2	64
NO30-1600A	0.30	6	1.8	0.04	13.3	2.2	115
NO30-1600A	0.30	6	1.8	0.40	133.3	22.2	110

Macroscope used to examine the test pieces was Wild Photomakroskop M400 with ToupCam XCAM1080 camera. The camera enabled taking photos of the test pieces during the examination. Examination focused on the slugs because the cut edge was easy to access and view. The examined cut edge area was the same for all slugs. This was ensured in the punching process by punching a small hole eccentric hole to the slug simultaneously when punching the test pieces. This small hole had the same angular position as the punch die wedge slot. This way it was ensured that if the punch and die have small misalignment, still the examined areas are comparable. The die tool wedge slot position mark (hole) is shown in Figure 23 above which also demonstrates the identification markings written on all slugs. Various zoom levels were used to examine the slugs and the selection was made based on maximizing the view area. Slugs were placed on the examination table in vertical position so that the positioning hole was pointing up.

Scanning electron microscope (SEM) used was Hitachi SU3500. It was used to examine only three samples to see how the coating is damaged due deformations caused by punching. No measurements were taken from the images, so they were merely for visual evaluation. SEM images were taken using ultra-variable-pressure detector (UVD) and backscattered-electron (BSE). UVD imaging reveals the topography of the target. BSE imaging shows the material contrasts. Lighter materials are shown in darker colour.

It was decided that the slug examinations would not include measuring of the burrs or damaged area of the coating. Instead, the examination focused on how the cut and shear phenomena of punching has happened in the sheet stack and in individual sheets. The reason for this was the questionable accuracy of the measurements. It was seen that only very rough estimations could have been made of the burr size. Since the maximum burr size is commonly around 10 % of the material thickness, no reliable judgment could have been made whether this quality could have been reached or not. Burr height of 10 % in the case of a single sheet of M270-35A would have meant only 0.035 mm, this is roughly the diameter of a human hair. Though, a stator with length 1000 mm made from 0.35 mm sheets would have roughly 2,850 sheets and if each sheet has 0.035 mm burr height, the total burr height is almost 100 mm. On the other hand, if the sheets are kept in the same direction as they were during punching, the burrs of the previous sheet will position in the roll-over depth of the next sheet.

2.2 Manufacturer interviews

Twenty companies were approached to acquire industrial point of view to the subject.

Three main types of manufacturers were contacted: manufacturers of electrical steel, companies that produce punching tools and machines and those who manufacture electric motor rotors or stators by punching electrical steel sheets. The questions were sent by e-mail and less than 50 % of the contacted companies responded. The overall goal was to establish a vision of what kind of parameters and phenomena there are in play in multilayer punching. Some of the questions were tailored depending on the company's area of expertise. Electrical steel manufacturers were asked how the punching method could affect the insulation coating, how it would affect the core losses and how the sheet thickness would affect the punching. Questions to punching tool and device manufacturers focused more on the effects of the method to the tool wear, required punching force and die clearance. Questions asked from stator and rotor manufacturers were a combination of all the above-mentioned.

3 RESULTS

Results of the research are presented in this chapter. They consist of the macroscopic images and SEM images of the slugs from punching laboratory tests and the comments from manufacturers related to the idea of multilayer punching.

3.1 Laboratory test results

All test result macroscope images are from slugs and presented so, that the top layer in the image was also the top layer during punching. Thus, the punch tool has been on the top and die tool on the bottom. The only exception are the SEM images where the stacks are “upside down”, so the top layer in the image was the bottom layer during punching. This helps to see the coating damage in the round area near the cut edge. Macroscopic images have a scale bar on the right upper corner of the figure with the length of a single sheet. SEM images have a measuring scale in the left lower corner where the full length of the scale is 2.00 mm.

Since the testing started as pre-tests with material M270-35A, the results are presented in the same order. The last figures are from the SEM imaging. It is worth noticing that the images gained more written information as the authors experience grew during the research. Most important is to observe the sheets and not the red or white text in the images.

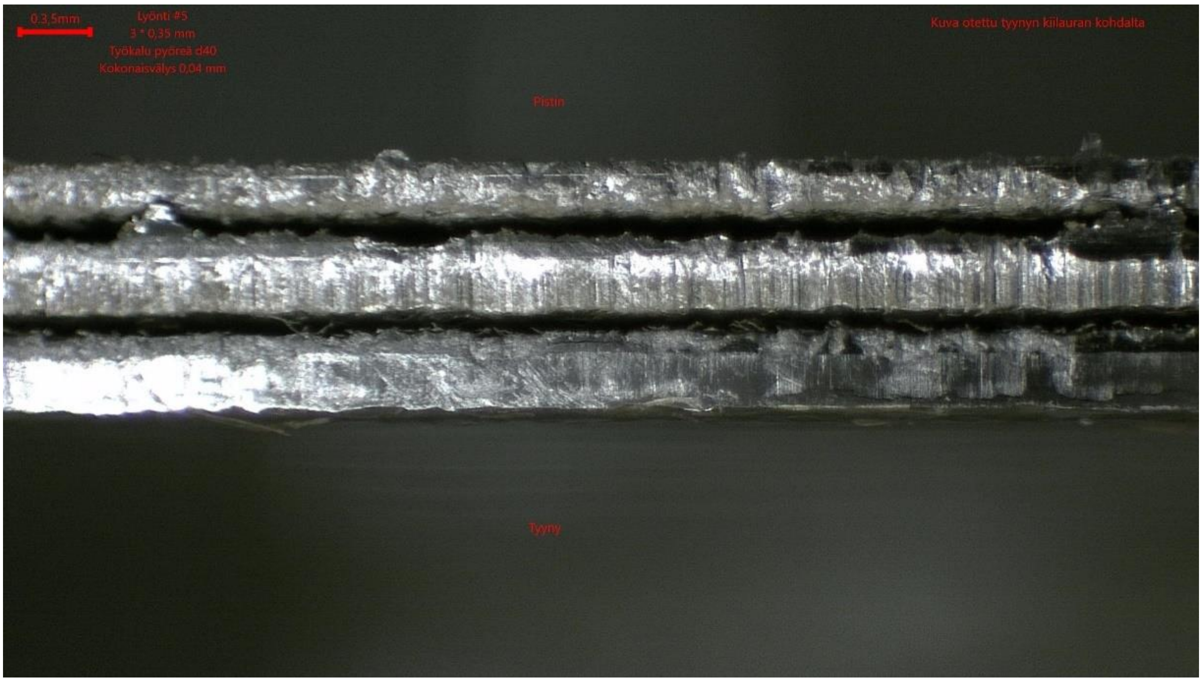

Figure 25. Stack of three M270-35A sheets, die clearance of 0.04 mm. Notice the clean cut of the stack and how the different cutting and fracture zones are divided between the sheets. Not much material has transferred from one sheet to another. Top layer looks nice, and burrs felt minimal when felt with fingertips. Worth noticing how the top layer looks thinner than the other two. Small flaking of the coating visible on the left side of the bottom layer.

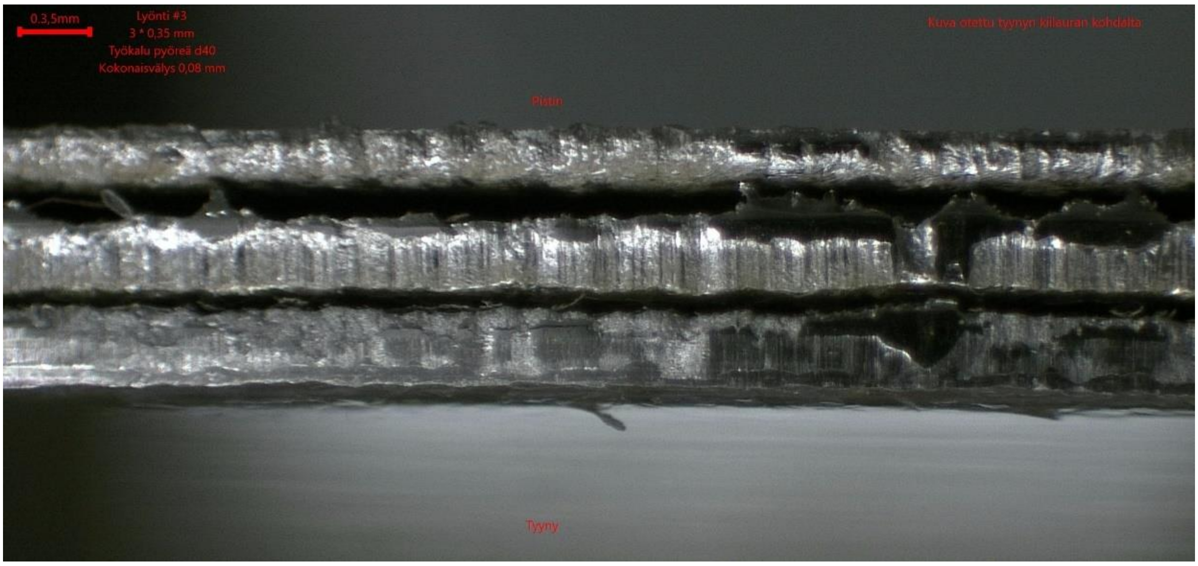

Figure 26. Stack of three M270-35A sheets, die clearance of 0.08 mm. Now more burnish zone is created, visible on the right side of the image. Material starts to transfer between the sheets. Overall appearance is worse than in Figure 25 and Figure 27. Top layer looks like it has more burrs and it also felt like it with fingertips. Bottom layer coating is flaking more.

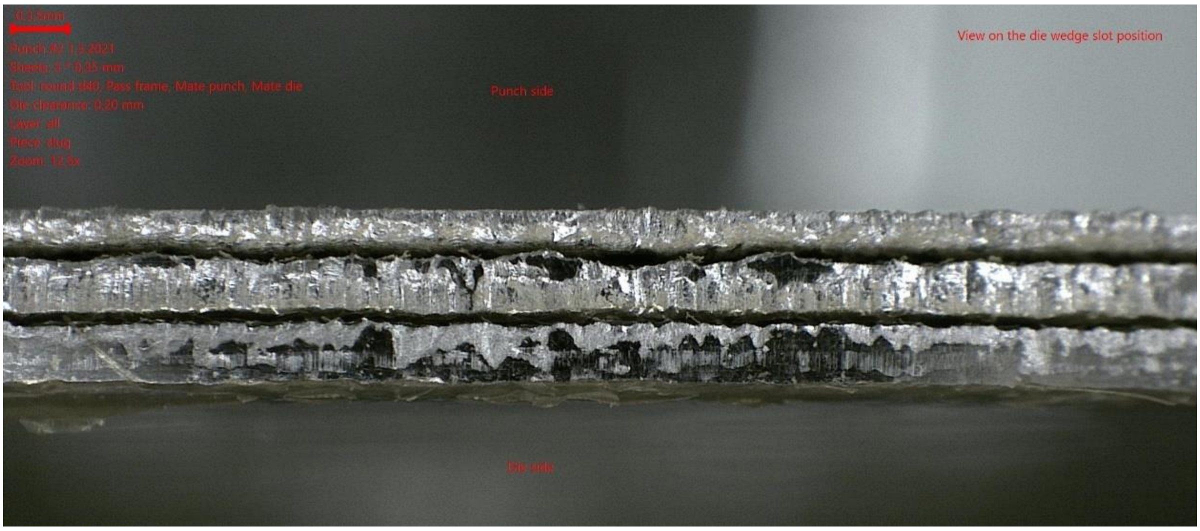

Figure 27. Stack of three M270-35A sheets, die clearance of 0.20 mm. Material transfer has decreased. Overall appearance is clean. Top layer looks fine. Coating is flaking badly due to increased rollover depth in the bottom layer. Burr size felt same as the stack in Figure 25.

Figure 28. Stack of six M270-35A sheets, die clearance of 0.04 mm. Somewhat material transfer that possibly creates electrical connections. Top layer burrs felt minimal. Some flaking in the bottom layer coating.

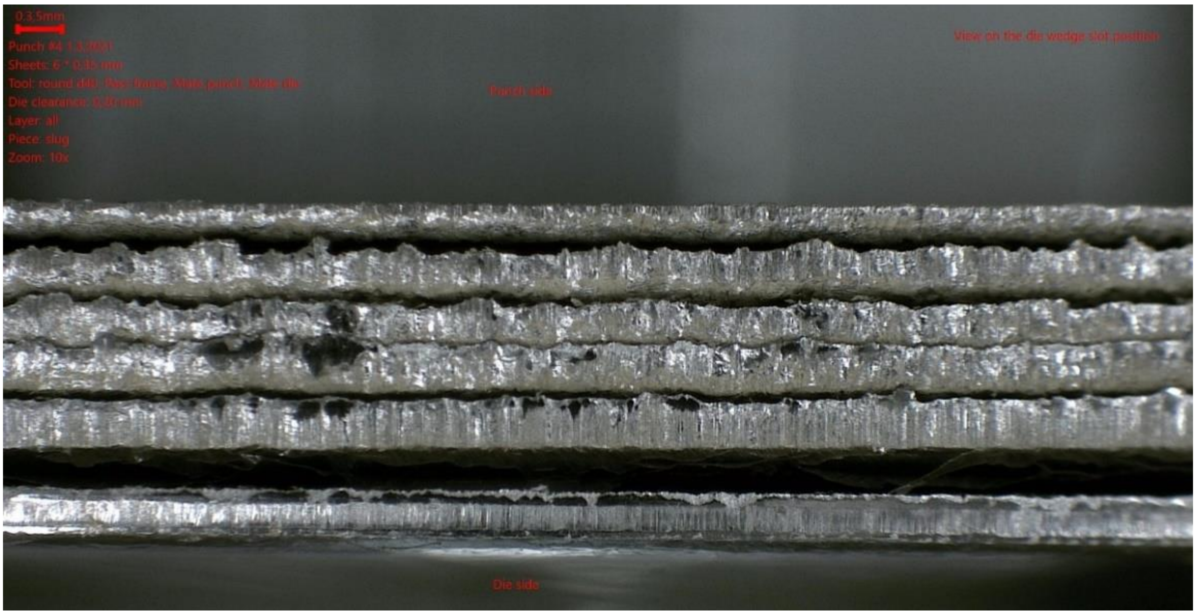

Figure 29. Stack of six M270-35A sheets, die clearance of 0.20 mm. Material transfer is still present. The burrs on layers 2 – 4 tend to turn into the rollover zone of the upper sheets. Bottom layer flaking not so visible. Burrs on the top layer felt worse than with clearances of 0.04 mm and 0.40 mm.

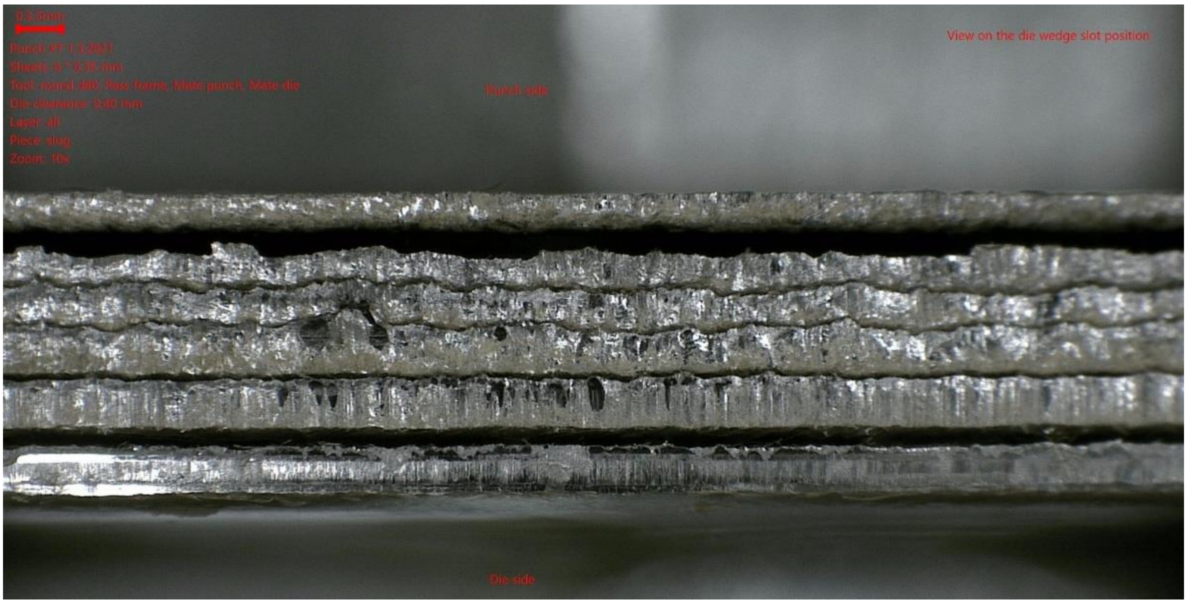

Figure 30. Stack of six M270-35A sheets, die clearance of 0.40 mm. The burrs really start to dig into the rollover (round area) depth of the upper sheets in the layers 2 – 4. Electrical connections can be assumed. Top layer looks like it has minimal burrs and felt like it as well. Bottom layer coating is flaking rather lot.

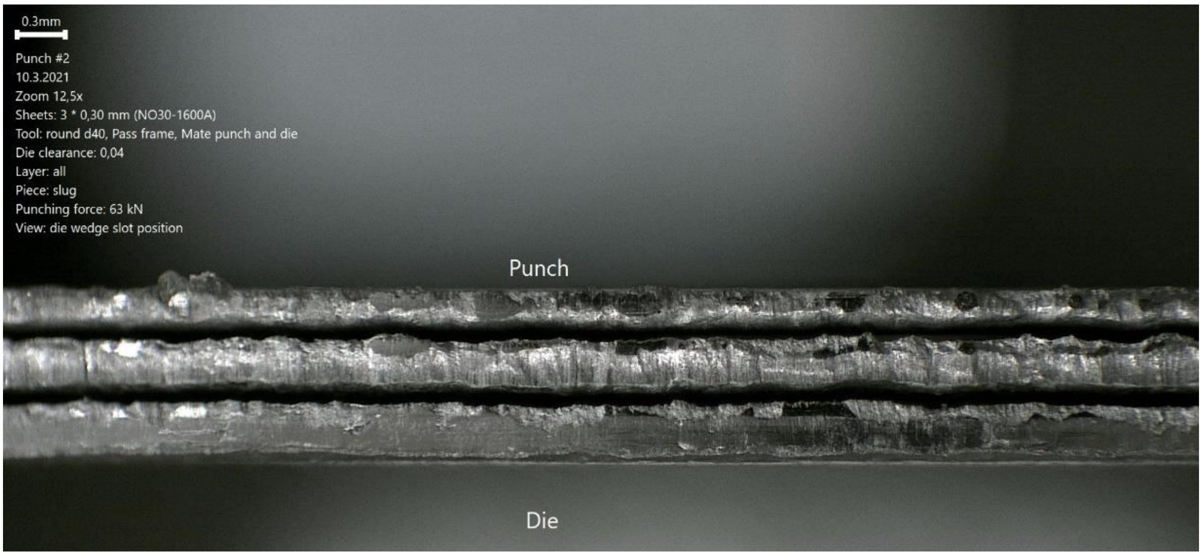

Figure 31. Stack of three NO30-1600A sheets, die clearance of 0.04 mm. Clean overall look, minimal burr height on the top layer. Also with this material, the top layer looks thinner than the other two. Cutting and fracture zones are divided similarly as with M270-35A material. Worth noticing that the bottom layer coating is not flaking.

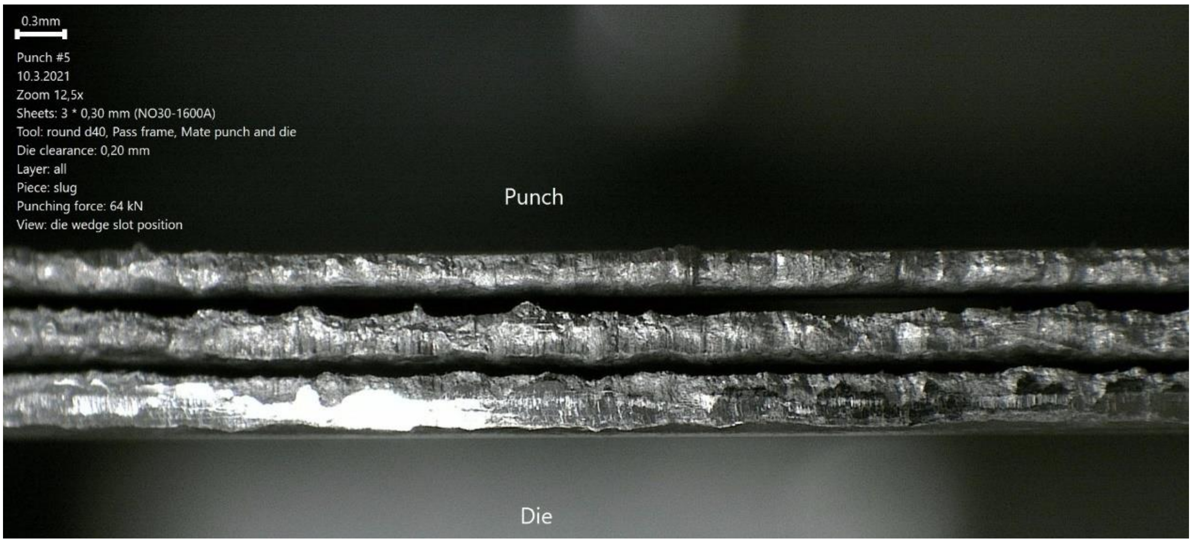

Figure 32. Stack of three NO30-1600A sheets, die clearance of 0.20 mm. Not so clean overall appearance, material starts to transfer between sheets. The penetration zone depth looks worse on the bottom layer than in Figure 33.

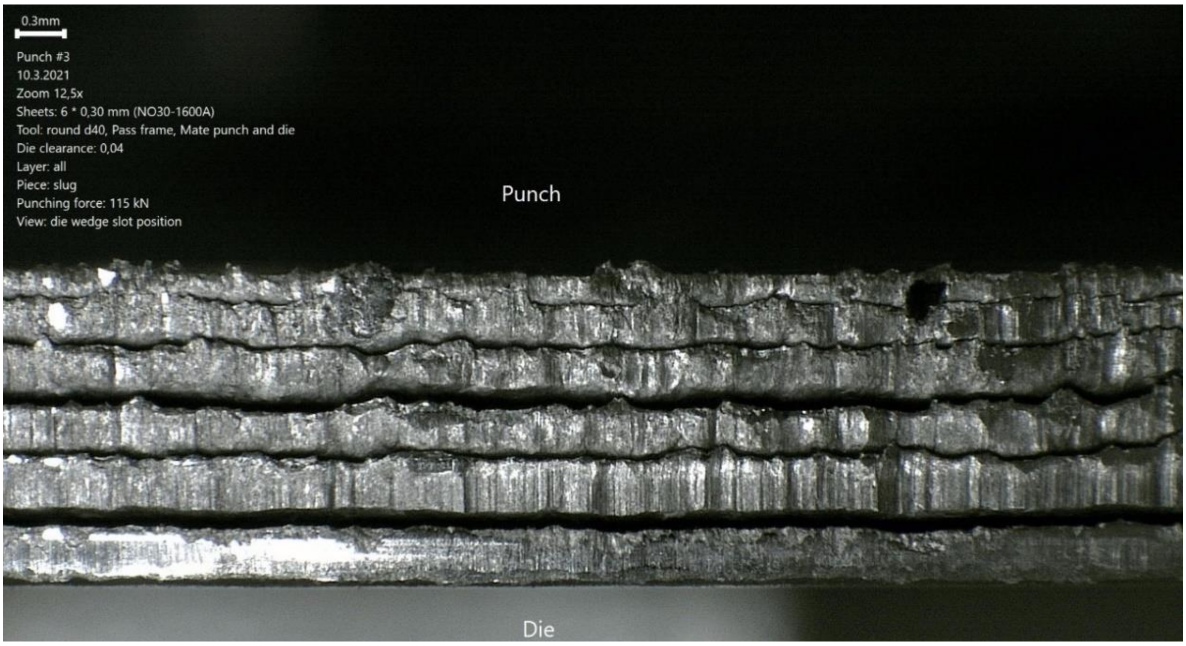

Figure 33. Stack of six NO30-1600A sheets, die clearance of 0.04 mm. The material has transferred rather lot between layers 1 – 3. Seems that only the bottom layer has penetration zone and after that the fracture zone starts. Top level has some burrs.

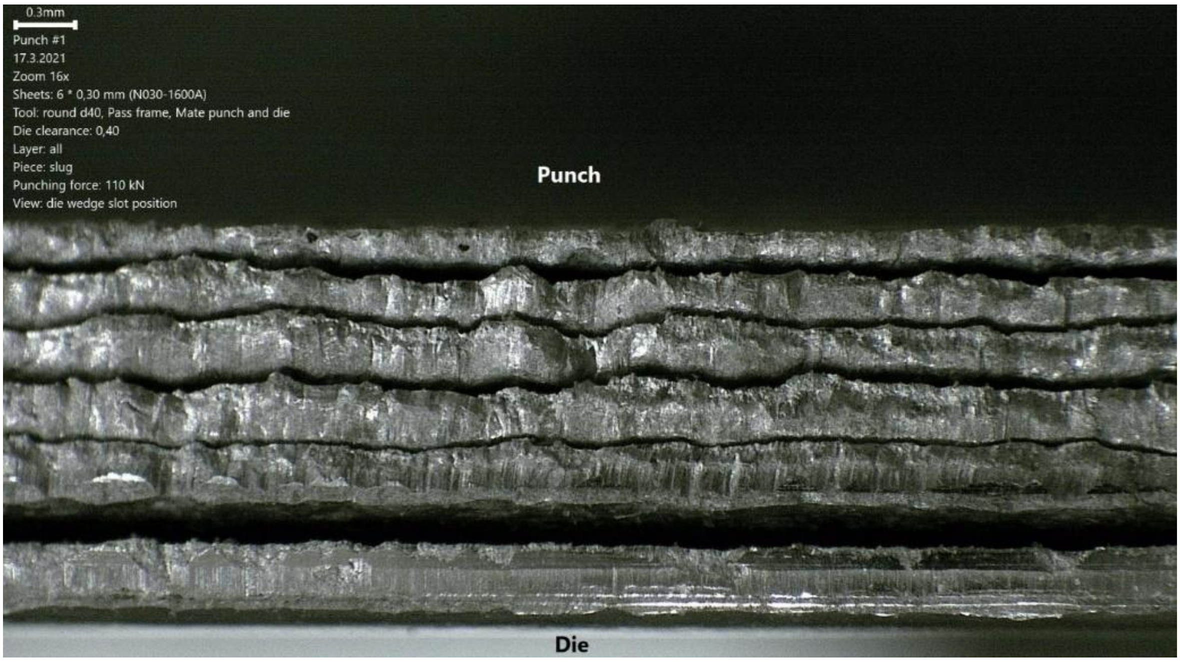

Figure 34. Stack of six NO30-1600A sheets, die clearance of 0.40 mm. The material has not transferred a lot, but the burrs of the previous sheets tend to turn into the rollover zone of the upper sheets. The penetration zone is only present in the bottom layer. No visible damages on the coating. No visible burrs on the top layer.

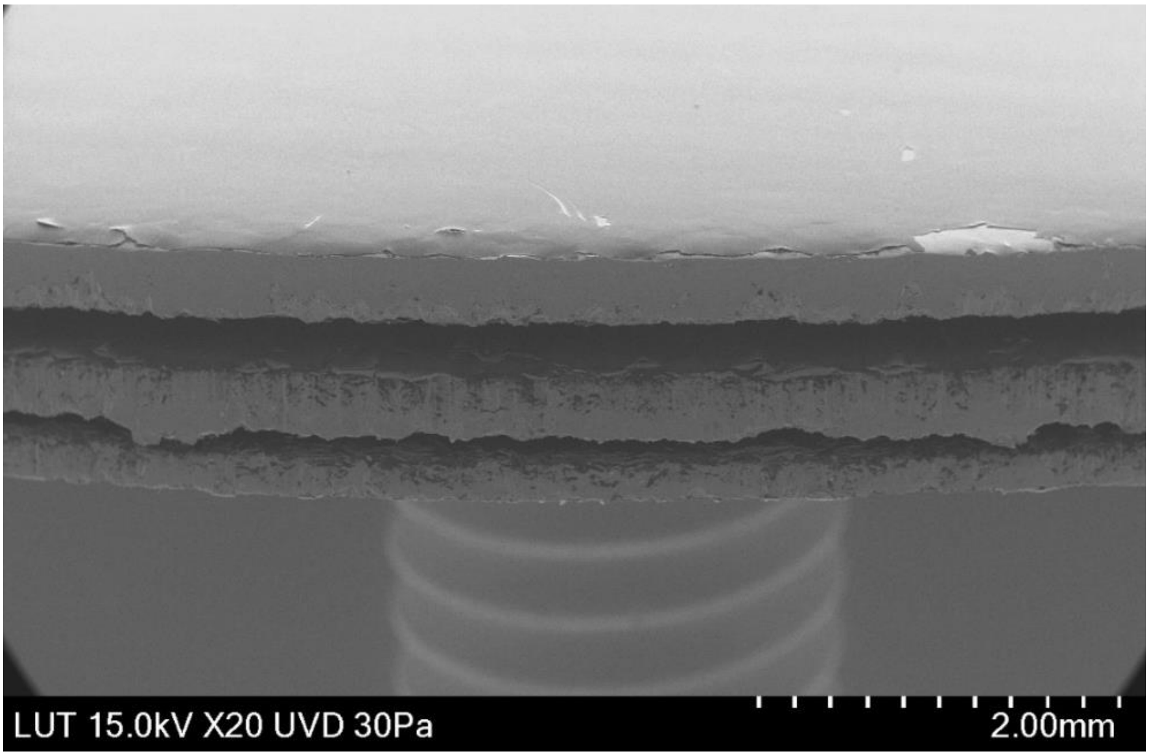

Figure 35. SEM UVD image of a stack of three M270-35A sheets, die clearance of 0.04 mm. Notice the coating damages on the top layer near the cut edge.

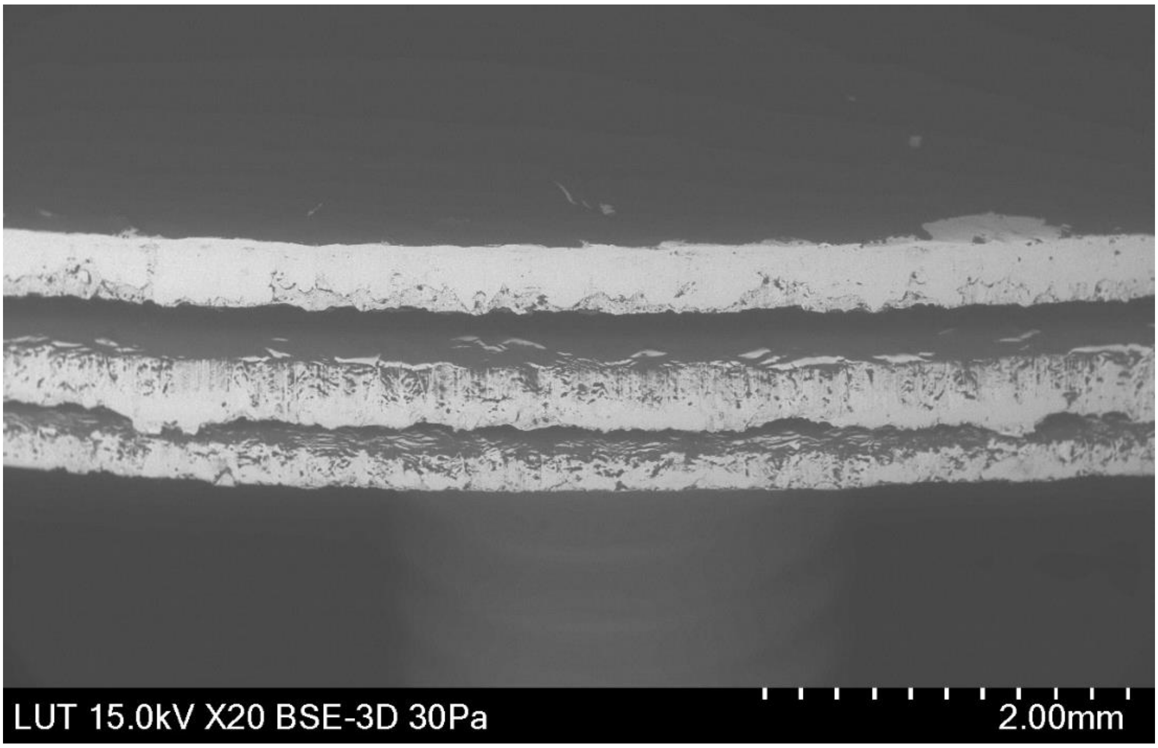

Figure 36. Same as Figure 35 above but with BSE imaging. Dark spots and areas in the cut edges are flakes of coating that have travelled from the sheet surfaces.

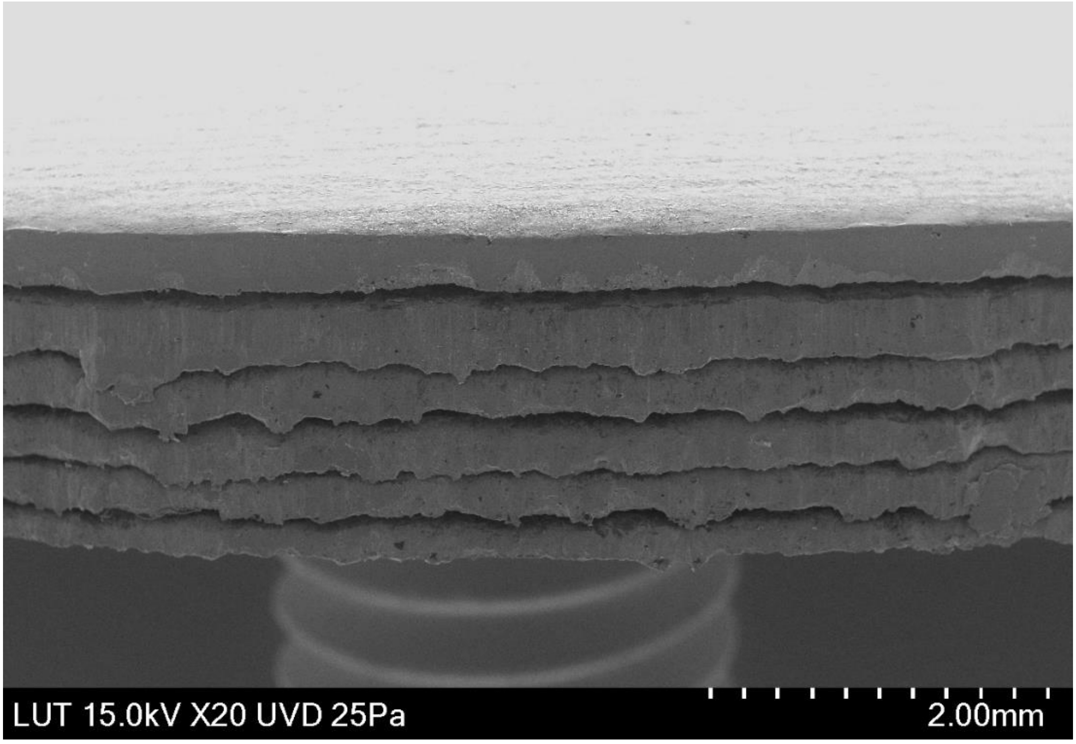

Figure 37. SEM UVD image of six layers of NO30-1600A, die clearance of 0.04 mm. Notice the faultlessness of the coating in the top layer near the cut edge.

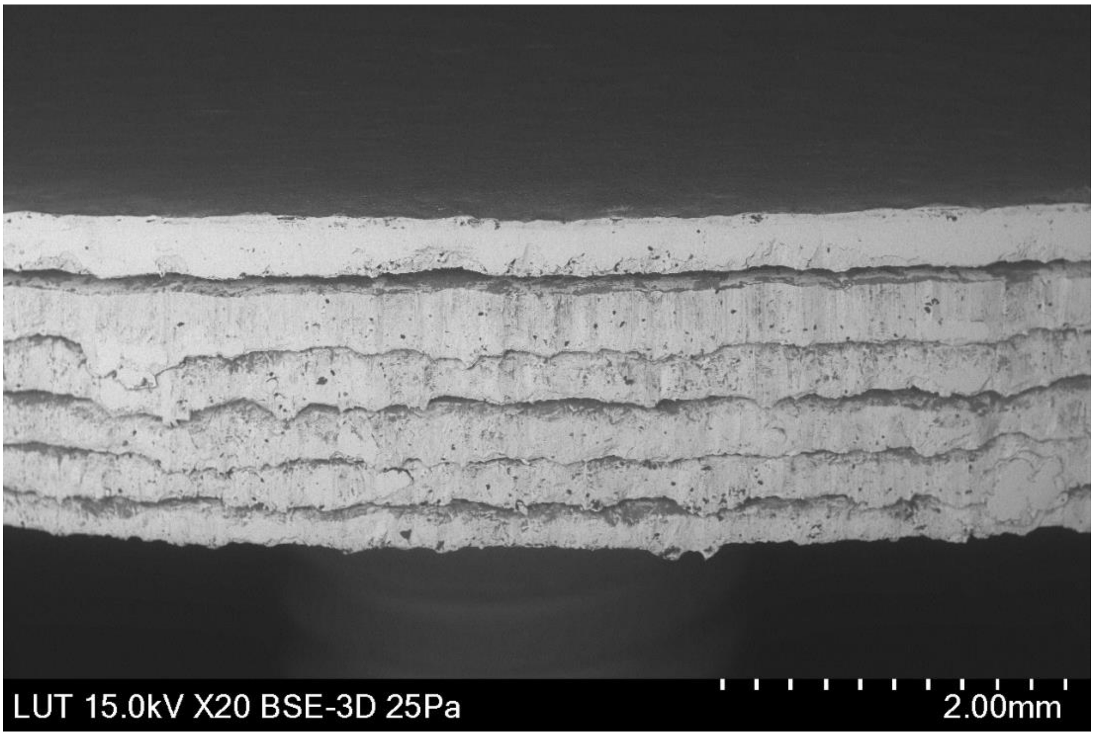

Figure 38. Same image as above but with BSE imaging. Small dark spots in the cut edges are coating flakes.

3.2 Manufacturer comments

Comments have been edited so that their spelling is correct and all essential information is provided. Comments from each company have been presented separately and the type of manufacturer is mentioned.

A French rotor and stator manufacturer was wondering how multiple sheets would be stacked so that they stay aligned through all the process phases. They pointed out that the punch tool cutting edge would only cut the first layer of the stack. The next layer would be cut by the slugs that compile on the punch tool's head. The behaviour of all laminations below the first lamination would have to support the efforts put on the laminations above. Their point of view was that the method is not possible. The tonnage of the press and the effort that will be put on the lamination stacks should be considered as well. During the stamping process, the lamination is on a hard and solid base. A stack of multiple sheets would have a sponge effect during stamping process when the punch starts putting pressure on the first lamination. The laminations should have to be held together tightly. The system would require same number of feeders as there would be sheets in a stack. The system itself is very complex. The required tolerances and quality would not be reached. (Wierenga, 2021).

A Chinese rotor and stator manufacturer commented that cutting several sheets as a stack is not possible with current technology due to the die clearances. One problem would be increased burr height. Also, the punch tool's cutting edge would be easily damaged, and punching force would increase which could lead to overloading the machine. More precise tolerances are required for thinner electric steel and this would increase the manufacturing costs. Multilayer punching would not have an influence on the iron loss in their opinion. (Nanjing Turbine & Electric Machinery (Group) Co., 2021).

According to a German electrical steel manufacturer the damage to the coatings in multilayer punching would depend a lot on the tools and their sharpness. Organic coatings prolong tool life but are damaged more easily near the sheet's cut edge. Inorganic coatings also prolong the tool life but less than organic coatings. Though, inorganic coatings are damaged less during punching. Still, there is always some damage to the coating near the sheet's cut edge.

The manufacturer had punching experience from a composite electrical steel which consists of two layers and an insulating adhesive in between. Selecting the die clearance for the composite sheet was based on a single sheet thickness. (Tietz & Walter, 2021).

A Swedish electrical steel manufacturer was not sure how the method would affect the coating of the sheets. If the sheets would move against each other during punching, it could damage the coating. They were more worried about reaching the tolerances of the punched sheets than the coating damages. Their experience was that a stack of sheets glued together behaves differently compared to a single sheet with the same thickness. Punching GO steels would be even more difficult due to different coatings used in them. Coating could be applied after punching but punching uncoated sheets increases tool wear. According to them, the magnetic properties near the sheet's cut edge are always damaged during punching. If multilayer punching leads to more deformation near the edge, then the damage to the magnetic properties will increase. They were not convinced that the method would create perfectly cut sheets in between the top and the bottom layer of a stack. The coating damage comes mostly from the punch "tearing down" material in the clearance between punch and die and not from the punch or die hitting the surface of the sheet. If the middle layers would behave differently than the top and the bottom layers with respect to this, they could become more deformed. They also pointed out that interlocking would be very difficult to achieve with multilayer punching. (Lindenmo, 2021).

An Austrian electrical steel manufacturer speculated that a stack of sheets might behave in a softer way in punching compared to a single sheet with the same thickness and material. Thus, punching parameters would have to be adapted. There might be a possibility of short circuits between the laminations in the shear affected zone of the cut. The effect to required punching force would depend on the thickness of the stack. Tool wear would increase with the required punching force. Tolerances will depend on the flatness of the steel strip and on the fixing technique of the multiple strips during punching. There were speculations that the "softer behaviour" of a sheet stack might result in a higher shear affected zone which leads to plastic deformation of the coating around the sheet's cut edge. They have found a relation between punching force, sheet thickness, material tensile strength and a constant that depends on the material strength. The constant is usually 0.8 for softer materials and between 0.6 – 0.7 for harder materials. Constant was believed to be higher in multilayer punching. If there would be any effects on material properties, they were believed to affect the mechanical properties more than the magnetic properties. It was believed that it is difficult to achieve acceptable quality of the cut. There could be short-circuits which would increase core losses. Coating punched sheets afterwards was believed to be an expensive process with questionable technical viability. They were also wondering how the sheets would be connected to form a stack. Would there be an adhesive in between the sheets? The sheets should be rotated when creating a stack to take the material's anisotropy of properties into account. (Walch, 2021).

According to a Finnish punching machine manufacturer the shape of the punch tool's head could affect to the cutting in multilayer punching. Different shapes of punch tool heads exist that might help to handle the slugs and pierce the sheet stack. There were speculations that tool wear could be less when punching a stack of sheet compared to a single sheet with same thickness. The punching force was believed to increase with the stack thickness. Removing the slugs during the process might be a problem but there are some solutions to this. Shape of the punch tool's head or a stud in the head and utilizing a vacuum in the process to suck the slugs away. The smaller the die clearance, the less burrs, but the more tool wear. To prevent the slugs doing the cutting, the punch tool head could have a concave shape to compile the slugs in it to keep the cutting edge clear. In electrical steel sheet punching the target is that the burr height is minimal and there is no need for deburring phase after punching. Though, there are deburring machines for sheet metals. (Fabritius, 2021).

A Finnish stator manufacturer commented that multilayer punching is not possible with current machines and devices. This is due expected increase in burr height, problem of defining the die clearance, requirement for developing a feeding system for multiple electrical steel coils and the increase in required punching force. (Veijonen, 2021).

4 DISCUSSION

In the beginning of the research before any tests were done there were only speculations how multilayer punching would work, or would it? Ideas and theories were shared between the research steering group how cut and fracture would take place in the sheet stack. Ideas developed during testing and examinations, some proved to be wrong, but some were on the right tracks as well. One question pondered everyone, should the die clearance be chosen based on the thickness of a single sheet or the stack?

The financial potential of using thinner electrical steel in electric motors has been proved in chapter *Financial potential.* With just around 0.5 % improved efficiency the monetary value of the saved electricity is roughly between 25,000 EUR – 54,000 EUR during the motors lifetime, depending on the discount rate. Based on the calculations it would be justified to study more the potential of multilayer punching as well. The required additional investments to a sheet feeding system, developing punching tools and sheet and stack holders could be reasonable due the unlocked potential of punching a multitude of sheets with only one punch stroke. The compromise between manufacturing costs and electric motor efficiency could be broken. Heading for thinner electrical steel sheets can be justified even if no change is done to the manufacturing methods. Manufacturing costs would increase but the energy saving potential could be explained and reasoned to the customers and thus, the higher selling price of an electric motor justified.

From all macroscope images at least one similarity can be seen, the sheet stacks have behaved as a whole, more or less similar way a single and solid sheet would. All the zones described in Figure 4 are present and have divided between the layers very much like they would in a single sheet. The observation was same for both materials. This is rather interesting discovery because it is not self-evident. Though, it is important to keep in mind that the examined cut edge area of the slugs is rather limited.

Three phases of punching were described in chapter *Process and phenomena.* When punching a single sheet with appropriate die clearance and tooling, the fracture lines meet easily, thus creating clean cut edge with minimum amount of burr. This is very hard to predict in multilayer punching. In a single sheet the fracture lines can meet more easily but, in a stack, there are multiple layers that may each behave differently and regardless of the other layers. This is even more interesting when keeping in mind, that the punch tool is only in touch with the first layer of the stack. After that, each layer is cut by the slug of the previous layer. The deeper the punch proceeds in the stack the more slugs there are on the tool's head. Obviously, the punch tool cutting edge is better for cutting sheet metal than a slug or a stack of slugs. Still, the overall quality of the cut is not that bad.

For easy comparing, all test result observations have been compiled in the Table 6 below. The results in the table are presented in the same order as their corresponding figures appear in the text. Three main observation were related to material transfer between the sheets, damaged coating in the rollover zone and the overall appearance and cleanliness of the cut. These observations were evaluated, and the results are presented in the table with grades. Grading is based on minus and plus signs. Minus sign means that the evaluated factor had a negative impact to the punching quality, whereas plus sign means that it had a positive impact. The maximum amount of minus or plus signs is three.

Table 6. Compilation of test result observations.

Material	*Sheet thickness [mm]*	*Sheets [pcs]*	*Die clearance [mm]*	*Clearance/ stack thickness [%]*	*Material transfer*	*Coating damages*	*Clean cut*	*Burrs*
M270-35A	0.35	3	0.04	3.8	++	++	+++	+++
M270-35A	0.35	3	0.08	7.6	-	+	-	--
M270-35A	0.35	3	0.20	19.0	++	--	++	+++
M270-35A	0.35	6	0.04	1.9	-	+	++	++
M270-35A	0.35	6	0.20	9.5	--	+	+	--
M270-35A	0.35	6	0.40	19.0	--	-	-	++

Table 6 continues. Compilation of test result observations.

Material	*Sheet thickness [mm]*	*Sheets [pcs]*	*Die clearance [mm]*	*Clearance/ stack thickness [%]*	*Material transfer*	*Coating damages*	*Clean cut*	*Burrs*
NO30-1600A	0.30	3	0.04	4.4	+++	+++	+++	+++
NO30-1600A	0.30	3	0.20	22.2	++	+++	+	++
NO30-1600A	0.30	6	0.04	2.2	--	+++	-	-
NO30-1600A	0.30	6	0.40	22.2	-	+++	-	+

The grades were tried to be given in relation, so that they are comparable between stacks with same number of sheets. This means that the grades of stacks with 3 sheets are comparable together but not comparable to stacks with 6 sheets. Thus, the comparison was sought to be kept fair.

According to Table 6, the best overall quality achieved with material M270-35A was with the smallest and the largest die clearances while the burrs have been the determinant. Of course, the grading is rather subjective, but it is based on the visual and hands on experience of the test results. For NO30-1600A there were no tests done with middle clearances due to time constraints. Test were done only with the smallest and largest clearances which were the same as with material M270-35A. This enabled to compare the materials.

As the burrs were not measured but only evaluated by finger feel, it cannot be judged whether the quality of the test pieces would have been acceptable. Since the test material of M270-35A were left over slugs from a stator manufacturer, the burr height on them could be compared to that of the test pieces. None of the test pieces could match the superb quality of the M270-35A test blanks. However, the best quality, which was found in the sheet stacks punched with 0.04 mm die clearance, was rather promising.

It is peculiar that, when punching three layers of sheets, the minimum burr height seemed to be present with die clearances of 0.04 mm and 0.20 mm. The burr height seemed to be higher when using die clearance of 0.08 mm. For a single 0.35 mm sheet, die clearance of 0.04 mm is about 11.4 % and for a stack of three layers it is about 3.8 %. Commonly the die clearance should be around 5 – 10 % so 0.04 mm somewhat meets this condition for both a single sheet and for a stack. Clearance of 0.08 mm for a single sheet and for a stack of three 0.35 mm sheets is respectively about 23 % and 7.6 %. So at least for the stack it meets the conditions. For 0.20 mm clearance, the numbers are 57 % and 19 % which both tend to be too much. Comparing Figures 30 – 32 it looks like die clearance of 0.04 mm has left clean burnish zone in the bottom layer after which the fracture has happened properly. With clearances of 0.08 mm and 0.20 mm the amount of tear-off surface seems to grow. This is probably due the fracture lines not meeting as they should. The best overall quality seems to be present with clearance of 0.04 mm in this case. It is important to keep in mind that the smaller the die clearance the higher the punching force and the more tool wear there is.

Now if we recall Figure 14, the results and observations described above do not correspond with the assumption of the die clearance and material thickness. Stack of three 0.35 mm sheet has the total thickness of 1.05 mm. According to Figure 14 the die clearance for material thickness 1.05 is somewhere between 0.05 mm and 0.10 mm. This matches with the observations for stacks punched with die clearance of 0.04 mm but not with die clearance of 0.20 mm. Based on Figure 14 the die clearance of 0.20 mm should be used with material thickness between 2 – 4 mm. Still, the quality of the stack of sheets punched with die clearance of 0.20 mm was quite good. It is especially strange that the punching test results for die clearance of 0.08 mm was worse than for 0.20 mm. Why is this? The chart in Figure 14 of course assumes that a single sheet is punched at a time, not a multitude of sheets. Could it be that the relation between die clearance and material thickness follows a different pattern in multilayer punching? Somehow it would seem that the fracture lines meet more easily with die clearances of 0.04 mm and 0.20 mm, thus resulting in better punching quality than with die clearance of 0.08 mm. Maybe punching with die clearance of 0.04 mm produces good quality because it is roughly 10 % of a single 0.35 mm sheet. Though, die clearance of 0.20 mm is almost 60 % of a single 0.35 mm sheet and almost 20 % of the 1.05 mm stack thickness it still produced nearly equal quality to die clearance of 0.04 mm. The only exception was the larger rollover depth, which resulted in increased coating damages. These same observations were true also for stacks with six sheets. Die clearances of 0.04 mm and 0.40 mm produced the best quality and in the middle the die clearance of 0.16 mm was worse.

It was found that the rollover depth (round area near cutting edge) of the bottom sheet increased with the die clearance. This is turn leads to coating damages with material M270-35A. The more rollover depth there was, the more damage was caused. Flakes of coating can be seen in bottom layer sheets in all macroscope images but most in Figures 26, 27 and 30. This did not occur with material NO30-1600. Probably the difference in the coating material and coating method affects to the vulnerability of the coating. M270-35A had phenolic resin-based organic coating which seemed more like a painted varnish, whereas NO30-1600 had inorganic phosphate-based coating with inorganic fillers and organic resin. The coating on NO30-1600 was not visible on the sheet surface in the same way as the coating on M270-35A.

Multilayer punching tests led to the observation that material was being transferred between the sheets, from bottom to top direction. This seemed to happen mostly on the middle layers and above them. Especially when punching stacks with six layers, material was practically always transferred between layers 2 – 4. The contribution of the punch tool return stroke to this event cannot be excluded. It could be so that, more burrs were formed on these layers during the punch tool down stroke and the punch tool return stroke bent them and left them pointing up. The problem with the material transfer is the risk of electrical connections between the layers. The coating on the sheets is meant to insulate the sheets when they are assembled as a stack for stator core. Electrical connections between the sheets would not directly make the sheets unusable but they would create local hot spots due to short circuiting. In critical areas of a stator this should be avoided.

One observation could possibly prevent or at least reduce the electrical connections in the areas where material has transferred. In the SEM BSE images, pieces of insulation coating are visible as small dark spots. It makes sense because not only the coating works as an insulating surface, but it operates as “lubrication” during punching. It would not function so well if it would not go in between the punch tool and the cut edge of the sheets. Comparing the punching forces between M270-70 and NO30-1600 while having same the same die clearance and number of sheets, NO30-1600 required always higher punching force. About 11.3 % more even though NO30-1600 sheet thickness was 0.05 mm less than M270-35A's. Though, the manufacturer description of the punchability of these coatings is different. The punchability of M270-35A has been described as very good compared to uncoated material while NO30-1600 coating was described from moderate to good depending on the coating thickness.

Since manufacturing of a stator core requires rather accurate dimensions and tolerances of the laminations, it could be beneficial to do further research on multilayer fineblanking. Fineblanking is a manufacturing method which is closely related to punching and blanking. Difference between fineblanking and conventional blanking is shown in Figure 39, where F_S is blanking force, F_R is Vee-ring force and F_G is counter force. In conventional blanking the cutting punch movement is top-down, and the punch is the only moving part. The channel for the slug is a conical shape opening in the die. Only one force is applied. In fineblanking the material is held still against the punch while the die plate and guide plate move the material up thus creating the cut. Not one, but three forces are applied in the process. (Süddeutscher Verlag onpact GmbH, 2014).

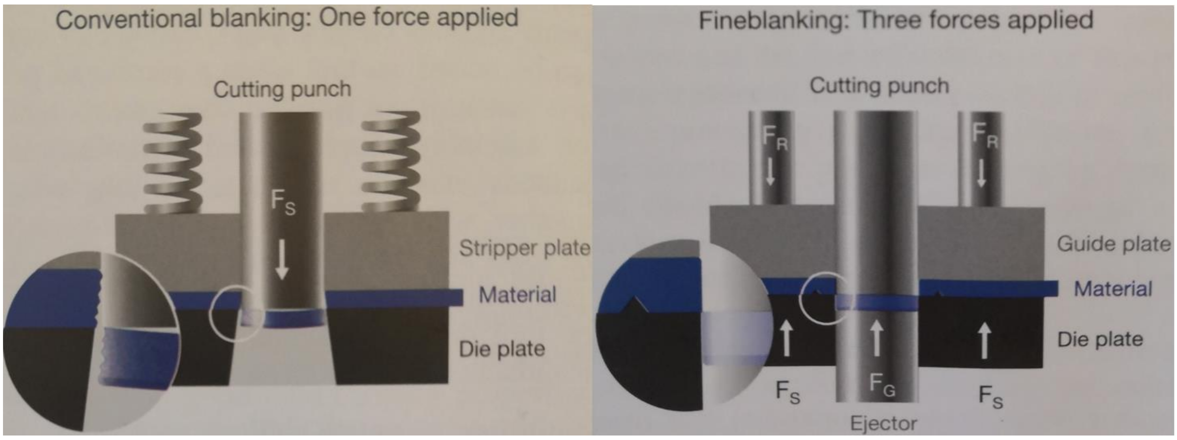

Figure 39. Difference between conventional blanking and fineblanking (Süddeutscher Verlag onpact GmbH, 2014).

The difference in die clearance between conventional blanking and fineblanking is substantial and is depicted in Figure 14. In conventional blanking die clearance is about 5 – 10 % of the workpiece material thickness when it is only about 0.5 % in fineblanking.

Fineblanking is used commonly in automotive industry where sheet metal parts must be produced with high accuracy without the need for after treatments. Thus, it would be interesting to test this method for multilayer punching of electrical steel. The three forces acting in fineblanking could possibly result in better quality and more accurate dimensions of the cut parts. Maybe the material transfer and creation of burrs could be reduced as well.

5 CONCLUSION

This Master's thesis focused on examining the feasibility and potential of multilayer punching of electrical steel sheets. Currently the electric motor manufacturing industry is compelled to make a compromise between manufacturing costs and motor efficiency. In general, the thinner the electrical steel sheets are, the less losses there are in the electric motor. Because the sheets are now produced by punching one sheet at a time the manufacturing time increases if the sheet thickness is decreased. This is because a fixed length of a stator or rotor core must be produced.

To investigate the multilayer punching, three methods were utilized, performing laboratory punching tests, reviewing the available literature, and interviewing manufacturers of the industry.

Based on the work, the research questions can be answered, and hypotheses evaluated. The questions were:

1) Why electrical steel sheets are commonly punched one at a time?
2) How does multilayer punching affect the punching force and tool parameters?
3) How will the cutting and fracture take place when punching a sheet stack?

One probable reason for electrical steel sheets being punched one at a time is that there are large number of parameters which affect the punching quality. Finding the best combination and controlling all the parameters is a challenging task. It requires a lot of testing and research as well. Even if the best combination of parameters is found for certain electrical steel type, it is not given that same punching quality can be reached with same parameters for a different steel type. If adequate punching quality is reached another set of question arise. How multiple sheets would be fed to the process? How the punched sheet stack would be controlled and conveyed further in the process? The amount of required research, testing and investments is vast.

The effects of multilayer punching on punching force and tool parameters were discovered during the work. Punching force increases with the number of the sheets in a stack. The coating type of the steel affects also the punching force due to its lubricative properties. Tool parameters in this case mean the die clearance. This is the most interesting part of the research due to its puzzling nature. In conventional punching the die clearance is chosen based on the sheet thickness. The problem is that in multilayer punching there are multiple sheets on top of each other, creating a stack. Should the die clearance be chosen based on a single sheet thickness or the thickness of the stack? Traditional way of determining the die clearance is somewhat out of question. It was demonstrated in the results and discussion that multilayer punching does not obey the traditional rules in this case. Rather good punching quality was reached with two die clearances with the confusing detail that a clearance chosen between these two, produced worse quality. Exact reason for this was not found but it can be said that multilayer punching requires a different approach when determining the die clearance.

Theories about cut and fracture were shared during the research and laboratory tests. It was wondered if each sheet in a stack would behave as individual sheets or would the sheet stack behave like a solid sheet. After first punching tests were done and samples were examined with a macroscope it became clear that a stack of sheets behaves very much like a solid, single sheet would. No matter how many sheets there were in the stack, all the features of a punched work piece presented in chapter *Process and phenomena* were present.

The hypotheses of the research were:

1) Multilayer punching is possible if the maximum sheet thickness of the punching machine and tool is not exceeded.
2) Multilayer punching creates perfectly cut sheets between top and bottom layer of a stack.

The first hypothesis was not fully tested in the laboratory tests. The maximum number of sheets in a punched stack was 6 and the stack total thickness was 2.1 mm. The maximum material thickness for the machine used in the tests for punching is 8 mm. Though, the maximum was not exceeded, and sheet stacks were successfully punched so it can be said that hypothesis number 1 is true.

Second hypothesis turned out not to be false. In fact, the worst sheets were in the middle of the stacks. These sheets had the most burrs and fractures.

Multilayer punching has a large potential for the sheet metal industry. Based on the patent applications found, it is continuously developed by the electrical steel industry, but detailed information and research are not public yet. Punching tests done during the thesis show that the method is feasible if it is studied more.

Further research on the topic is recommended. More testing should be done. Author recommends studying and testing of multilayer fineblanking. Additional systems and devices should be studied as well. Feeding the sheets to the punching machine, holding the stack during punching, and keeping the stack together after punching should be studied. Very important thing would be doing electrical measurements to the punched sheet stacks to find out if they are short-circuiting. Magnetic properties should be measured as well to see if multilayer punching deteriorates them more than conventional punching. Further research could also include examining the effects of multilayer punching on the punching tool life.

Using more efficient electric motors has significant financial potential. Thus, it justified to gradually shift towards using thinner electrical steel sheets in rotor and stator production.

LIST OF REFERENCES

Akyürek, F., Yaman, K. & Tekiner, Z., 2017. An ExperimentalWork on ToolWear Affected by Die Clearance. *Arabian Journal for Science and Engineering,* Issue 42, p. 4683–4692.

Arfken, G. B., Griffing, D. F., Kelly, D. C. & Priest, J., 1984. ELECTRO-MAGNETIC INDUCTION. In: *International Edition University Physics.* s.l.:Elsevier, pp. 650-666.

AW Precision, 2019. *Everything You Need to Know About CNC Punching.* [Online] Available at: https://www.awprecision.co.uk/everything-need-know-about-cnc-punching/ [Accessed 3 March 2021].

Beckley, P., 2002. *Manufacturing methods.* London: Institution of Electrical Engineers.

Boljanovic, V., 2014. *Sheet Metal Forming Processes and Die Design.* 2nd ed. New York: Industrial Press, Inc.

Buschow, K. J. et al., 2001. Magnetovolume, Invar Effect, and Magnetostriction. In: *The Encyclopedia of Materials : Science and Technology.* s.l.:Elsevier, p. 2068.

Cai, G., Li, C., Cai, B. & Wang, Q., 2017. An investigation on the role of texture evolution and ordered phase transition in soft magnetic properties of Fe–6.5 wt%Si electrical steel. *Journal of Magnetism and Magnetic Materials,* Volume 430, pp. 70-77.

Chaudhury, A. et al., 2007. Low silicon non-grain-oriented electrical steel: Linking magnetic properties with metallurgical factors. *Journal of Magnetism and Magnetic Materials,* 313(1), pp. 21-28.

Cogent Power, 2020. *Download: Tata Steel Europe.* [Online] Available at: https://www.tatasteeleurope.com/ts/sites/default/files/Cogent%20NO%20brochure%202016.pdf
[Accessed 20 February 2021].

Cornu, M.-J.et al., 2014. Behaviour of tetramine inhibitors during pickling of hot rolled steels. *Applied Surface Science,* Volume 293, pp. 24-36.

Ding, Y. et al., 2014. Coating induced residual stress in nonoriented electrical steel laminations. *Journal of Materials Research,* 29(16), pp. 1737-1746.

Dongguan Hongkai Precision Technology Co., Ltd., 2019. *Improvement process of motor stator core press-fit die.* [Online] Available at: http://www.hkmold.cc/en/nd.jsp?id=13 [Accessed 20 March 2021].

Egawa, T. & Totsuka, H., 1995. *Steel plate punching method.* Japan, Patent No. JPH08300061A.

Electrical Engineering Tool Box, 2016. *Basic Parts of a Three Phase (3-Φ) Squirrel Cage Induction Motor.* [Online] Available at: https://www.electricalengineeringtoolbox.com/2016/12/basic-parts-of-three-phase-3-squirrel.html
[Accessed 5 March 2021].

EUR-Lex, 2009. *Electric motors.* [Online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009R0640
[Accessed 11 March 2021].

Evans, K., 2016. *Programming of CNC Machines.* 4th ed. South Norwalk: Industrial Press, Inc..

Fabritius, T., 2021. *Finn-Power Oy. Online meeting* [Interview] (21 January 2021).

Finnish Standards Association, 2005. *SFS-EN 10342: Magnetic materials. Classification of surface insulations of electrical steel sheet, strip and laminations.* Helsinki: Finnish Standards Association.

Finnish Standards Association, 2015. *SFS-EN 10303: Thin magnetic steel strip and sheet for use at medium frequencies.* Helsinki: Finnish Standards Association.

Gallo, A., 2014. *A Refresher on Net Present Value.* [Online] Available at: https://hbr.org/2014/11/a-refresher-on-net-present-value [Accessed 10 April 2021].

Goel, V. et al., 2016. Application of Co–Ni–P Coating on Grain-Oriented Electrical Steel. *IEEE Transactions on Magnetics* , 52(4).

Hambli, R., Guerin, F. & Dumon, B., 2003. Numerical Evaluation of the Tool Wear Influence on Metal-Punching Processes. *The International Journal of Advanced Manufacturing Technology,* 21(7), pp. 483-493.

Harstick, H., Ritter, M., Plath, A. & Riehemann, W., 2014. EBSD Investigations on Cutting Edges of Non-Oriented Electrical Steel. *Metallography, Microstructure, and Analysis volume,* Volume 3, pp. 244-251.

Harstick, H., Ritter, M. & Werner, R., 2014. Influence of Punching and Tool Wear on the Magnetic Properties of Nonoriented Electrical Steel. *IEEE Transactions on Magnetics,* 50(4), pp. 1-4.

Hason Precision Mould Fittings Co., Ltd., n.d. *Thick Turret Tooling.* [Online] Available at: http://www.hasonindustry.com/thick-turret-tooling/turret-punch-tool-and-die.html
[Accessed 28 February 2021].

Hoffmann, H. & Hörmann, F., 2007. Clean-sheared and rectangular edges through counter-shaving. *Production Engineering* , Volume 1, pp. 157-162.

Iwamoto, T., Nakamura, A., Onishi, H. & Suzuki, S., 1979. *Blanking method for overlapped double sheets for iron core of electrical machinery and apparatus.* Japan, Patent No. JPS55156623A.

Jahangiri, M., Bajgholi, A. & Zhaam, A., 2014. Development of a new three-stage cold rolling manufacturing. *International Journal of Advanced Manufacturing Technology,* Volume 75, p. 1291–1298.

Jin, Z., Li, W. & Li, Y., 2011. *Effect of Hot-rolled microstructure on the recrystallization Texture of Cold-rolled non-oriented electrical steel.* Dürnten, Trans Tech Publications Ltd..

Kibe, Y., Okada, Y. & Mitsui, K., 2007. Machining accuracy for shearing process of thin-sheet metals—Development of initial tool position adjustment system. *International journal of machine tools & manufacture,* 47(11), pp. 1728-1737.

Klingenberg, W., Boer, d. & T.W, 2008. Condition-based maintenance in punching/blanking of sheet metal. *International Journal of Machine Tools and Manufacture,* 48(5), pp. 589-598.

Koopmans, S. et al., 2017. *Process for blanking of metal parts.* Europe, Patent No. EP3439809A1.

Koopmans, S. & Janssen, T. M. H., 2018. *Multi-layer fine blanking process for manufacturing metal parts and fine blanking device for carrying out such process.* Netherlands, Patent No. NL1043111B1.

Korpinen, L., 1998. *Sähkövoimatekniikkaopus.* [Online] Available at: http://leenakorpinen.com/fi/julkaisut/opetusaineistoja/ [Accessed 4 March 2021].

Kärkkäinen, H., 2015. *CONVERTER-FED INDUCTION MOTOR LOSSES: DETERMINATION WITH IEC.* Lappeenranta: Lappeenranta University of Technology.

Lamprecht, E., Hömme, M. & Albrecht, T., 2012. *Investigations of eddy current losses in laminated cores due to the impact of various stacking processes.* Nuremberg, IEEE.

Lindenmo, M., 2021. *Cogent Power. E-mail* [Interview] (1 February 2021).

Lindenmo, M., Coombs, A. & Snell, D., 2000. Advantages, properties and types of coatings on non-oriented electrical steels. *Journal of Magnetism and Magnetic Materials,* Volume 215-216, pp. 79-82.

Loisos, G., Moses, A. & Beckley, P., 2003. Electrical stress on electrical steel coatings. *Journal of Magnetism and Magnetic Materials,* Volume 254-255, pp. 340-342.

Mate Precision Technologies, 2021. *UltraTEC® High Performance.* [Online] Available at: https://www.mate.com/product/punch-press-tooling/thick-turret-tooling/ultra-thick-turret-tooling-system/ultratec-high-performance/#fndtn-tab1
[Accessed 2 March 2021].

Matsuno, T. et al., 2010. *Method and apparatus for punching metal plate and method for manufacturing rotary electric iron core.* Japan, Patent No. JP5494448B2.

Mehdi, M., He, Y., Hilinski, E. J. & Edrisy, A., 2017. Effect of skin pass rolling reduction rate on the texture evolution of a non-oriented electrical steel after inclined cold rolling. *Journal of Magnetism and Magnetic Materials,* Volume 429, pp. 148-160.

Mehdi, M. et al., 2019. Non-oriented electrical steel with core losses comparable to grain-oriented electrical steel. *Journal of Magnetism and Magnetic Materials,* Volume 491.

Menga, L. et al., 2021. Evolution of texture and microstructure in preparation of ultra-thin grain-oriented silicon steel. *Journal of Magnetism and Magnetic Materials,* Volume 523.

Moses, A., Anderson, P. & Jenkins, K., 2019. Electrical Steels. In: *Volume 1: Fundamentals and basic concepts.* s.l.:Stevenage: The Institution of Engineering and Technology, pp. 403-416.

Mucha, J., 2010. An experimental analysis of effects of various material tool's wear on burr during generator sheets blanking. *The International Journal of Advanced Manufacturing Technology ,* Volume 50, pp. 495-507.

Nanjing Turbine & Electric Machinery (Group) Co., L., 2021. *E-mail* [Interview] (21 January 2021).

Ningbo Ketai Magnetic Material Co.,ltd, 2017. *What is the coercivity (bHc), what is the intrinsic coercivity (jHc).* [Online]
Available at: http://www.ketai-magnets.com/What-is-the-coercivity-bHc-what-is-the-intrinsic-coercivity-jHc-/
[Accessed 27 February 2021].

Osakada, K., Mori, K., Altan, T. & Groche, P., 2011. Mechanical servo press technology for metal forming. *CIRP Annals,* 60(2), pp. 651-672.

Ouyanga, G. et al., 2019. Review of Fe-6.5 wt%Si high silicon steel—A promising soft magnetic material for sub-kHz application. *Journal of Magnetism and Magnetic Materials,* Volume 481, pp. 234-250.

Pan, H., Zhang, Z., Mo, Y. & Xie, J., 2016. Strong recrystallization texture component in 6.5 wt% Si electrical steel thin sheets by secondary cold rolling and annealing. *Journal of Magnetism and Magnetic Materials,* Volume 419, pp. 500-511.

Park, H.-K.et al., 2020. Comparison of the Crystallization Behavior of Silica Between Mg- and Al-Phosphate Used in Tension Coatings of Grain-Oriented Electrical Steel. *Metals and Materials International volume,* Volume 26, pp. 321-325.

PRIMA INDUSTRIE S.p.A., n.d. *Punch Genius.* [Online] Available at: https://www.primapower.com/turret-punch-press-punch-genius/ [Accessed 28 February 2021].

Prima Power, n.d. *Combi Genius.* [Online] Available at: https://www.primapower.com/uk2/combi-machine-combi-genius/#1448982719858-0eaae0f8-b51dfc72-a00fae4f-fbac
[Accessed 15 March 2021].

Pärmi, H., 2019. *Thick Turret Tool Guidelines.* Seinäjoki: Seinäjoki UAS, School of Technology.

Radhakrishnan, P., 2015. CNC TURRET PUNCH PRESS. In: *Computer Numerical Control Machines and Computer Aided Manufacture.* s.l.:New Academic Science, p. 64.

Ripka, J., 2014. *Maximum sheet metal punching, minimal distortion.* [Online] Available at: https://www.thefabricator.com/thefabricator/article/punching/maximum-sheet-metal-punching-minimal-distortion-article
[Accessed 28 February 2021].

Senda, K., Uesaka, M. & Oda, Y., 2015. *PUNCHING METHOD AND METHOD FOR MANUFACTURING LAMINATED CORE.* Japan, Patent No. JP5958565B2.

Senda, K., Uesaka, M. & Oda, Y., 2016. *Punch processing method for electrical steel sheets and method for manufacturing laminated core.* Japan, Patent No. JP6288201B1.

Smid, P., 2007. *CNC Programming Handbook - A Comprehensive Guide to Practical CNC Programming.* 3rd ed. New York: Industrial Press.

Soshin, C., 1997. *Physics of ferromagnetism.* 2nd ed. Oxford: OUP Oxford.

Strom-Report, 2021. *Electricity prices in Europe - who pays the most?.* [Online] Available at: https://strom-report.de/electricity-prices-europe/ [Accessed 10 April 2021].

Suuronen, O., 2020. *Electromagnetic calculations.* Lappeenranta: The Switch Drive Systems Oy.

Süddeutscher Verlag onpact GmbH, 2014. *Forming and Fineblanking.* 1st ed. Münich: Süddeutscher Verlag onpact GmbH.

Szary, P., Kahveci, A., Lewe, T. & Schrauf, M., 2018. *Stamping and packaging of lamellas from a composite material.* Germany, Patent No. DE102018133204A1.

Szary, P., Lewe, T., Machalitza, K. & Kessler, L., 2018. *Stamping of at least two metal sheets arranged one above the other.* Germany, Patent No. DE102018133202A1.

Takeshi, O. et al., 2015. Effect of Hardness and Thickness of Nonoriented Electrical Steel Sheets on Iron Loss Deterioration by Shearing Process. *IEEE Transactions on Magnetics* , 51(11).

Thyssenkrupp Electrical Steel GmbH, 2021. *Publications.* [Online] Available at: https://www.thyssenkrupp-steel.com/media/content_1/produkte/elektroband/electrical_steel_integration/thyssenkrupp_electrical_steel_product_range.pdf
[Accessed 11 March 2021].

thyssenkrupp Materials Processing Europe GmbH, 2019. *Composite material: thyssenkrupp Materials Processing Europe GmbH.* [Online] Available at: https://www.thyssenkrupp-materials-processing-europe.com/en/products/composite-material
[Accessed 26 February 2021].

Thyssenkrupp Steel Europe, A., 2019. *Publications.* [Online] Available at: https://www.thyssenkrupp-steel.com/media/content_1/publikationen/lieferprogramme/thyssenkrupp_product-range_no-electrical-steel_powercore_steel_en.pdf
[Accessed 26 February 2021].

Tietz, M., 2021. *Head of Technical Customer Service* [Interview] (15 January 2021).

Tietz, M. & Walter, A., 2021. *thyssenkrupp Steel Europe AG. E-mail* [Interview] (14 January 2021).

Tong, W., 2014. *Mechanical Design of Electric Motors.* 1st ed. Radford: CRC Press.

Ulintz, P., 2013. *Defining Acceptable Burr Height.* [Online] Available at: https://www.metalformingmagazine.com/article/?/management/consulting-and-training/defining-acceptable-burr-height
[Accessed 3 April 2021].

V&F Sheetmetal Co. Ltd, 2021. *WHAT IS CNC PUNCHING?.* [Online] Available at: http://www.vandf.co.uk/tooling/what-is-cnc-punching/
[Accessed 2 March 2021].

Veijonen, J., 2021. *HTV-Power Oy. E-mail* [Interview] (14 January 2021).

Walch, C., 2021. *Voestalpine AG. E-mail* [Interview] (10 February 2021).

Wegener, K., 2014. Forming Presses (Hydraulic, Mechanical, Servo). In: T. I. A. f. P. Engineering, L. Laperrière & G. Reinhart, eds. *CIRP Encyclopedia of Production Engineering.* s.l.:Springer, Berlin, Heidelberg, pp. 547-553.

Wierenga, H., 2021. *r. Bourgeois. E-mail* [Interview] (18 January 2021).

Xie, Z., Kang, Y. & Wang, Q., 2008. Developments in the production of grain-oriented electrical steel. *Journal of Magnetism and Magnetic Materials,* 320(23), pp. 3229-3233.

Zhang, S., 2021. *Automatic Stamping Production Line: The Basic Guide.* [Online] Available at: https://www.machinemfg.com/automatic-stamping-production-line/
[Accessed 11 May 2021].