POLITECNICO DI TORINO

MsC in Automotive Engineering

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

MASTER’S DEGREE THESIS

Artificial Intelligence for Smart Manufacturing

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SUMMARY

The purpose of the thesis is to give thorough understanding of the image processing working on the samples of resistance spot welds from the real case study.

At the beginning there is provided general introduction about Industry 4.0 paradigm and motivation of working on topic. Then, theory about artificial intelligence and its branch such as machine learning is subjected, mainly about impact in the manufacturing branch. Having understood theory about data processing, some explanation of resistance spot welding process is determined. To analyze images, material in the form of hundreds of pictures previously collected from the dataset of spot welds have been supplied and used as a case study. Machine learning concepts have been used to analyze quality of the spots in the order of data analyzing as measuring different values of the spot welds using various libraries of python.

Conclusions of the work can be used as a further step on the way to improve modern manufacturing and analyze limitations before the next project. Growing number of data to be analyzed motivates invention of new technologies and methods to improve manufacturing processes. By concluding this thesis next step to improve quality assessment has been done.

Keywords:

Artificial Intelligence, Image Processing, Industry 4.0, Smart Manufacturing, Resistance Spot Welding

ABSTRACT

The purpose of this work is to give understanding of the application of image processing using machine learning concept: how innovation in form of AI can drive modern manufacturing company or industry sector.

Work is demonstrated by a case study related to resistance spot welding process and results in the benefits related to production optimization and assessment in preliminary quality control stage. Experimental part of the thesis provides example of solution how various python libraries can be used in the similar projects. Final results illustrates graphs with electrode parameters over time and characterizes behavior of electrode in form of variation of diameter, area and distances from the center of electrode, which gives interesting conclusion being compared to previously described theoretical data.

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CHAPTER 1 – INTRODUCTION

1.1 Literature overview

The rising impact of smart manufacturing sector creates opportunities for technological innovations. Manufacturers are creators who are continuously looking for better, more efficient ways to create products. Ways with less waste and less defects.

There is no clear time span when paradigm “Industry 4.0” was established. It is said that in 2011 German government project to digitalize manufacturing opened officially new way of fabrication of products. More and more attention started to be paid on smart systems and smart machines fueled by data. [1]

To bring some examples of the project, we can highlight on branches as robotics and automation, additive manufacturing and 3D printing or Internet of Things.

First statement describes collaboration between robots and humans, popularly called Corobots. They are designed to work near to human operators who teach them what to do and in which order. Consecutive steps of production are then optimized. Automation takes place as the improvement in the sector starting from the auto industry to food and consumer goods. [1]

Additive manufacturing, process used to create physical model by putting layer of materials on by one. On the contrary to subtractive manufacturing that creates its final product by cutting a block, additive manufacturing adds parts to form final product. 3D printing market according to recent prediction is expected to gain $35 billion by 2025. [1]

Last paradigm called “The Internet of Things” is briefly described as giant network of computers, machines and systems that exchange each other information and data. Some of the most relevant benefits related to this innovation are real-time monitoring, remote equipment management, condition-based downtime alerts, indentifying and correcting quality issues or using predictive maintenance to minimize equipment failure and service cost in digital factories. [1]

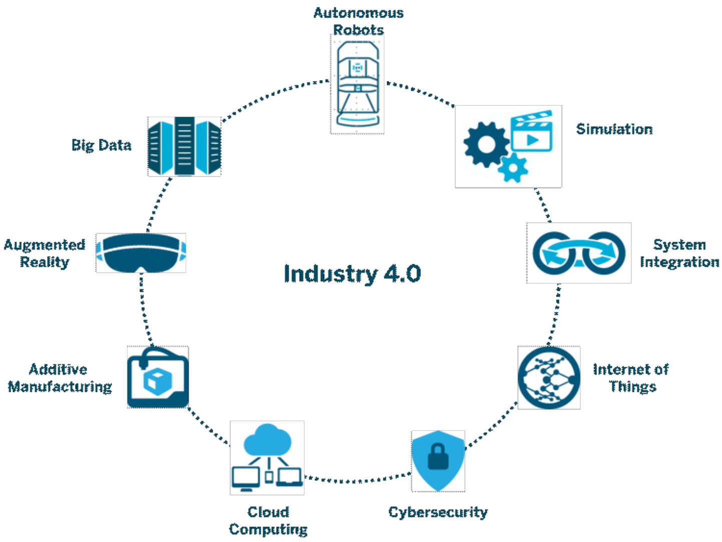

Figure 1: Main elements of Industry 4.0

1.2 Smart manufacturing

Over the past years topic related to Smart Manufacturing have been well-known among manufacturers, strategists and business leaders. In a large number of front lines of manufacturing articles and journals it appeared to highlight importance for the future of industrial transition. There is provided completely new, unique approach to production in which history, current status and definitive way is given to obtain a product. [2]

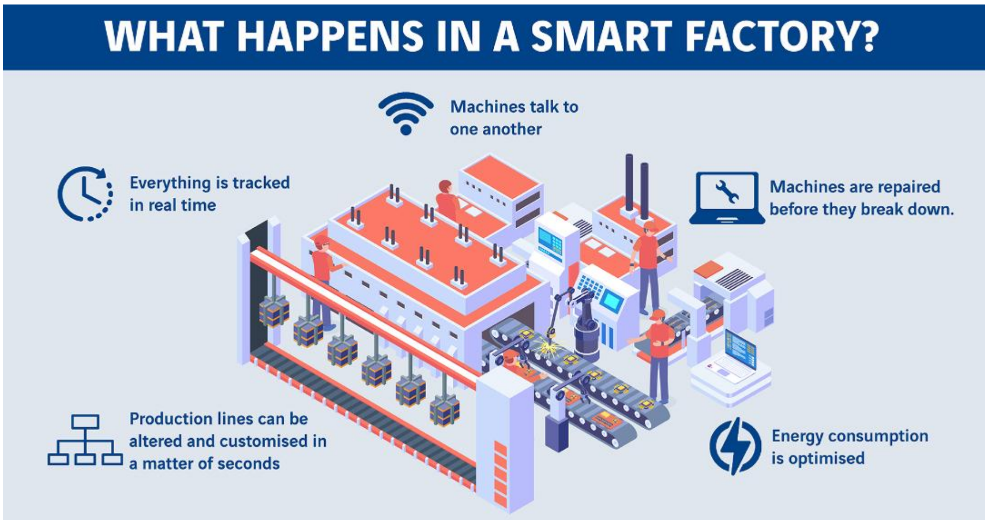

Figure 2 : Key benefits of smart factory

There is plenty of various definitions possible to describe above mentioned term and some of them according to the article are:

- *National Institute of Standards and Technology (NIST) – Smart Manufacturing are systems that are „fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs". [2]*

- *Smart Manufacturing Leadership Coalition (SMLC) – Smart Manufacturing is the ability to solve existing and future problems via an open infrastructure that allows solutions to be implemented at the speed of business while creating advantaged value. [2]*

Smart manufacturing as it was described integrates multiple data from different applications and translates them to form new solutions. It can be applied both to single machine, whole factory or even in the supply chain between line of the factories. Tools included in smart manufacturing allows manage operations with higher precision and better collaboration between employees, suppliers and partners.

The main benefits associated with above mentioned innovation of industry creates higher quality products, improved productivity, increased energy efficiency.

Alongside physical factors related to the product as an item, there are another benefits for a specific countries mainly in which labor cost plays significant role. For a smart manufacturing organization it means becoming more competitive and having possibility to access new segments of the business and growth its own business intelligence. Analysis of data and test simulations can effectively improve performance, productivity and design.

1.3 Market growth, trends, impact and forecast

Development of Industry 4.0 sector promises growth in the new business models, creation of value and for start-ups creation. Gathering information about customer's wants and desires builds not only database about products identification, but as well additional information about societies and economies globally. Manufacturing market currently dominated by US, China and Europe has an opportunity to move to another, less developed countries. [3]

As it was after first industrial revolution, we can fairly predict that after fourth industrial revolution which occurs significantly faster than the previous ones world will appear in completely new reality: global supply chain, interactive worldwide markets in which information is transferred with extremely high-speed. Moreover, there is equitably expected transformation not only in manufacturing but also design, operation, service of products by connecting all of those sectors into reasonable networks. [3]

According to the Mordor Intelligence Report, smart manufacturing market was valued at USD 194 billion in 2020 and is expected to reach 315 billion by 2026. Together with the growth of market there is apparent trend of creating organizations composing society of industrial revolution such as Smart Manufacturing Leadership Coalition (SMLC) or Industrial Internet Consortium (IIC) which aim is to bring together advanced technologies and organizations aimed to accelerate automation growth. [3]

In the automotive industry world, length of the project and later quick return-on-investment composed with low-cost automation and innovation are key factors which helps producers increase competitiveness among productivity improvement. As an example industrial robots play a relevant role in digital manufacturing creating virtual and connected ecosystem. Their impressive growth forecast is shown in the picture attached below. [3]

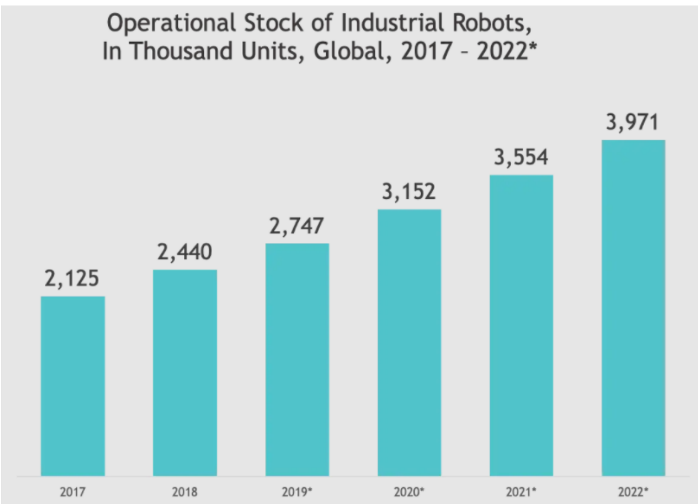

Figure 3 : Global growth of Industrial Robots

China’s manufacturing accomplished higher growth in the last years and became the largest manufacturing country globally. In the dozens of industry sectors, including steel, hi-tech or machinery China represents unbeatable leader. [3]

According to the National Development and Reform Commission (NDRC), investments of China in the high-tech industry grew up of 12% between 2019 and 2020. After implementing Made in China 2025 policy in the country emerged significant focus on the entire manufacturing and this sector became the largest in the country. Alongside, government’s initiatives significantly increased interest in the smart manufacturing technology, placing China’s productivity with the market share of 20% globally. To became competitive in the future perspective, China implements various technologies related to Industry 4.0 and Internet of Things. [3]

Such example was provided to highlight drive and importance of smart manufacturing. Between various number of countries and companies there is apparent race in the technological innovation, market share and profitability.

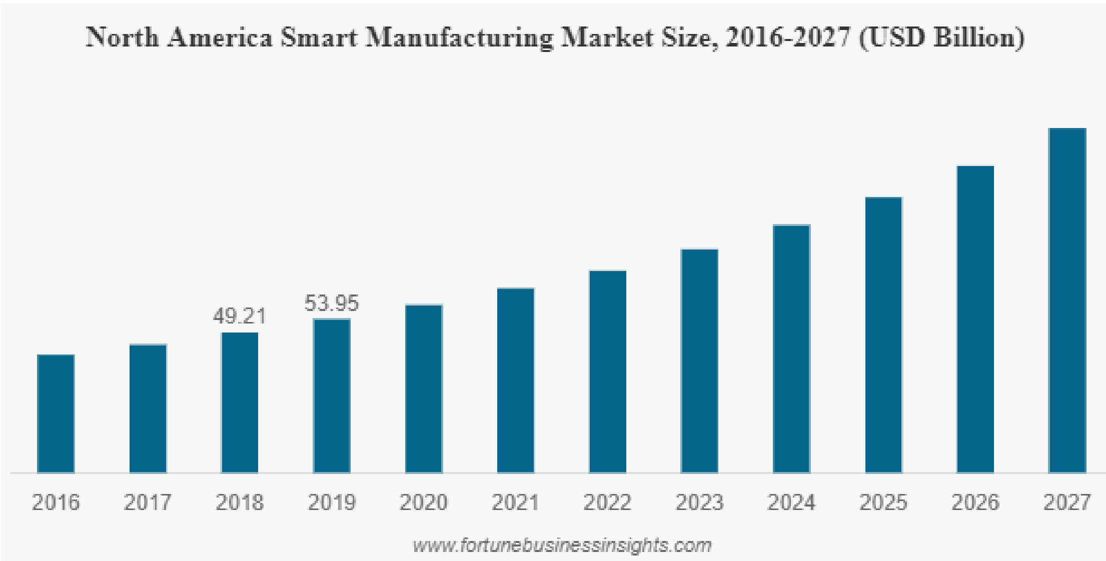

Figure 4 : Prediction of the market size growth in Smart Manufacturing in United States

1.4 Impact of COVID-19

Above mentioned topic of the thesis has been developed during world's pandemics caused by COVID-19, thus it is comprehensible to correlate recent statistics related to smart manufacturing with pandemic's impact. As the first example it comes to mind intuitively correlation of how smart manufacturing can replace human's manual work during the times when in-person presence at the work is often limited. Evident impact on manufacturing cause overall supply chain and production processes downtime. Surprisingly, pandemics and therefore crisis is expected to rise and build huge financial impact on the advanced manufacturing sector, especially this related to highly skilled workers. It is apparent trend to shift capably focus on advanced technologies such as 3D printing, artificial intelligence or others in order to reduce COVID-19 impact on the business results. Scenario of lockdown created for the companies unusual motive for even faster than anybody expected industrial revolution, which is aimed and predicted to result in overall production cost reduction. Moreover, companies are also developing AI-enabled platforms to monitor real-time production in the factories. This considerably reduces the need for workers onsite. [4]

CHAPTER 2 – INDUSTRY 4.0

2.1 Industrial revolution

The industry 4.0 or Fourth Industrial Revolution is causing a relevant change of conventional manufacturing system. Nowadays we experience more and more innovative solutions to manufacture various products, but there will be explain first of all roots of production and significant milestones in this sector of industry.

First Industrial Revolution reaches 18th century in Europe, when use of steam and water power caused transition from hand to machine production methods. It is worth to notice, that term "revolution" in that times was related to tens of years and was prolonged relatively slowly. Main production sectors influence on that transition were iron industry, agriculture and mining. [5]

Second Industrial Revolution or in another words Technological Revolution occurred between 18th and 19th century. The crucial milestones as development of electricity, change type of production into mass production and thus assembly line resulted in build of railroad and telegraph network and it consequently allowed for quicker transfer of people and ideas. This period is considered as well as a huge economic growth in which increased productivity played main role. [5]

In the meanwhile, after the oil crisis of the early 1970s it was practically developed Toyota Production System having roots in Japan, another relevant milestone in the manufacturing evolution. The main goal of this system was to keep a continuous flow throughout manufacturing. That was achieved by several factors including philosophy of "pull system" in which user of material determine the timing and volume of the needed material, "Kanban" cards for manual control of flows or "just in time" to minimize inventory management. [6]

Third Industrial Revolution or Digital Revolution appeared in the middle of 20th century and was motivated by the need of industrial and technological growth after second world war. The main developments contain invention of computers or supercomputers which started to substitute human power in the production process. [5]

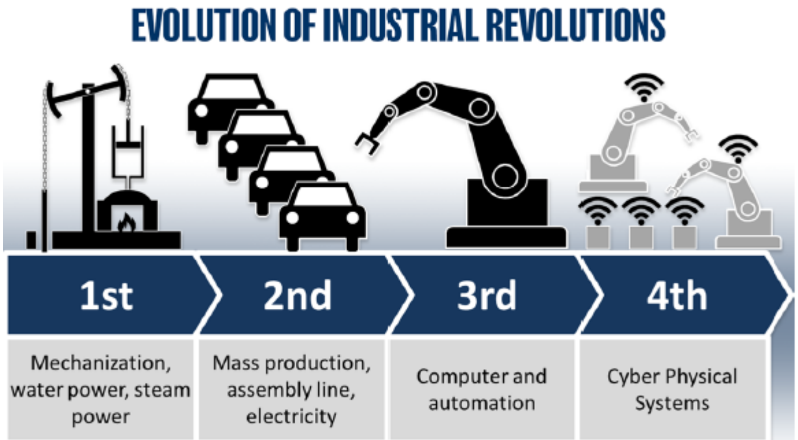

Figure 5 : Evolution of industrial revolutions

Finally, Fourth Industrial revolution finds its roots in the German government project in 2011 in which computerization of manufacturing started to be promoted.

"Through the fusion of the physical and virtual world, interoperability, advanced artificial intelligence and autonomy will be integral parts of the new industrial era".

In imitation of Germans direction, another countries and their factories started to deeplier understand need of translating business objectives into technology innovations targeting in operational efficiency. It has been accomplished by integrating machine-to-machine.

"Learning machines that will literally operate at the speed of light; they will change the way we pursue intelligence; they will be utilized for indications and warning; they will be used in cases where human reaction speed is simply not up to the task".

Four main principles of the Industry 4.0: [5]

- Interconnection – ability of machines, people or other devices to communicate with each other by Internet of things,
- Information transparency – after collecting dataset and information from given points of manufacturing process, ability to identify key sectors to be improved in order to increase efficiency,

- Technical assistance – assist humans by machines in order to improve decision-making and problem-solving process,
- Decentralized decisions – the ability of the physical systems to make decisions autonomously.

2.2 Main components

Industry 4.0 is not only related to using amount of data during manufacturing processes. It somehow describes and reorganizes total product and process life cycle to ensure that customer's demand is adequately found. Moreover better understanding between producer, supplier and final customer is provided by effective data analysis. In the future it is estimated that businesses will compose global networks with comprised systems of smart machines, storage systems and production objects autonomously exchanging information. In the same time opportunity of production optimization is expected.

List below describes nine main elements of Industry 4.0, which will drive cost-effective products: [7]

- Adaptive robotics – Smart Factories in which proceeds adaptation of the robots to the dynamic conditions or parameters of the manufacturing system,
- Data analytics & Artificial intelligence – facilitation of prediction of failures, by preventive action and reduction cost as inventory, over-production and defective items transportation,
- Simulation – quantification and observation of the factory or production systems which help in the optimization of alternative solutions,
- Embedded systems – integration among physical systems by means of sensors and wireless communication technologies,
- Communication & Networking – smart devices are communicating with some assistance from humans,
- Cyber security – one of the biggest challenge; interconnected driven operations and digital transformation means higher risk in term of cyber attacks,

- Cloud technologies – decentralizes computing systems, provides higher security, up-to-date systems, merges multiple data streams
- Additive Manufacturing – customization of the product through smoother correlation between design and manufacturing according to the customer requirement; may reduce lead time of the products, waiting, inventory, waste and defective parts,
- Visualization technologies – augmented reality helps in work instruction and complicated parts explanation and design,
- Sensors & Actuators – complex diagnostics can be quickly transferred using standardized protocols
- Mobile technologies – 5G as a new generation of mobile network.

Through the Total Productive Maintenance (TPM) overall production effectiveness is improved by reduction of time and rise of speed and quality. Focusing closer to the topic of the thesis, it is reasonable to direct attention of the work into artificial intelligence and quality control phase of production system (Poka Yoke). Through the implementation of the recognition technology, visual detection of the defective parts and products by cameras can be obtained, what will be explained in the following chapters.

Figure 6: Total productive maintenance objective

CHAPTER 3 - ARTIFICIAL INTELLIGENCE

3.1 Impact of Artificial Intelligence in the industry

A common goal nowadays for a modern company is to become smarter. What is written behind the word smarter means to reduce prices having less human errors and more extraordinary total performance of the product. Before going brightly into AI description into manufacturing sector, it is reasonable to put some general definition.

According to Prof. John McCarthy, expert from Stanford University:

"It is a science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable". [8]

Thanks to advantages of artificial intelligence and its sub-segments, companies are reaching another levels of efficiency which drives entire business. It is possible to recognize any inefficiencies in the production or at the end bottleneck of the line. Moreover AI has its contribution into extracting manufacturing data, developing tool in the communication between machines and people and reducing cost by increased useful life of a tool which is the main topic of this work.

New manufacturing model based on artificial intelligence, science and technology which generates also growth for design, production and management is called intelligent manufacturing. Its main purpose includes optimization of manufacturing resources, business value and safety improvement.

Being into sector of intelligent manufacturing, there is place to write about genesis and different types of maintenance. The concept of increased reliability appeared at the beginning of 20^{th} century when attention on maintenance started to be not only on solving but also preventing failures. Since the beginnings and upon evolution of technologies several types of maintenance have been created depends upon their resources: corrective, preventive and predictive maintenance.

3.2 Artificial intelligence division

The main division of AI can be classified as a set of three collections in which machine learning and deep learning consists internal groups. Nowadays it is common mistake, that definitions of AI, ML and DL are not precisely understood or treated and often confused, thus at the beginning of this chapter various types of AI will be distinguished and in further step thorough analysis of each segment will be provided.

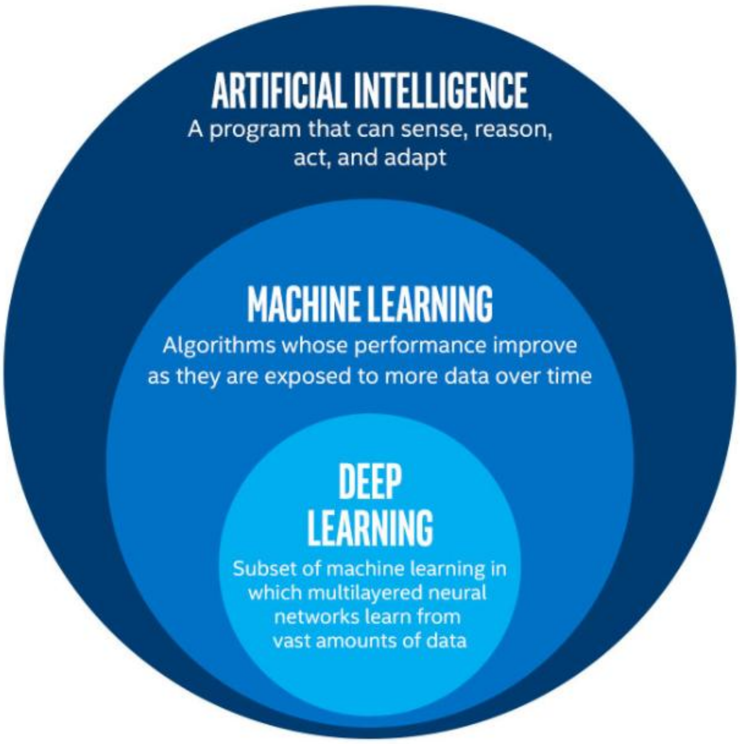

Figure 7: Division of Artificial intelligence

3.2.1 Types of AI: weak, strong and super intelligence

Weak AI which is also called Narrow AI or Artificial Narrow Intelligence (ANI) is type trained and aimed to do specific tasks which is not matching human intelligence and is not trying to. The statement "narrow" which is rather accurate to describe this type than "weak" finds its roots in the limited range of abilities, which are mostly aim-oriented to perform different tasks. It is commonly used today in the environment, enabling some of robust applications. [9]

Strong AI formed by Artificial General Intelligence (AGI) and Artificial Super Intelligence (ASI) is a form where machine has intelligence equaled to humans or in another words self-aware consciousness with ability for problem solving, learning and planning for the future. Analyzing this type it is possible to imagine robots which are human-like working. They can decide by themselves and learn without intervention of people.

At this point reader should know also about another type which is Artificial Super Intelligence (ASI) which is a type of self-conscious computers that can practically outmaster human intelligence and ability of the brain. Nevertheless, the last type is nowadays still mostly theoretical or treated as a point of research. [10]

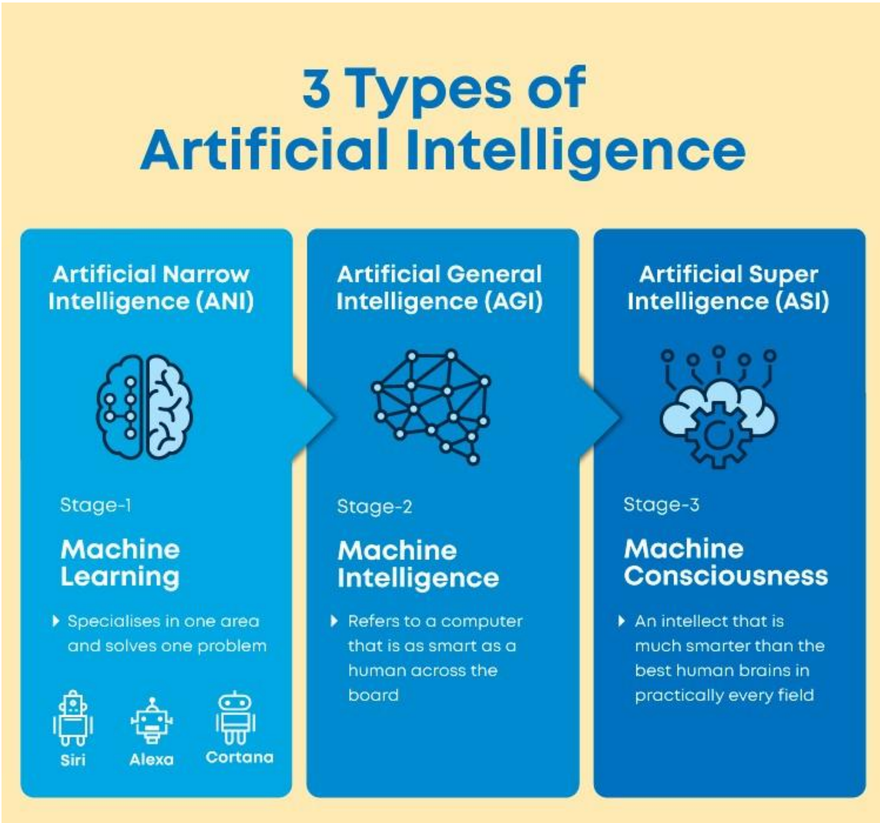

Figure 8: Three main types of Artificial Intelligence

3.2.2 Machine learning

Machine learning is part of AI dedicated to algorithms, which improve themselves through experience and use of data.[11] Another definition says, that ML refers to the field of study which enables machines for keeping improved performance without the need for programming. Statement that machine learns is true whenever it changes a structure, program or data (based on any input or as a respond to external information) and based on a fact, that further improvement is expected. [12] After having provided general explanation it is reasonable to ask the question: How can a particular machine learn ?

First of all, three components are always needed for learning operation which are algorithm, dataset and features.

Data set collection plays a vital role to build reliable system. It is collection of similar entities and values that can be read individually or as a whole item structured with a data structure. Usually it is time-consuming operation. User can collect data for a model in two ways: based on open-source data or collect them in a direct way.

Features are special data objects necessary in the solution solving. They are observed during experiment or individual measures. Selection of a key features is essential for effective pattern recognition, classification and regression algorithms. They advises machine in which direction attention should be paid.

The aim of algorithms is to allow system to learn and develop own experience without being programmed. There is wide range of algorithms with specific use as deep learning, coevolutionary networks or recommendation system whose description will be further provided.

3.2.3 Types of Machine Learning

Based on the kind of learning expected from the algorithms can be distinguished four primary types of ML: Supervised Learning (SL), Unsupervised Learning (UL), Semi-supervised Learning and Reinforcement Learning (RL). [13] Further division is explained in the following sub-chapters.

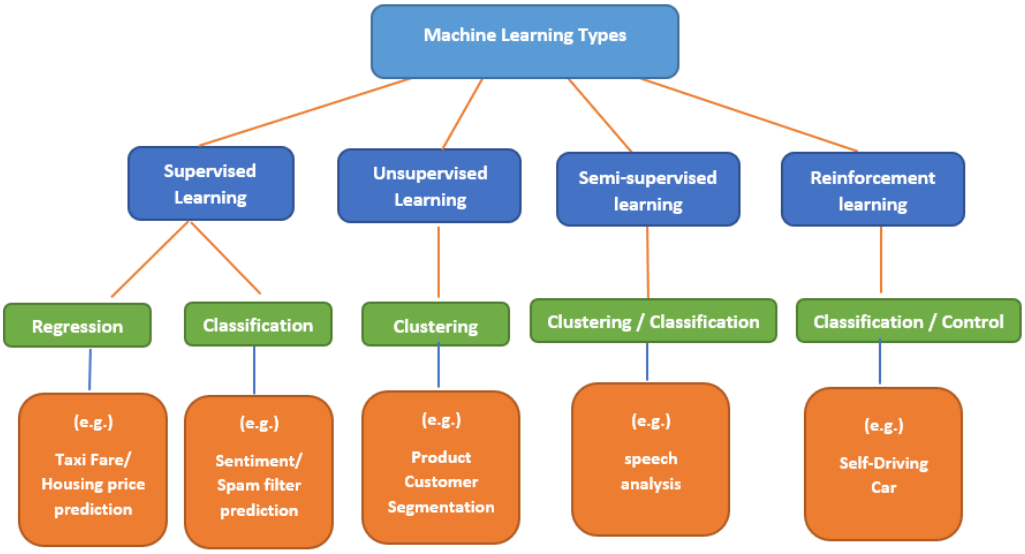

Figure 9: Types of Machine Learning

3.2.3.1 Supervised Learning

First type of ML algorithm is characterized by classified or labeled dataset output which can be predicted accurately. Upon apply of input data into the model, it is adjusted and weighted until the model is fitted appropriately. This process ensures, that overfitting or underfitting is avoided in the model overfitting or underfitting. Supervised learning helps in solving general, real problems as spam classifying.

To work effectively in SL process, various algorithms learning methods and computation techniques are used . [14]

Neural networks process training data by imitating interconnection of human brain by group of nodes. Each node has its input, weight, bias and output. In case of exceeding any threshold by output value, then another passing node is activated in the network. [15]

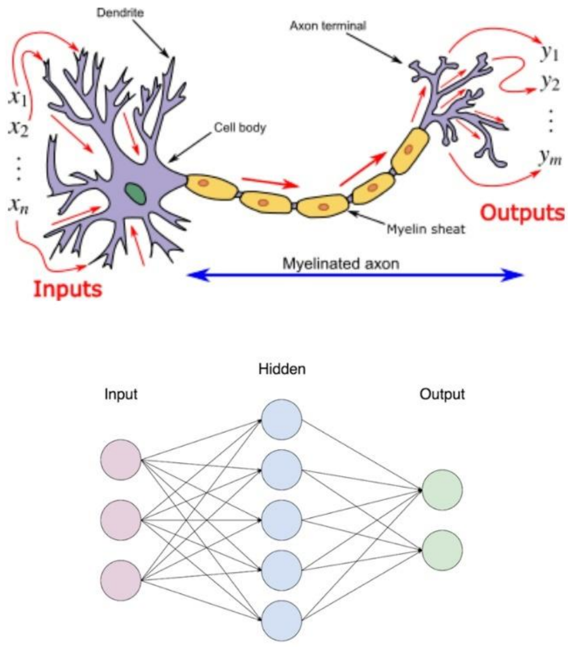

Figure 10:Example of visualization of neural network

Supervised learning models thanks to accurate and predictable output found its place in the various applications. Some examples consists predictive analytics, customer sentiment analysis, spam detection and image and object recognition. Last instance, as a crucial theme of this work will be wider explained in the following chapters.

Two major prediction problems of machine learning derived from type of supervised learning are regression and classification. Their difference have been shortly described below.

Classification – process of finding or discovering a model or function which helps in separating the data into multiple categorical classes, for example discrete values. In classification, data is categorized under different labels according to some parameters given in input and then the labels are predicted for the data. The derived mapping function could be demonstrated in the form of "IF-THEN" rules. The classification process deal with the problems where the data can be divided into binary or multiple discrete labels. *[23]*

Regression – process of finding a model or function for distinguishing the data into continuous real values. It can also identify the distribution movement depending on the historical data. Because a regression predictive model predicts a quantity, therefore, the skills of the model must be reported as an error in those predictions. [23]

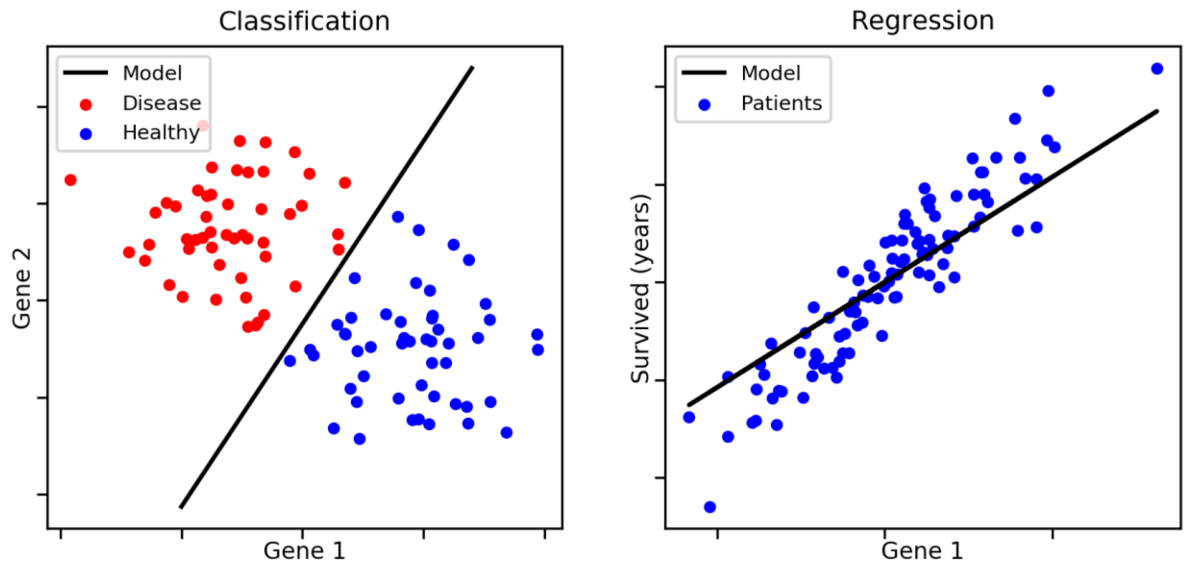

Figure 11: Difference between scope of Classification and Regression

As it might be distinguished based partially on the above graph, classification is type of process based on discrete values predicted in unordered way, while regression works with continuous values in which data is predicted in ordered way. Examples of the former's algorithms are decision tree or logistic regression, whereas later solution brings regression tree or linear regression etc. [23]

3.2.3.2 Unsupervised Learning

Unlike previously explained ML type, in Unsupervised Learning user is unaware of the final output. There is no need to supervise the model and moreover classification or labeled output are not at his disposal. It allows the model to work on its own and discover previously undetected patterns and information. One of the main reason for use UL is ability to find all kind of unknown patterns in data. Moreover, it is adaptable to find features useful for categorization and by taking place in real time (all the input data to be analyzed and labeled with the presence of learners). Their three main tasks are clustering, association and dimensionality reduction. [16]

Clustering – methods used to find similarity and relationship patterns among data sample and cluster them into groups keeping similarity based on their features. It plays important role due to determination of the intrinsic grouping among the present unlabeled data and in addition make assumption related to data points to constitute their similarity. [22]

3.2.3.3 Semi-supervised Learning

Another type of ML is characterized by involvement of a small number of labeled examples and large number of unlabeled examples, from which model aims at learning and making predictions on new examples. As its name signalizes, it is type which is placed between and has common points from both supervised and unsupervised learning. Semi-supervised learning technique is mostly useful when is both not enough labeled data to produce an accurate model and is no possibility or resources to find more data. Then, by using semi-supervised technique, increase of the size of training data can be done. [17]

3.2.3.4 Reinforcement Learning

Aim of the last mentioned type of Machine Learning is to face closed-loop problems in which learning system's actions influence its later inputs. In addition, learner does not know which action should take, but instead must discover it by trying them out. In some, extraordinary cases actions may affect not only immediate response, but also next situation and thus all the subsequent responses. To summarize, three factors characterizes reinforcement learning, which are closed-loop, lack of direct instruction of what action to take and where consequences of actions are crucial for extended time period. One of the challenges placed for Reinforcement Learning are exploration and exploitation. To obtain a lot of reward, agent has to prefer actions tried in the past and found to be effective. On the other way to discover such actions, it has to try what was not selected before. Another key aspect of reinforcement learning is consideration of the whole, goal-directed problem interacting in the uncertain environment. Finally, one of the most interesting aspect of a modern reinforced learning is productive interaction with another engineering and scientific disciplines such as psychology or neuroscience. [18]

3.2.4 Deep Learning

Deep learning, in other words deep structured learning or hierarchical learning has emerged as a new area, new subsegment of machine learning research.[19] Before providing a detailed description, general definition will illustrate sense of this segment.

"Deep Learning is a new area of Machine Learning research, which has been introduced with the objective of moving Machine Learning closer to one of its original goals: Artificial Intelligence. Deep Learning is about learning multiple levels of representation and abstraction that help to make sense of data such as images, sound and text." [20]

Deep learning is one of the basis in cognitive computing. Nowadays, growth of interest with this technology emerges by popularity of cognitive computing, which allows applications understand human's input signals and response in the form understood for people. Technology deep learning significantly improved computer's ability for classification, identification, detection and description of data, so in brief ability to understand them. Another advantage of this technique is that it founds wide application in the field, which requires numerical data such as image classification, speech recognition or object recognition. [21]

Through modern discoveries and technologies, deep learning is in the rapid phase of development. Progress in the field of algorithm's development adds up to growth of effective methods deep learning. In addition, increased accuracy of machine's learning methods brings tremendous business value. As a result of new classes of neural networks, fields of study as text translators or image classification finds its growth of interest and usefulness. [21]

Considering iterative nature of algorithms, their complexity rises along with higher number of layers and with amount of data essential for network's learning. In this connection, problem solving with deep learning method requires huge computing power. [21]

Adaptive nature of learning method's and their ability to continuous self-improvement and adjustment do changes gives tremendous possibilities for implementation more dynamic than deterministic solutions. Additional capabilities brings progression of accuracy and efficiency in applications, in which neural networks are used since a long time. Through better algorithms and higher computational power it is possible to get more precise image of analyzed data. [21]

3.2.5 Underfitting and overfitting – two ways to calculate the accuracy of machine learning model

Whenever dataset works on to predict or classify a problem, firstly is detected accuracy by apply a design model to train and test set. In case of satisfactory level of accuracy, data feature is increased or decreased in machine learning model. Having poor results of the model means that effect of underfitting or overfitting has occurred. [24]

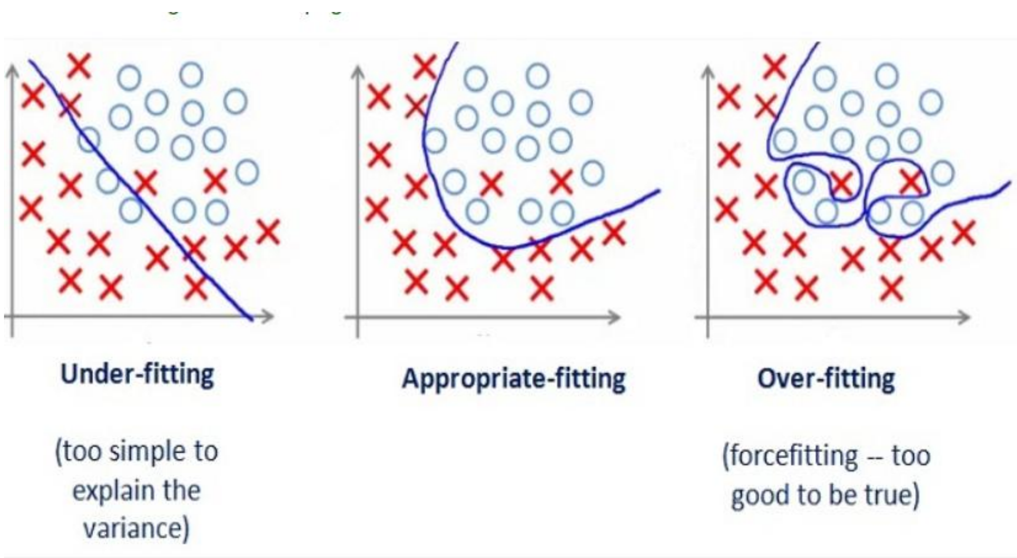

Figure 12: Underfitting and overfitting - visualization of the difference

At the above mentioned graph, it is observable that line does not cover all the shown points which means, that model is underfitted. In contradiction, observing model at the right side it is visualized, that line covers all the points, which means that assumption might be misinterpreted. In reality, predicted line at this graph covers all point but also included points with noise, which will cause poor results due to high complexity. Graph located in the middle in the Figure 12 shows a well predicted line, because it covers enough section of points maintaining balance between bias and variance. In machine learning, prediction and classification of data is performed in a more generalized form. In result, to solve problem with underfitting or overfitting, model has to be generalized. [24]

3.2.6 Types of maintenance in machine learning

One of the major operating cost in the industry sector is so called maintenance cost. Just without taking into account unplanned downtime, mentioned cost can represent even 50% of the total production costs. Upon above mentioned information it can be noticed, that company's productivity and more accurately profitability depends largely on the maintenance processes, thus it has to be maximally ensured and considered, that whole equipment works in the most possible reliable way. [25]

Below, it have been described and compared 3 main types of maintenance: corrective, preventive and predictive.

3.2.6.1 Corrective maintenance

The first mentioned type of maintenance aim is to solve faults which already happened, so only take place when machine is in critical condition. Typically, it lead to production stop which results in reduction of production and finally increase of cost. The repair time and thus prediction or plan for the correction can not be easily scheduled, thus this time is used in machining processes, which failures do not have a relevant impact on production. Normally, corrective maintenance is performed by a human technical. [26]

3.2.6.2 Preventive maintenance

Second mentioned type which is preventive maintenance focus on scheduled maintenance actions directed to the prevention of spontaneous breakdown or failures and degradation of a piece of equipment, component or spare part. Usually it is placed outside of production time and is done by periodic overview of the system. For a more effective lead of process, it is useful to keep history of the previous failures of parts or machine. This type of maintenance is considered as demanding, requiring precise supervision and plan, performed by qualified personnel. Wrong application of preventive maintenance may occur breakdown, which results in downtime of production and increase of cost. [27]

3.2.6.3 Preventive maintenance

This type of maintenance is not new in the industry, however plays a relevant role and has its development in the Industry 4.0 scheme. It is described in the thesis extensively due to connection to afterwards analyzed experimental part. In this case, maintenance normally occurs before breakdown happens. It is based on exact formulas, sensor measurement and is performed with the analysis of the measured parameters. The main goal is to guarantee maximum intervals between consecutive repairs and to minimize cost and number of planned maintenance operations. [28]

In the process of predictive maintenance are distinguished three steps: data acquisition, data processing and machine decision making. Each of them will be further articulated in the separate chapter while analysis of the case study.

CHAPTER 4 – RESISTANCE SPOT WELDING PROCESS

4.1 Introduction to the process

Resistance spot welding (RSW) is a relevant sheet metal joining process in a wide range of industries as automotive, domestic appliances or air crafts. It is a process strictly related with synchronic effect on the material two fundamental type of energy: heat and mechanical. Thanks to its efficiency it is broadly used in the sheet metal assemblies, for example just in one car there are approximately 3000-6000 spot welds, which shows its level of importance. The main, crucial advantages of the process are low cost, high production rate and adaptability for automation which builds its use share in various applications. Technological progress for the design, control and programming of machine welding is continuously developed and adapted to the current standards and requirements in the industry which makes its process more effective. Furthermore, resistance spot welding is one of the oldest and still used method for metal connection today in the industry. The process was primary introduced in the 1880s by Prof. Elihu Thomson. He firstly found this in a way of joining copper wire together and soon discovered that it has a dozen of other uses. [29] The main physical parameters of the spot weld, which will be further explained more accurately are heat (dependent of current), pressure and time. Those parameters together with diameter of the spot and tensile strength determines quality of the joint, which has to be precisely evaluated before processed component will cross to the next step of workstation. [30] Wrong design or quality control of spot welds tends to further failure of the processed components during its service life time, therefore it is very significant to understand the behavior of spot welds and their characteristics of failure. [29]

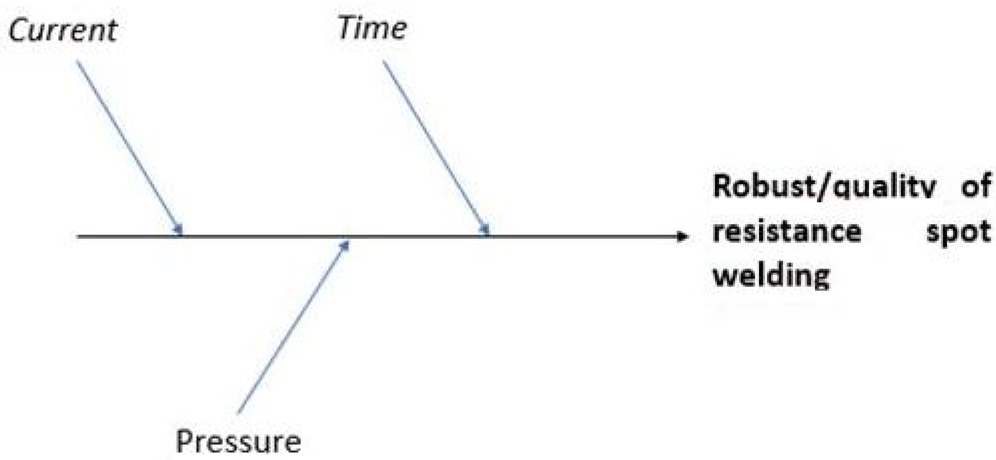

Figure 13: Main parameters determining quality of resistance spot welding

4.2 Physical fundamentals of resistance welding

Resistance welding is a process, in which solid joint is obtained in result of heating up connected plates by flowing current into them and by deformation this area as a result of applying clamp force. Direction of the energy transformation occurred during resistance process was depicted in the picture below. [31]

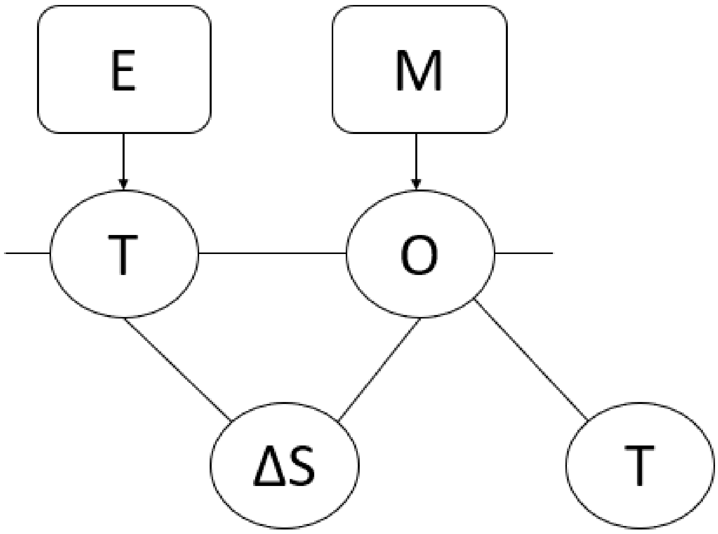

Figure 14: General scheme introducing energy transformation in the resistance welding process

On the above graph, the following symbols presents: [31]

- E – electrical energy
- M – mechanical energy
- T – thermal energy
- O – deformation energy of welded material
- ΔS – change of internal energy in the join

During resistance welding of metals is simultaneously introduced range of metallurgical-physical phenomenon as: heat release, heat and mass transport, phase transitions, metal melting and crystallization, hot and cold metal deformation, stress generation and relaxation. [31]

Depending on type of performed connection, resistance welding can be subdivided into:

- Resistance Spot Welding
- Resistance Projection Welding
- Resistance Seam Welding
- Resistance Butt Welding

In the case study related to this work attention is directed just into resistance spot welding.

Amount of heat extracted in the welded area is depicted by Joule heating law written below: [31]

$$Q = \int_{0}^{t_w} {I_{(t)}}^2 * R_{(t)} * dt$$

Where:

- $I_{(t)}$ – welding amperage
- $R_{(t)} - absolute$ resistance of the welded area
- t_w – time of amperage flow

Welding current is fundamental parameter of resistance welding, thus the most attention of research is directed into appropriate dosing and time passing of current. It determines the heat generation by a power of square, what was shown in the previous formula. It is very often challenging work of welding engineers to optimize welding current and time for each individual solution.

Secondly, at the above mentioned formula it is illustrated proportional influence of welding time on heat generation. A minimum welding time together with minimum welding current are crucial parameters to make a weld due to the phenomenon of heat transfer from the weld zone to the metal's substructure and to electrodes as well as heat loss from the surface to surroundings. Setting parameters with too low welding time and too high welding current and vice-versa may establish wrong processing with result of electrode stick to the workpiece. [32]

Another crucial parameter during welding process is resistance of the contact points, which depends of the class of surface coating and clamp force of electrodes. [31]

Preparation of sheet metal surface	Resistance of contact points [μΩ]
Sanding	110-160
Flat file	280
Shaper	1200
Corroded	80000
Mill scale	80000
Rust	500000

Table 1: Example of resistance of contact points R for different class of metal sheet surface. Steel sheet thickness 3mm, Clamp force electrodes 2000N.

Along with increase of electrodes clamp force, resistance between contact points decreases.

At this point it is reasonable and necessary to point out influence of contact resistance with the change of temperature.

The figure below shows results of contact resistance at different temperatures and pressures.

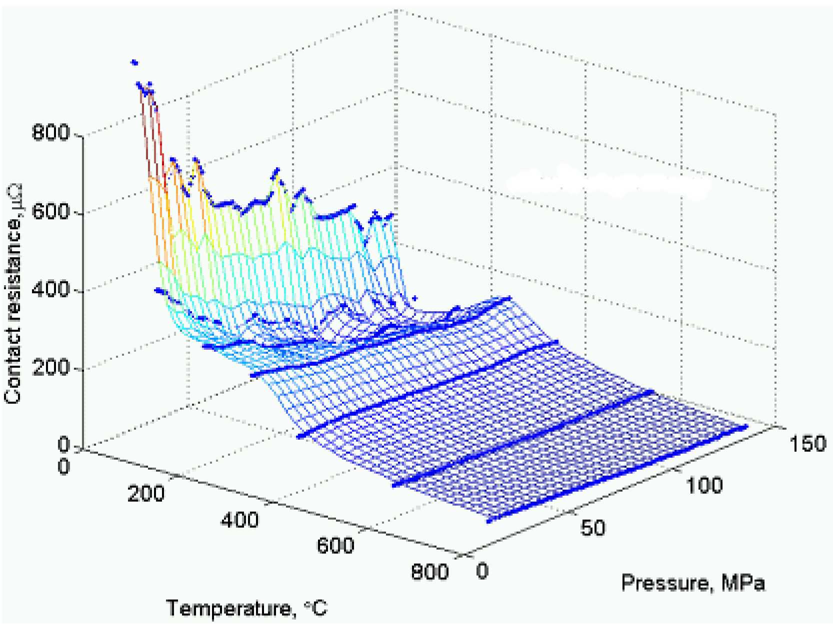

Figure 15: Contact resistance of mild steel at different temperatures and pressures.

It is observable, that contact resistance decreases with increasing temperature, but it has local disparity at the temperature around 300 °C. Moreover, when welding force and together with it contact pressure increases the real contact area also increases due to its deformation on the rough surface. In result, contact resistance decreases and as a result heat generation and size of weld nugget is reduced. [32]

Alongside with Joule effect, Peltier and Thomson effects influence way of heated material in the welded area. Those effects works in case of welding with direct current.

Peltier effect is one of the thermoelectric effect which is stated on heat extraction or absorption between two different conductors depending on direction of flowing current. [31]

$$Q = \pi_{AB}(T) * I$$

Where:

- π_{AB} – $Peltier\ coefficient, depends\ of\ the\ bonding\ temperature\ and\ type\ of\ conductors,$

Above described Peltier effect influences diversified heating of the material, especially in the joint point between sheet and electrode, what cause asymmetry of the entire thermal cycle.

Last mentioned, Thomson effect which is also thermoelectric effect affects extraction (or absorption) of additional heat on a whole length of homogenous conductor (except contact points) in which flows electrical current and is temperature gradient $(\frac{dT}{dx})$. [31]

$$Q = \tau * I * (\frac{dT}{dx})$$

Where:

- τ – Thomson coefficient

Thomson, Seebeck and Peltier effects are correlated each other and have a whole effect on asymmetry of thermal cycle in the resistance welding sphere. In case of welding with direct current, they have to be taken into account, because impact on weld and non-uniform wear of electrodes. [31]

4.3 Instrument for resistance spot welding

4.3.1 Resistance welder

Fundamental tool for resistance spot welding is resistance welder. It can be distinguished between the following devices: stationary, mobile or suspended. Outside of those welders, to complete welding line it is included welded generator and auxiliary devices. Typical resistance welder is composed of: system of energy supply for electrodes, system for control of programs and welding parameters, electrode's clamp mechanism, cooling system of electrodes, transformer, secondary circle. [31]

Resistance welders are devices receiving electrical energy and work practically in a state adequate to short circuit, for a very short time. They can be driven by alternating or direct current. Energy needed for creation of weld is enclosed for a very short time as an impulse with very high current (up to thousand amperes). [31]

Electrodes are components, which transport current directly do the welding area and bring clamp to connected parts. For the purpose of fulfilling exploitation requirements they are designed to ensure high thermal and electrical conductance, high hardness and durability in high temperature. The most chosen material for electrodes due to its properties is copper alloy. [31]

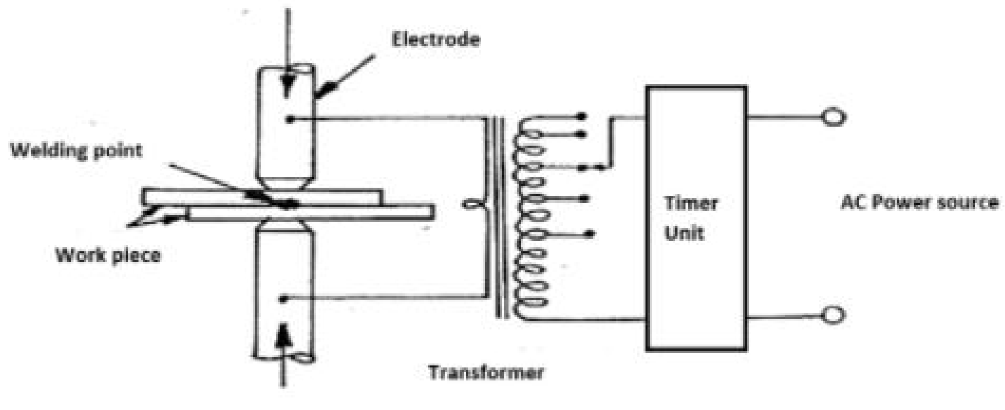

Figure 16:Resistance spot welding machine circuit

4.3.2 Durability of electrodes, its degradation and tip dressing

One of the most important factors affecting quality of resistance welding is durability of electrodes. It composes base for efficiency of welding process, quality of spots and in result quality of products. High durability of electrodes determines possibility of use process automation for serial build products. [31]

Durability of electrodes is dependent upon the following factors: [31]

- chemical composition of electrodes material,
- physical properties,
- shape and dimension of working parts,
- parameters and program of welding,
- cooling intensity,
- condition of the surface of welded parts.

Choice of material with appropriate chemical composition, adequate to the type of welded material and used welding method allows for processing without slivers or joining electrodes with the surface of processed elements. Soften process of electrodes and as well its durability has influence parameters and welding program. It is important to notice, that for hard parameters, characterized by very short time and high clamping force, heating of electrodes and elements is lower. In contrary, for soft parameters, described by long welding time and low clamping force, heating in the joints is significantly higher. Inadequacy of the choice of proper elements can be partially neutralized by use of intensive cooling of electrodes. [31]

Negative influence for a durability of electrodes has bad condition of the welded elements surface. It is depicted by equation below illustrating tendency of spot electrodes by welding thin metal sheets made by standard carbon steel. [31]

$$n = a * (H - 100)^2$$

Where:

a – coefficient of a metal sheet surface condition

a = 2, for metal sheet cold-rolled and greasy

a = 8, for metal sheet crystally clean

H - hardness of electrodes,

n – amount of possibly done welds on metal sheet with thickness 1mm made by low carbon steel

Conditions with not proper use of high current and pressure during resistance welding reveals the risk of electrode's degradation. With increasing number of welds can be noticed two major changes on the electrode tips: geometric and metallurgical. First will influence grow of diameter tip due to deformation and wear, while second will cause alloying with sheet and coating materials and softening caused by overheating. Difference on listed changes is shown at the picture below. [32]

Figure 17:Difference in wear on new and used tip of electrode.

The increase of tip diameter of a used electrode arises contact area between electrode and sheet which results in reduction of current density. In addition, alloying of the electrode material means reduction of conductivity. Both of effects cause progressive reduction of weld nugget size. After some number of welds, a weld nugget will not fulfill requirements about minimum nugget size to maintain weld quality. The number of nuggets accomplishable until the weld nugget drops below the limit is named the "electrode life". [32]

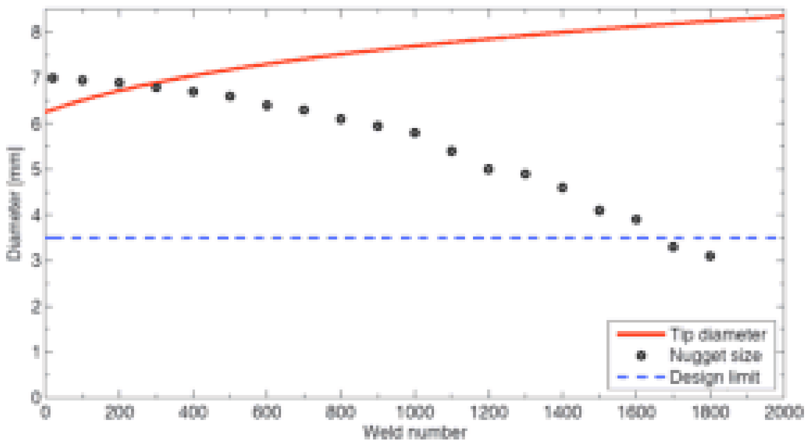

Figure 18:Dependence of tip diameter and weld number for a sample of metal sheet.

Except adaptation of new materials and design of electrodes, in production are commonly used two methods for the compensation of electrode degradation. In order to keep quality of weld and increase the electrode life it is used step current or electrode tip-dressing process. The first method signifies planning spot welding process with a stepwise increase weld current after certain number of welds in order to equalize loss of current density caused by increasing tip diameter. Such a process is demanding and time-consuming due to the need of number of tests or simulations, but can extend electrode life and compensate overall costs. Second method called electrode tip-dressing is mechanical re-shaping or cleaning the electrode tip after given number of welds to preserve near tip diameter and surface condition. [32]

4.4 Technological process of resistance spot welding

4.4.1 Principle of spot welding

Spot welding is a process of joining two elements by spot welds. There can be distinguished three fundamental phases: clamping elements by welder's electrodes, warm elements and creation of the weld's core, getting cold of core and arising homogenous joint – spot weld. [31]

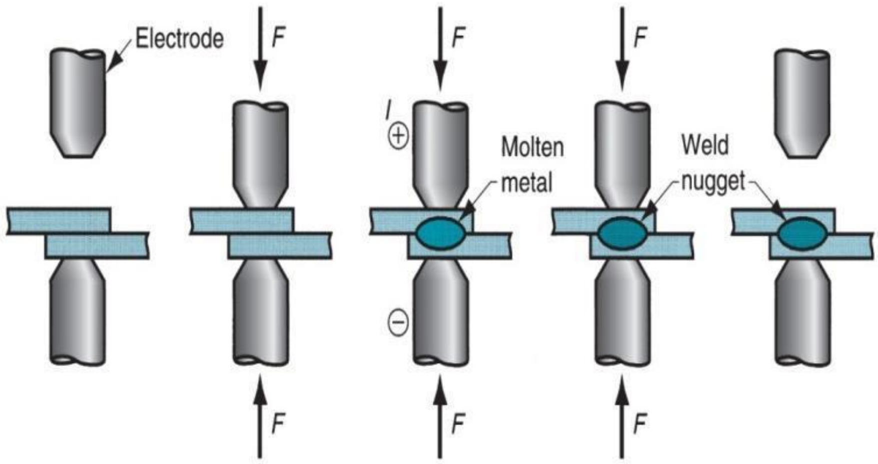

Figure 19: Schematic of resistance spot welding process

Finally, it can be distinguished four main steps of the resistance spot welding process:

1) Squeeze time – alignment and clamp two elements together and providing required electrical contact,
2) Weld time – time of the flow of current until the temperature reaches melting point,
3) Hold time – time for maintenance of the pressure, without the current,
4) Off time – pressure of the electrode is released and plate can be positioned for the next spot.

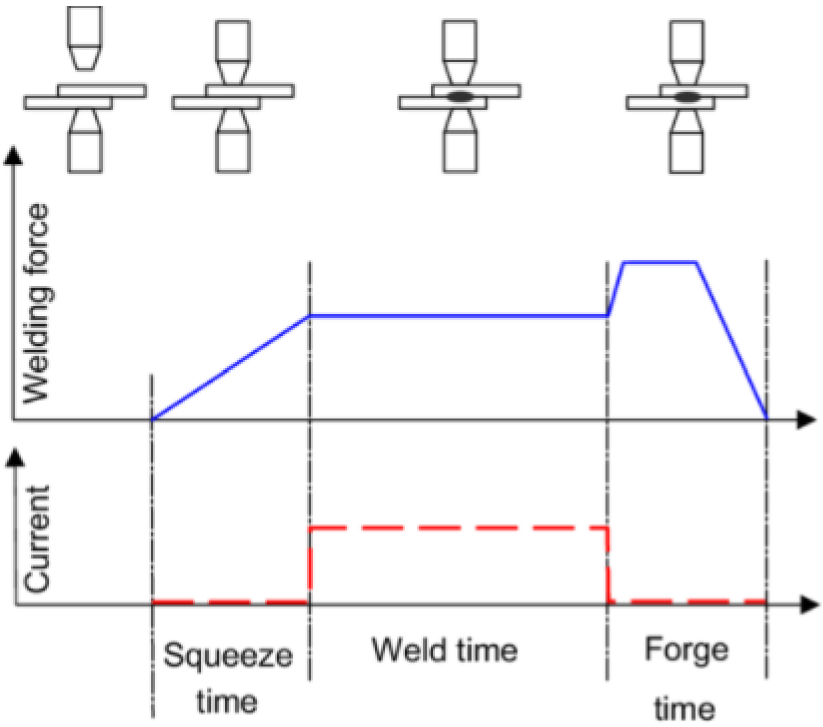

Figure 20: Typical spot-welding cycle

4.5 Application and use

Spot welding is primarily used for connection elements made by carbon or alloy steel, nickel, titanium, aluminum, copper and its alloys, metallized metal sheets (galvanized, leaded, nickel plated). In addition, spot welding principle is broadly used for joining various other elements as cables or electrical connectors. Thickness of welded elements depends of type of welded materials and way of leading to them welding current. It is usually limited by the power of welding devices. Usually thickness of processed elements is between 0,05 up to 20mm. In practice, spot welding is used for joining: components of means of transport (cars, motorcycles, bicycles), elements of domestic appliance, elements of electrical and electronic devices etc. In view of high efficiency of the process, relatively low cost of production, adaptability for automation and also due to possibility of parameter's control this method is considered as competitive for another types of mechanical and welding connections. As every process, it has also some disadvantages as necessity of clamping force on jointed elements, use of high current density or ensure of high surface quality in the connection area. [31]

4.6 General recommendations

During design of welded constructions and formulation of technological processes the following rules listed in a short version below are recommended. Those recommendations are posted in this work due to their further importance in the case study analysis. [31]

1) Diameter of weld is predefined depending on thickness of metal sheet, adequately to class of weld quality required for given construction.

$$d_z = 5 * \sqrt{g}$$

Where:

g – thickness of metal sheet [mm],

d_z – weld diameter,

2) Surface of the jointed elements should be flat and parallel. They should not have inequalities or corrugations. In the place of connections it has to be metallically clean, without rust, grease or contaminants. For elements covered with paint or glue it should be defined another conditions of welding, taken into account existence of these preparations.
3) Due to difficulties of clamping together more than two sheets, especially thick, it is not recommended to join with one weld more than 3 metal sheets.
4) Spot welding connection should be designed to work against shear forces. It should be avoided design, where spot welds work against tension or torsion.
5) Welds can not be performed too close each other to avoid flow of current in the adjoining weld and in consequence loss of amperage. This aberration usually takes place in the manual operation due to short experience of operator.
6) Surface of the working part of electrodes can be flat or spherical. Diameter of the working section of electrode is chosen according to the equation written below:

$$d_e = 5 * \sqrt{g} \,,$$

$where$:

$d_e - diameter\ of\ a\ working\ part\ of\ electrode,$

g – thickness of steel sheet.

7) Mechanism of a weld creation varies with shape of electrode. In case of spherical electrode there is phenomenon of a change of current magnitude. It is mainly used in case of welding aluminum alloys.

4.7 Programs and parameters

Parameters of spot welding are selected according to the choice of the following variables: amperage, time of the current flow and clamping force. Welding parameters are taken on base of kind of material, thickness of the plates and their formation. In practice, there can be distinguished three kind of the welding parameters: hard, middle and soft. Under the statement hard parameters it is explained short time and high amperage with high clamping force. Those connections are characterized by the smallest indentation on the metal. On the contrary to the previous type, soft parameters means long time and low amperage together with low clamping force. These parameters are not often used in the mass production due to thermal effects and deformations. Lastly, middle parameters with characteristics taken both from the hard and soft type are considered as the most optimal in the industry. Their joints are marked by proper weld build and high mechanical properties. [31]

CHAPTER 5 – PYTHON FOR FEATURE EXTRACTION –

EXPERIMENTAL PART OF THE THESIS

5.1 Goal of the experimental part of thesis

The goal of the experimental part of the thesis was to introduce capabilities of the python programming language in the field of image processing on the base of spot welds imprints. To obtain final results in form of graphs representing trend of the electrode, several libraries have been used as numpy, cv2, math, os, measure, matplotlib. pyplot. Final chart introduces trend of the electrode diameter, black area represented in percentages and both minimum and maximum distances from the center of the electrode. Finally, obtained results of the experiment could be compared with the theoretical trends previously explained in the theoretical part of thesis work.

5.2 Preparation of the database

For the experimental purpose of this work have been provided numbered imprints on the scanned sheet of paper.

To obtain data prepared for processing, each imprint have been trimmed from the sheet shown before. To get proper accuracy of the results, each image of the imprint has the same resolution (384 x 377 pixels) and in addition to avoid abnormality, black points and lines not included in the electrode, out of electrode imprint have been removed.

Finally, each imprint file have been named according to the number in the picture and database in one folder have been concluded. For the future work and analysis, it would be reasonable to prepare imprints directly in the form of separated images with the same resolution.

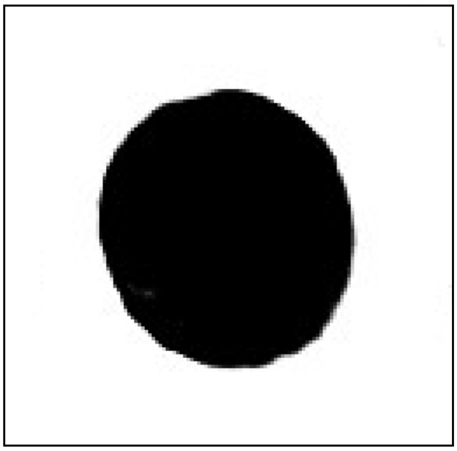

Figure 21: Imprint nr 1

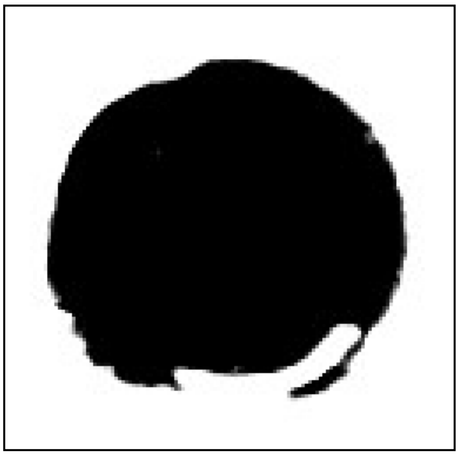

Figure 22: Imprint nr 414

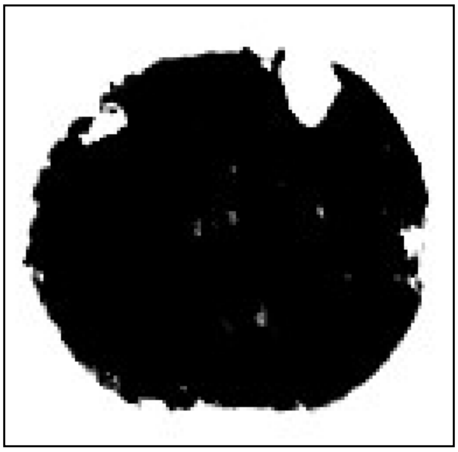

Figure 23: Imprint nr 1089

5.3 Libraries used in the project.

One of the goals of the experimental part done during the project was to introduce possible libraries used for the image processing. In the following subchapters there were described all of libraries used for the given project.

5.3.1 NumPy

The first fundamental scientific library introduced in this chapter is NumPy. That library gives a multidimensional array object, various derived objects and range of routines for quick operations on arrays, including mathematical, logical, shape manipulation, sorting, selecting.

Most of advantages of use above mentioned library is due to vectorization method for coding, so simplify and easier to read code. Secondly, less codes of lines in theory means less bugs and is approximately 50 times faster compared to traditional Python list. The reason why NumPy is much faster than lists comes from the way of store which is continuous place in memory, so it can be processed and manipulated very efficiently. NumPy is library of Python and is written in some parts in this language, but most of the elements requiring computation are written in C or C++ code. To summarize, three advantages of NumPy comparing to Python arrays are: less memory requirement, faster processing, convenience of use. [33]

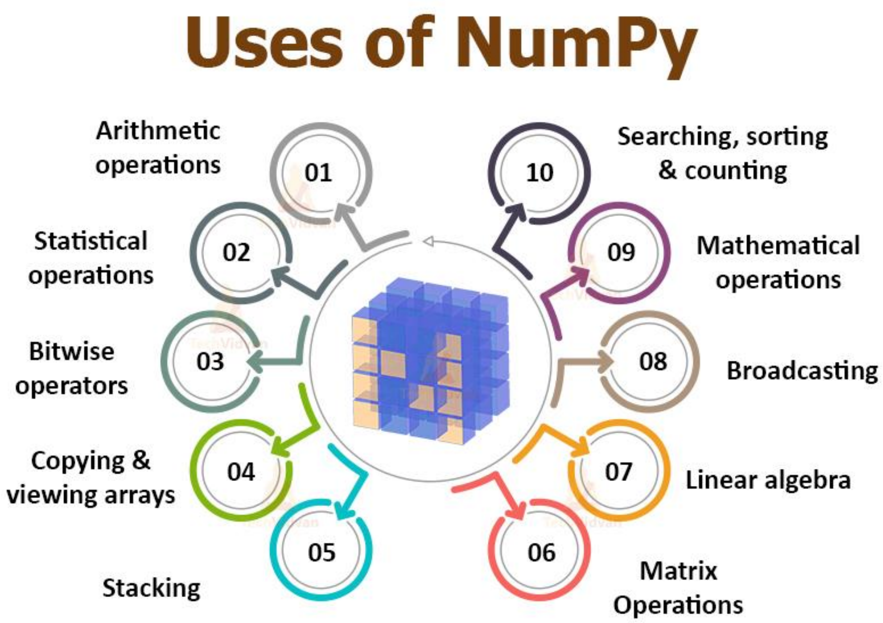

Figure 24:Possible use of NumPy

5.3.2 OpenCV – cv2

One of the most crucial library used in the given project is OpenCV. It is open-source library mainly used for computer vision, machine learning and image processing. In the given work it was used in python language, however can work as well with C++, Java and another languages. The main role of this library is identification of the objects, faces, shapes. In the given work it was used to find data and identify parameters of the spot weld such as diameter or black area. Cv2 combined with previously explained library NumPy gives tremendous capability to optimize code in Python. Apart of the application provided in the project, user can put into action OpenCV source to the dozen of various tasks such as face detection, object detection, video analysis, image segmentation, filtering etc.

5.3.3 Math

Math module is commonly used to cover simple mathematical operations such as sum, exponential, modulus. The main advantage of using this library instead of common python functions is quicker time.

5.3.4 Os

Os library used in Python gives a function for an interaction of the program with the operating system. In the given work above mentioned library was captured to get sorted list of images further processed in the program.

5.3.5 Skimage

Sci-kit-image is a Python library applied in order to proceed with image processing or to depict more accurately preprocessing. In the mentioned work have been used cut-off "skimage" as a function in subpackage. The main goal of the use it in the project was to measure boundaries and regions in the imprints further being base for the graphs.

5.3.6 Matplotlib.pyplot

Finally, to get graphs introducing trends of the electrode behavior it have been used matplotlib.pyplot library. Each of pyplot function can do some change of figure, for example create a figure or plotting area in the figure or as in the project plot lines in a plotting area. Another functions of mentioned library are related to customization of existing graphs such as properties of lines, font or axes.

5.4 Obtained results

As a result, several figures representing various trends of the electrode behavior have been obtained. In all of cases have been analyzed behavior of the electrode with the interval of fifteen positions starting from the initial position as a new electrode and ending with the electrode with number 1242.

5.4.1 Diameter of the electrode

The first graph depicted on the picture below represents trend of the electrode diameter. At the beginning of the operation diameter value was 6 mm. This data was taken on the base of separate technical drawing attached to the database. In fact, minimum noticed value of the electrode diameter was 5.85 mm for the electrode number eighteen. In contrary, the maximum obtained value was for 1136 number of electrode and diameter equal 9.89 mm. It is thus observable, that with the number of electrode spots reaching 1242, the increase of diameter according to the experimental research was of 69%.

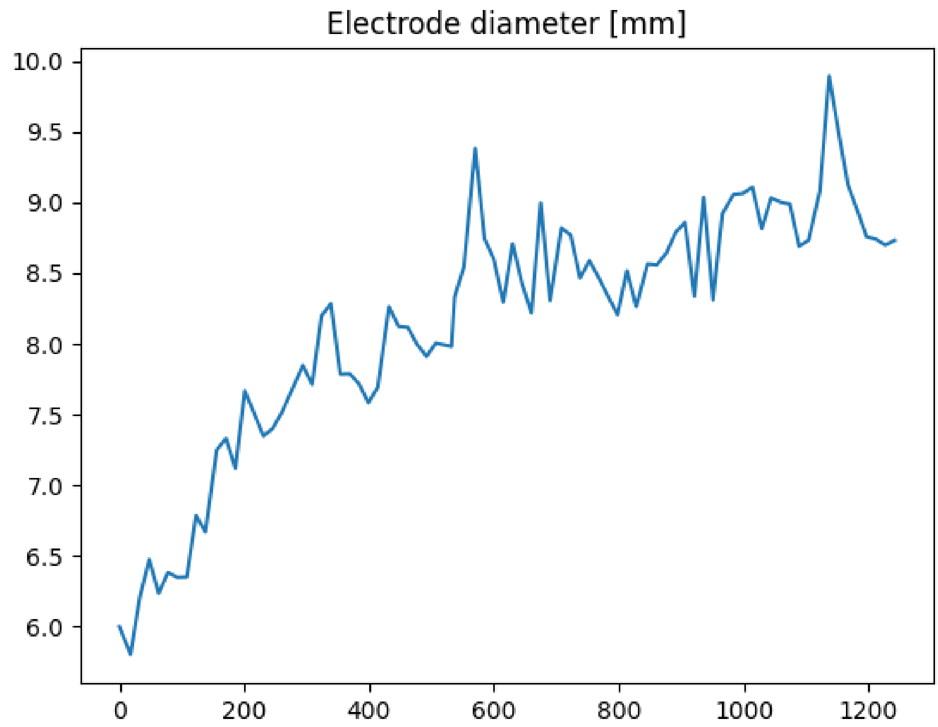

Figure 25: Trend of electrode diameter [mm]

5.4.2 Percentage of the black area

Second measured and analyzed case was to capture black pixels from the imprint in order to represent change of the area of the electrode. It was depicted in form of percentages, since each picture has the same dimension and thus provided solution and its results is plausible. Providing data of the above mentioned experiment, the minimum obtained value was 25.7% for the electrode nr 18, while at the beginning for the electrode nr 1 this value was 27.6%. Nextly, the maximum value equal 66.2% for the electrode nr 1137 and 55.7% for the last one electrode nr 1242. At this moment it is observable trend, that both for the black area and diameter of the electrode minimum and maximum values were for the electrodes 18 and 1137. Lastly, in the given part of the experiment results were provided in a scale of percentages instead of area measured in square values, because obtained results would have been in any case proportional.

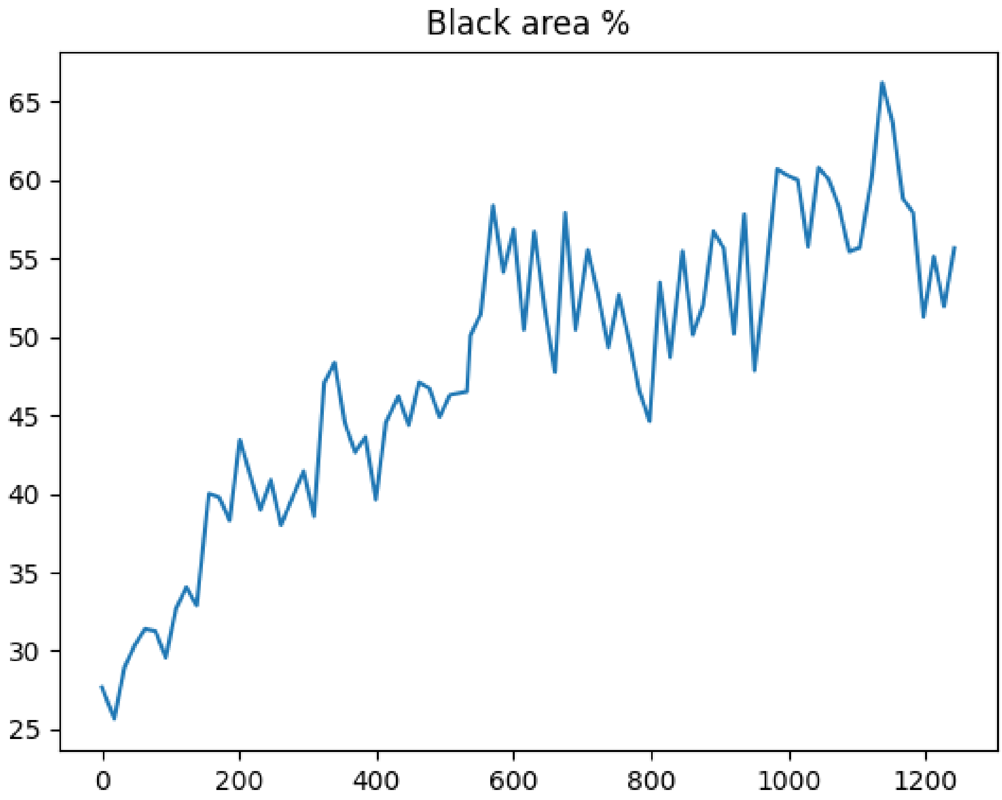

Figure 26: Trend of percentage of black area

5.4.3 Minimum and maximum distance of the electrode from the centre

At the following graph, using another functions of the python's libraries were depicted both minimum and maximum distances of the electrode's edge. Marked with blue color is minimum external and with orange maximum external distance from found centre.

First of all it is observable, that for most of measured points, trend of increase for values of the distance is proportional both for minimum and maximum distance from the centre of the electrode. Secondly, some of the results for example 310, 615 or 690 were caused due to wear in the internal part of the electrode. Given results were described in the table below.

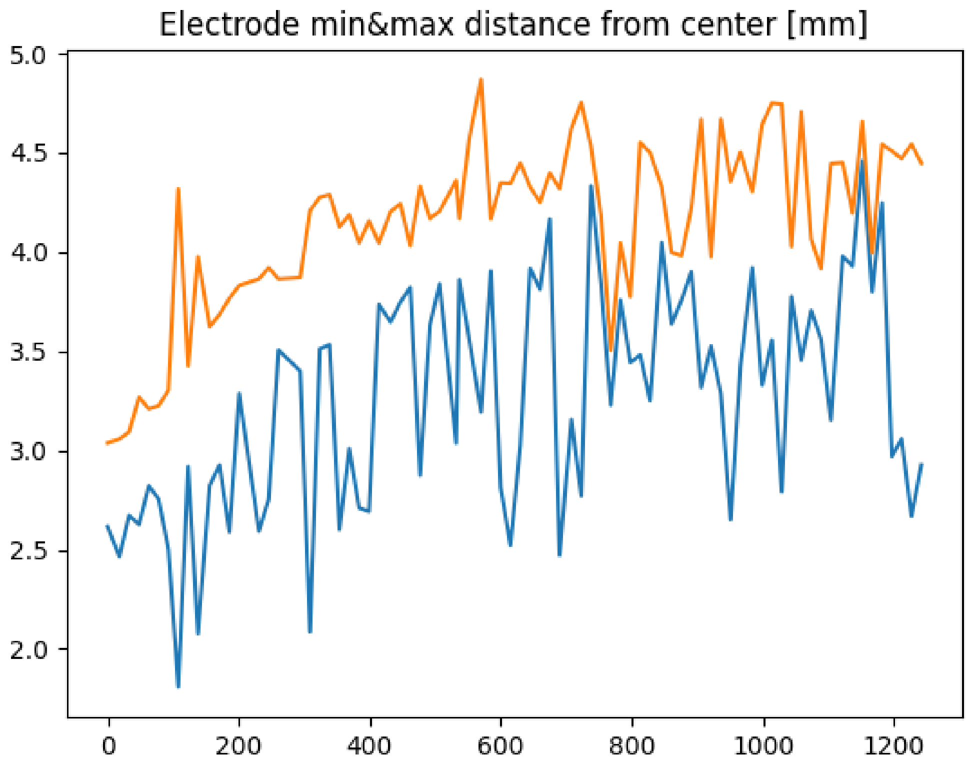

Figure 27: Trend of electrode minimum and maximum distance from the center

5.5 Comparison of the theoretical vs experimental tests

In the previous chapter 4.1 was described graph characterizing theoretical prediction of the electrode wear. Based on results generated by python code, it was possible to compare given data with the obtained experimental values.

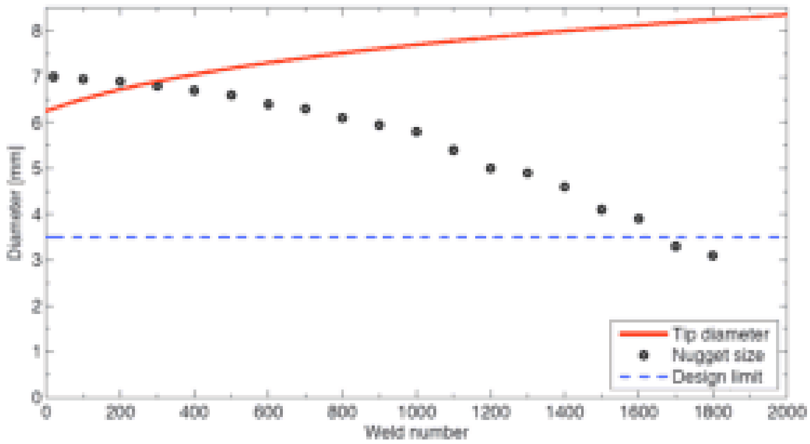

Figure 28:Theoretical trend of the electrode's diameter

According to the data provided by the theoretical graph, taking into account 1200 number of spots, tip diameter increased starting from 6.2 mm and ending with around 7.7 mm which gives increase of 24.2%.

Comparing those data with the experimental values it is observable, that in the research done on practical case working on 1200 number of welds diameter of the electrode increased up to 69%. Such a difference might be caused by not accurate, not perfect parameters of the electrode described in the previous chapters such as current, time or pressure. Moreover, it would be reasonable for the future research to compare change of the diameter of the electrode in several cases considering various physical parameters of the resistance spot welding process.

5.6 Recommendation for the future work as continuity of the project

It would be reasonable for the future research to compare values of electrode's diameter in several cases considering various physical parameters of the resistance spot welding process. Apart of that, it is possible to take into account imprints of the electrode from the lateral view and compare trends with the top view developed in the given project. Example of use of feature extraction can be accurately followed for another issues related to quality control of technological processes by the development of another various functions, not mentioned in this work.

6. APPENDIX 1 FINAL CODE

```
import numpy as np
import cv2
import math
import os
from skimage import measure
import matplotlib.pyplot as plt

def get_list_all_images():
    return sorted(os.listdir('images'), key=image_name_to_number)
    return ["0.PNG"]

def image_name_to_number(image_name):
    return int(image_name[:-len('.PNG')])

def calculate_diameter(img):
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    blurred = cv2.medianBlur(gray, 25)
    canny = cv2.Canny(blurred, 100, 200)
    #circles
    points = np.argwhere(canny > 0)
    center, radius = cv2.minEnclosingCircle(points)
    diameter = 2 * radius
    return diameter

def calculate_min_max_dist(img):
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    # blur
    blur = cv2.GaussianBlur(gray, (3, 3), 0)
    thresh = cv2.threshold(blur, 0, 255, cv2.THRESH_BINARY_INV +
cv2.THRESH_OTSU)[1]
    kernel = cv2.getStructuringElement(cv2.MORPH_ELLIPSE, (5, 5))
    binary = cv2.morphologyEx(thresh, cv2.MORPH_OPEN, kernel,
iterations=2)
    contours, hierarchy = cv2.findContours(binary, cv2.RETR_EXTERNAL,
cv2.CHAIN_APPROX_NONE)
    regions = measure.regionprops(binary)
    circle = regions[0]
    yc, xc = circle.centroid

    max_dist = 0
    min_dist = 999999999999999
    all_contours = contours[0]
    for cnt in all_contours:
        y = cnt[0][0]
        x = cnt[0][1]
        dist = math.sqrt((yc - y)**2 + (xc - x)**2)
        if dist > max_dist:
            max_dist = dist
        if dist < min_dist:
            min_dist = dist

    return min_dist, max_dist

def calculate_black_area(img):
    # convert to grayscale
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    # blur
    blur = cv2.GaussianBlur(gray, (3, 3), 0)
```

```
    # threshold
    thresh = cv2.threshold(blur, 0, 255, cv2.THRESH_BINARY_INV +
                           cv2.THRESH_OTSU)[1]
    # apply morphology open with a circular shaped kernel
    kernel = cv2.getStructuringElement(cv2.MORPH_ELLIPSE, (5, 5))
    binary = cv2.morphologyEx(thresh, cv2.MORPH_OPEN, kernel,
iterations=2)

    threshold = 20
    white = 0
    black = 0
    height, width = binary.shape[:2]
    for y in range(height):
        for x in range(width):
            if (img[y][x][0] < threshold and img[y][x][1] < threshold
and img[y][x][2] < threshold):
                black += 1
            else:
                white += 1
    return black / (white + black) * 100

    # https://www.geeksforgeeks.org/opencv-counting-the-number-of-
black-and-white-pixels-in-the-image/
    # black_pixels = np.sum(binary == 0)
    # white_pixels = np.sum(binary == 255)
    # all_pixels = np.sum(binary)
    # print(white_pixels)
    # print(black_pixels)
    # print(all_pixels)
    # return black_pixels / (white_pixels + black_pixels) * 100

def debug_show_processed_image(img):
    # convert to grayscale
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    # blur
    blur = cv2.GaussianBlur(gray, (3, 3), 0)
    # threshold
    thresh = cv2.threshold(blur, 0, 255, cv2.THRESH_BINARY_INV +
                           cv2.THRESH_OTSU)[1]
    # apply morphology open with a circular shaped kernel
    kernel = cv2.getStructuringElement(cv2.MORPH_ELLIPSE, (5, 5))
    binary = cv2.morphologyEx(thresh, cv2.MORPH_OPEN, kernel,
iterations=2)
    # find contour and draw on input (for comparison with circle)
    cnts = cv2.findContours(binary, cv2.RETR_EXTERNAL,
cv2.CHAIN_APPROX_SIMPLE)
    cnts = cnts[0] if len(cnts) == 2 else cnts[1]
    c = cnts[0]
    result = img.copy()
    cv2.drawContours(result, [c], -1, (0, 255, 0), 1)
    # find radius and center of equivalent circle from binary image
and draw circle
    # see https://scikit-
image.org/docs/dev/api/skimage.measure.html#skimage.measure.regionprop
s
    regions = measure.regionprops(binary)
    circle = regions[0]
    yc, xc = circle.centroid
    radius = circle.equivalent_diameter / 2.0
    print("radius =", radius, " center =", xc, ",", yc)
    xx = int(round(xc))
```

```python
    yy = int(round(yc))
    rr = int(round(radius))
    cv2.circle(result, (xx, yy), rr, (0, 0, 255), 1)
    # write result to disk
    cv2.imwrite("dark_circle_fit.png", result)
    # display it
    cv2.imshow("image", img)
    cv2.imshow("thresh", thresh)
    cv2.imshow("binary", binary)
    cv2.imshow("result", result)


def main():
    image_no = []
    image_diameter = []
    image_min_dist = []
    image_max_dist = []
    image_black_area = []

    for image_name in get_list_all_images():
        img = cv2.imread('images/' + str(image_name))

        image_no.append(image_name_to_number(image_name))

        diameter = calculate_diameter(img)
        print('Diameter {}: {}'.format(image_name, diameter))
        image_diameter.append(diameter)

        min_dist, max_dist = calculate_min_max_dist(img)
        print('Min dist {}: {}'.format(image_name, min_dist))
        print('Max dist {}: {}'.format(image_name, max_dist))
        image_min_dist.append(min_dist)
        image_max_dist.append(max_dist)

        black_area = calculate_black_area(img)
        print('Black area % {}: {}'.format(image_name, black_area))
        image_black_area.append(black_area)

    cv2.waitKey(0)
    cv2.destroyAllWindows()

    plt.title('Electrode diameter')
    plt.plot(image_no, image_diameter)
    plt.show()

    plt.title('Black area %')
    plt.plot(image_no, image_black_area)
    plt.show()

    plt.title("Electrode min&max distance from center")
    plt.plot(image_no, image_min_dist, label="min dist")
    plt.plot(image_no, image_max_dist, label="max dist")
    plt.show()

    # figure, axis = plt.subplots(3)
    #
    # axis[0].plot(image_no, image_diameter)
    # axis[0].set_title("Electrode diameter")
    #
    # axis[1].plot(image_no, image_min_dist, label="min dist")
    # axis[1].plot(image_no, image_max_dist, label="max dist")
```

```
    # axis[1].set_title("Electrode min&max distance from center")
    #
    # axis[2].plot(image_no, image_black_area)
    # axis[2].set_title('Black area %')
    #
    # plt.show()

main()
```

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