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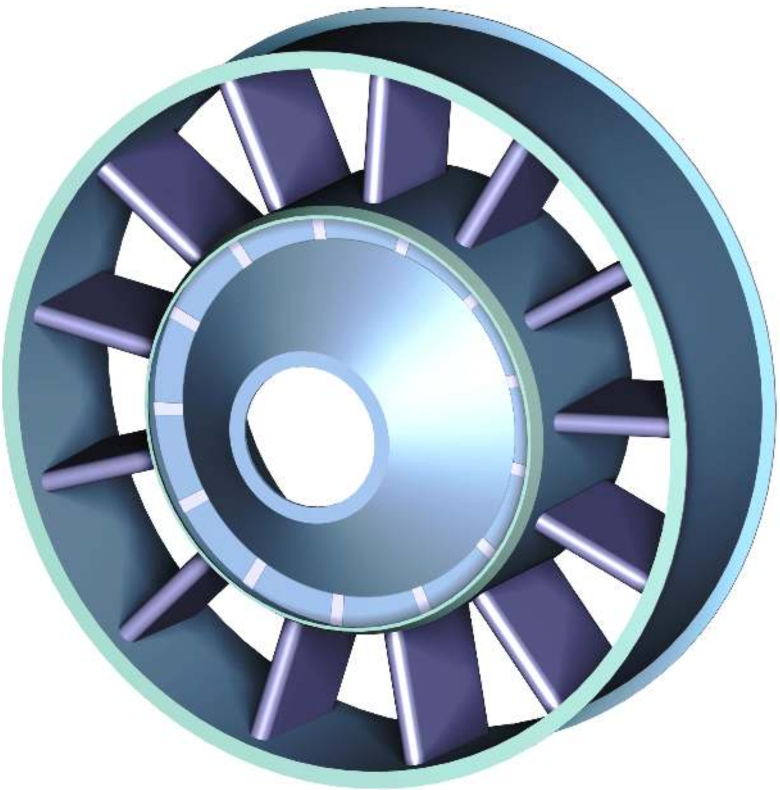

Quality Parameter Analysis at GKN Aerospace Sweden

Master's thesis in Production Engineering

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Department of Product & Production Development
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Cover:
A general Engine component model

Chalmers Reproservice
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Abstract

The product and production development within the aerospace industry has evolved through new strategies to achieve high functionality of the components. The approach has been to decompose large structures into smaller components that are later assembled through various joining techniques.

Though advantageous in terms of design freedom and weight reduction, decomposition has added complexity into the process influencing the producibility (i.e. ease of production) thereby affecting the quality. There are many influencing parameters and factors but their relation to the component's quality stands unclear today.

This thesis work was carried out to address the gap by creating a platform that characterizes the influencing parameters and factors. The turbine structure was the product in focus and weld quality was addressed as the key issue.

Information was collected from various sources to better understand the product and manufacturing processes. It was then systematized in the form of a map to show the relation between influencing parameters and their relation to the weld quality. Various cases studies of weld joints were conducted to validate the content of the map. Detailed analysis of production data was carried out to further strengthen it.

Case studies confirmed the relevancy of content within the map and could be applicable for several joint types. However, the map and corresponding support documents and statistics are not able to provide a basis for making predictions of the quality outcome of the component.

To strengthen the present platform, experiments and consistent data management within production is recommended to improve the understanding of influencing parameters, their relation and impact. This will help taking better decisions in design and manufacturing and ultimately increasing the producibility at the company.

Keywords: welding, quality, parameters, defects

Preface

This master thesis is made as a completion of the Production Engineering master program at the Department of Product and Production Development, Chalmers University of Technology. The work has been carried out at GKN Aerospace Trollhättan Sweden and comprises the area of weld quality from a design and manufacturing perspective.

This work is a contribution to the research project titled *Producibility and Design for Manufacturing of Aerospace Engine Components* in collaboration with Chalmers Wingquist Laboratory and GKN Aerospace Engine Systems, Sweden.

Acknowledgements

We would like to thank Kristina Wärmefjord, Chalmers University of Technology and Johan Vallhagen, GKN Aerospace for providing us the opportunity to perform this thesis.

We express our deepest appreciation to Johan Vallhagen, our supervisor at GKN Aerospace for his continuous support and guidance throughout the thesis. Without his supervision and encouragement this work would not have been possible.

We would like to thank Julia Madrid, our supervisor at Chalmers University for helping us lay the foundation for the thesis and supporting us throughout the project.

We are deeply grateful to Rikard Söderberg for his insightful comments and suggestions.

Special thanks to Johan Lööf whose advices and comments were of great help.

We owe a very important debt to Kenth Erixon, who made enormous contribution to our work. His suggestions and comments were invaluable.

We appreciate the feedbacks offered by Fredrik Kullenberg, Sören Knuts, Jerry Isoaho, Peter Andersson, Joel Andersson. Their varied perspectives helped us in strengthening our work.

Finally, thank you to all the operators who gave their time and insight into their experience with the processes.

Gothenburg, June 2014

Christian Larsson & Vaishak Sagar

List of acronyms

AC/DC	—	Alternate/Direct Current
CAD	—	Computer Aided Design
CAT	—	Computer Aided Tolerancing
CNC	—	Computer Numerical Control
DFMEA	—	Design Failure Mode and Effect Analysis
DOE	—	Design Of Experiments
EBW	—	Electron Beam Welding
FMEA	—	Failure Mode and Effect Analysis
FPI	—	Fluorescent Penetrant Inspection
FTA	—	Fault Tree Analysis
GAS	—	GKN Aerospace Sweden
GOM	—	Optical measuring technique
HAZ	—	Heat Affected Zone
HIP	—	Hot Isostatic Pressing
HoQ	—	House of Quality
KPS	—	Data management system for following up quality
LBW	—	Laser Beam Welding
NDT	—	Non-Destructive Testing
PAW	—	Plasma Arc Welding
PFMEA	—	Process Failure Mode and Effect Analysis
PMZ	—	Partially Melted Zone
PWHT	—	Post Weld Heat Treatment
QFD	—	Quality Function Deployment
RPN	—	Risk Priority Number
TACK-welding	—	A weld method to join parts before the actual weld operation
Engine component	—	The product in focus of this thesis
TIG	—	Tungsten Inert Gas
wt%	—	Mass fraction

Contents

1 Introduction

This chapter presents the background of the project and the problem areas. A number of research questions have been stated and serve as the core of the project. Furthermore, the objectives and boundaries are defined to clearly set the scope. This chapter is rounded up by a brief introduction to the company GKN Aerospace Engine Systems and the products in focus for this thesis.

1.1 Background

GKN Aerospace Engine Systems in Trollhättan, Sweden (GAS) designs, develops and manufactures high precision components for jet engines [2]. The strategy for designing structural components is to use fabrication instead of large forgings and castings. The word fabrication is used in the sense of dividing a component into several parts which are then joined together. High number of parts along with tough functional requirements makes the fabrication process (assembly) significantly complex and influences the quality and key characteristics. To get a clear understanding on choosing requirements and solutions from a manufacturing perspective, the relation between alternative solutions and parameters influencing producibility (the ease of manufacturing a component) needs to be better defined. Weld quality is a key issue in manufacturing that needs to be addressed.

1.2 Problem formulation

As for today, there are some systematic representation of what causes the weld quality issues in Engine component production. However, gaps exist in the current approach which inhibits understanding the interrelation of causes. Though several continuous improvement projects are carried out to improve the quality outcome of the Engine component, the gaps are yet to be fully understood and addressed.

Therefore, understanding the occurrences and root-causes of weld defects and non-conformances will help in exploring them at a larger scale. Thus having a common platform consisting of the essential knowledge will aid product/production development.

The products in focus are considerably complex as the number of parts within assemblies are many. Also, there are several production steps involving different manufacturing techniques, further complicating the problem and their representation. Therefore, a number of research questions have been raised to address and clarify the problem. The questions are as follows:

1. How can the relations between different design, product, process parameters and the quality of welds be represented?

2. How can this representation be generic i.e. applicable for several projects within the Engine component-platform?

3. How can new information or data as more knowledge and experience are obtained?

4. How will the representation help in identifying where there is a lack of knowledge or understanding on how to achieve good weld quality?

1.2.1 Purpose

The purpose of the project is to create a platform which identifies the parameters and factors affecting the quality of fabricated products. The model should serve as an aid in product/production development.

1.2.2 Objective

The objective of the project is to carry out literature studies about robust design, manufacturing methods and weld quality characteristics. This information is used to identify the parameters influencing the quality of a fabricated product. On identification, parameters are related using appropriate tools and visualization techniques. This is then practically verified and tested by performing one or several case studies on a sub-assembly.

1.2.3 Goal

The goal of the project is to define the relation between design and manufacturing parameters with respect to quality. This is done by creating a systematic representation for quality related parameters and analyzing it. At the end of the project, conclusions are drawn as to how design and manufacturing processes can be better integrated in order to achieve increased producibility.

1.2.4 Delimitations

The scope covered in the project comprises a certain product family i.e. Engine component. Thus other product types and families produced at GKN are not considered in this study.
As quality of welds is the key issue in manufacturing of the Engine component, focus is mainly on the weld defects occurring due to pre-welding (e.g. material removal), welding and post-welding (e.g. heat treatment) activities. Quality aspects are delimited to welding defects and geometrical distortions in this work.
Welding defects are delimited to defect types that are recurring in production at the company. Non-recurring defects are thus beyond the scope and are not included in this project.

1.3 GKN Aerospace

GKN Aerospace Engine Systems located in Trollhättan, Sweden (GAS) designs, develops and manufactures high precision components for aircrafts, rocket engines and gas turbines in cooperation with world's leading producers [3]. GAS also offers a wide range of services consisting of sales of aircraft engines and their spare parts, leasing of aircraft engines and maintenance. Their services also include overhauling and repairing of aircraft engines and industrial gas turbines.

GAS is part of GKN Aerospace with its Headquarters based in Redditch, United Kingdom. Today, GKN Aerospace is one of the world's largest tier one supplier to the global aviation industry. They cater customers from both civil and defense sectors providing wide range of solutions.

1.4 The Engine component

A brief description of jet engines and their functioning is provided in this section to understand the product in focus, the Engine component, a structural component attached to a jet engine. An overview of important structural components of a jet engine is shown in Figure 1.1.

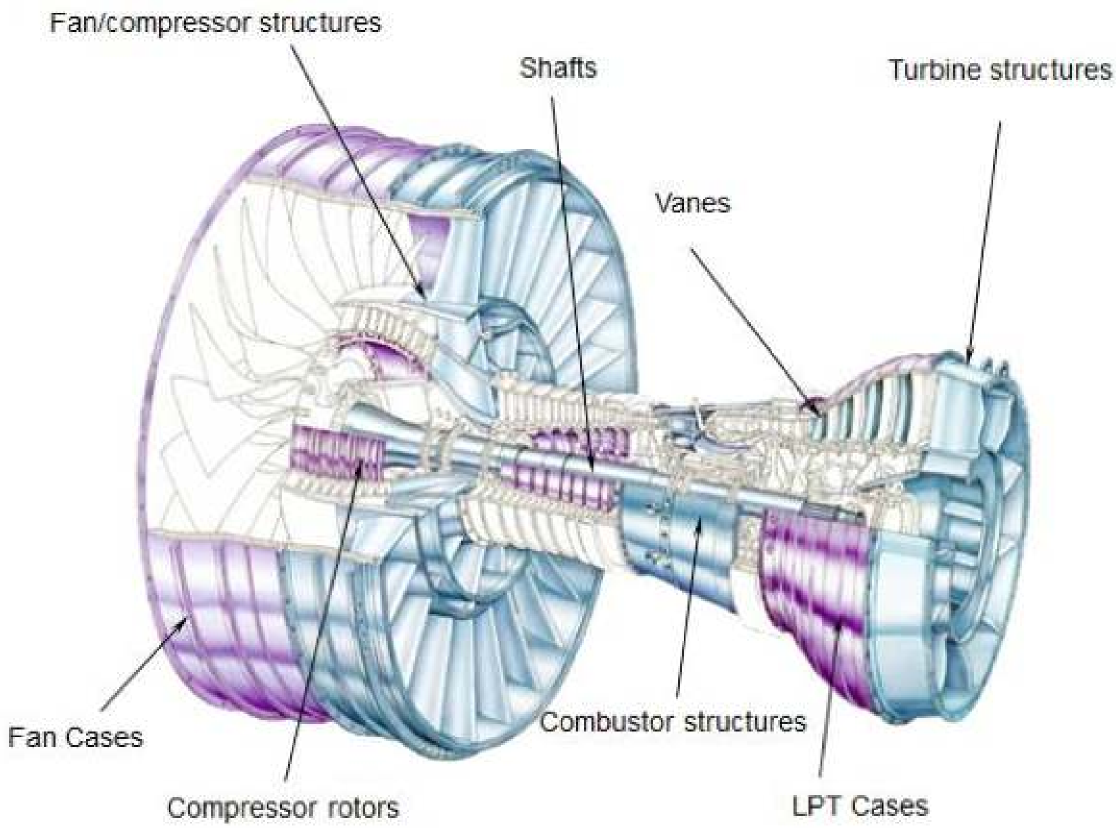

Figure 1.1: *A typical jet engine and its corresponding key components [3].*

A jet engine can be divided into two parts: cold structures and hot structures. Cold structures mainly consist of turbofan, the low and high pressure compressor while hot structures consist of the combustion chamber, low and high pressure turbine and the exhaust.

Air is drawn in through the turbofan and gets compressed as it passes through the compressor. The compressed air-fuel mixture undergoes combustion in the combustion chamber. The resultant high pressure gas passes through the turbine which drives the fan, and exits through the turbine exhaust structure providing the necessary thrust. For modern engines, a majority of air at the inlet bypasses the core of the engine and exits through the nozzle providing additional thrust. The temperature of the air exiting through exhaust is very high. It has to withstand very high pressures and loads built up by the hot air passing through at elevated temperatures. Requirements on Engine components are thus high both regarding design and manufacturing in order to achieve ultimate performance.

An Engine component consists of sub-assemblies referred as sectors. Each sector consists of an inner hub, a guide vane and an outer panel (shroud), which are joined together. The number of sectors present in an Engine component varies between different Engine component-projects. These sectors along with additional components as cones and flanges are joined together, forming the Engine component. The complete Engine component is made out of superalloys (nickel-based).

Previous fabrication strategy consisted of single piece castings and forgings. The new fabrication strategy is according to the principle of developing components with reduced weight and increased freedom for design and manufacturing alternatives by utilizing smaller components. Furthermore, having smaller components increases the number of supplier alternatives which may have economical benefits. But the new strategy increases the amount of effort to be put in production (more manufacturing activities) and the probability of having disturbances and defects are raised.

2 Theory

This chapter reviews the literature studies carried out initially in the project. Manufacturing processes, robust design, weld quality and quality management are the four main areas covered. The section manufacturing processes reviews the typical methods and equipments used in fabricating an Engine component. Additionally, inspection techniques for measuring quality of manufactured parts are also included. The robust design section explains the theory behind robust design, available tools and benefits of employing the concept. A section dedicated to weld quality is reviewed; what determines a good weld quality, the mechanisms behind occurrence of defects and how these could be avoided. The chapter concludes with a section of quality management explaining the common tools and techniques employed in manufacturing industries.

2.1 Manufacturing processes

The production of an Engine component involves several manufacturing steps that are used in building the product. As a first step, incoming parts from suppliers undergo material removal processes on the weld interfaces. This is done in order to assure good mating conditions for the subsequent operations.

The second step is welding where a joint between two parts is created by local heating above the melting temperature of the material. A melt pool is created that fuses the parts together through metallurgical bonding upon solidification. Several welding techniques are used for different applications and are based on different principles. There are four specific welding methods of interest in the production of the Engine component and they are described under the sections of Arc welding and High energy density beam welding.

2.1.1 Material removal process

Parts manufactured through casting, forging and forming processes often require additional processing or finishing operations to meet desired dimensions. For this purpose, different material removal processes are employed. A conventional removal process is often divided into two areas; cutting and abrasive processes [4]. The cutting process generally involves single- or multi-point cutting tools and is often realized through machining. An abrasive process on the other hand uses abrasive particles of different grit-size to perform finishing operations with low material removal rate e.g. grinding. The material removal principle is however the same for both types, where a tooltip moves along the workpiece at a certain velocity and a depth of cut. Chips are continuously formed ahead of the tool through shearing of the material along a shear-plane [5].

The material removal process is complex to tame due to the many parameters and factors that have to be considered in order to achieve satisfying results. Cutting conditions that set the material removal rate are feed, depth of cut and cutting velocity. Tool geometry, tool holders, fixtures and machines come in large variants and can be tailored for a specific workpiece and application. The material of the workpiece combined with cutting tool material is also of importance in the process. The energy that is dissipated in machining operations is converted into heat which will as a consequence, raise the temperature in the cutting zone [5]. Understanding of heat generation is important since it alters the strength, wear and hardness of the cutting tool material [5]. It also affects the dimensional stability since the temperature rise in the workpiece and the cutting tool will be a source of distortion [4]. Thermal damages on the workpiece surface is another consequence which may affect its properties and service life aspects [4]. Therefore, coolants and lubricants are employed to control the heat levels and to diminish frictional forces [5]. Vibrations should be evaded in order to obtain good surface finish, dimensional accuracy and avoiding failure of machine-tool components and tool wear [4].

Machinability of a material is a general property that is hard to quantify, but can be expressed through four factors: surface finish and integrity of the machined workpiece, tool life, force and power demand, and chip control [4]. A material with good machinability should have good surface finish and integrity, long tool life, low power consumption and good chip control. It should not interrupt or interfere with the cutting action [4]. For superalloys, machining can be considered to be challenging compared to materials such as e.g. aluminum. That is due to their high hardness and strength at elevated temperatures, and low thermal diffusivity [6]. Therefore, tool materials and processing parameters must be carefully chosen to assure good processing conditions.

In welding assembly, material removal processes are used to machine the edges of a part to be welded i.e. weld preparation process. The aim is to have edges with accurate dimensions that are free from contaminations on the surfaces e.g. surface oxides. Keeping dimensional accuracy during weld preparation is important since it sets the prerequisites for having good mating conditions and a good weld geometry.

2.1.2 Arc welding

In arc welding, the intense heat needed to melt the metal is produced by an electric arc supplied through an electrical power source. The arc is formed between the workpiece to be welded and the electrode that is moved along the joint.

An electrode has the function to create one of the polarities, for which the workpiece act as the counteracting pole. Depending on weld technique used, the electrode can either be consumable or not. The consumable type serves as a filler material for the weld joint. Additional filler material can be supplied externally by introducing it to the arc. If a process is properly performed, the joint is ought to have similar properties as the workpiece.

Two arc welding techniques, gas tungsten arc welding (TIG) and plasma arc welding (PAW) are described in this subsection.

Gas tungsten arc welding

Gas tungsten arc welding also known as tungsten inert gas (TIG) welding involves a welding torch that holds a non-consumable electrode of tungsten, see Figure 2.1. Electrical power and shielding gas is supplied to the welding torch. Heat is generated through an electrical arc that forms between electrode and workpiece [7]. The electrode is not consumed during the process which enables a stable arc gap to be maintained at a constant level of current [4]. A filler material in the form of a wire or a welding rod is typically added and must have a material composition similar to metals to be welded [4].

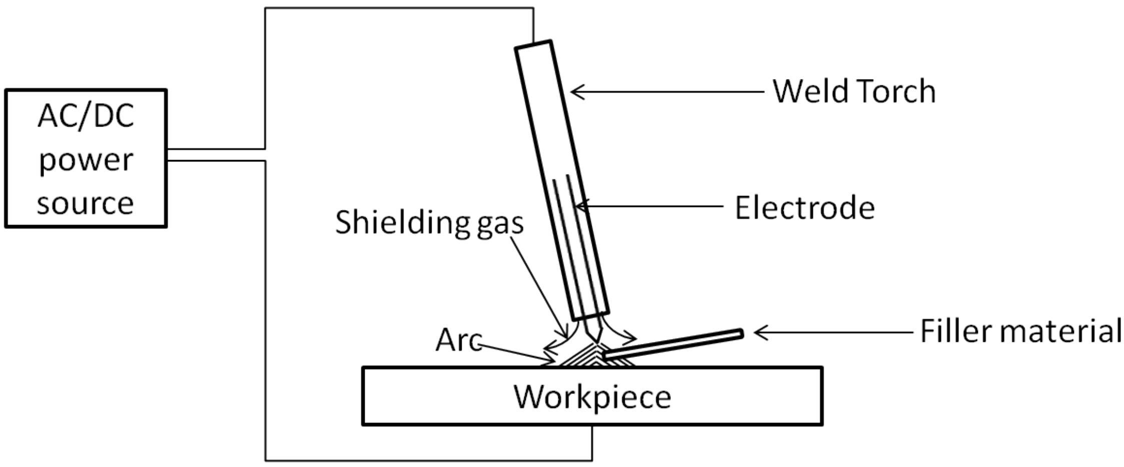

Figure 2.1: *Schematic illustration of a TIG welding torch.*

There are several alternatives to set the polarity between the workpiece and the electrode. For direct current (DC), the electrode can either be connected to the negative or the positive terminal of the power supply [7], [8]. For a negative charged electrode, electrons are emitted and accelerated from the electrode towards the positive charged workpiece which results in a higher energy release at the workpiece region [7]. This set-up will result in opportunities to create deeper and relatively narrower welds [7]. For a positive charged electrode, the energy release is towards the electrode region which results in shallower welds [7]. Positive ions from the shielding gas will bombard the workpiece surface, removing oxide films and produce a clean weld surface [7]. The electrode must however be cooled for this set-up in order to prevent it from melting [7]. This method is beneficial to utilize for workpieces made of thin sheets where deeper penetration is not required and for materials that forms strong oxide films e.g. aluminum and magnesium [7]. A third option is to use alternate current (AC) power supply that serves as an intermediate method between the two direct current settings where reasonably good penetration and oxide cleaning properties are possible [7].

Tungsten electrodes alloyed with either cerium or thorium (up to 2 wt%) have been proven to have better electron emissivity (ability to emit electrons), resistance to contamination and current-carrying capacity compared to electrodes made of pure tungsten [7], [8]. The above mentioned alloying additives help in easier arc start up and provide a more stable arc [7], [8]. However, thorium is a radioactive element which must be taken into consideration when selecting electrode type from an environmental perspective.

An inert shielding gas (usually helium or argon) is commonly used to protect the electrode, the arc and the locally heated material from corrosion and contaminations that promote defects [4]. An advantage of using argon over helium is the better shielding properties due to the higher density [7]. Furthermore, argon has under certain electrode polarity configurations (positive polarity at the electrode or AC) much greater oxide cleaning properties compared to helium [7].

Due to limitations in heat generation, TIG welding is more suitable for thin sections [7]. The process is considerably clean and can therefore be used for welding reactive metals as e.g. titanium, aluminum and magnesium [7].
The deposition rate in TIG welding is low which might lead to excessive welding currents melting of the electrode. This results in brittle tungsten inclusions within the weld pool [7]. Therefore an electrode must be well maintained to avoid contaminating the molten metal as it might cause discontinuities in the weld affecting the weld quality [4].

Plasma arc welding

Plasma arc welding has several similarities to TIG welding and is schematically described in Figure 2.2. The technique uses a welding torch that holds a tungsten electrode. Power supply, shielding gas, plasma gas and cooling water is supplied to the equipment. Normally a DC power supply is used (along with negative polarity of the electrode) but variable polarity solutions have also been developed [7]. A filler material may be introduced to the process for applications where it is necessary. The torch produces a concentrated and stable plasma arc that is directed to the weld area. Plasma is an ionized gas composed of equal portion of electrons and ions, which is created between the electrode and the orifice [4]. The uniqueness of the process is the possibility to create a concentrated arc when the plasma is forced through the small orifice [4]. An outer shielding ring provides the shielding gas that serves the same purpose as described in the TIG process. Compared to TIG, PAW has a higher concentration of energy which provides prerequisites to create deeper and narrower welds and the arc is considered to be more stable [4]. Since the arc is constricted to the plasma gas nozzle, expansion of the arc is maintained at a low spread for increasing arc lengths [7].

Advantages of PAW over TIG is that it produces a stable arc that is less sensitive to variations with respect to e.g. heat input [7]. It is possible to weld in a keyhole welding mode, that is a weld mode that has the ability to ramp up the welding speed and assure full penetration [7]. This welding mode can however only be run at a certain thickness range. The process of PAW is however more complicated than TIG due to high requirements on proper configuration of the overall equipment, positioning and process parameters [7]. PAW equipment is costlier than TIG equipment and includes more instruments and devices [7].

In both reviewed arc welding processes, the operation parameters are very crucial and influence the weld quality. Welding parameters include voltage and current input, shielding gas rate and weld speed while torch parameters include the work angle, travel angle, orifice diameter and electrode conditions [9]. The distance between the torch and the workpiece along with the above mentioned parameters influence the weld quality. In addition, weld defects might also arise due to worn or damaged nozzle orifice [9]. The concentricity of the nozzle orifice diameter, the alignment of the electrode and nozzle orifice are very important [9]. Electrode tip conditions should be continuously monitored and upon wear the electrode must be ground and cleaned on a regular basis.

Weld defects could be the result of a combination of operator errors and improper equipment setup. Most common weld defect are undercuts (see Section 2.3.3), one- or two sided [9]. One sided undercuts occurs due to

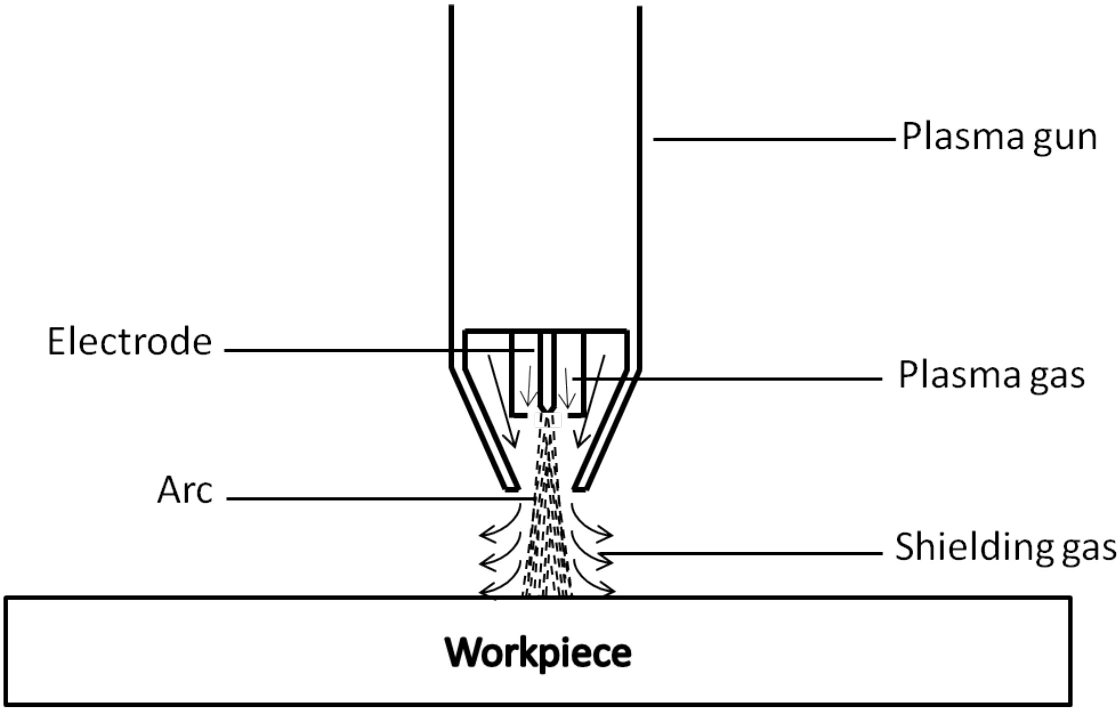

Figure 2.2: *Schematic illustration of a plasma welding torch.*

misalignment of the torch, electrode and orifice, or even mismatch in workpiece mating conditions, while two sided undercuts can occur when welded above certain threshold weld speeds depending on the material type and its thickness [9]. Therefore, right operation parameters and good operator skills are essential in carrying out the welding processes [9].

2.1.3 High energy density beam welding

In this category of welding process, a beam of electrons or photons are focused to melt and vaporize the workpieces being joined. High energy density beam can be used to produce welds with high depth-to-width aspect ratios, small heat affected zones and reduced distortion. Two types of welding methods, electron beam (EB) and laser beam welding will be discussed in this section.

Electron Beam welding

In EB welding, the heat is generated by high-velocity beam electrons. The kinetic energy stored in the electrons is converted into heat upon impact with the workpiece [4]. The high power density plus the extremely small intrinsic penetration of electrons into the work piece causes an almost instantaneous local melting and vaporization of the workpiece material [10]. Formation of a vapor hole (i.e. a keyhole) is possible for an electron beam with high intensity [7]. A schematic illustration of an EB welding equipment setup is shown in Figure 2.3.

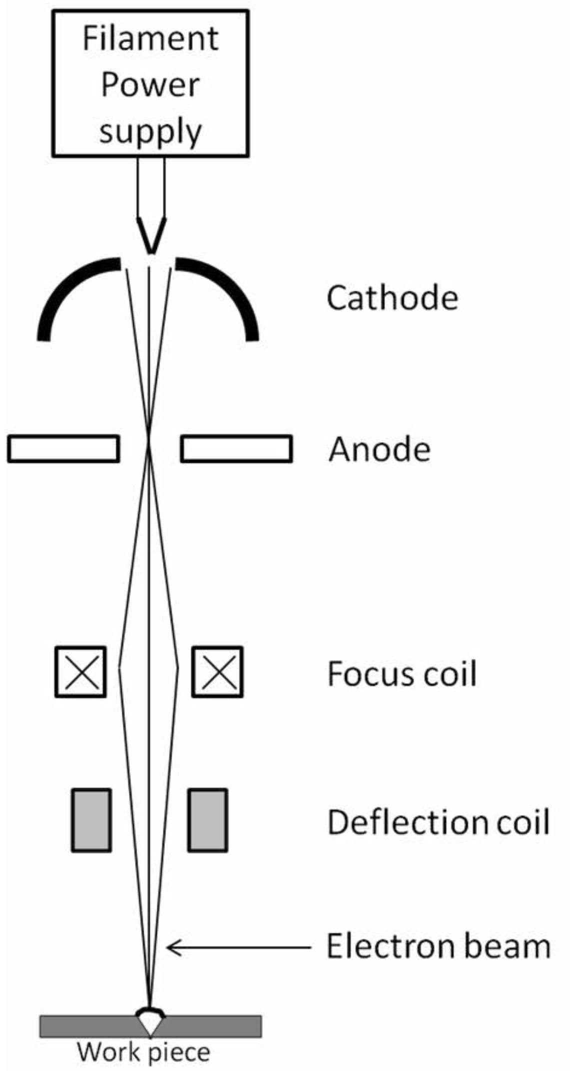

Figure 2.3: *A principal illustration of an EB welding technique [10].*

To focus the beam onto the workpiece, vacuum is required, and the higher the vacuum, the deeper the beam can penetrate into the workpiece [4]. The electron beam diameter decreases with decreasing ambient pressure since electrons colliding with air molecules gets scattered [7]. This is the main reason for performing welding within a vacuum chamber. Apart from vacuum requirements, the process produces x-ray emissions that has to be managed.

EB welding is beneficial when joining thicker sections but is not suitable for insufficiently degassed materials [7]. Due to rapid cooling and high weld speeds, residual gases trapped in the workpiece fail to escape the weld. These gases will remain as porosities [7].

Other process parameters such as e.g accelerating voltage, beam current, filament design and peaking, along with vacuum, control the spot size of the beam [10]. The process generally requires no shielding gas or filler metal. One of the biggest advantages of EB welding is the capability of producing narrow welds that have small heat affected zones [4]. Weld quality is maintained high as shrinkage and distortions can be held to a minimum and high purity can be obtained [4]. A drawback with the process is that the equipment itself requires proper monitoring and frequent maintenance [4]. The narrow beam size puts high requirements on precision both regarding direction of the beam and the mating conditions of the workpieces to be joined [7]. Hence, the process can be regarded as sensitive to variations and mismatch in joint set-up. EB equipment is very costly and the requirements to maintain a high vacuum plus x-ray shielding equipment makes the process more complex and time consuming [7].

Laser beam welding

Laser beam welding (LBW) is a welding technique that uses a high-power laser beam as heat source to create joints. The technology allows the laser beam to be focused to very small diameters of high power density [11]. High power density can be maintained which makes deep penetration possible, and thus capable of creating deep and narrow joints [11]. Similar to PAW and EB, laser welding can also be used in keyhole welding mode. Two common techniques in laser welding are solid state laser and gas laser [7].

In solid state laser, a single crystal is doped with small partitions of either transition elements or rare earth elements, for which the electrons of the crystal can be excited to higher energy states upon exposure to high-intensity flash lamps [7]. A laser is created as the electrons return to the normal energy state by emitting photons, which are guided through optical instruments such as mirrors and focal lenses [7].
For a gas laser, a mixture of CO_2, N_2 and He is continuously excited by discharged electrodes supplied from a power source [7]. Increased laser power can be obtained in gas laser welding compared to solid state laser welding[7].

Process efficiency is dependent on the reflectivity of the workpiece material, meaning that the laser beam is partly absorbed, penetrated and reflected by the material [11]. Modification of the workpiece surface through roughening, oxidizing and coating can remedy reflectivity to an extent [7]. Additionally, performing welding in keyhole mode leads to absorption of the energy within the hole due to entrapment of internally reflected beams [7].

Gases may be used as additions to improve the process. Typically, oxygen is employed for welding steels and inert gases for non-ferrous metals [4]. Plasma (ionized gas) is produced when welding with laser, and especially at high power levels due to ionization by the beam [7]. It is important to remove or suppress the plasma from the welding area as the plasma have the ability to absorb and scatter the laser beam which affects the penetration depth and thus the process performance [7]. Using inert gases e.g. helium or argon to blow or deflect the plasma away from the weld path will act as a shield during the process [7]. However, the shielding gas may also partly be ionized and become a part of the plasma. For such cases, helium is a better choice since it is less likely to transform [7]. The disadvantage on the other hand is that helium does not displace the air as good as argon due to its density being less than air [7].

The technology can be automated to a high level and used for most typical metals, alloys, and superalloys in particular [4]. Quality of the welds can be maintained due to narrow weld beads which minimizes the shrinkage effects and geometrical distortions [4], [11]. Laser welds hold high strength and are also generally of high ductility and free from porosities [4]. Unlike EB welding, laser-beam welding does not require any vacuum environment and does not generate any x-rays which make this process more manageable, and welds are generally of better quality [4]. Laser welding equipment is however, just like EB welding equipment, very costly. Alignment of the parts is critical as the typical focal spot diameter range for a laser beam is small (ranging in size from 0.1 to 1 mm) [12]. Therefore, precision of mating workpieces is essential for having good welding conditions.

2.1.4 Inspection techniques

Inspection of manufactured components is essential for assuring quality and to detect defects that may not be apparent to the naked eye. Apart from defect detection, inspection techniques are also used to measure distortions in order to assure quality of geometrical features. Inspection techniques are commonly divided in two categories: non-destructive testing (NDT) and destructive testing. Obviously, NDT is the preferred method in production since the tested object is maintained after inspection.

NDT techniques can be carried out at every stage of the fabrication process to detect defects and take corrective measures. Though these tests detect the presence of defects, it is not always possible to determine the severity [13].

NDT methods such as visual inspection, penetrant testing, x-ray radiography testing, magnetic particle testing, eddy current testing, ultrasonic testing, coordinate measurement inspection and optical measurement inspection will be reviewed in this section.

Visual inspection

Visual inspection is the first inspection step where thorough examination of the weld is carried out. Much information about the result from a welding process can be obtained from an initial inspection, depending on working experience and knowledge of the examiner. Weld geometry such as weld bead height and bead size can be measured using mechanical gauges. Devices are also available to measure the depth of large undercuts that are visually detected [13].

Parts with complicated design are difficult to inspect due to tool accessibility issues. Tools like boroscopes and flexible endoscopes are available for circumstances where accessibility is a key issue. However, the vision might be altered by the equipment which must be considered [13].

Penetrant inspection

One of the simplest and most widely used inspection techniques is the liquid penetrant inspection [14]. The method is limited to detect flaws at the surface of a material [14]. Any surface defect can be detected as long as it is open and located at the surface.

As the name suggests, liquid penetrants are applied onto the material surface. The liquid dwells over a short time penetrating through defects such as cracks or cavities due to capillary action. Before penetrant liquid is applied, thorough cleaning of the material surface is important for the inspection conditions. After adequate time, the excess penetrant is wiped off from the surface while the liquid within a defect remains. On application of developer, the trapped penetrant liquid is drawn up by capillary forces. [13].
Most commonly used penetrants are red or fluorescent penetrants, but are used in different viewing conditions. While the red penetrants are visible only with good daylight conditions, the fluorescent penetrant requires a dark environment. The advantage of using fluorescent penetrant is that very small flaws can be detected which can go unnoticed if red penetrants are used [13].

Magnetic particle inspection

Magnetic particle testing method is employed when the material can be magnetized. The test material is magnetized either by electric current or by using permanent magnets thereby creating a magnetic flux.

Magnetic particles are applied onto the surface. Any presence of surface defects causes magnetic flux leakage and attracts the particles. A cluster of particles is formed in the area where flux leakage occurs thereby confirming presence of surface defect.

Defects such as cracks might be parallel or perpendicular to the surface. Therefore it is important to magnetize the material in both the directions as cracks parallel to the field can go unnoticed [13].

Eddy current inspection

The principle of eddy current testing is based on the phenomenon of electromagnetic induction, which is applicable to all electrically conductive materials [14]. This testing method is similar to magnetic particle testing, where the defects are detected due the discontinuities caused in the electromagnetic field generated.

A coil is supplied with alternating current generating an electric field. As the coil is moved closer, it induces eddy current in the material. When the coil is moved across the test material, the presence of any defect will fluctuate the impedance value [13]. Information can be taken out from the difference between the modulated impedance and the nominal impedance of the coil-equipped probe [14]. Presence of defects, physical, chemical and microstructural properties can be investigated using this method [14]. As the equipment uses induction for examination, the distance between the probe and the material have a significant effect on the eddy current response signal. Therefore a properly designed probe which always assures contact between the coil and the material must be used [14].

Eddy current inspection can be employed for examining sub-surface irregularities but only to a certain limit. As the eddy currents drop exponentially with increasing depth of the material, the technique becomes more effective close to the surface [14]. This testing method can also be used to quantify the size of defects e.g. depth of cracks by comparing the impedance values with the standard values for a known depth.[13].

Radiography inspection

Radiography testing is one of the most commonly used methods for detecting internal defects. The technique uses X-rays as a detecting medium and utilizes the property of a material's ability to absorb the medium [14]. A dense material (e.g. lead) will be able to absorb most of the radiation compared to air which lets the radiation through [14]. This is the principle used for detecting irregularities within a material e.g. cavities and cracks.

In radiographic inspection, X-rays penetrate through the test material and are captured on a film. The material absorbs a portion of the radiation while internal irregularities present absorbs less radiation. As a consequence, a shift in intensity occurs and will be stored and visually presented on the film. The screen resolution and the contrast obtained in radiography films are of high quality [13]. It is also important how the source is directed towards the material since a defect can be aligned in different directions. More a portion of a defect that lies in parallel to the source, the easier it can be detected.

Radiography is indeed a powerful NDT method to use for inspection and has the capability to penetrate through considerably thick materials. However, the method requires preparatory work and set-up activities that are time consuming. In order to reduce the processing time, advancements in the field have been made where sensitive screens are used and scanned using cameras. But this technique compromises on the resolution and contrast of the image obtained [13]. Another drawback with the method is that X-ray's are hazardous by nature and the costs of acquiring and running the equipment is high, for which industries are opting for safer testing methods e.g. eddy currents and ultrasonics.

Ultrasonic inspection

In this method, ultrasonic waves are transmitted into the material in a particular direction. The reflections from the sound waves are measured. The measurements are done using a probe and the results from reflections can be seen on a cathode ray oscilloscope. The measurements provide the amplitude data and the reflector's distance from the probe's position. Any deviation in the values obtained confirms the presence of internal defect.

Some of the important process parameters are beam angle, ultrasound frequency, transducer diameter and wave mode. Parts with complex design are hard to test using this method due to probe accessibility issues [13].

Coordinate measuring machine

This inspection technique is mainly used to verify the geometry of a fabricated part. A coordinate measuring machine (CMM) is used to carry out inspections of this characteristic.
The CMM consists of a probe to measure the geometry at different coordinates. The measured data is compared to the virtual data or the CAD data with respect to the size, shape and position of the parts and checked for any deviations [15].

Optical instruments

Due to large sizes and complex shapes of the parts manufactured, it becomes difficult to use CMMs to verify the geometry of the part. In such cases, optical measurement machines are used to perform inspection e.g. GOM.

A three dimensional scanner is used to scan the part and replicate it in the virtual environment. It is then compared with the original CAD model to check for deviations. Through color-coding, the virtual model can be visualized as to where the variations are peaking and dipping respectively. The benefit of this inspection technique is that it can be used to check whether geometrical features are within or exceeding required geometrical dimensions.

2.2 Robust design

Design and manufacturing companies are under constant pressure to increase product functionality, improve quality, reduce lead-time and costs. One approach to enhance quality of products is to manage the factors within design and manufacturing that upon variation, have an influence on the end quality [16]. There are many methodologies and practices used in variation management and this section will review the common concepts.

2.2.1 The concept of robust design

All processes within production of a component are inducing variations which affect the actual value of the product dimension. Robust design is a methodology used in early product development phases and examines how the effects of variation can be managed to secure functionality, form and assemblability [17]. The main goal is to assure that a product can be produced with reduced lead time and costs at an early phase of a project [17].

At an early product development phase, tolerances are assigned to the geometrical features of a design, so as to set the allowed variation. Tolerances must be set without jeopardizing function and form. By using a top-down approach, tolerances can be allocated at a product level and further down to components and single geometrical features. The optimized design is then verified against the intended production system by using statistical tolerance analysis [17]. At this stage, production is prepared and both adjustments to product design and production system are executed before start of full production [17].

Tolerances set the boundaries for how much variation a product can tolerate. In order to achieve robustness and control the variation, definition of locating features for assembling is essential. The principle of locating schemes is to fixate part(s) in space by locking its six degrees of freedom [17]. Consider a solid part in space defined by an orthogonal axis (X, Y, Z) shown in Figure 2.4. One system of locking the part in space is to use the 3-2-1 locating scheme, meaning that six points lock three translations (TX, TY, TZ) in the axial direction and three rotations (RX, RY, RZ) around the axes [17].

The procedure is to first select three points (A1, A2, A3) defining a plane, which locks one translation and two rotations (TZ, RX, RY). Secondly, select 2 points (B1, B2) defining a line, which locks one translation and one rotation (TX, RZ). Conclude by selecting a point (C1) to lock the final translation (TY).

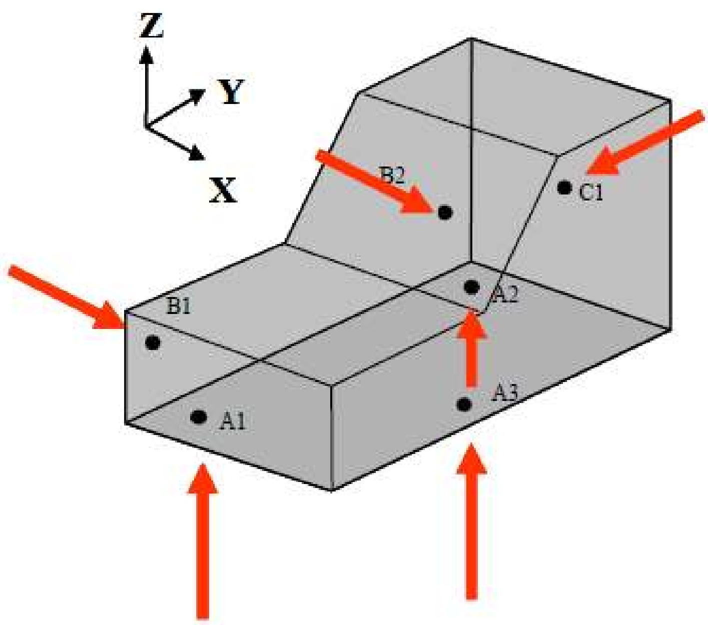

Figure 2.4: *Example of the 3-2-1 locating scheme system [17].*

Robust locating schemes helps to assure dimensional stability on individual parts. During assembly, several measurements must be kept under control between mating parts. Measures of importance between e.g. two mating surfaces are gap, flush and parallelism [18]. These parameters determine how parts are positioned relative to each other. Schematics are represented in Figure 2.5 and Figure 2.6.

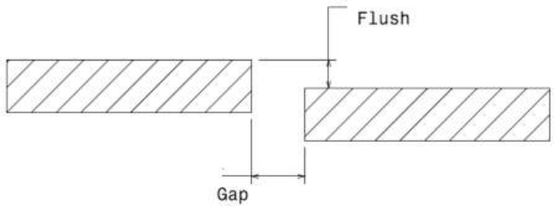

Figure 2.5: *Gap and flush between two surfaces.*

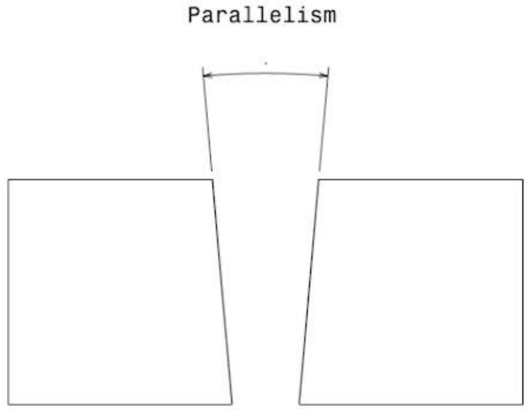

Figure 2.6: *Parallelism between two edges.*

2.2.2 Tools for robust design

There are several useful tools to support geometry assurance in design and production, such as variation simulation, contribution analysis and stability analysis [17]. Computer Aided Tolerance (CAT) software is used for these types of analysis. CAT tools are useful for conducting root cause analysis regarding dimensional variations in e.g. product assembly [18]. Through utilization of these tools, opportunities of implementing an optimized locating scheme on parts and fixtures can be provided.

Variation simulation is a statistical tool used to determine the distribution of an output (e.g. critical dimension) based on the given inputs to the part (locating schemes, tolerance range and distribution types). Specifically, this tool is used to simulate geometrical variations in critical areas of a part. Monte Carlo iterations are executed, where each input is assigned a randomly selected value within the defined tolerance limits, and a part is assembled to its mating part. Output values are assessed statistically and shows the distribution of geometrical deviations in the assembly.

Contribution analysis is a tool to determine which input parameter contribute the most to output variation. Input parameters can thus be ranked according to their individual impact on the output variation. The procedure of analysis is to vary all input parameters (one at the time) within their tolerances on a number of default levels. Maximum output from each input parameter is stored and compared to the accumulated output.

Stability analysis is a tool that evaluates the robustness of a part by analyzing the locating scheme and its influence on variation amplification and critical product dimensions. The analysis is used to assure or to find alternative ways to optimize the locating scheme (rearrange locating positions) to improve robustness.

2.3 Weld quality

Size and the amount of defects apparent in the welded part defines the quality of the joint. A defect can either be internally located or at the surface. Occurrence of defects in welded materials could be a result of imperfections in product design, manufacturing process, material properties or a combination of these.

Other important factors tied to welding conditions that influence the weld quality are e.g. joint design, weld preparation, shielding, cleanliness and weld technique [19]. Some of the common defects discussed in this section are porosities, inclusions, fusion errors, weld shape and cracks. Furthermore, geometrical distortions due to welding can also significantly affect producibility. Cracks are the most complex defect types as they develop due to metallurgical behavior and welding circumstances. A schematic representation of some common defect types are shown in Figure 2.7.

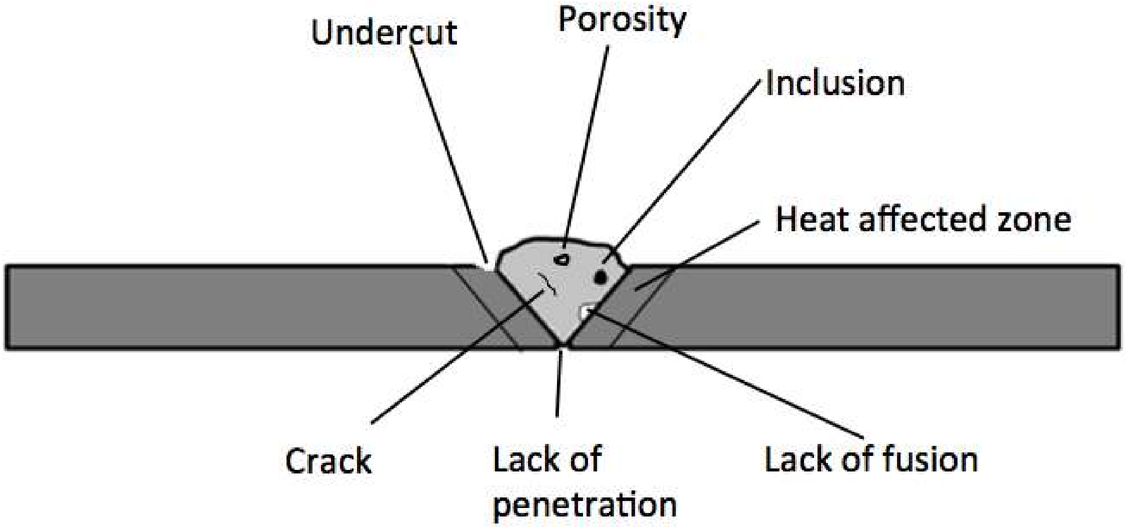

Figure 2.7: *A generalized illustration of common defect types and their appearance in a weld cross section.*

2.3.1 Porosities

Porosities are common defects that occur when gases are trapped in the melt pool during the welding process. Chemical reactions and contaminations also promote porosities [4]. By choosing the appropriate filler materials, cleaning the workpiece before the operation thoroughly, controlling the heat input rate and the welding speed, this type of defect can be reduced [4]. Pores in welds can take many sizes and shapes, i.e. from small to considerably large voids, and from spherical to elongated shapes [19]. Distribution of pores may be uniform along the weld or concentrated to specific areas such as the root and the top of the weld [19]. From a severity aspect, pores can be considered as one of the least harmful defect types. However, excessive amount of pores will have an effect on the load bearing area of the weld causing reduced static strength [19].

2.3.2 Inclusions

Inclusions are non-metallic compounds e.g. oxides that are trapped in the weld zone, causing deterioration in material properties. Oxides can be prevented by assuring proper shielding in the welding region through sufficient shielding gas supply [4]. Additionally, proper cleaning/deburring of the joint before welding is important to assure clean surfaces.

2.3.3 Weld shape

The shape of the weld profile is important, since a bad shape will affect the mechanical properties of the weld. Common discontinuities are underfill (insufficient amount of weld metal in joint), undercut (development of grooves in the weld-base material interface) and overlap (excessive amount of weld metal in joint) [4].
The shape of the pool is affected by the heat input and the welding speed [7], [20]. Temperature distributions (isotherms) calculated from Rosenthal's equations show that increasing heat inputs along with welding speed

changes the pool shape from elliptical to teardrop [7]. Figure 2.8 shows the principle of how the weld pool shape is shifted, where the dot indicates the electrode position relative to the weld pool. The higher the welding speed, the higher lag of the isotherm's geometrical center [7]. Crystal growth direction is also altered for different welding speeds and is directly related to the weld pool shape [21]. For a material with a lower thermal conductivity, this phenomenon becomes more prominent as the ability for the weld pool to dissipate heat and solidify reduces [7].

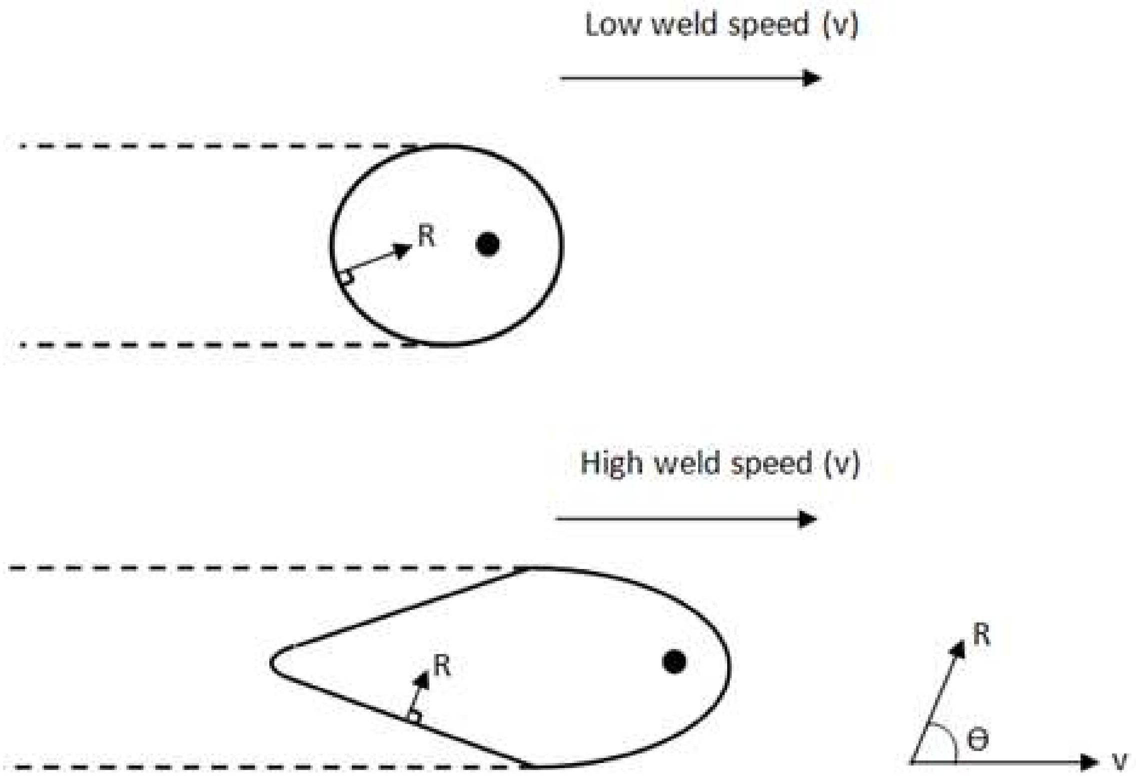

Figure 2.8: *Crystal growth direction (R) and pool shape affected by the weld speed.*

Fusion errors

Lack of fusion is a type of defect that results in bad weld beads. It is determined by the degree of fusion between the base metal and the filler material. Defects of this type are found on the sidewalls of a joint i.e. at the fusion zone. The causes of lack of fusion can be many, but generally concern joint design, heat input, welding technique and cleanliness [19]. Improper joint design or mating conditions prevent accessibility to the weld torch and should be avoided [19]. In order to melt the underlying metal through the joint, sufficient heat input is required [19]. Welding technique such as positioning of the weld torch and travel speed are influencing parameters and have to be set according to welding circumstances [19]. Additionally, thorough cleaning of mating surfaces inhibit contaminants disturbing the fusion process during welding [19].

Another way of preventing lack of fusion is preheating the workpiece prior to welding in order to reach sufficient heat levels [4]. Additionally, shielding gas supply must be sufficient and for processes in which an electrode is used, a well ground electrode is important for the process [19].

Lack of penetration is a discontinuity due to insufficient heat penetration at the welded joint. Penetration can be improved by increasing the heat input, diminishing of welding speeds and assuring proper fit between the two parts being welded [4]. However, a proper balance between affecting parameters is required in order to avoid the opposite problem: excessive penetration. In excessive penetration, excess of weld metal is present at the root side of the joint. In the worst case scenario, a weld torch can ultimately burn through the joint.

2.3.4 Residual stresses and geometrical distortions

Local heating of the workpiece during welding builds up thermal stresses that remain as residual stresses. Stresses are built up from the weld area as metal solidifies. The weld pool initially has no strength to withstand any loads, but at a distance from the heat source, stresses are built up in the area [7]. Tensile stresses grow gradually in the weld pool while compressive stresses develop at the adjacent base metal [7]. Residual stresses are normal in welding processes but should be kept within limits to avoid risks of premature failure. Undesirable amount of residual stresses can be reduced by performing stress relieving heat treatments or through non-thermal methods e.g. shot peening.

As the weld metal shrinks and thermally contracts upon solidification, the whole workpiece has the tendency to distort. Distortions can occur in longitudinal, transverse and angular directions over the weld joint [22]. Angular distortion is typically observed in welds with uneven distribution of weld metal in the top- and root-side, which causes uneven shrinkage and thermal contraction (Figure 2.9) [7]. Wide welds generally contribute to angular distortion and becomes larger with increasing joint thickness [7].

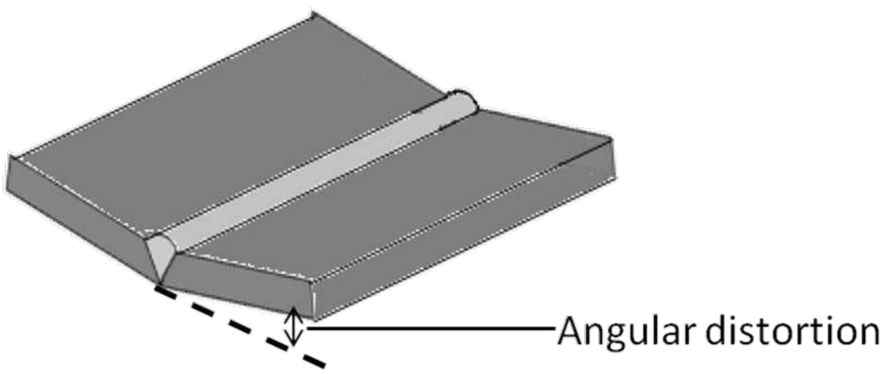

Figure 2.9: *A weld seam with uneven distribution of weld metal at the cross section creates angular distortions.*

Distortions can be reduced by minimizing the volume of weld metal in the joint. Typically, a squared butt joint design requires less amount of weld metal compared to grooved joints, see Figure 2.10 [7]. The amount of distortion in a workpiece is also dependent on the chosen weld technique, where distortion increases in the following order: EB, LBW, PAW, TIG.
Another preventing action is pre-setting, where the job is arranged according to the expected distortions. If distortions can be estimated, the mating parts can be aligned to compensate for expected displacements. In contrary, parts to be welded can be forced in positions to assure geometry. There is however a risk of buildup in stress levels which may lead to failure [22], [23].

Figure 2.10: *An illustration of weld cross sections for different joint designs: squared butt joint (left) and a grooved joint (right).*

2.3.5 Cracks

Cracks are defects that develop inside and outside the weld zone. Generally, cracks can be divided in two subcategories: hot- and cold-cracks. Hot-cracks are developed under elevated temperatures i.e. during welding, while cold-cracks are developed at near room-temperature due to residual stresses and stress concentrations. The causes for crack formation are many and sometimes interrelated [4]. Welding process parameters e.g. heat input and weld speed are set of factors that determine the development of cracks.

Examples of causes are temperature gradients promoting thermal stresses in the weld zone, variation of composition in material at the weld zone causing different contraction behavior, and the inability of two parts to contract may promote cracks [4]. Temperature gradients are generally affected by heat input and speed, whereas the latter one affects the direction of the gradients (as described through Rosenthal's equations) [7]. The direction of temperature gradients at the weld pool are of importance as it determines in which direction crystals are formed i.e. the solidification process [7]. At excessive weld speeds, the susceptibility of solidification cracking increases as the thermal strain reaches critical levels [24].

Cracks can be prevented by pre-heating the workpiece prior to welding, changing welding parameters/procedure and modifying the joint design to reduce thermal stresses due to shrinkage [4]. However, these preventive actions are of basic practice and are in reality far more complex. Determining the susceptibility of a material to crack requires deeper knowledge about the material structure and mechanisms that triggers cracking phenomena. Metallurgical behavior of superalloys are briefly reviewed in the subsequent section.

2.3.6 Metallurgy

Metallurgical behavior in welding process is a very important aspect that sets the conditions of the weld quality. Apart from material specifications, the manufacturing process used in producing a component plays a significant role for having a good weld quality.

Incoming parts to the production plant are processed using different manufacturing techniques at the supplier's end. These manufacturing activities performed set the initial material and geometrical properties. Quality of the end product is influenced by the incoming conditions of a part. The area of metallurgy is characterized by large complexity and challenges, where much resources and efforts have been invested to further build up knowledge about material behavior. However, there are still several phenomenas left to be answered. In this section, a brief introduction to metallurgical related aspects will be highlighted from weldability point of view, i.e. what are the important parameters and factors that have to be kept in mind with respect to welding activities.

Nickel-based superalloys

Hot sections of jet engines such as the Engine component, demand high performance materials for which superalloys and in particular Nickel-based superalloys have been used extensively since their introduction in the mid 20th century [25]. Superalloys are used in hot sections due to their high performance at elevated temperatures and corrosive environments. Based on the type of strengthening mechanism, these materials can be divided into three categories; precipitation, solid solution and oxide dispersion strengthened alloys [25].

Weldability of superalloys can be addressed to their susceptibility of forming cracks during welding which is of major importance for the service life of the product. There are three types of cracking phenomenon that are of high importance in the welding action. These are solidification, HAZ liquation and strain age cracking. Solidification cracking occurs in the weld, HAZ liquation cracking in the partially melted zone (PMZ) or at the HAZ [25]. Strain age cracking is a phenomenon which is specifically connected to post weld heat treatment (PWHT) processes [25].

Chemistry

Superalloys are materials that contain many elements complicating the chemical composition [25]. Due to the amount of elements present in the material, several secondary phases will be present in which all affect the alloy [25]. Impurity elements e.g. sulfur (S), phosphorous (P), and boron (B) are elements inducing hot cracks and their composition should be kept within the limits [26], [27],[20].

Carbon (C) is an element influencing the solidification stages which can be related to susceptibility of solidification cracking [25], [20]. Niobium (Nb) takes part in forming certain strengthening phases, carbides and additional phases [25]. The ratio between Nb and C are crucial for the susceptibility of solidification cracking [7]. A high ratio can significantly reduce the susceptibility by evading the low temperature liquid to austenite + Laves ($L \rightarrow \gamma + Laves$) reaction, which can extend the solidification temperature range [7]. Laves are one of many phases that are observed in nickel based superalloys and are mentioned in a subsequent section.

Phases and constituents

Phases and constituents are important properties as they determine the material structure and behavior. There exists a wide range of phases among nickel based superalloys and a draft is represented in Table 2.1. The types of phases can generally be divided into the matrix phase, precipitation strengthening phases, metal carbide phases (where M corresponds to a metallic element), detrimental phases and miscellaneous phases [28], [20]. A nickel based superalloy constitutes an austenitic phase (γ), and within that matrix, secondary phases may be present as mentioned in Table 2.1.

Table 2.1: A set of common phases found in superalloys and typical chemical formulas [28].

Phase	**Phase type**	**Typical formulas**
γ	Matrix	$Ni(Cr, Fe, Mo)$
γ'	Precipitation strengthening	$Ni_3(Al, Ti)$
γ''	Precipitation strengthening	Ni_3Nb
MC	Metal carbide	TiC, NbC
$M_{23}C_6$	Metal carbide	$Cr_{23}C_6, (Cr, Fe,)$
M_6	Metal carbide	Fe_3Mo_3C
σ	Detrimental	$FeCr, FeCrMo, CrFeMoNi, CrNiMo$
μ	Detrimental	$Co_2W_6, (Fe, Co)_7(Mo, W)_6$
$Laves$	Detrimental	$Fe_2(Nb, Ti, Mo), Co_2(Ta, Ti)$
δ	Miscellaneous	Ni_3Nb
η	Miscellaneous	Ni_3Ti

The γ' and γ'' phases are the most important precipitation strengthening phases in the nickel based superalloys [25]. The γ' and γ'' phases can transform to η and δ phases respectively if exposed to elevated temperatures for long time periods [25]. The presence of detrimental phases (σ, μ and $Laves$) in trace amounts are not of great concern, but becomes considerably important for higher amounts [28]. These phases are known to be very brittle and their presence are undesirable [25]. Phases of this character develop as a consequence of either long term service or heat treatment [25]. As explained in the previous section, the presence of reactions where $Laves$ take part has shown to aggravate solidification cracking and HAZ liquation cracking as the solidification temperature range is extended [25].
Metal carbides are present in all nickel based superalloys. The benefit of carbides is the strengthening effect at the grain boundaries, but has shown to have detrimental effects on ductility and service life [25].

Manufacturing method

Parts used in the Engine component are made out of castings, forgings and sheet metals which are later joined together. The different processing methods have an influence on the material properties which at a later stage will influence weldability. A short description of each manufacturing method is carried out to exemplify differences between them.

Parts made out of sheet forming process are characterized as components manufactured by plastically deforming sheet metals. The deformation activities have the objective to significantly alter the shape of the workpiece and keep the cross-sectional changes to a minimum [29]. However, a portion of cross-sectional change is unavoidable in the process and has to be taken into consideration [29]. The formability of a workpiece is dependent on the materials ability to undergo deformation before failure. Mechanical properties such as flow stress and anisotropy are factors of importance in processing, where anisotropy implies directional dependent physical properties [29]. Other factors guiding formability are strain-hardening and tensile ductility [30]. Hence, sheet metal forming alters the physical properties in the material which can affect subsequent processing steps such as welding.

While sheet metal is deformed through tensile stresses in forming processes, compressive loads are used in forgings to form a workpiece. Forged materials typically yield high strength as the grains deform in the shape of the part being processed, resulting in a more homogenous material [31], [28]. One of the keys for having successful forging processes in nickel-based alloys is the development of fine grain size that can be maintained in the material [31], [28]. Finer grain size is favorable for having good weld quality.

Casted materials are made out of a molten metal that is poured into a mould and upon solidification creates the final shape. The manufacturing method is flexible and in some cases, a more economically sustainable alternative for several applications. However, casting is a manufacturing method that deals with solidification which can be considered to be more complex to tame as compared to methods where materials are shaped in solid state. The solidification process that takes place during casting will result in a microstructure that determines the physical properties [32]. The amount of alloying elements present in typical nickel-based superalloys may further complicate the solidification activities. Heat treatment can be used to modify the microstructure but the outcome of this additional processing step is greatly affected by the initial microstructure developed during solidification [32].

Typical problem areas within casting of nickel based superalloys are dimensional discrepancies, inclusions, porosities and large grain sizes [28]. Castings are generally hot isostatic pressed (HIP) in order to reduce porosities and generally improve the quality of a casted component [28]. Casted components also yield larger grain sizes compared to a forged counterpart [28].

The overall conclusion regarding the choice of manufacturing method is that materials are altered differently depending on the method chosen. Physical properties will vary due to the microstructure present and will thus determine the weldability.

Heat treatment

During manufacturing activities such as casting, forging and welding, several kinds of heat treatments are performed to relieve residual stresses, hardening and homogenization [25]. For nickel-based superalloys, precipitation hardening (also called aging) is performed to achieve the high strength. Heat treatment is carried out in mainly two steps. At first, solution heat treatment to bring out the precipitation strengthening phases into the matrix, followed by additional age heat treatment(s) to precipitate the strengthening phases [25].

There are several proposals for the occurrence of cracking during heat treatment. Generally, cracking occur due to the low ductility and high strains in the HAZ [7]. There are several theories about the main reasons for low ductility in the HAZ. Embrittlement of the grain boundary caused by actions in the welding process or during the heat treatment itself are examples of possible influencing mechanisms [7]. High strains in the HAZ are typically related to welding stresses, and thermal expansion and contraction in the material [7].

Material behavior during heat treatment is diverse and so is the susceptibility of cracking. There are superalloy brands that have been designed specifically for having good immunity towards PWHT cracking e.g. Inconel 718.

2.4 Quality management

Industries employ various tools and techniques to improve the quality of their products and processes. The input data required vary for different tools and techniques. Therefore, good knowledge of the prerequisites is important in choosing the appropriate tool and technique.

Examples of the tools and techniques commonly used are Statistical Process Control (SPC), Quality Function Deployment (QFD), Failure Mode and Effect Analysis (FMEA) and the seven basic quality tools.

A tool can be defined as an application with fewer, well defined steps that are direct and relatively easy to use, while a technique has much broader scope and requires more skill and expertise to apply them. A technique can consist of different tools that could be used during one its process steps. For example, SPC is a technique while control chart is a tool used within SPC. A basic introduction to the tools and techniques will be explained in this section.

2.4.1 Statistical Process Control

SPC is a technique used for monitoring processes by analyzing their input and output data using statistical methods. This technique measures the performance of the process through the data collected, highlights the deviations prompting to take control measures [33]. Thus, it is a technique for analyzing the behavior of a production system.

The seven basic quality tools are used in process analysis and each tool interprets the data in different ways. These tools help in identifying the variations and possible root causes [34]. The seven basic tools and their uses will be explained in detail at the end of this section.

Lack of technique knowledge can lead to wrong choice of tools. Incompetency in collecting the data, their analysis and interpretation are some of the common issues faced in industries due to lack of training. Therefore training the users about the applicability of each tool is important to achieve concrete results [33].

2.4.2 Quality Function Deployment

QFD is a technique used in realizing the customer requirements by translating them into design specifications. The critical features are highlighted and the right manufacturing processes are then chosen to achieve the quality requirements [33], [35].

QFD uses four forms or matrices called Quality tables. These forms define the relationship between different functions and are used at various stages of the project. The forms used are product planning matrix, part deployment matrix, process planning matrix, and process- and quality-control matrix [36].

As a first step in product planning, House of Quality matrix (HoQ) is constructed for translating the customer requirements (Figure 2.11). It is a matrix where the relationship between the requirements and how to achieve them are derived. Upon translation to product specifications, other forms are used to realize the product [36]. QFD is time consuming process and requires all cross functional teams to participate throughout the process.

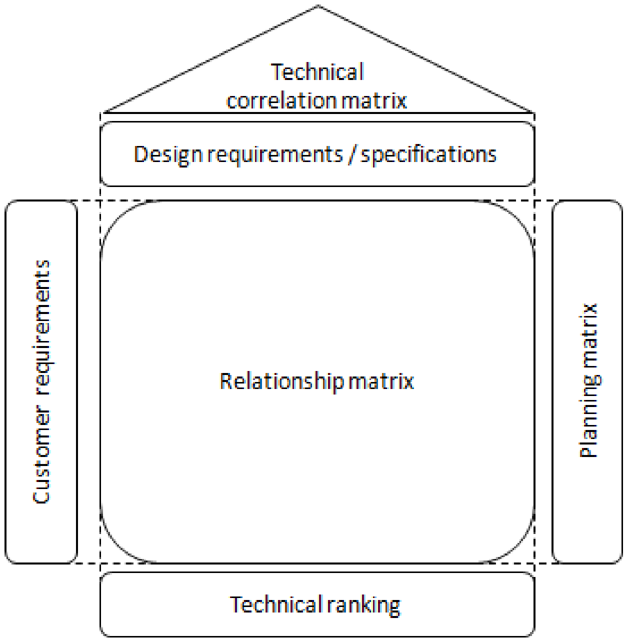

Figure 2.11: *Schematic representation of HoQ.*

2.4.3 Failure Mode and Effect Analysis

FMEA is a tool used in assessing the possible potential failures that could occur, their effects and root causes thereby allowing preventive measures to be taken in early stages. By knowing the severity, the level of risk can be estimated [37], [35].

Two most commonly performed FMEA's are Design FMEA (DFMEA) and Process FMEA (PFMEA). DFMEA is performed to identify the potential failures due to shortcomings in design and PFMEA is performed to identify the possible deviations in manufacturing process and failures that could arise from them [33].

The FMEA process consists of identifying a possible mode of failure, probability of its occurrence, its severity and probability of being detected. A risk priority number (RPN) is then calculated by multiplying these factors. This is repeated for all possible failure modes and they are prioritized based on their risk priority number [37], [35].
FMEA is a team work involving members from cross functional teams. The analysis is carried out based on experience from similar products or based on simple logic about the possible consequences. Therefore, deep knowledge about both product and process is crucial in order to have a reliable platform [33].

2.4.4 The seven basic quality tools

Basic quality tools are used for assessing and continuously improving the process quality. Each tool is unique, highlighting the issues and their possible contributors [33]. Some of the basic quality tools are Control charts, Pareto charts, Root cause analysis, Histograms, Check sheets, Flow charts and Scatter diagrams [33]. Typical appearances of quality tools are shown in Figure 2.12.

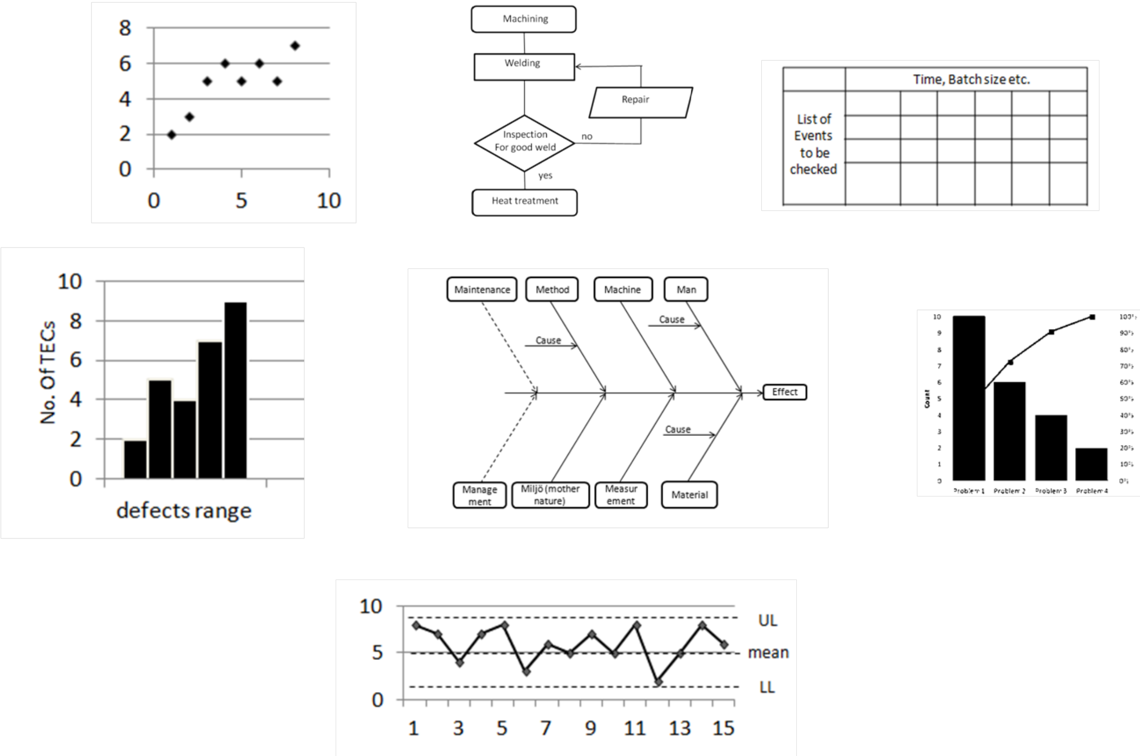

Figure 2.12: *Schematic representations of quality tools: scatter diagram (upper left), flow charts (top), check sheet (upper right), histogram (left), cause and effect diagram (middle), pareto chart (right) and control charts (bottom).*

1. Control Charts:

   A control chart is used to assess the capability of a process. It is extensively used in the statistical process to monitor the process stability by analyzing the data [38].

   The data collected is graphically represented. Through statistical methods, mean value, upper and lower control limits are determined for the process. Any deviation above or below the upper and lower limits respectively highlights instability in the process [38].

   Variable and Attribute control charts are two chart types used depending on data calculated and output required [38].

2. Check Sheets:

   A check sheet is the simplest tool for documenting and analyzing data. It consists of selecting the characteristics or events that requires monitoring. On selection, their occurrence is recorded through process observation. Improvements can then be planned by prioritizing the events based on their frequency of occurrence [38].

3. Histograms:

   A Histogram is type of bar graph used to analyze large amount of data that is hard to understand and analyze when represented in tabular form. It can be used to study the distribution of the data through which variation and possible gaps in the process can be identified [38].

4. Pareto Charts:

   Pareto charts are used to highlight and rank the causes in descending order of their occurrence. They are based on the 80/20 rule which means that 20% of the causes lead to 80% of defects [38].

They are a combination of bar and line graphs. The bar graph ranks the causes in the descending order of their occurrence from left to right, while the line graph represents the cumulative values of the causes and effects. The cumulative analysis is also known as ABC analysis where 80% of the effects are categorized in group A, 80-96% in group B and the rest in group C. The grouping helps in prioritizing the causes requiring immediate attention [38].

5. Flow charts:

   These charts are used to symbolically depict the process flow. They are used for representing the activities in sequence. Any deviation in activities or non value adding activities can be identified and eliminated. Mostly used in representing manufacturing process flow, steps such as operation, transport, delay, storage and inspection are symbolically represented [38].

6. Scatter Diagram:

   These diagrams are used to determine the relationship between two factors or events whether it is linear or non-linear. They are generally used before regression analysis and after cause and effect analysis in determining if there are any possible correlations between causes. However, this tool cannot be used to relate causes and effects [38].

7. Cause and effect diagram:

   Most commonly known as Ishikawa diagram. It is used in identifying potential root causes for a certain type of effect. It is also called a fishbone diagram due to its representation in the form of a fishbone skeleton [38], [35].

   When represented in the form of fishbone, the head of the fishbone consists of the effect to be analyzed and the bones and their sub branches consist of possible causes [38], [35].

   There are different types of fish bone diagrams based on the classification of the main branches. The most commonly used type is the 6Ms fishbone. The main branches are Machine, Method, Material, Measurement, Man power and Mother nature- environment [38]. In some cases, two additional branches Maintenance and Management are used.

   It is often a group activity where members from cross functional teams contribute to the process.

3 Method

The problem and the scope of the project were vast, for which a structured and logical approach was employed. Initially, efforts were put in collecting information and contacting key-people at the company to extract useful information. A schematic of the procedure followed in the project is illustrated in Figure 3.1.

The complexity of the problem required a thorough literature study about several topics within manufacturing processes and weld defects to better understand the case. Additional topics such as robust design and quality management were also studied to understand how assembly and quality issues are ought to be handled. This served as a basis for the whole project and was required to have at hand when further examining the product and the production at GKN Aerospace. All information gathered throughout the project was used for mapping the quality related parameters. This map is supposed to serve as a foundation for examining specific weld joints on a product. Upon examination, the aim is to be able to determine quality risks and make estimations of the quality outcome with the help of production data (e.g. expected amount of defects). Case studies were carried out to verify and validate the map. The approach and its individual steps are deeper described in subsequent sections.

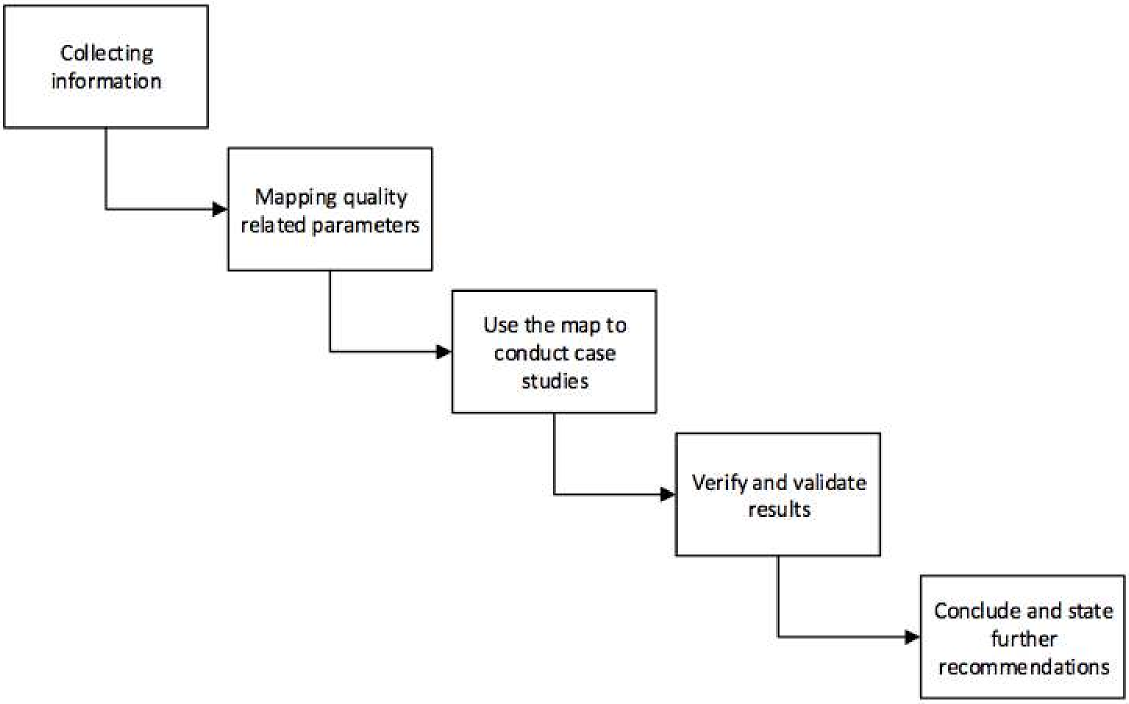

Figure 3.1: *Schematic representation of the approach followed in the project.*

3.1 Collecting information

To deeper understand the complexity and the challenges of the problem, the initial activities consisted of collecting information from several sources. Information was collected through literature reviews, both scientific and internal documents. Interviews with key-people were held at the company to capture their experience and knowledge. Engineers from several areas ranging from design to material and manufacturing were interviewed on a regular basis. Observations through walkthroughs in the production plant were also a source of interpreting the problem. The initial activities at the start of the project gave a base for understanding the products, processes and the current scenario regarding weld quality.

3.1.1 Literature review

Initially in the project, literature studies were conducted to acquire knowledge about mainly manufacturing processes, weld quality and robust design. Internal documents at GKN Aerospace were reviewed and used to understand more about the Engine component and the present state of development. In addition, documents and reports from previous projects regarding the Engine component were reviewed and some information was re-used. Access to databases of the Engine component production was also granted and quality issues could be studied to some extent. Before data could be studied, the content had to be elaborated and rearranged to get a better view of the production situation.

3.1.2 Interviews

Information collection was carried out through meetings with key-people at the company, ranging from design to manufacturing engineers. Several people essaying the same roles in different Engine component projects were interviewed to cover a broader scope. The interviews were of unstructured character in the initial phase with open questions which to some extent resulted in non specific answers. This was necessary in order to create a network of different competencies and to get a hint of different roles present in the company. As the project progressed, meetings regarding specific topics for discussion were carried out. The purpose of these meetings was to understand how each individual perceived the problem. Thus, this activity became a medium to share knowledge and experience.

3.1.3 Observations

Major information collection was done through individual observations, mainly in the production facilities. Several walkthroughs of operations and processes were not only beneficial for self experience, but also gave opportunities to extract information from operators. It proved useful as many had longtime experience and held useful information about how the production has evolved. Visits to welding and inspection stations were prioritized as these operations were considered to be of most importance. Thus, an insight of the working conditions and habits could be studied and reflected. The observations from the walkthroughs were either used as direct content in the mapping of quality related parameters or as complimentary information.

3.2 Mapping quality related parameters

Information and knowledge gathered from activities in the previous phase were systematized and structured in terms of factors and parameters influencing weld quality. Here, factors can be considered to be non-quantifiable and parameters quantifiable. The defined parameters covered both product and production aspects of the Engine component. Individual contribution of the defined factors and parameters were of interest in order to decompose weld quality into several areas. This was necessary since weld quality is determined through the types of defects present in the component.

There are several alternative strategies to assess factors and parameters, for which root-cause diagram is a commonly used tool in manufacturing industries. The benefits of this type of assessment is that a problem can easily be visualized and systematically arranged in different categories making it comprehensive to grasp. However, the complexity of weld quality does not only concern one specific defect type but many defect types leading to component failure. Additionally, a parameter or a factor may not necessarily be related to a specific defect type, but to several defect types. Thus, further complicating the ability to map parameters in a comprehensive manner.

An alternative interpretation of the root-cause diagram was created where the main problem was defined as weld defects, which was further branched into different types of defects. Factors of relevance (causes) were arranged in each defect branch. A quasi diagram, describing the structure of the alternative root-cause diagram is shown in Figure 3.2. The left side shows the typical classifications of possible root causes that originates from the 6M's: Man, Machine, Measurement, Mother nature (Environment), Method and Material. Here, all possible contributors to weld defects are addressed irrespective of defect type. On the right side of the map, weld defects are decomposed into different types of defects, for which the parameters and factors of relevance are addressed based on the 6M's. Through this representation, an overview of influencing parameters is shown and its relation to a certain defect type is defined. Efforts have been made to keep the map generic i.e. independent of specific design features, manufacturing methods and other resources making the content applicable for any Engine component product.

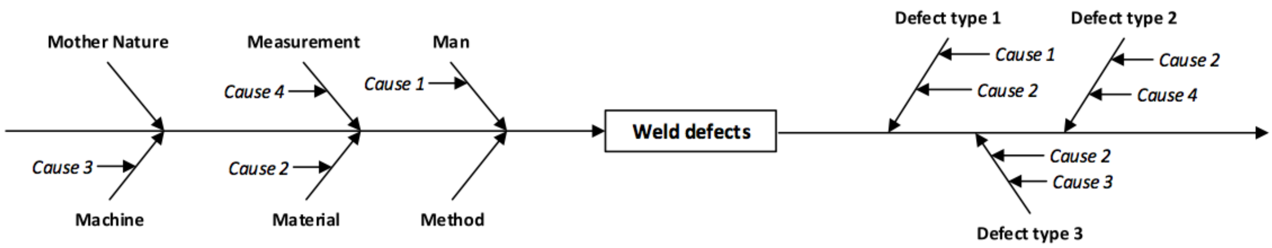

Figure 3.2: *Example of the quasi diagram, showing all influencing parameters (i.e. causes) within different classes, and for which defect type these apply.*

The purpose of mapping the influencing parameters is to use it in problem solving e.g. investigating a certain weld joint in the Engine component or on the contrary, investigating a certain defect type that occurs in production. Thus, providing the examiner a classification system for investigating the quality risks on a given weld joint and additional conditions/circumstances. The map ultimately sets the boundaries for which experiments and analysis should be carried out and studied by the examiner to have clarity on the relations between causes and defects.

Alternative ways of creating the map were explored in parallel over time, e.g. by expressing the situation through fault tree analysis (FTA), however due to the complexity and size of the problem, all the information could not be accommodated through this approach. The idea was to have the map systematized and stored in a neutral format that could be applicable to all the existing and future projects. Neutral in a sense that the content and the hierarchy could be changed over time and new information could be stored. Irrespective of format, having all the influencing factors/parameters and corresponding relations systematized was the main target during this phase for which the chosen approach was preferred.

3.3 Use the map to conduct case studies

As explained in the previous section, the idea of having a map was to be able to apply it on any given weld joint of an Engine component (see Figure 3.3 as an example). It should then be possible to identify parameters and factors of relevance to be elaborated with. This is used in identification of possible risks for the weld joint being assessed.

As probable risks are identified, the task is to quantify the risks. This is where the complexity arises for the problem. Some parameters might be deterministic and can be predicted, but several factors are hard to estimate for given conditions. In fact, several areas are still not fully understood or investigated due to the complexity within that particular area. Additionally, factors within e.g. environmental and human aspects are inducing variation to the process, thus affecting the outcome.

The analysis of a case study is thus dependent on rich input and output data (within design and production) in order to be able to draw relationships between factors and parameters. It may be possible to create relations of set of parameters but to a limited extent, which requires all other parameters to be frozen into nominal conditions.

One way of determining the weld quality outcome was to study statistics and history collected from previous produced Engine components. Experimental data from e.g. DOE were also considered to feed information into the model (based on the root-cause diagram). The created map was applied on number of case studies and are described to some extent in the subsequent sections (detailed descriptions are confidential and cannot be published in this report due to secrecy).

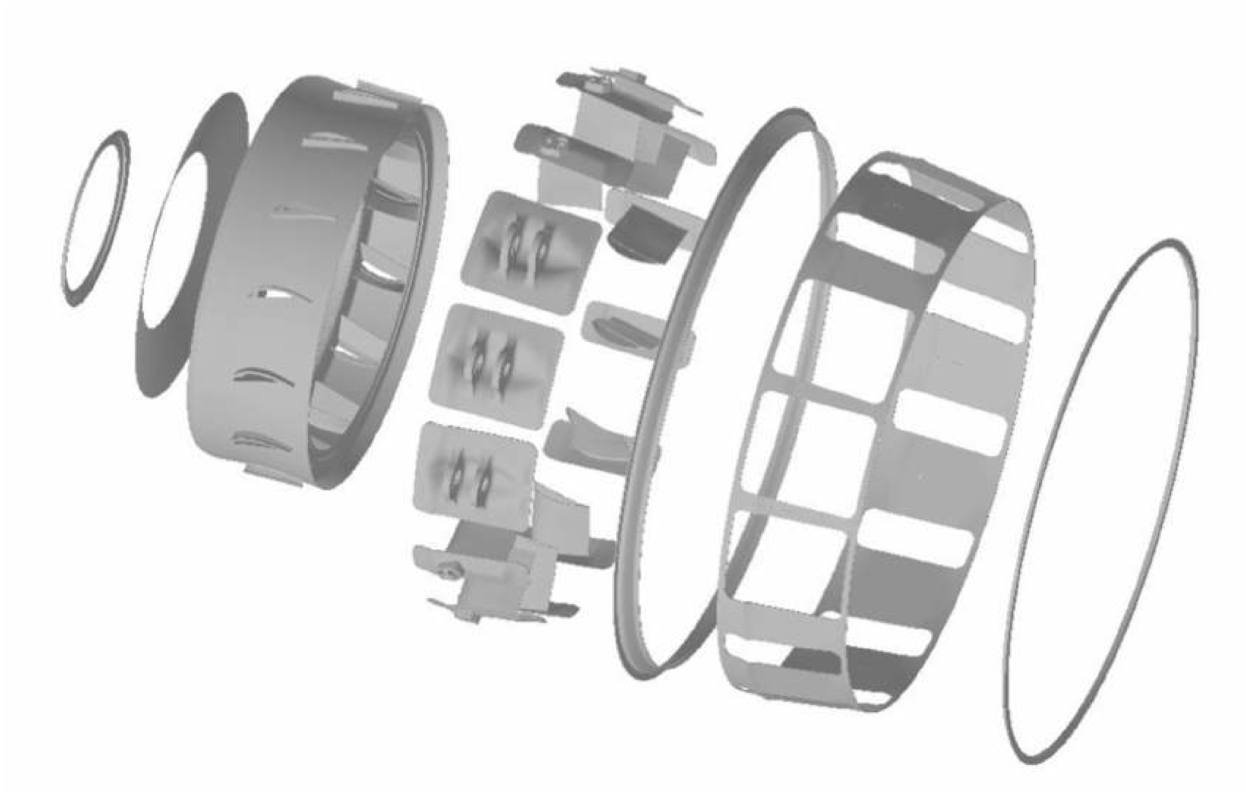

Figure 3.3: *An example of an Engine component product in exploded view showing a set of joint interfaces.*

3.3.1 Case study I

A circumferential weld on the Engine component was chosen for a case study. The joint is located towards the hub at the front of the Engine component (see Appendix A for full description of weld joints). Material type is the same apart from the manufacturing method between the mating parts. Welding is performed both manual (TACK-welding) and robotic. Aligning the mating parts in the TACK-welding sequence is performed through "best fit" practice. "Best fit" meaning that operators have to align the parts sufficiently well. Parts are being weld prepared (i.e. machined) before the assembly operation. Along the weld path there are several intersecting joints present, i.e. welds done in a previous step. Intersecting joints in the weld path are anomalies that must be considered from a welding point of view.

These are some of the conditions for the weld which are necessary to be aware of when exploring the map. Relevant factors and parameters are to be checked and assessed in order to identify possible risks and draw assumptions of expected quality outcome.

3.3.2 Case study II

The vane weld is a closed joint and is illustrated in Figure 3.4. Material type is again different with respect to manufacturing method between mating parts. There are several types of vanes available and must be considered individually. Target systems are available for the hub, but the vane is aligned through "best fit" practice. Before joining, the parts are being weld prepared. Parts are first aligned through TACK-welding before undergoing robotic welding.

Figure 3.4: *Schematic picture of a vane (left) and the corresponding cross-section (right).*

3.3.3 Case study III

Axial welds at the outer case are characterized for being straight i.e. no closed joints. Its a squared butt joint and the material configurations are differing among members with respect to the manufacturing method. Target systems are available for outer cases. Part are weld prepared and once TACK-welding is completed, robotic welding is used.

The findings from these case studies are presented in Section 4.3, 4.4 and 4.5.

3.4 Verify and validate results

The objective of conducting case studies was to check the relevancy of quality related parameters and factors. To verify this, available data and documents of weld quality were examined to assure proper connections between the proposed factors and parameters, and the actual weld quality outcome. Additionally, the map was handed out to key-people at the company in order to have feedback and further strengthen its validity.

3.5 Conclude and state further recommendations

Before closing the project, emphasis was put to document the findings in a comprehensive way. The area of weld quality is vast and still have several gaps and unknown factors. Thus, it becomes important to have a map that is possible to continuously develop. Exploring weld quality issues can then become a progressive process where the available foundation can be enhanced by filling up the gaps through experiments and improved documentation of weld quality issues.

At this stage of the project, gaps and missing links that hinders the possibility of making accurate estimations of future weld quality outcome were captured. Additionally, reflecting upon the chosen mapping method and how it could be further enhanced was also considered at the end of the project.

4 Result

In this section, the results from activities carried out are presented in brief (detailed descriptions are confidential and cannot be published in this report due to secrecy). Literature reviews documented in Section 2 are used in creating the map. In addition to scientific literature, inputs from employees at the company and documentation of quality within production have been re-used in the quality parameter assessment.

4.1 Analysis of weld quality in production

As a part of the production process walkthrough, documentations of quality in welds were analyzed for an Engine component program (referred as Engine component Project A). Defects observed in every inspection station have been stored and quantified with respect to size, location (both along the joint path and at which area, e.g. weld, HAZ, unaffected area) and for which specific weld it was observed. Pareto charts were made to address the frequency of defects and their cumulative percentages for the complete Engine component, the individual joints and the defect types. A normalized diagram for the complete Engine component is presented in Figure 4.1 and shows the occurrence of defects in decreasing order (The cumulative percentages are represented in table form for individual joints in Appendix B). Several unique defects that seldom occur have been observed but are left out in the analysis.

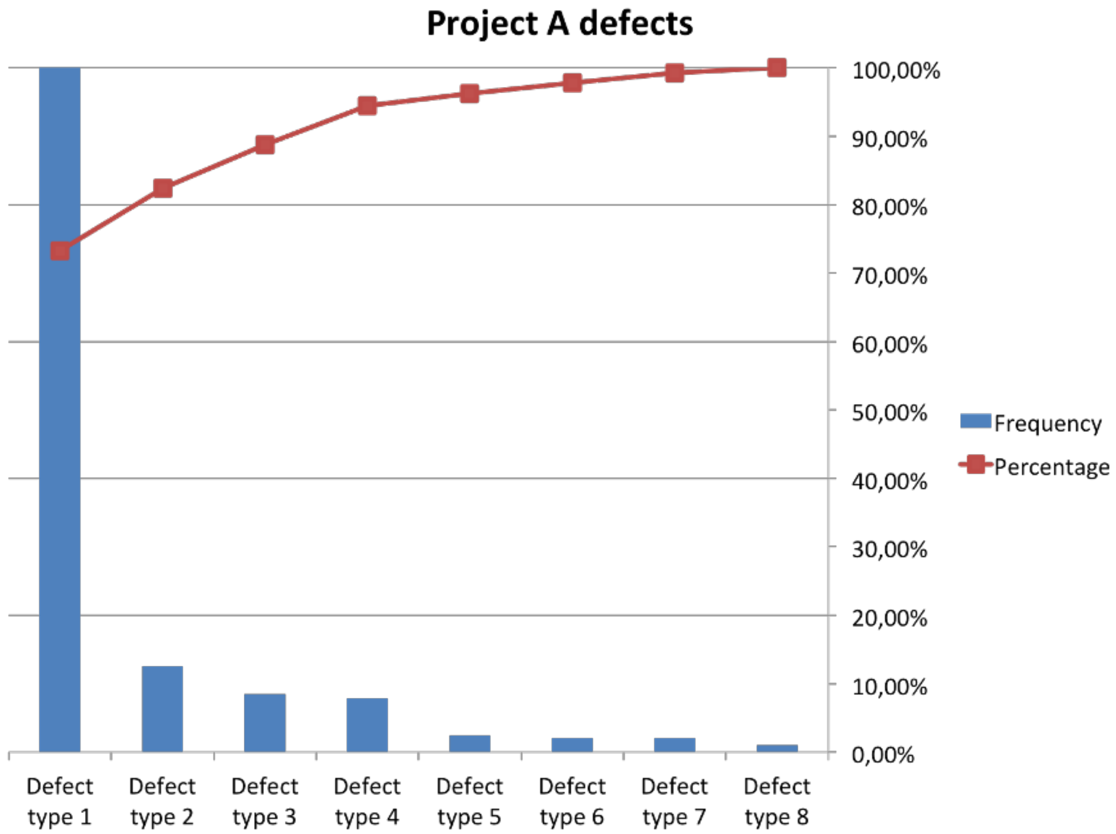

Figure 4.1: *Occurrence of defects for Engine component project A.*

The diagram shows that type 1 defects are in general the primary defect type observed in production (73,28 %). Type 2 defects can directly be addressed to defects originating back to supplier's end.

Type 1 and type 4 defects are mainly found in the weld joints associated to the vane. These joints are challenging in production as geometrical complexity combined with tough project requirements have a significant influence. Work operations through manual welding have been employed to complete the joint. From a welding point of view this is not optimal as additional heat affection in the material is introduced, which increases the susceptibility of having defects.

Type 1 defects are also found in another joint towards the front side of the Engine component. Through discussions with manufacturing engineers it has been concluded that this joint is a challenge since the part welded is non-rigid and the aligning method is relying on "best fit" practice. The joint also intersects axial welds performed in previous steps. Intersecting joints are not optimal for welding as the areas are exposed to additional heat affection which increases the risks of having defects.

In subsequent heat treatment operations, defects in general can possibly develop or propagate.
In general, type 1 defects can occur in all types of weld joints and is the most common defect type observed. It is however normal in the process as a majority of type 1 defects are created due to metallurgical factors i.e. material behavior during welding. The use of certain material types for a majority of parts in this Engine component project is typically addressed as a big contributor to promotion of type 1 defects. An example of a relative comparison between different material types with respect to manufacturing method can be seen on joint 5. This weld consists of three different material configurations of mating parts: Config A, Config B and Config C. The distribution of type 1 defects between different configurations are represented in Figure 4.2. The charts shows that a certain configuration (Config A) have a bigger influence on the defect type present.

Type 3 defects are anomalies that have been observed mostly at the weld joints of the vane. From observations, it was clear that this defect type was more evident towards the root-side of the weld. This, due to complex geometry which inhibits the robot welding capability. Similar to type 1 defects, type 3 defects pattern is repeated for different material configurations, see Figure 4.3.

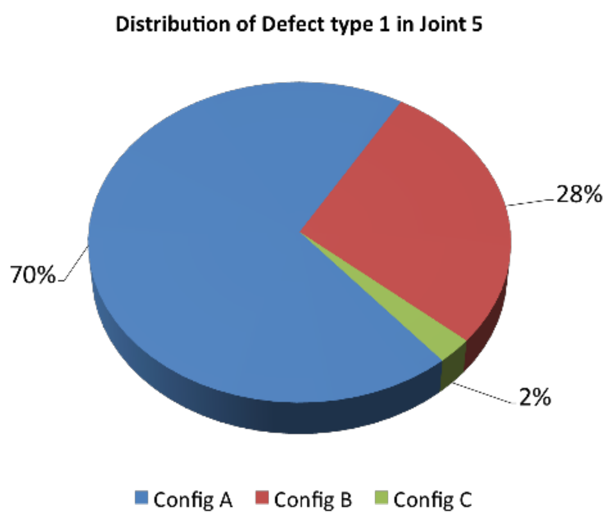

Figure 4.2: *Distribution of defect type 1 among different material configurations.*

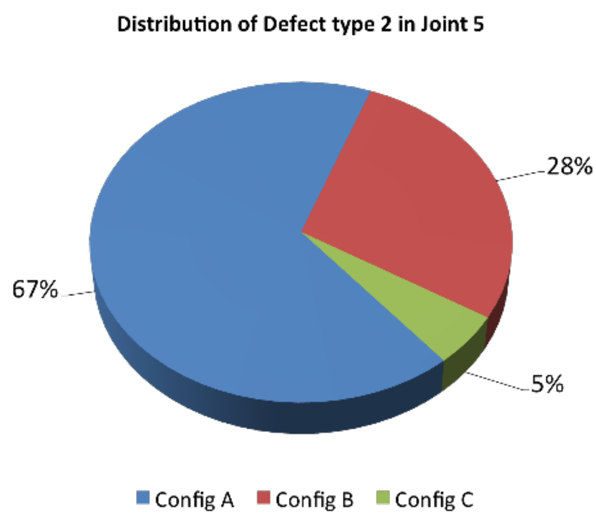

Figure 4.3: *Distribution of defect type 4 among different material configurations.*

Type 6 defect have been found in welds where at least one of the mated parts is fabricated through a certain manufacturing method (applies for Config A and Config B). Joints at a sector level are again susceptible for this type of defect. Thicker sections of the Engine component have been found to be less susceptible of having these defect types (but are however joined with alternative welding methods). The occurrence of type 6 defects is very few compared to type 1 defects and have been observed in very few occasions in the production. These are not concentrated to a specific timeline of the Engine component production phase, but are rather distributed.

Type 7 defects have been observed to be approximately the same in number as type 6 defects. These are typically found in welds in the sector assembly and in welds between sector assemblies. Welds are performed at the same station and with the same weld method. Through discussions with welding experts it has been concluded that the weld method is challenging to employ on superalloys with respect to occurrence of type 7 defects. The very root-cause for this issue is unknown or not fully investigated, but the problem is said to be not as crucial when alternative welding methods is used.

Type 9 defects (not represented in Figure 4.1) are recorded to some extent in production. After weld preparation, critical features are measured and reported in KPS. Through discussions with machining operators it has been confirmed that operations are in general stable regarding dimensional tolerances for individual parts. However, weld preparations at sector or a complete Engine component stage are prone to type 9 defects due to welding actions.

In sector assembly, type 9 defects arise which affect subsequent assembly operations. GOM inspections have been used for a number of sectors to evaluate the behavior in this area. Investigations have shown that the sector tends to bend towards a determined direction. In the following assembly operations, the defect type inhibit proper alignment in the fixture.

As sectors are joined together during the Engine component assembly, alignment between interfaces is not assured by the fixture. The welder has to make manual adjustments through bending (cold forming). Fixture practice is however systematic in terms of how sectors are aligned relative one another. Upon robotic welding, sectors tend to shrink in a determined direction. The fixture allows movement in this specific direction to a certain extent during the operation. Eventual type 9 defects from this operation are affecting subsequent operations where additional components are assembled. As a consequence, these subsequent operations become more difficult to execute.

4.1.1 Comparison among other Engine component projects

Production data from another Engine component program (Project B) was examined. On analysis, the data revealed that type 1 defects are the most recurring defect type observed in production. Deeper analysis could not be conducted as electronically stored data did not reveal the specific positions of specific defect types.

Similar approach to the problem was employed in 2013 in another project [39]. The findings in the work were similar to the trends observed in the Engine component project A. Type 1 defects were the dominant defect types observed in Engine component project B. Joints in the sector were found to be critical due to complex geometry and process incapability [39]. Similar material type is used in project B as project A, indicating the influence of materials.

Other Engine component programs (Project C and Project D) were considered for comparison. However, deeper analysis could not be conducted as these projects were in their early phase. FMEA had been conducted based on the few products that were produced at that stage. It revealed that the joints in the sector assembly were critical joint due to similar reasons already addressed.

On comparing the projects, it can be confirmed that the issues faced in producing the products are very similar in nature. These results from observations and comparison further strengthen the purpose of considering the parameters and factors listed in the map.

4.2 Map of quality related parameters

Through information collection from different sources, factors and parameters have been allocated through a hierarchy similarly as suggested in Section 3.2. A modification from the common 6M classification has been employed. The class "Measurement" has been replaced by "Design Parameters" and the other classes have been maintained.

Weld defects of relevance that have been captured through observations and documentation in production (reviewed in Section 4.1) have been categorized similar to previously mentioned defect types. An additional class that is not specifically a weld defect type but a consequence of the welding action is geometrical distortion. In total, six classes of defect types are defined in the map.

Design Parameters comprises the parameters related to geometrical features that are critical on a component to be welded. Apart from specific geometrical factors on a component, robust design aspects are covered i.e. type of reference system employed and allowed tolerances at weld interfaces (gap, flush, parallelism).

Method is a class that highlights factors that are incorporated in the working procedure. How fixture practice is carried out and corresponding restraint are examples of method aspects which influence the weld quality. Additionally, in what order joints are being welded together are of importance typically for the final assembly.

Joints are prepared through machining before undergoing welding. The process parameters employed are applicable for all joints and directly influence the quality outcome. Apart from mentioned processes, heat treatment cycles are also included as defects develop in the furnace.

Environmental factors causing weld failure are typically contaminations present in the weld area. Cleanliness is considered for the equipment, components, filler materials and the surroundings.

Man comprises the human factors that becomes apparent in manual working operations e.g. TACK welding. Any deviations from certain standards caused by man should also be considered.
Operators are also different from one another in terms of accuracy etcetera, which is a source of variation that has to be addressed.

Material consist of the parameters and factors related to chemistry and manufacturing methods of a part. Important elements that should be kept within limits are addressed and the manufacturing methods determines e.g. grain sizes and phases/constituents present in the material matrix. Material specifications can also be different when comparing specifications delivered by the customer and what the supplier is able to deliver.

The map of influencing parameters comes with an attachment referred as guidelines. It is a document where each factor and parameter and its relevance is described in detail. Guidelines thus becomes a source where important information is stored e.g. best practices. Through the document, the user will become aware of possible risks when considering parameters and factors from the map. The map and guidelines are attached in Appendix C and Appendix D respectively.

4.3 Case study I

When studying the circumferential weld, several aspects can be localized in the map provided in Appendix C.

Due to the relative simple joint geometry and weld path, several design aspects are left out. What can be observed is that there are still several parameters remaining and the possibilities for having defects are still many. Production history has shown that this joint is susceptible of having type 1 defects.

The circumstances during welding have shown to be very dependent on human factors. This is due to the limited ability to align the mating parts in a predefined way. Upon aligning, the roundness of the mating parts are measured using a probe. Then it is up to the operator to make the best possible alignment i.e. employing "best fit" practice. The joint is also considerably thin, thus being non-rigid, making alignment even more challenging. Furthermore, local work hardening of areas at the hub has to be performed, which adds stresses into the component.

Studies of documented defects in production show that approximately 30 % of type 1 defects are found at intersection between the circumferential weld and the axial weld. This is of significance as the intersections are small areas compared to the entire circumferential weld. The remaining percentage is distributed in other areas of the circumferential weld. Type 1 defects generally appear on the surface at the heat affected (HAZ) region. It is also observed that several type 1 defects develop during the heat treatment process, which could possibly be due to an uneven cooling rate.

Through historical data, it can be seen that the amount of defects in the weld is fluctuating. Trends are thus not predictable but comprising variance.

4.4 Case study II

This weld is one of the first welds performed in the production sequence. Most parameters and factors from the map applies to this joint. Geometry of the part is one of the aspects hindering the robot from performing the weld in a single pass. Manual welding is performed in addition to complete the joint.

The weld has shown to be susceptible to type 1 defects, similar to the previous case study. Type 1 defects are exclusively detected at edges. A majority of all documented defects in the weld are type 1 defects. Type 1 defects are equally distributed over the weld and the HAZ area. Type 4 defects are occasionally observed defects and are generally found at one of the edges.

As mentioned, the geometrical aspects inhibit the welding robot from performing the optimal process (i.e. single pass). Additional welding operations raise the risks of having type 1 defects as the material undergoes several heat affection cycles. Achieving good root-sides at the edge is difficult due to geometry.

4.5 Case study III

Major defect types observed during inspection are type 1 defects and are found both in weld and HAZ. Due to shrinkages, stresses are expected to build up between sectors. Sectors are though able to move in the fixture to some extent, compensating for shrinkage effects.

Secondly most common defect is type 4 defects. Material type, thickness and the welding procedure are possible factors influencing the recurrence of this defect type.

Type 7 defects have previously been a common issue for axial welds. According to welding experts, the welding technology in combination with the material type tend to develop type 7 defects at certain positions. The issue has however been solved to certain extent in present time.

4.6 Comments on the case studies

The map together with attached guidelines are highlighting the important aspects that have to be considered. Though case studies are very different in design, the map can be utilized for each case as long as elementary knowledge about the joints are known.
The number of parameters and factors present in each case study inhibit the ability of making reliable predictions of the quality outcome. Even for the simplest joint type, the relevant parameters and factors are many. Joints cannot be compared due to dissimilarities between them. However, type 1 defects are present and stand for a majority of all errors observed in a component irrespective of weld joints. Available statistics are also limited in terms of amount of data and degree of consistency. To conclude, making predictions of the weld quality outcome will not be possible to perform accurately at a present stage. An example of the approach when examining a case study is given in Appendix E.

5 Discussion

The purpose of this project was to create a map of factors and parameters that influenced weld quality of a product. A map was initially created based on information gathered from literature reviews, observations, interviews and walkthroughs. In parallel, production data was obtained from one Engine component project. The plan was to make use of recorded defects in production and statistically predict or estimate the quality outcome. This step proved to be challenging as the amount of parameters and factors were many and in some occasions hard to quantify (e.g. human related factors).

In the early phase of the project, general weld quality was studied and systematized in the form of fishbone diagram. Weld quality could be decomposed into defect types and an additional consequence related to welding (i.e. geometrical distortions) was also added. The content in the map was considered to be reliable as factors and parameters were carefully chosen. Understanding of individual parameters and their influence were of importance to strengthen its relevance. Therefore, all parameters included in the map are based on a scientific ground. Relevance of the content could to some extent be confirmed by performing interviews and walkthroughs at the company.

The map underwent several changes along the project as new information and knowledge were obtained. Quality records in production from one Engine component project were used to determine which defect types were most common and recurring. Additional documents studied were quality records from two projects and FMEA documents from another two projects. The studies revealed that Engine component projects to some extent shared the same challenges in the area of weld quality (see Appendix F for internal references). At the same time, the differences between different Engine component programs in terms of design and production was of significance but comparisons were not possible to conduct.

It was difficult to utilize the current data in order to perform accurate estimations of the weld quality outcome. The amount of factors and parameters present limited the ability to draw solid conclusions. Quality records could however provide hints about factors or parameters of significance. Discussions with key people at the company were performed to clarify such findings. Data had to be considered cautiously since continuous improvement projects have been carried out which changed the trends in quality outcome.

To recapture the scientific questions stated in Section 1.2, these are recited in this section along with comments.

1. *How can the relations between different design, product, process parameters and the quality of welds be represented?*

Relations between different parameters and weld quality has been represented in the form of a map. The idea was to have a representation that showed the relations and help understanding the complexity of the problem, both at the same time.

A map in the form of a fishbone structure has been created to hierarchically represent the relation between weld quality and various parameters and factors. The map is able to highlight the different design, product and process parameters and their connection to weld quality. By representing the map through a fishbone structure, the benefits are that parameters can be systematized and visually comprehensive to read.

A modification of the diagram was though necessary to be done as weld quality comprises several defect types. Therefore, the information in the map has been structured in two ways. In first, parameters have been grouped under machine, method, man, material, mother nature and design as main categories. In second, the parameters have been grouped under defect types as main categories. This arrangement helps in exploring a certain defect type.

2. *How can this representation be generic i.e. applicable for several projects within the Engine component-platform?*

The map was structured in a way that it could be independent of the product type. There are significant differences between Engine component projects when it comes to design and process aspects. All parameters and factors represented in the map are thus not necessarily applicable for any Engine component project. Some parameters might be irrelevant for a certain Engine component for which it can be ruled out. Basic knowledge of an Engine component regarding its design and production method is important to have at hand in order to tailor the content in the map for the specific product. Therefore, the map can be considered to be generic and applicable to any given Engine component.

3. *How can new information or data as more knowledge and experience are obtained?*

The generic format of the map allows alteration of the content at any level within the hierarchy. In future, new parameters and factors of importance will most likely occur and have to be added. Also, It will be possible to eliminate factors and parameters if found to be irrelevant or of minor importance. Already during the project, the map has been evolving continuously as for keeping it up to date and according to present knowledge.

4. *How will the representation help in identifying where there is a lack of knowledge or understanding on how to achieve good weld quality?*

Identifying gaps and missing links is important as to be able to enhance the present platform. Through the mapping approach, it has been possible to identify factors and parameters influencing quality, relate these to some extent. However, there are still some uncertainties of how factors and parameters are relating. Additionally, how big is the impact from different parameters and factors are yet to be fully discovered.

In a subsequent section, proposals as for how to deal with present uncertainties are given. The proposals aim to bridge the gaps and strengthen the knowledge about how influencing factors and parameters relate to each other.

6 Recommendations

As discussed in the earlier sections, knowledge gaps have been identified through the mapping process. In order to address the gaps, it is important to have a clear understanding of each parameter's contribution and their relation with other parameters.

Therefore, it is recommended to rank the defects based on their occurrence. Using the map, the most influencing parameters should be listed and their individual contribution should be assessed through DOE. This will help in establishing definite relationships between parameters and refine the map. This procedure should be carried out for all the parameters in order to identify and bridge the gaps. Though time consuming, this procedure is beneficial from a long term perspective.

Today, production documentation differs amongst projects. The data required for analysis is either unclear or unavailable. Therefore, it is recommended to standardize and improve documentation practices in production. The map will help in identifying the factors that need attention during production and that should be made part of documentation. Standardization of documentation procedure among projects will help in easy follow up and comparison of projects.

Though there are many trial and error experiments conducted at present, the information remains within the project group. This information should then be documented as standard practices and shared with other project teams. It creates awareness about the problems faced and corrective actions taken. It prevents similar errors being repeated in other projects. One way to share information could be to set up a database.

The parameters and defects in the map should be listed in the database. The possible relationships highlighted in the map should be recreated in the database making it a relational database. An example of how such a database can be designed is illustrated in Figure 6.1.

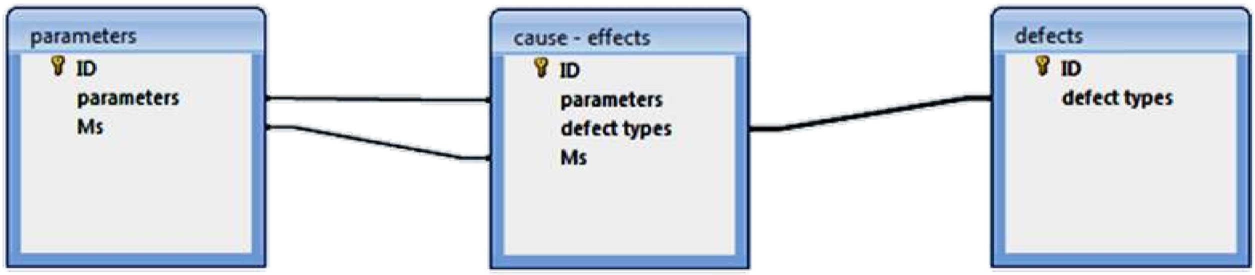

Figure 6.1: *A relational database (center) tying parameters (left) to defect types (right).*

The parameters could then be linked to the guidelines. These guidelines will explain each parameter and their limits. This will be supported by the standard documents or practices developed at the company.

Learnings from various projects should be documented and made part of the database. These documents will educate users about difficulties faced and measures taken to overcome the issues. This will create awareness among the users preventing similar mistakes being repeated. Additionally, it will also be a support document to the guidelines as it will reveal possible consequences if deviated from the guidelines. An illustration of how information flow could be carried out is shown in Figure 6.2.

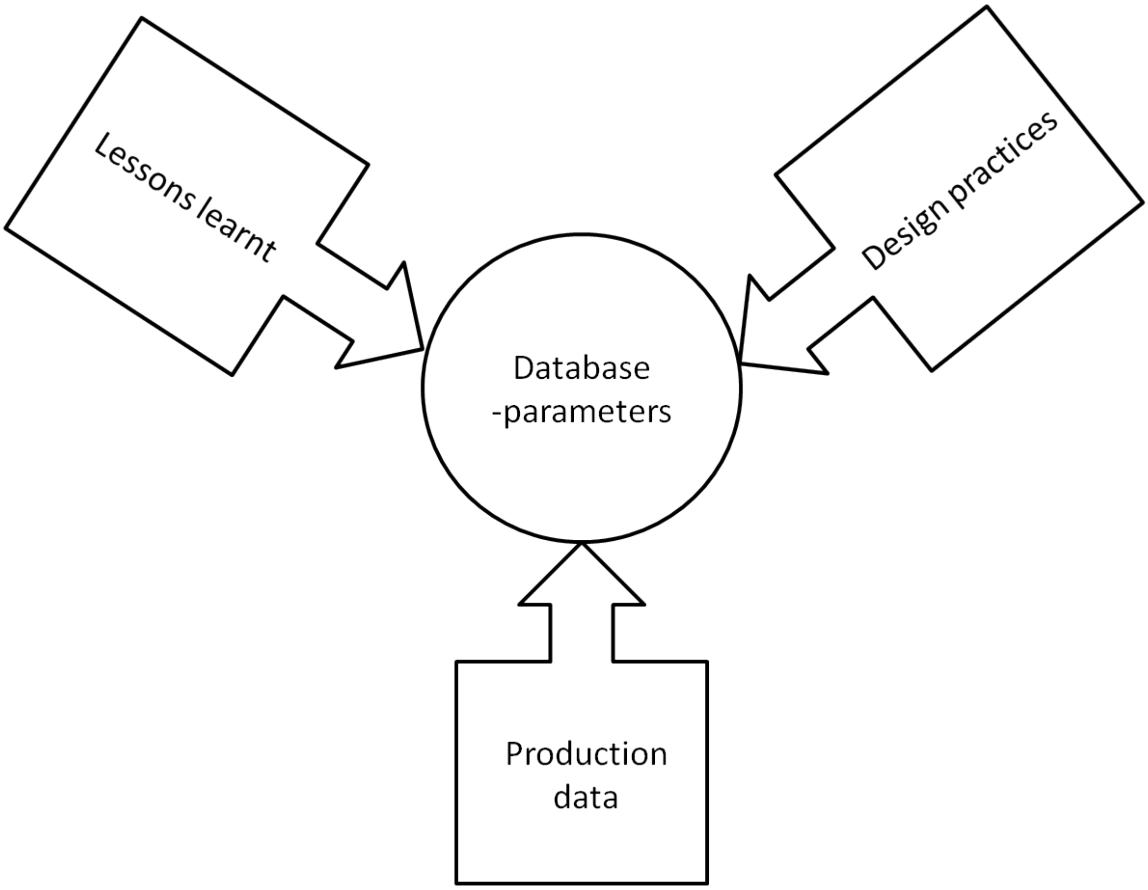

Figure 6.2: *A schematic representation of the information flow and how it relates to the proposed database.*

7 Conclusion

Producibility is a topic that has received bigger attention at GKN since the new fabrication strategy was implemented. The new strategy required better understanding of manufacturing technologies used in the company in order to have a robust product/production development process.

In this thesis, an investigation was carried out as to how factors and parameters regarding design and manufacturing and quality of welds could be systematized in a map. This work was able to answer the possibilities of creating a map, tying the parameters and factors and corresponding weld quality issues present at the company.

Though factors and parameters could individually be tied to specific defect types, the impact and interaction between these parameters are not fully defined due to them being high in number. Furthermore, certain parameters are still unknown as of what mechanisms these actually induce e.g. metallurgical behavior. Ultimately, the problem has proven to be extensive for which there are most likely additional factors and parameters left to be discovered and assessed in the map.

There is a coherence among engineers at the company that it will be beneficial in having a common platform where information can be systemized and arranged in a comprehensive way to improve the cooperation between departments. Increasing the awareness of producibility aspects is an area where much effort must be invested. This should be done in order to close the gap between design and manufacturing.

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