CHALMERS
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Quality modeling case study at GKN Aerospace Sweden

Master of Science thesis in Quality and Operations Management

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

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Abstract

The aerospace industry is becoming increasingly competitive and it is important for manufacturers to ensure that their products maintain low weight with high performances, while still offers a lower price to the customer compared to their competitors.

GKN Aerospace Sweden in Trollhättan manufactures jet engine components by a fabrication process where smaller parts are welded together to a complete product by using different manufacturing methods. The company faces challenges during manufacturing because requirements on product characteristics are difficult to fulfill in an efficient way due to geometrical variation and weld quality issues. GKN Aerospace Sweden now wants to develop more knowledge about their fabrication process in order to know how to control it and reduce its variation. This thesis purpose is to decompose product requirements down to requirements on each manufacturing step in order to identify what parameters that control the fabrication process. Due to limitations in time, focus in this thesis is to look at weld geometry and the parameters that control requirements on weld geometry are fulfilled. As support, a conceptual framework that recently has been developed will be used to perform this investigation in a systematic way. This thesis is created to examine if this type of framework can support a company to learn more about their manufacturing methods and further lead to that they can re-use technology and predict their ability to produce products earlier in product and production development.

The result of this thesis is based on interviews, observations and internal documents that together explain the requirements of the product TEC A and how the fabrication process is designed to ensure that all requirements on product characteristics are fulfilled. The conceptual framework is used to map the fabrication process and describe how requirements on product characteristics in one manufacturing step have to be fulfilled in order to succeed with the following operation. Parameters will control each manufacturing operation, and each parameter is explained in which way they will affect product characteristics. The relationship is described in more detail through interrelationship diagrams by showing positive or negative correlations between product characteristics and parameters as well as how different characteristics will affect each other. In the result, it also turns out that each product has its own complex geometry and that the design solution that is developed by the development team of TEC A is to a large extent adapted to the product’s conditions.

In the discussion it is clear that the conceptual framework can support in product and production development by working more systematically to learn how to control their processes. Recommendations are based on that GKN Aerospace Sweden should continue to analyze how parameters affect weld geometry in order to work more systematically in the future when putting efforts in how to improve their fabrication processes.

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Gothenburg, June 2015

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Abbreviations and nomenclature

GAS	GKN Aerospace Sweden in Trollhättan
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
KC	Key Characteristic
NDT	Non-Destructive-Testing
Operand	Consists of Qs
Operator	Consists of qs
Producibility	The ability to produce a product
TEC	Turbine Exhaust Case
TIG	Tungsten Inert Gas
RDM	Robust Design Methodology
q	A parameter or factor
Q	A product characteristic

1. Introduction

In this chapter an introduction to the thesis is provided. The theoretical and company background brings an overview of the complexity that exists today in the aerospace industry together with what efforts that are made to face those challenges. Further, an introduction to the complete corporation GKN is provided and how GKN Aerospace Sweden contributes to GKN´s aerospace division. This is finally followed by an introduction to the case study with a description of the problem, purpose and the limitations of this thesis.

1.1 Theoretical background

To stay competitive in today's global market it is essential to constantly improve and develop a company's processes (Bergman & Klefsjö, 2012). Without working with continuous improvements, companies will quickly fall behind in development and competitors will end up being a better alternative that can provide products or services with a lower price and better performance (Ljungström, 2005).

Within the aerospace industry it is of high relevance that companies continuously improve their products by reducing weight of their current and future jet engines while still improving or maintaining same performance, strength, durability and safety (Vallhagen et al., 2011). By putting extra effort on the product development process it is possible in an early stage to change the product design and its functionality, which can reduce the number of costly changes that needs to be made in a later stage of the product lifecycle (Thornton et al. 2000). This is still a problem in today's aerospace industry where there is a low level of automation in production where manufacturing specialists has to face complex challenges to overcome this problem. During welding activities, two of these reasons are geometrical variation and weld quality issues that needs to be dealt with before a component can proceed to next step in production (Madrid et al, 2015; Vallhagen et al., 2011). To approach this variation, there are efforts made to achieve a robust design, which means a state when a product or process is insensitive to sources of unwanted variation (Hasenkamp et al, 2009). Arvidsson and Gremyr (2007) describe these efforts as a part of what has come to be called Robust Design Methodology (RDM). By working with RDM there is no certain order of what method or step that should be executed, rather it should be used by companies to create structure of why, what and how to work with robust design (Hasenkamp et al., 2009).

1.2 Company background

GKN Aerospace Sweden in Trollhättan, here and after only referred to as GAS, is a part of GKN, originally named Guest, Keen and Nettlefolds. GKN is a multi-national engineering group with approximately 50 000 employees operating in 33 countries and is divided into four divisions; GKN Aerospace, GKN Driveline, GKN Powder Metallurgy and GKN Land Systems (GKN, 2015). The company was founded in 1759 and started a business within the ironwork industry. Today GKN have yearly sales over 7 billion pounds with a constant drive to grow through their strategically objectives to always be in the lead and be present all over the globe with the latest technology and high quality (GKN, 2015).

Since over 100 years the company has been involved in the aeronautic sector where GKN have been designing, developing and manufacturing complex, high technological and high value aero structures and engine components. This thesis will be conducted within GKN Aerospace division and more specifically within the sub-division of engine systems at GAS. GKN Aerospace division has about 12 000 employees, with yearly sales over 2 billion pounds (GKN, 2015). Their main focus is within the civil airline industry with 75% of its business activities but they are also supplier to the military aviation sector with for instance engine components. In total, 90% of all civil airplanes contain parts that are produced by GAS.

At GAS the focus is to design develop and manufacture engine components to world leading companies. This work is done in collaboration with customers such as Rolls Royce, Pratt and Whitney and General Electric. Their strategy is for continuous growth to be in the lead and deliver products that are weight optimized and therefore energy efficient. GAS capabilities are developed through investments, innovation and a continuous willingness to become best in class.

A vital part within the aerospace industry is safety and for product and production development to meet those requirements there are a huge amount of engineering hours spent. In addition to this, customers usually have their own particular requirements and policies, which make the product development hard to generalize (Project engineer, 2015-02-09). The aerospace industry’s customers usually order small batches as well in comparison to other industries (e.g. car industry), which has led to that GAS strive for long term collaborations with their customers and it is not unusual that products are manufactured for 30 years. Because of the large amount of engineering hours a big focus at GAS has therefore recently been to put focus on reducing quality related problems early in the development process in order to reduce costly design changes and rework.

GAS designs and manufactures high precision components (e.g. turbine exhaust case) for jet engines. To be competitive in today’s global market GAS changed their way of manufacturing components from first buying large forgings and castings to instead assembly smaller parts through a fabrication process to produce their products (Fig. 1). A fabrication process usually consists of several manufacturing steps where tack welding, welding and machining are critical operations in order to achieve correct dimensions of the product.

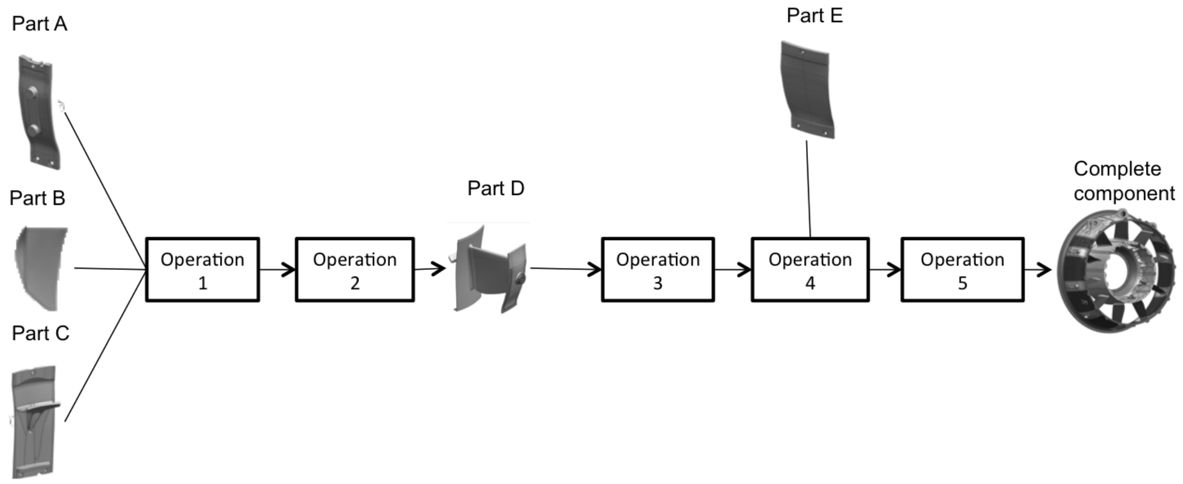


Figure 1. A simplified fabrication process at GAS

This way of manufacturing is highly competitive because it makes the component less expensive to manufacture and it is possible to reduce the total weight, which is an essential aspect within the aircraft industry. However, due to this new manufacturing method GAS need to continue develop their knowledge in how variation in the manufacturing steps in the fabrication process affect final product properties and the overall quality. GAS is working with several improvement projects by integrating RDM practices with the objective to increase the level of automation but there has not yet been a sufficient solution that covers the whole fabrication process.

A fabrication process is a complex manufacturing process because there are several manufacturing steps that have to work as a system to join parts together to a complete product. As a result from this, the product's characteristics often vary from their target values after each manufacturing step. These deviations are detected during inspections and the extra rework to ensure that right quality of the product is achieved is both costly and creates delays in production. Without creating knowledge and understanding of how a fabrication process is controlled, the ability to produce a product, producibility, and the level of automation in production will remain uncertain.

There is now a conceptual framework that has been developed that systematically maps a product's fabrication process (Madrid et al, 2015). The framework describes the requirements on product characteristics that each manufacturing step demands from previous operation and what parameters that control that right product characteristics are obtained. By developing better understanding of the fabrication process, GAS wants to be able to reduce variation and predict producibility already in an early design phase. By doing this, GAS can improve their automation in production, decrease number of inspections and reduce the amount of rework in the fabrication process.

1.3 Problem description and research questions

One problem at GAS is the uncertainty of how to control their fabrication processes in the early product and production development phase. As a result from this, GAS fabrication processes' continue to yield varying results and this has led to that components require several occasions of rework in order to fulfill product specifications.

To be able to predict producibility, increase automation of the fabrication process and deliver products that meet customers' requirements, GAS wants to develop better knowledge of the fabrication process. This knowledge should include how different characteristics are affecting each other during production as well as what parameters are controlling those requirements on product characteristics.

In order to improve quality as well as working proactive to reduce variation this thesis is going to examine GAS' fabrication process in order to increase knowledge in manufacturing. The earlier mentioned conceptual framework is going to be used as a systematic approach on a case study where one product will be under investigation. The following research questions have been developed to clarify the problem:

1. How can better knowledge of the product's characteristics and its fabrication process' parameters lead to increased quality and efficiency?

2. What parameters from the process steps have significant impact on the quality of the product?

3. How can a conceptual framework that describes the relation between significant process parameters and resulting product quality support in product and production development at GAS?

1.4 Purpose

To validate how a recently developed conceptual framework can be used in a generic way for fabrication processes at GAS, the objectives for this thesis is to decompose one product's final requirements into requirements on product characteristics for each manufacturing step. The intention for this is to then be able to identify what process parameters that have an influence to the characteristics of the product. By identifying these parameters, the purpose of this thesis is to create more knowledge of how GAS control their fabrication process to ensure that requirements on final product characteristics are fulfilled.

What is of great importance is that by using the conceptual framework this can lead to employees at GAS can take process parameters into consideration early in the product development phase, create a more robust design solution and faster finding optimal parameter settings, which will fulfill requirements on product characteristics. By creating this way of systematic work in product and production development a future goal for GAS would be to reduce the time it takes to estimate if a fabrication process is capable to meet new demands from customers and thus be able to respond faster to requests.

1.5 Limitations

To limit the work of this thesis it has been decided to only study operations within GAS and not take suppliers operations into consideration. However, any data that can be of relevance when analyzing the fabrication process is considered valuable and is not only limited to data produced at GAS. Moreover, this study is limited to only observe one product in order to be able to look deeply into the product characteristics and its related parameters and thereby be able to get more detailed information and understanding of this specified case. Because of time constraints, this research will mainly focus on a product’s weld geometry characteristics during the first five manufacturing steps of the fabrication process of the product. Each manufacturing step includes visual inspections that also are going to be examined. There are other inspection techniques used at GAS to confirm a product’s quality but these has not been taken into consideration because they are not included in the manufacturing steps, while visual inspections are procedures in each manufacturing step that can lead to varying results.

To be able to use identified parameters for future work at GAS when computing a fabrication process’ capabilities there is a need of knowing to what degree parameters are affecting the product. Due to that there is no model developed for this purpose yet, this thesis is limited to reach to an understanding of how parameters are affecting a product’s characteristics and why they are important for GAS, but not to what degree they have an impact.

Lastly, GAS wants to protect their intellectual property and this thesis is not allowed to publish data that can reveal valuable information about the company or its operations. The two researchers’ supervisor at GAS will control that data that is published is allowed by GAS. Data that will be listed as classified will only be published in GAS' internal edition of this thesis.

2. Theoretical framework

This chapter presents the theoretical framework that was conducted in the thesis. First, engineering design provides an insight in how engineers secure that customer requirements are met through product-and process development. This is followed by that robust design describes problems with variation and how geometrical assurance and Robust Design Methodology can support the work in how to make a product insensitive to variation. This is followed by an explanation of Key Characteristics, which are used in industry to ensure high quality and right focus. Lastly, quality management tools that were used during this thesis are described followed by an explanation of those manufacturing steps that represents the fabrication process in the case study.

2.1 Engineering design

Competition has become global, intense and dynamic and this turbulent environment forces companies to put extraordinary efforts in product and process development to stand out from the crowd (Wheelwright & Clark, 1992). Engineers are also constrained by technical and social related requirements (e.g. material, legal, environmental) in their work to find appropriate solutions to their new products. Due to this interdisciplinary work environment, product and process development has become an interplay between design and development engineers that first forms a mental creation of the product's performance, where production engineers then make the physical realization of it (Pahl et al., 2007). Wheelwright and Clark (1992) states that this interplay between functions, where high performance and ability to manufacture a product is what an excellent engineering design really is about.

For design and development engineers to be successful in their work and to optimize their technical solutions they have to deal with constraints, which not unusually will be in conflict with each other. These constraints are usually communicated by a set of functional requirements that comes from a customer (Pahl et al., 2007). Functional requirements defines what the product, component or part should perform, do or be and may include an expected lifetime, environmental impact and how the product should work in an assembly (Jakobsen et al., 1991). These requirements are usually described more specific in technical terms (e.g. material, weight and component tolerances) at the company to create clear formulations of what the customer needs. To respond to these requirements design and development engineers commonly consult with experts within certain disciplines (e.g. aerodynamics, stress or material). It is also important to consult with production engineers about whether manufacturing requires certain tools (e.g. machines, fixtures) or inspection techniques for production of the product (Pahl et al., 2007).

In order for engineers to design a product and solve technical problems that occur during development, it is critical to understand relationships between relevant disciplines to secure that the proposed solution will be reproducible. However, there is still the possibility that a solution is exposed to disturbing factors (e.g. variations in material thickness) that will make the result deviate. This can lead to both technical and economic consequences where the designer is forced to make adjustments to the solution. For this reason, designers are today trying to make robust solutions where the results become less dependent on prerequisites (Pahl et al., 2007).

2.2 Robust design

One of the causes to why there is failure occurrence in today’s manufacturing is because of variation. This variation often leads to that a product’s characteristic deviates from its target value, which leads to a reduced quality of the product and increased costs for the company (Bergman et al. 2009). Not only can it be time consuming to identify a source that contributes to variation, *a noise factor*, but as well difficult and expensive to eliminate it. What is a more appropriate solution is to instead create a product or process that is insensitive to variation, or more commonly referred to as achieving a robust design (Hasenkamp et al. 2008).

The concept of Robust Design was introduced in 1950s in Japan when an engineer named Genichi Taguchi made successful efforts when studying how to make products and systems insensitive to variation (Bergman & Klefsjö, 2010). Since his work reached international attention there has been numerous of concepts described in how to reduce variation in product characteristics such as robust engineering, robust design and Taguchi methods among others (Arvidsson & Gremyr, 2008).

What is of great essence when working with robust design is to understand the system (e.g. a product or process), the contributing sources of variation that has an impact to the system's behavior, and how this in turn affects a customer or user of the system. A system is exposed to different types of variation during its lifetime and can be divided into five categories. First, variation that exists in the manufacturing process and creates variation between each produced unit is called unit-to-unit variation. The second category is when variation occurs due to maintenance activities, deterioration and wear when the system produces a product. The additional three categories that concern variations are; variation when using the product, variation when the product is exposed to different environments, and lastly the variation when a product interacts with other systems (Bergman & Klefsjö, 2010).

2.2.1 Robust Design Methodology

Today there are several methods that support the work of robust design and how to identify what is causing variation. Arvidsson and Gremyr (2008) divide the term of robust design into two pieces; the condition itself and a systematic effort to reach it, namely Robust Design Methodology (RDM). RDM includes different approaches and tools with the intention to be supportive during the whole product development process from concept stage till the production of a product. What is of great essence is that certain methods can be more or less appropriate than others depending on the circumstances, but the intention with RDM is to systematically find a robust design with an awareness of variation where efforts can be applied in the entire development phase. Hasenkamp et al. (2009) also highlights that there should be a clear scope of; why there is a RDM initiative, what should be done to address it, and how to achieve it. One example is by using RDM one should be able to create a product that is insensitive to noise factors, the why, and by exploiting nonlinearities and interactions, the what, when using a transfer function, the how, this initiative should be obtained.

2.2.2 Awareness of variation

Bergman and Klefsjö (2010) emphasize the importance to be aware of variation already in the concept stage of product development in order to have the possibility to save time and money by eliminating already known noise factors when designing the system. However, to address remaining variation the next step is to apply design parameters to the system in order to determine the functionality of the system. There should be careful considerations taken when setting values of the design parameters because of the uncertainty of to what degree design parameters will be sensitive towards variation. To understand the behavior of the system there is a need to know how the output from the system depends on the input when there are certain values of the design parameters and noise factors that influence the system. The process can be explained through the transfer function and is illustrated below in what is called a P-diagram (Fig. 2) (Bergman & Klefsjö, 2010).

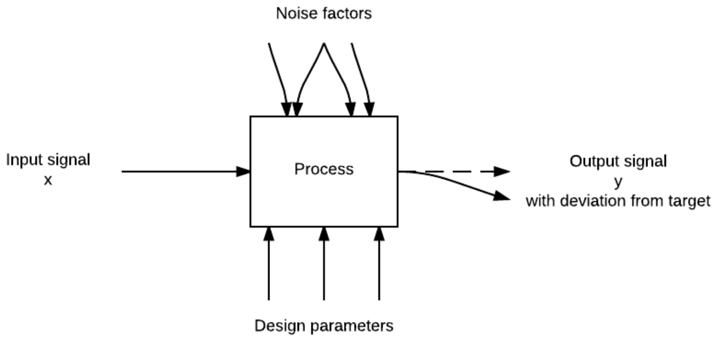


Figure 2. A P-diagram (Bergman & Klefsjö, 2010, p. 201)

The P-diagram illustrates the functional relationship between an input signal x and output signal y in a system under the influence of noise factors and design parameters (Johansson, 2005). In an ideal world the same output will be produced each time exactly on target. However this is not the case since noise factors are disturbing the process and causing variation, which leads to deviation from target. It is also important to estimate the loss a deviation from a target value can create due to noise factors when working with systematic design work. A common model to describe this loss is through the quadratic loss function (Fig. 3), which has a central role in Taguchi's philosophy. The curve illustrates a quadratic function that shows how loss is evolving depending on the deviation from the target value. The traditional view of loss has been that as long as parameters are within their tolerance levels, there is no loss while Taguchi's opinion is that all deviation from target value causes a loss (Bergman & Klefsjö, 2010).

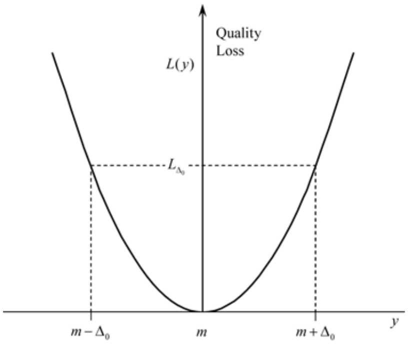


Figure 3. The quadratic loss function (Bergman & Klefsjö, 2010, p. 202)

2.2.3 Robust Design and Geometry Assurance

A common problem in manufacturing is that a product's geometrical dimensions may deviate from nominal value (Lööf, 2010). This variation is normal and it is not possible to mass-produce parts with the exact same geometric dimensions (Poli, 2001). Reasons for geometrical variation to occur can be because of variation in ingoing parts' properties or there could be dislocations when parts are placed in fixtures, which creates problem during assembly (Forslund et al., 2011; Söderberg, 1998). To overcome these problems, engineers use geometry assurance to minimize the effect of geometrical variation. Geometry assurance is the common term used to gather all activities that aim to secure that a product's geometry quality is fulfilled. Geometry assurance is dependent on both a product's variation in production as well as its insensitivity to variation in the design concept (i.e. a product's robust design) to ensure all variation is considered during a product's development (Jareteg et al., 2014).

One main activity to use in geometry assurance is to develop robust locating schemes. (Jareteg et al., 2014). A locating scheme's main purpose is to keep the workpiece in position to prevent it from any movements and keep the material from being exposed to heavy deformations. To do this companies are using a traditional target system called 3-2-1 (Fig. 4), where the workpiece is locked at three different non-parallel faces by making use of nonaligned contact points. Figure 4 shows a descriptive example of how the 3-2-1 system works. Point A1, A2 and A3 are located at one face and will lock two rotations and one translation. Point B1 and B2 locks one rotation and one translation while point C locks the final translation in the plane (Vallhagen et al., 2011; Xiong et al., 2013).

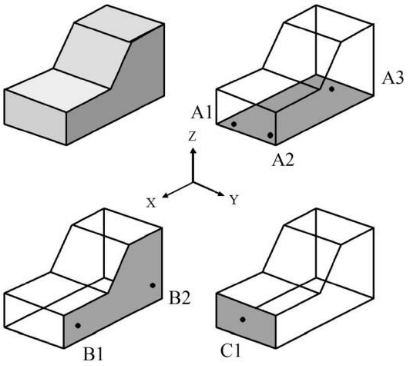


Figure 4. An example of a 3-2-1 locating scheme (Vallhagen et al., 2011, p. 2)

Furthermore it is important to strive for robustness when developing locating schemes. To do this, it is important that locators are placed on the body in a way that secure that variation in locators will not increase variation of a product's dimensions (Vallhagen et al., 2011).

Engineering designers also manage geometrical variation by allowing variation to exist to some extent by specifying tolerances. A tolerance is the allowed variation that can occur in a dimension or geometric characteristic of a part and is defined by designers in order to control that the right functionality of the product will be produced (Poli, 2001). A tolerance is usually based on a trade-off between the manufacturing's capability to produce, the possibility to measure the tolerance and the acceptable functionality of the product that needs to be fulfilled (Colosimo & Senin, 2011). If a product is assembled in production, tolerance limits have to be specified by the assembly's accumulated variation. In addition to this, cost is also an important factor when deciding what tolerance level to set. While engineering designers strive to have tight tolerances to ensure that a product will fulfill specifications, manufacturing engineers wants looser tolerances to be able to choose cheaper manufacturing methods (Lööf, 2010).

2.2.4 Robust Parameter Design

Robust Parameter design is an engineering methodology that is used to reduce performance variation in a product or process. By identifying appropriate settings of input variables the system (e.g. product or process) becomes less sensitive to variation (Mukerjee & Wu, 2006). These variables are divided into two categories, namely control factors and noise factors. The values of control factors will remain fixed once they are chosen and represent the design parameters in product or process design. Noise factors are those variables that are difficult to control during the process, and when performing experiments of parameter design these variables' values are systematically varied to create a similar representation of their variation in normal conditions (Wu & Hamada, 2000).

Appropriate settings of design parameters are critical in order to control a system's output. However, there are often limitations when setting the values of design parameters but by utilizing the interaction between design parameters and noise it is possible to decrease the amount of variation that occurs in the process (Bergman & Klefsjö, 2010). The relationship between output y, design parameter x and noise factor z can be explained by the model:

$$y = f\ (x, z)$$

Where the variation of z will be transmitted to y. However, there is still a possibility that x and z interacts with each other to produce the value of y, which makes it possible to instead adjust the value of x to influence the relationship between y and z (Wu & Hamada, 2000). The relationship can be further explained by the identification of such a relationship by:

$$y = \mu + \alpha x_1 + \beta z + \gamma x_2 z + \varepsilon$$

$$= \mu + \alpha x_1 + (\beta + \gamma x_2) z + \varepsilon$$

where y is the output, x_1 and x_2 are two design parameters, z as a noise factor and ε represents remaining variation that is not captured by z. By choosing the appropriate value of x_2, coefficient of $\beta + \gamma x_2$ can be set to as small as possible and lower the effect of z (Wu & Hamada, 2000). To determine what particular settings to use for design parameters Taguchi both proposed techniques in experimental design for identification as well as for analysis of the studies (Robinson et al., 2004). Design of experiments (e. g. fractional factorial or full factorial designs) are effective because by analyzing the result it is possible to make estimations of what average level different parameter combinations results in when variation has an influence. Additionally to this, it is possible to derive from the results if certain parameter combinations are more sensitive to variation than others. This can enable the designer to create a robust design by choosing parameter values that are less sensitive to noise factors while still reaching the target value for the output (e.g. a Key Characteristic). Lastly, if parameters are identified in an experiment that neither is sensitive to noise factors nor influence the output it is possible to set these parameter values to the most economical options (Bergman & Klefsjö, 2010).

2.3 Key characteristics

One way for companies to improve quality today is to set narrow specification limits to their processes. Unfortunately, this approach usually leads to high costs and reduced efficiency. Instead Thornton (2004) proposes to choose appropriate quality levels of the processes by identifying acceptable levels of variation. One method to do this is to monitor and control Key Characteristics (KCs) of products or processes (Tang et al., 2014). The intention with KCs is for a company to be able to recognize how quality is being created in order to follow up with determining what parameters that are sensitive to variation (Hasenkamp et al., 2009). Thornton has (2004, pp. 35) defined a KC as:

"A key characteristic is a quantifiable feature of a product or its assemblies, parts, or processes whose expected variation from target has an unacceptable impact on the cost, performance, or safety of the product."

The definition is based on four concepts. First, a KC must contain both a quantifiable target value and tolerance level in order to be able to assess it. Second, a KC can be identified and controlled at any level, from a product KC down to a process KC. Third, a KC must have a significant impact to product cost, performance or safety when it deviates from its targeted value. Lastly, variation should be likely to occur if it should be defined as a KC (Thornton, 2004).

The selection- and evaluation process of KCs can be done throughout the whole product life cycle and are today supported by a number of methods and tools where the choice often is based on the situation and goal of using KCs. KCs usually appear in a drawing or in a specification list where design engineers has given each KC a unique label. The label's purpose is to track and map related data from the production processes where the KC value is created (Zheng et al., 2008). To identify and select what KCs to work with, several authors have advocated the use of a KC flowdown (Thornton, 2004; Whitney, 2006; Zheng et al., 2008). A KC flowdown (Fig. 4) is a systematic approach that supports the work of mapping the composition of one KC, i.e. how a KC's requirements are broken down into several sub-requirements (Whitney, 2006). A KC flowdown makes it possible to identify; what features that should be controlled; where adjustments in the manufacturing process can impact the product’s quality; and what is the root causes of having quality problems. The KC flowdown also shows the link between what quality that needs to be delivered and what possibilities there are to control a process (Thornton, 2004).

Thornton (2004) describes a KC flowdown with six different layers (Fig. 4). First layer is the product KC layer that is the product or customer requirements that are identified to be sensitive to variation. Second layer concerns the systems KCs that are based on partly the customer requirements and interface constraints between parts, but also from the manufacturing requirements. The third layer is the assembly KCs that are requirements from the assembly that contributes to variation in the system. Fourth layer is the part KCs that are requirements on each part that has an impact to the assembly’s KCs. The fifth layer is the process KCs which varying requirements in tooling, operators and machines have an impact to the variation that occurs in the part and assemblies KCs. Last is the external noise factors layer that has an impact to the process (Thornton, 2004).

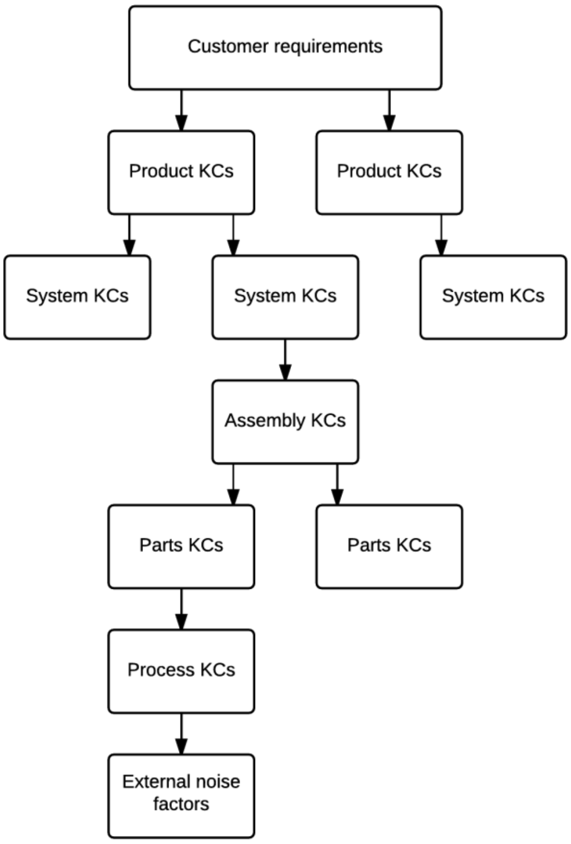


Figure 4. A generic KC flowdown (Thornton, 2004, p. 40)

A KC is delivered when the value is within its specified tolerance levels. However, if a KC is used in an assembly or a fabrication process, it is dependent by a system of parts that needs to work together. To be able to deliver a KC then these parts also requires geometrical or dimensional constraints throughout the process (Whitney, 2006). Whitney (2006) also argues that every design process of how to deliver KCs should be defined by answering two questions. First, what strategy should be used to ensure that the KC is delivered? This requires careful consideration to that all parts should be in the right place with respect to each other, ensuring that their target values result in that the KC is on target. The second question is to respond to what strategy to use to defend a KC that is exposed to variation in parts manufacture and assembly, i.e. how will variation affect the KC and what should be done to counteract this? This can be achieved by using different tools to identify relationships. For example, a relationship matrix can be used to assure correct geometrical and dimensional constraints between parts, followed by a variation analysis to examine if the defined KCs will meet specified tolerance levels (Whitney, 2006).

2.4 Quality management

Companies use different kinds of quality tools in order to improve their products and processes. Although all quality tools strive to reach for improvements, they still differ in their approach and required input data. It is for this reason important to have sufficient knowledge of the prerequisites to use each tool (Larsson & Sagar, 2014).

2.4.1 Cause and effect diagrams

Cause and effect diagrams or also known as Ishikawa diagrams (Fig. 5) are used to find the root causes of an identified quality problem (Bergman & Klefsjö, 2010). Cause and effect diagrams provides a systematic work method where the causes that can produce an observed quality problem are identified and broken down into pieces by example using brainstorming methods (George et al., 2005). A complete cause and effect diagram should be divided into several sub-bones in order to be helpful and give a complete breakdown of the identified problem and its´ root causes (Bergman & Klefsjö, 2010). The diagram helps you explore the possible root causes that can lead you to the problem instead of searching for solutions (George et al. 2005). By using the cause and effect diagram in the early product development process one can identify possible root causes of the identified main problem already in the product design phase and to as large extend as possible eliminate or reduce their occurrence and thereby save large amount of time and money.

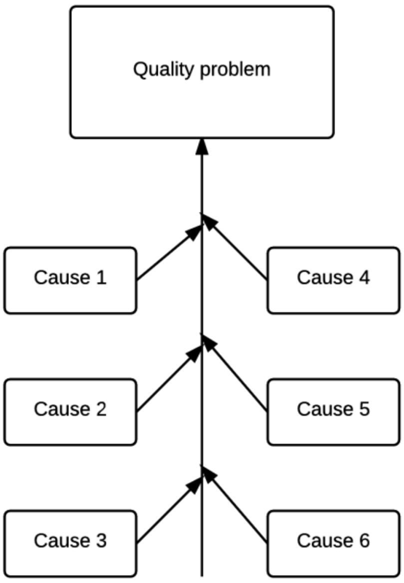


Figure 5. A cause and effect diagram (Bergman & Klefsjö, 2010, p. 237)

In the diagram the identified quality problem is illustrated as the head of the fishbone, which is the problem that is being analyzed. Causes leading to this problem are then illustrated as the bones, which provide additional insight to the problem. The causes are usually divided into seven Ms, representing Man, Machine, Method, Material, Measurement, Mother nature (Milieu) and Management (Bergman & Klefsjö, 2010). By dividing the problem into those bones one usually covers all the important aspects of the problem hence are the seven Ms leading to a broad start of possible causes.

2.4.2 Interrelationship matrix

An interrelationship matrix (IRM) or matrix flow chart is a diagram showing the relationship between two groups of variables in a matrix made up by rows and columns. The IRM was designed to in an easy way describe and clarify complex intertwined causal relationship and making it easy to find a suitable solution (Doggett, 2005). Karlsson et al. (2010) developed a matrix flow chart or interrelationship matrix in order to present data and relationship in a generalized and easy way between weld geometry characteristics and parameters that influence characteristics which is shown in figure 6. The matrix flow chart was furthermore developed with the purpose to easily transfer knowledge between different projects concerning how parameters affects weld geometry characteristics (Karlsson et al. 2010). Doggett (2005) states that interrelationship diagrams have evolved in to a problem-solving tool used for solving cause and effect relationship in order to identify key factors and focus on solving them.

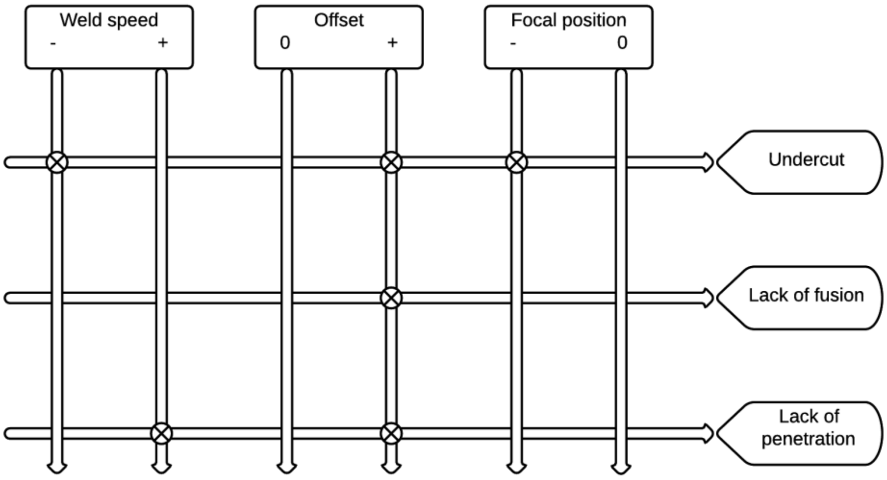


Figure 6. A matrix flow chart describing interrelationship between product characteristics and parameters (Karlsson et al., 2010, p.190)

2.5 Manufacturing methods

A fabrication process usually consists of several manufacturing steps that assemble and join smaller parts together to create a complete product (Vallhagen et al., 2011). The process consists of different manufacturing steps that treat the material to make a product come closer to its final properties. The choice of which manufacturing method to include in the fabrication process is usually dependent on functional requirements, choice of materials, required accuracy, geometrical requirements, production volume and production cost. Additionally to this there could be complicated relationships between choice of material and manufacturing method because of different properties of the material. This result in that certain manufacturing methods are more appropriate in the fabrication process (Jarfors et al., 2007).

2.5.1 Fusion Welding Processes

A fusion welding process is a joining process between materials that creates a weld joint by using fusion of the base metal (Kou, 2003). The joining process generally includes a heating-, melting-, and solidification process where the heat input can be supplied from different types of heat sources such as a gas flame, an electric arc or a high-energy beam (Ueda et al., 2012). By increasing the power density of the heat source, the required heat input to create a weld is decreased. However, there is a possibility for deformations through distortion or weakening if the workpiece is exposed to an excessive heat input (Kou, 2003). The joining process can be completed using different joining techniques (e.g. a butt or fillet welding), where each technique can create different types of joints (Fig. 7). What technique that is the most appropriate one depends on how the shape characteristics of the components structure appear (Ueda et al, 2012).

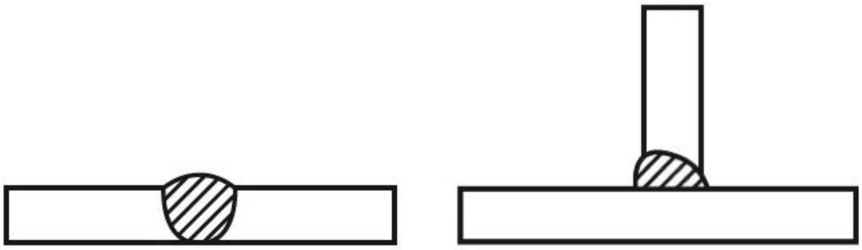


Figure 7. Two types of weld joints. The left weld joint is called a butt joint. The weld joint to the right is called a cross joint (Ueda et al., 2012, p. 3)

During the welding process there are certain areas of the workpiece that are affected by heat in different ways and thus divided into certain zones. The first zone is called the fusion zone and it is the area where the material melts into a liquid composition and then solidifies to create a weld. The weld is seldom in a uniform composition after the solidification, but instead depends on different branches of physics such as thermodynamics and kinetics. Second zone is called the partially melted zone, and is located immediately outside the fusion zone. Within this area there is a possibility that severe liquidation can occur and change the microstructure of the material. The last zone is of major concern in welding and is named the heat-affected-zone, further on referred to as HAZ. In the HAZ temperatures are not high enough to cause melting but still there could be significant changes in the microstructure and properties of the materials that leads to weakening (Kou, 2003).

2.5.1.1 Gas Tungsten Arc Welding

The Gas Tungsten Arc Welding (GTAW), also referred to as Tungsten Inert Gas (TIG) is a common process in the aero-engineering industry that is mainly used for welding thin material or for precision welding of heavier components (Kou, 2003) (Kalpakjian & Schmid, 2010). TIG welding is performed by melting and joining metals together by applying heat from an arc. The arc is established by an interaction between a non-consumable tungsten electrode and the workpiece where the entire process is supported by electrical power and shielding gas (Fig. 8). The shielding gas usually consists of argon or helium to prevent the electrode, the arc and the locally heated material from contaminations and corrosion since these effects can lead to defects in the material. When welding thicker materials together there is usually a filler material that is continuously applied to the process that has to consist of a material composition that is similar to the parent material. An advantage with filler material is that it is independent of the welding current, which makes it possible to control the size of the weld during the process (Kou, 2003).

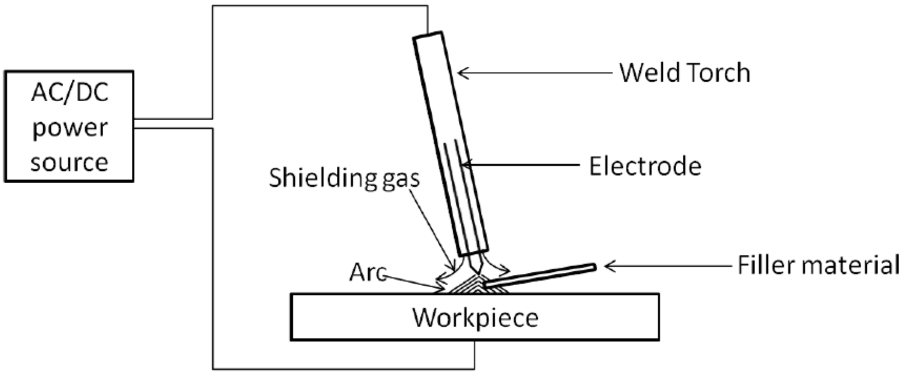


Figure 8. A TIG welding process (Larsson & Sagar, 2014, p. 5)

There are several advantages of using TIG as a weld technique. First, TIG is flexible because it is possible to perform welding both manually or by using a robot, it can be used with or without filler material and it can perform several weld joint and weld position configurations. Secondly, TIG has a stable arc that generates high quality welds with smooth and even welds without spatter or slag when the material thickness is between 0.4- 3.0 millimeters. However, TIG inflicts large amount of heat input that creates deformations and residual stresses to the workpiece and the performance of TIG welding decreases when the material thickness exceeds 3.0 millimeters (Internal document).

Lastly, TIG weld technique is also a common choice for tack welding (Internal document). Tack welding is often performed to temporarily fixate a weld setup by placing tack welds to prevent parts from moving from their original position (Heinze et al., 2012). However, tack welds influence on weld quality is complex and may cause welding distortion and residual stresses (Heinze et al., 2012). These problems can arise from a number of different causes such as weld sequence, thickness of material, type of material and type of weld joint.

2.5.1.2 Laser Beam Welding

The laser beam welding process (Fig. 9) melts and joins metals using a heat source that is produced by a laser beam. By adjusting the laser beam's focus and direction by optical means it is possible to adjust the power density to create an appropriate weld quality (Kou, 2003). There are mainly two types of lasers, pulsed wave and continuous wave laser (Assuncao & Williams, 2013). The pulsed wave laser has a power that is pulsated in time intervals while continuous wave laser has a constant power over time (Katayama, 2013). One difference between them has previously shown that the pulse wave laser has higher penetration efficiency between the two, thus require less heat input than a continuous wave laser to achieve the same penetration depth (Assuncao & Williams, 2013).

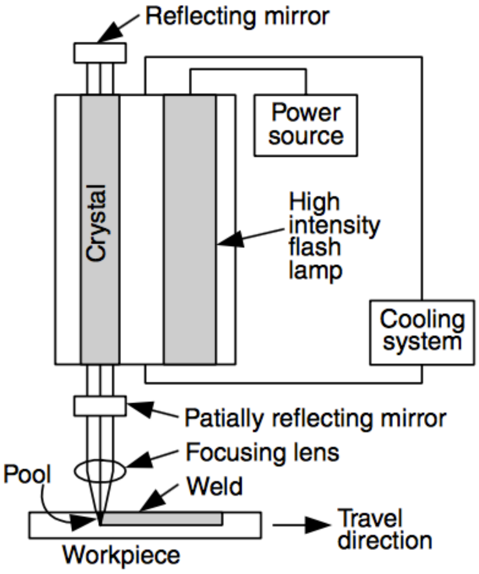


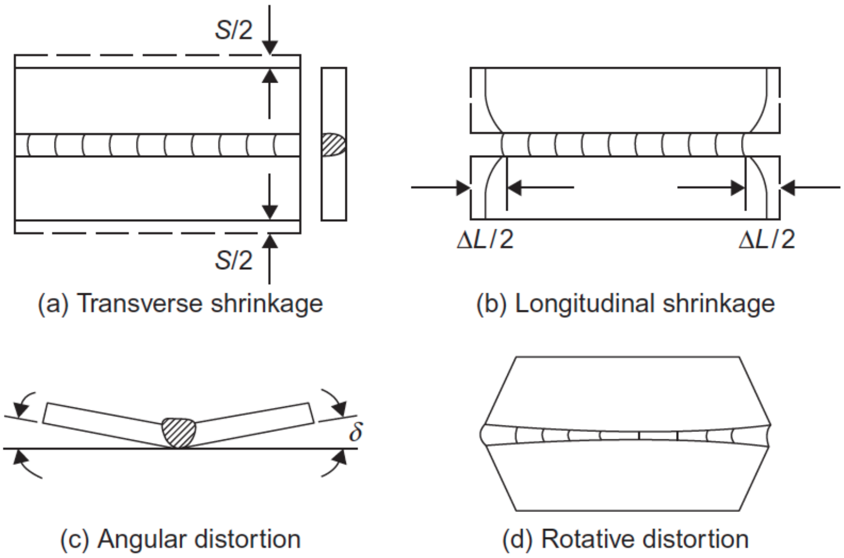
Figure 9. A laser beam welding process (Kou, 2003, p. 30)

A significant advantage by choosing laser beam welding is that it can operate with a high weld speed and produce deep and narrow welds with a narrow HAZ and little distortion to the workpiece. Laser beam welding can also perform keyhole, which gives the weld method a positive indication to achieve full penetration in the weld. Keyholing is when a sharply focused laser beam forms a keyhole in the workpiece instantaneously in order to complete the weld (Kou, 2003). The weld shrinkage in laser beam welding is also four times less than in TIG, which makes it very beneficial. Other advantages by using laser beam welding is that it is flexible, meaning it can operate for thicknesses between 2 to up to 10 millimeters both with or without filler material (Internal document).However, a common problem with laser beam welding is the reflectivity that occurs by the metal surface during welding and depending on the type of laser there are situations where up to 95% of the beam power can be reflected (Kou, 2003). What happens is that the welding process' efficiency is affected by to what degree the laser beam will be absorbed, penetrated and reflected by the material (Larsson &

Sagar, 2014). Unfortunately, there are difficulties to predict this by creating a complete weld process model because of the number of variables that has an impact to the weld quality. By changing one variable in the process it could lead to significant differences in weld result (Ion, 2005).

2.5.1.3 Residual stress, distortion and fatigue

There are several implications that can occur due to welding. One of these implications is residual stress in the workpiece, which are stresses that exist in a body without any other external loads applied to it (Kou, 2003). Residual stresses occur in the workpiece due to shrinkage, which is when there has been a thermal expansion and shrinkage during thermal processes when welding. Shrinkage can occur both in longitudinal and transverse direction and is also one cause to a second implication in welding, namely deformation of the workpiece (Ueda et al., 2012). Deformation of the workpiece can appear through transverse shrinkage, longitudinal shrinkage, angular distortion and rotative distortion (Fig. 10) (Ueda et al., 2012).



(a) Transverse shrinkage

(b) Longitudinal shrinkage

(c) Angular distortion

(d) Rotative distortion

Figure 10. Different types of welding deformation (Ueda et al., 2012, p. 6)

A third implication is fatigue, which is when a failure occurs in the weld due to repeated loads being applied. Fatigue is divided into three different phases; crack initiation, crack propagation, and fracture. During a fatigue cycle the surface of the material is being exposed to tensile and compressive forces that can result in abnormalities along the slip plane, which later can lead to initial cracks to form along the slip plane (Kou, 2003). The fatigue cycle can be influenced by different reasons. First, the weld geometry is of significant importance because depending on the shape of the weld the stress concentration will change. Second, there are several imperfections in weld quality such as porosity, slag inclusions, lack of fusion and lack of weld penetration that can contribute to alternative ways of stress concentration and set the fatigue cycle in motion (Maddox, 1991). Distortion, residual stress and cracks can all lead to deterioration of the strength in the welded structure, which could lead to decreased reliability of the component (Ueda et al., 2012).

2.5.2 Material-Removal process

Material-Removal processes, or more commonly described as machining, are operation procedures that are able to shape a manufactured part’s dimensions by removing undesirable material (Jarfors et al., 2007). Machining processes are preferred in today’s industry because of their ability to create dimensional accuracy, form geometric features, smooth out distortions and produce special surface characteristics (Kalpakjian & Schmid, 2003).

Machining is a common term for different processes, which can be divided into; cutting, abrasive processes, and advanced machining processes where all three uses different techniques and sources of energy for material-removal. A cutting process removes material from the workpiece's surface by creating chips. The cutting is executed when a tool moves along the surface at a certain velocity and depth of cut. The actual chip is then produced just in front of the tool (Kalpakjian & Schmid, 2003). Two types of cutting techniques are milling and drilling, which usually machine the surface with multi-point cutting tools. A multipoint cutting tool has one or more cutting edges and the majority of tools use rotation to cut (Fig. 11) (Nee, 2014).

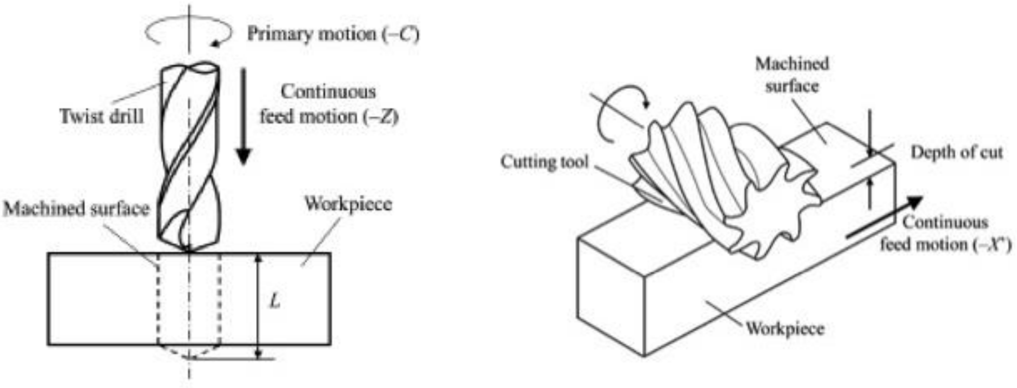


Figure 11. Two types of machining processes. The one to the left is drilling and the one to the right is milling (Nee, 2014, p. 826 and p. 830)

A machining process can be controlled by several parameters in order to achieve a good result. Common parameters that need to be controlled are feed motion, cutting depth, workpiece material, characteristics of the machine tool and fixtures. By changing the setup of these parameters there is a possibility that conditions in the process are affected such as; temperature in the affected zone; surface finish of the workpiece; and force and energy to the process. The goal with machining is due to these ramifications to understand and control these conditions by gaining knowledge about each specific parameter (Jarfors et al., 2007).

2.5.3 Inspection techniques

To ensure high reliability of manufactured products in today's aircraft industry, companies are today using Non-Destructive-Testing (NDT) to evaluate that the component holds the expected requirements on product characteristics or if there are any defects in the material or component. The procedures are commonly performed as continuous monitoring of a process and can lead to increased knowledge of material behavior and thus support designers to optimize the material consumption. There exist several types of NDT techniques (e.g. liquid penetrant inspection, radiography or visual inspection) to support in the evaluation where certain methods are broader used while others are designed to concentrate on specific processes (Prakash, 2012).

Visual inspection is a simple method that only requires manual optical inspection at the simplest form. The methods are beneficial because of its low cost and it is commonly used to check surface finish or type and location of defects on the surface. To increase the possibility to inspect properly there are numbers of optical aids that can be used to either permit access or enlarge the surface that is being inspected, such as boroscopes or magnifying lenses (Prakash, 2012). A visual inspection can also be supported by mechanical gauge to measure certain geometries of a component (e.g. a weld bead height) (Larsson & Sagar, 2014). However, it is important to be aware of that a measurement method can be unreliable for several reasons (e.g. different people that measures). Therefore it is important to ensure that the measurement method only presents actual differences and not differences that occur because of variation that exist in the measurement method (George et al., 2005).

3. Methodology

This chapter describes the methodology of the thesis. The research strategy and design provide an explanation to why certain methods were used to conduct the thesis while the research process then describe how different methods were used to collect data. The conceptual framework is presented and explained how it was used throughout this thesis to create a systematic approach and to support in analyze data. Lastly, the quality of the research is discussed to bring an insight into the case study's validity and reliability.

3. 1 Research strategy and design

A research strategy can be explained as a general approach to use when conducting business research. Bryman and Bell (2011) separates business research into two clusters, namely qualitative and quantitative research, to enable a separation between two research strategies. The quantitative approach emphasizes the use of quantifying data in the collection and analysis phases while the qualitative approach most often use words in the collection and analysis of data.

To conduct the business research in an efficient way Mohapatra et al. (2014) proposes the construction of a research design that should contain necessary procedures to fulfill the purpose of the research. Bryman and Bell (2011) propose five different types of designs; experimental, cross-sectional, longitudinal, case study and comparative. This thesis was carried out using a case study design. A case study can be explained as doing a detailed analysis of one specific case where the case’s complexity and unique characteristics are of interest. Bell (2010) emphasizes the importance to have a systematic approach to bring evidence, analyze the relationship between identified variables and to plan the investigation methodically to bring a depth into the case study.

A case study can be either a qualitative or a quantitative research depending on how the researcher wants to examine the case, whereas the former is mostly favored because it supports for a more comprehensive investigation to the examination (Bryman & Bell, 2010). A case study is a method that can contain several sub-methods in form of interviews, document analysis and observations. By using several sub-methods, called multi-method approach, it is possible to bring valid conclusions about the case if the sub-methods show the same results. However, if the different methods would not bring the same results it does not indicate that the data sets are wrong but that the case is more complex than assumed. This verification of data from different sources is called triangulation and is a good way to enable the researcher to bring confidence into the research or to question the chosen research methods if the results would be different from each other (Gillham, 2010). This thesis used both interviews and observations with employees at GAS as well as literature reviews and analysis of internal documentation.

Additionally, Bryman and Bell (2011) further explains the use of theory as not only being something that works as a framework for the collection and analysis of data but that theory can be generated from the research's findings of data. The former view is referred to as deductive theory where the researcher develops a hypothesis on theory to precede the research problem. The latter view is referred to as inductive theory and even though the theory in this sense is generated from findings, there are researchers that use grounded theory for their empirical study in order to develop additional theory (Bryman & Bell, 2011). Due to claims that both methods lack the ability to bring knowledge to something new or not already existing there is a third approach to generate theory, namely abduction, with the purpose of study facts and develop theory that explains them (Haig, 2005). This mind-set is used as inspiration when Dubois and Gadde (2002) develops what is called systematic combining that implies that the purpose of research is that the empirical world should confront theory throughout the whole research process. Systematic combining was used throughout the thesis for two reasons. First, there was uncertainty of what theory that was going to be used and by letting the investigation into the case study start in parallel it was then more clear what theory to examine. Second, because of the complexity of process parameter setup in the aerospace industry, theory had to be revisited on how to make appropriate analysis of the case study but as well to come to realization of why certain parameters tend to have an impact to quality (Vallhagen et al., 2011).

3. 2 Research process

The research process (Fig. 12) was launched by first defining the problem; to identify what parameters in the fabrication process that has an impact to the product's quality. However, the problem derives from a complex situation where requirements from the customer are translated into several in-house operations at GAS. To understand what product quality meant for GAS it was first necessary to understand why GAS wants to fulfill certain requirements on product characteristics and then identify their associated parameters. While the definition of the problem was established it was decided together with GAS how to delimit the research by deciding what product that was going to be examined in the case study. From this point, the research process was then decided to continue with creating the literature framework in parallel with carrying out the empirical study through interviews, observations and document analysis. Gillham (2010) prefers this approach because when performing a case study there is a lot of literature that cannot contribute to the project thus it is important to get to know the case while exploring the literature. Lastly, the analysis of data could then link together the empirical findings together with theory by using the conceptual framework as a basis to gain a systematic approach to interpret data (Madrid et al, 2015).

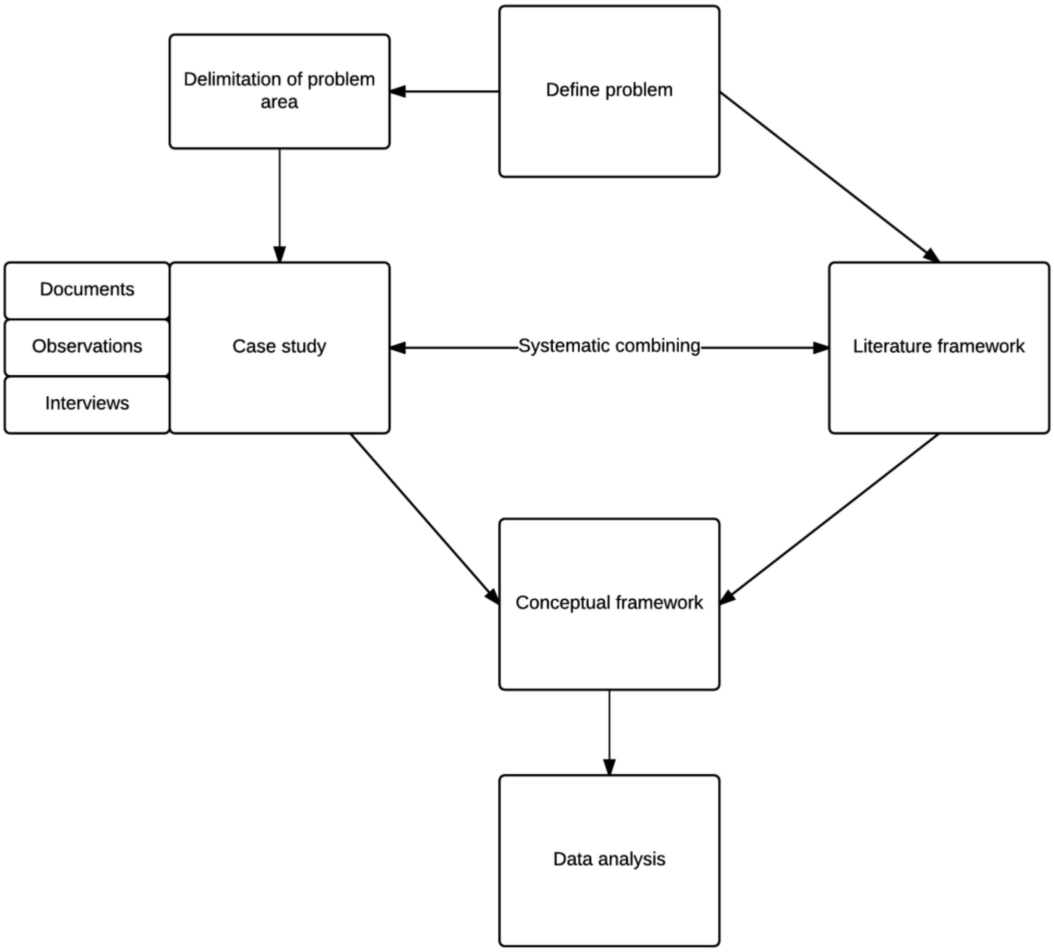


Figure 12. This thesis' research process

3. 2. 1 Literature framework

The purpose of reviewing the literature is to gain an insight into what has already been written about the chosen topic. The literature can also confirm that nothing has been written about the research problem, which reduces the possibility to 'reinvent the wheel'. The literature review can additional bring suggestions in how the topic before has been approached and it could reveal important aspects to consider in the work such as inconsistencies or controversies (Bryman & Bell, 2011).

The first step was to get a broad overview of the topics robust design, quality methods and manufacturing methods. The books and scientific articles were collected both from supervisors at Chalmers and GAS as well as from Chalmers library and from previous courses at Chalmers. The literature study first served as a basis to understand the connection between manufacturing and quality management but evolved to focus more on aerospace industry and specific manufacturing steps (e.g. welding and machining). The review of literature continued by digging deeper into relevant subjects where findings from articles and books lead to the discovery of new sources. Bryman and Bell (2011) also refers to this principle as snowballing sampling, where the literature framework keeps growing like a snowball rolling down a hill.

3. 2. 2 Collection of data

Since the fabrication process of TEC A is complex with several advanced manufacturing steps there was no clear starting point. The uncertainty of where to begin lead to that interviews, observations as well as collection of documents was performed simultaneously to get a broad overview. To assure that data was up to date, there was a constant comparison against reality and documented procedures about the process. This way of triangulation was carried out as much as possible during this thesis to bring consistency between departments at GAS.

3. 2. 2. 1 Interviews

The interview is a widely used method by researchers to elicit information from a person. There are several types of interviewing such as structured, semi-structured and unstructured whereas the difference between each other lies in level of formality (Bryman & Bell, 2011). Which kind of interview method that should be applied depends on what the purpose of the interview is and the one that could lead to achieve the most promising output should be selected (Patel & Davidsson, 2003).

Interviews was first held using the unstructured method to get the opportunity to gain the individual’s own perception of the fabrication process but as well to make the interviewee feel relaxed (Qu & Dumay, 2011). By applying an unstructured interview approach one have the possibilities to ask questions that not are prepared in order to get more information or better explanation of the answer (Scheinberg, 2014). This approach also led to that a broad overview of the topic was gained which was relevant in order to understand the complex system that exists when a product is manufactured. The unstructured interview can be compared to a regular conversation where the interaction between the interviewer and respondent is not regulated depending on rules or similar limitations (Bryman & Bell, 2011). The persons that were interviewed were chosen based on their professional background and availability. What was of significant importance in the research process were that the interviews lead to clues of where to collect additional data.

Semi structured interviews has the purpose of using prepared questions but depending on the answers rearrange the series of questions in order to be more flexible (Bryman & Bell, 2011). Semi structured questions are usually to some extend more general with the purpose of being able to ask more specific questions to significant replies from the interviewee (Bryman & Bell, 2011). Exact answers are usually not expected when applying a semi structured approach. Semi structured question was mainly used when suitable knowledge was created to ask more specific questions and when performing interviews in the workshop. The intention with this was also to create a relaxed atmosphere at the same time as achieving some extend of standardization and structure to get higher reliability.

Structured interviews are the most commonly used form of interviews in business research because of its degree of formalization (Bryman & Bell, 2011). The aim of a structured interview is that all interviewees are going to be given exactly the same context of questioning. The reason for this according to Bryman and Bell (2011) is because of the importance of standardization of the process of measurement. By standardizing the way questions are asked and the way the answers are recorded one make sure that the interviews are properly executed and the answers will capture the real variation of the context instead of variation caused by error (Bryman & Bell, 2011). When performing a structured interview one can decide whether to use open or closed questions (Bryman & Bell, 2011). With an open question the interviewee can respond in its own way and terms while with closed questions the interviewee is presented a set of alternatives and select the best suited. During this thesis structured questions was used later in the work process when enough knowledge and understanding of the product and different operations was gathered. When coming to the stage in the work process when the most relevant process parameters had to be pointed out and exact relationship between different characteristics as well as interrelationship between parameters had to be clarified, structured interviews with open questions was carried out.

3. 2. 2. 2 Observations

Observations were carried out during the whole data collection process of the thesis to understand the fabrication process. Ghauri and Gronhaug (2005) points out the advantages of observations because there is an opportunity to collect information and observe what is happening in the situation that is not possible through a questionnaire for example.

The observations were performed in what Bryman and Bell (2011) refers to as participant observations where the researcher includes him or herself in the social environment that is being studied with the intention to elicit as much information as possible to understand the impact to environment. The observations gained insights about the level of automation that was applied to the fabrication process and how operators executed the craftsman work in the shops. Additionally to this there were several observations made at the office when discussing the product. These observations brought several insights in how the development team worked.

3. 2. 2. 3 Documents

Collecting and interpreting documents can be a time-consuming and complex process depending on its purpose. Documents that are not produced upon the researcher’s request can be both difficult to interpret but as well not being of relevance for the research (Bryman and Bell, 2011). However, as mentioned by Yin (2003) can documents support in the process of verifying information that has been gathered from other sources. There were several documents collected at GAS that was of high relevance to both verify what respondents in interviews explained but as well documents that revealed information about the fabrication process. There were especially three documents that were of significant importance for the thesis. First, the technical requirements contributed to answer to what the customer was expecting from the product (internal document). Second, the drawings of the product was collected to identify how GAS had designed the product and it was by using these drawings that made it possible to understand where the third document, operations lists, origin from. The operation lists contained a translation of the drawings into how each manufacturing step was supposed to be executed and contained inspection descriptions, requirements on product characteristics and certain process parameters.

3. 3 Conceptual framework

Julia Madrid, a Ph.D. student at Chalmers, developed a conceptual framework that worked as a basis for this thesis' methodology. The framework's purpose was to systematically describe how a product's performance is affected by variation that occurs throughout its own fabrication process. Results from these findings could later be followed up by performing a producibility analysis in order to evaluate the quality performance of a product's design solution. The idea behind the framework is to become more competitive by re-using knowledge of manufacturing methods within the company and create a platform to use as a base in future product development programs (Madrid et al, 2015).

Julia Madrid (2015) takes inspiration from several sources during development of the conceptual framework. The literature behind the framework has been covered in chapter 2 in this thesis where the theory behind system thinking, parameter design, key characteristics, KC breakdown, and quality tools together creates a systematic approach to examine different manufacturing methods in order to reach a robust design of a product. The conceptual framework (Fig. 13) first describes a transformation process for one operation in the fabrication process (Fig. 13 a). This is followed up by that the framework describes how this transformation process is a part of a larger system (Fig. 13 b).

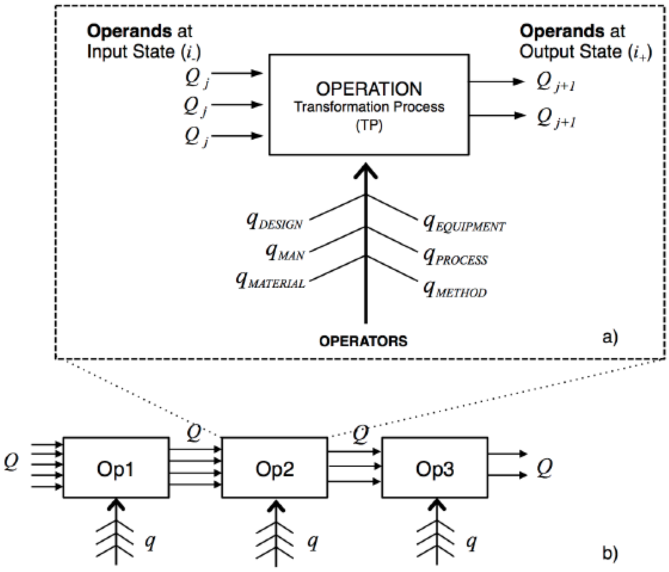


Figure 13. The conceptual framework showing a transformation process in more detail and how it is a part of a larger system (Madrid et al, 2015, p. 4)

The system is a sequential process that contains several transformation processes and describes how they together should result in that final properties of a product are met in the end. The important part is to understand that final requirements are only met if each operation transmits right requirements on product characteristics to its next operation. Final requirements can be from either an external or internal supplier depending on how the researcher is delimiting the scope of the research and this is where the systematic approach of the conceptual framework will start. By subsequently decompose final requirements of the product into product characteristics that each operation produce, it is possible to examine how final requirements are met and assure that inspections and similar procedures in production has a purpose. Simultaneously should each operation be examined to define what the transformation process demands in terms of requirements on product characteristics. Lastly should the researcher identify what factors or parameters that control the transformation process that produce the right requirements on product characteristics and identify these as causes to why variation occur (Madrid et al, 2015).

3. 3. 1 Nomenclature explained

The fabrication process requirements are represented as operands, which are the ones being transformed from an input state to an output state in the operation of the manufacturing step. Operands consist of Qs, which are similar to key characteristics because their significant impact on a product’s final requirements when their value deviates from target. Qs' are highly relevant and important to control in order to achieve right pre-conditions for next operation. To each operation there are operators that can have an impact on the manufacturing step's expected result. Operators consist of qs, which are factors or parameters that due to variation can influence Q's target value and result in operation failure. The operators are represented in the framework as Ishikawa diagrams where factors or parameters with similar nature (e.g. design, equipment) are divided in separate categories (Madrid et al, 2015).

3. 3. 2 Conceptual framework as research method

As previously mentioned, the conceptual framework was used as a systematic approach for this thesis’ work in order to examine the fabrication process of one product. To do this, the initial step was set to identify customer, or general requirements that existed on the product. General requirements of product quality in the aerospace industry were grouped into performance measures and all responded to different disciplines (e. g. aerodynamics, life and weight) and together represented requirements of a jet engine component. Second step was set to trace how those requirements were translated into a design solution that later would serve as a basis for the production department to develop a fabrication process. Last step was set to examine how the production department chose the right manufacturing methods and inspection techniques to secure that each manufacturing step transformed the product characteristics to make it come closer to its final requirements.

3. 4 Data analysis with the conceptual framework

Hennink et al., (2011) describes the analysis of data as a continuous immersion into the study’s data to be able to identify important findings from the interviews, observations and documents and use these findings as evidence to create an understanding of the research problem. Bryman and Bell (2011) emphasizes the difficulties to handle qualitative data because of its tendency to become large amounts of data in different forms. To ensure that the qualitative data analysis is managed with a structured approach there are different guidelines that can support in the analysis even though the field is not as developed as the analysis of quantitative data (Bryman & Bell, 2011; Hennink et al., 2011). One tool that is widely used in qualitative data analysis is coding. By starting as soon as possible with coding the data, there is a possibility to both gain a better understanding of the data and reduce the amount to be more manageable (Bryman & Bell, 2011). The coding in this thesis was performed using the systematic approach from the conceptual framework and by making use of keywords that was already used by GAS.

The first step in the analysis was to review all information that was collected during the initial interviews and meetings in order to identify GAS’ internal terminology of the fabrication process and to identify the logical flow of information that was distributed through GAS. In parallel with this, the conceptual framework’s layout was examined in order to use the same terminology in coding as the founder of the framework.

The conceptual framework was introduced after data collection was completed. The first step by using the framework was to create structure. By assigning each manufacturing step one transformation process sheet and to put them in the right sequential order it brought a good overview of the fabrication process. Remaining data was examined and deployed depending on manufacturing steps and whether or not it was an operand or an operator. If data could not be deployed to the framework it was saved in another document. Lastly, each manufacturing step was explained shortly by means of what place in the fabrication process it belonged, its impact to the product and how quality was assured before and after the operation.

To reduce the risk of the framework to be flooded with text and difficult to interpret, the framework’s content was divided into two parts; informational and explanatory. The former document (see appendix: 1) was the layout of the framework together with operands, operators and each manufacturing step’s parameters. To bring sense into how a manufacturing step transform product characteristics, a numerical system was used where one product characteristic adopted an initial value, zero, to after the operation adopt an incremental value if any changes would occur. The explanatory document (see chapter 4) was developed to contain detailed information about the fabrication process and why product characteristics and parameters have an impact to quality of the product.

3. 5 Research Quality

To evaluate the research quality of a case study both Remenyi (1998) and Yin (2003) lists four different tests that can be carried out. These tests are; construct validity, internal validity, external validity and reliability.

Construct validity concerns whether the research's operational measurements are reflecting the case study or not. To verify that the measurements are properly developed the researcher should chose the type of changes that should be studied and show how they origin from the original objectives of the study. Only then should the researcher show how operational measurements are reflecting the selected change (Yin, 2003). To meet the problem with construct validity the thesis used the conceptual framework and mindset of the P-diagram, which both describes how parameters controls that the process yields an expected result. The verification is done when there is a product characteristic that change when a parameter is varying.

Internal validity verifies if the researchers conclusions about causal relationships between for example factors x and y is justified with considerations taken to if there is a third variable z that can have caused y. Internal validity also considers the research's content of inferences. For example every time there is an event that cannot be observed a researcher have to make inferences where the event resulted from previous occurrences where this conclusion is based on other sources as interviews or documents. To achieve internal validity it is possible to use pattern-matching where empirical based pattern is matched together with a predicted one and the relationship between the two can clarify the internal validity the case study possess (Yin, 2003). This thesis had trouble with its internal validity since there was no time or money to perform design of experiments and therefore new findings on parameters contribution to a products quality was based on qualitative judgments. In addition to this, the research process was conducted through triangulation to have a continuous verification that documents, observations and interviews yield the same results in order to decrease the risk that findings were based on inferences.

External validity concerns if the study's findings are possible to generalize to a broader population then the specific study (Ghauri & Grønhaug, 2005). Whether or not it is possible to achieve external validity in a case study has been a problem whereas several critics points out the poor basis that case studies offer in order to achieve generalization of the findings. However, Yin (2003) explains that case studies rely on analytical generalization whereas the researcher wants to generalize a specific set of findings to some broader theory. External validity of the theory can then be supported by replication of the case study's findings on two or more cases. Even though the case study at GAS is unique, the findings from this thesis will represent quality related parameters from five different manufacturing steps that are used in other products' fabrication process. However, each product has its own design that in turn will contribute to different kinds of complexity when it comes to geometrical variation and weld quality.

Reliability concerns if a study's findings and conclusions will be the same when repeating the case study by using the same research methods as the original researcher (Yin, 2003). Ejvegård (2003) points out the potential risk to have a low reliability because that the original researcher is usually the one that develops the research methods. The purpose with testing reliability of the case study is to minimize the errors and biases that could exist and for a researcher to be able to repeat the case study there is a need of having the original case study's research procedures documented. To mitigate the risk of having a problem with the reliability in the case study it is important to make the research steps operational and to conduct research with the attitude that someone will review your work (Yin, 2003). This research process faces several issues with reliability due to availability. Firstly, since results are to some extent yield through experts with long experience at the company it is important for future researchers to have the same availability to expertise at GAS. Second, work methods are continuously developed and improved at GAS, which could lead to that either documents or observations could change thus leaving future researchers with other conditions. Third, even though the product should be produced for the next thirty years from now, the production will eventually expire from GAS. What has been done to increase the level of reliability is to use already well known research methods and verification processes' to create a comprehensive research process.

4. Results

This chapter provides the results from this thesis. First, there is a description of the case study of TEC A, which is followed by findings on general requirements on TEC A and how requirements on weld geometry are defined and achieved. Additionally, the fabrication process is explained and findings on TEC A's product characteristics and parameters are described in why they contribute to the final properties of TEC A and their impact to quality when deviating from their target values. Lastly the results are presented with the conceptual framework and an interrelationship diagram.

4.1 Product description of TEC A

The product Turbine Exhaust Case (TEC A) is an engine component that is located in the rear part of the jet engine A, just rear of the low-pressure turbine (Fig. 14). The component is a part of the engine's hot structure and is exposed to high temperatures during normal flight conditions. TEC A works as a mounting device to secure that the engine is attached to the aircraft's wing. The component should also work as a load carrier for other systems and adjust the air stream from low-pressure turbine to create efficient propulsion for the aircraft.

TEC A has been under development for several years and is currently under a ramp up phase in production where GAS estimate that TEC A will be produced for approximately the next 30 years, which is in line with the normal product lifecycle in the aerospace industry.

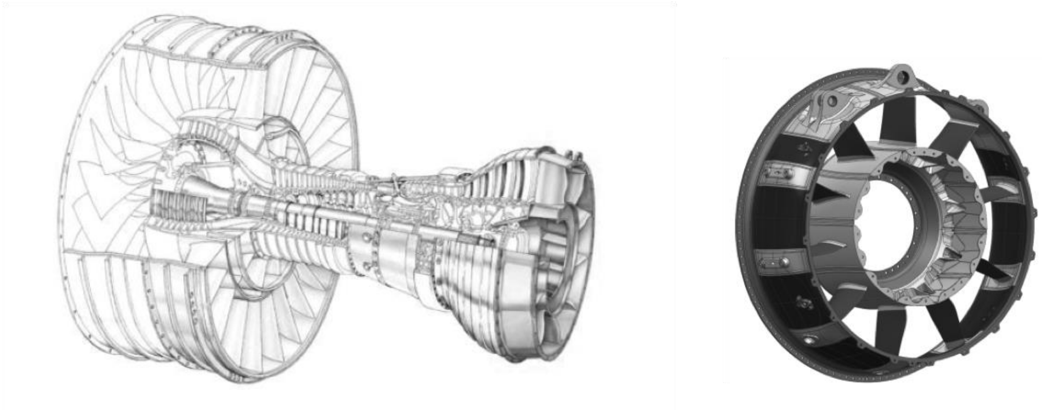


Figure 14. To the left is the engine structure and to the right is the TEC A structure

4. 2 Findings on general requirements for TEC A

GAS developed the requirements on TEC A together with the customer (Internal document). The requirements are based on certifications, certain standards and earlier projects' documentation and together are they representing the inseparable structure of TEC A. The document contains both requirements on TEC A's expected performance as a whole, but as well as a component within the system of jet engine A. GAS uses these requirements as a baseline in product development where each requirement specifies an expected performance on the product (e.g. pressure loads on the TEC A during the jet engines steady-state mode).

To meet the customer's requirements, GAS has to respond by translating these requirements into a design solution. However, product development at GAS is seldom only linked to technical requirements because of cost, lead time and producibility among other aspects has to be taken into consideration to make the production profitable. The TEC A's final design is for this reason a long, iterative process between different departments that shares knowledge and making compromises before all requirements (e.g. aerodynamic, strength and life) are fulfilled (Design engineer 1, 2015-02-17).

The final design solution is translated into drawings that later becomes the basis for other departments' work (e.g. development of operation lists in production). These drawings are justified by a specification (Internal document) that presents why drawing requirements within specific zones has been defined due to certain demands from GAS' departments (e.g. the aerodynamic department).

4.2.1 Findings on how requirements for weld geometry are set

Weld geometry is an important part of development of TEC A's design solution due to its impact on aerodynamic performance, strength, life and interaction with surrounding interfaces. Weld geometry is defined by different product characteristics (e.g. weld bead height, weld bead angle) and to decide upon appropriate weld geometry for a weld zone, departments have to contribute with their special requirements. Weld geometry at GAS is divided in different weld classes (Internal document) where each class has their own requirements on product characteristics of weld geometry. The process of how a weld class is assigned to a certain weld zone at GAS can be described by a simplified flow diagram below (Fig. 15).

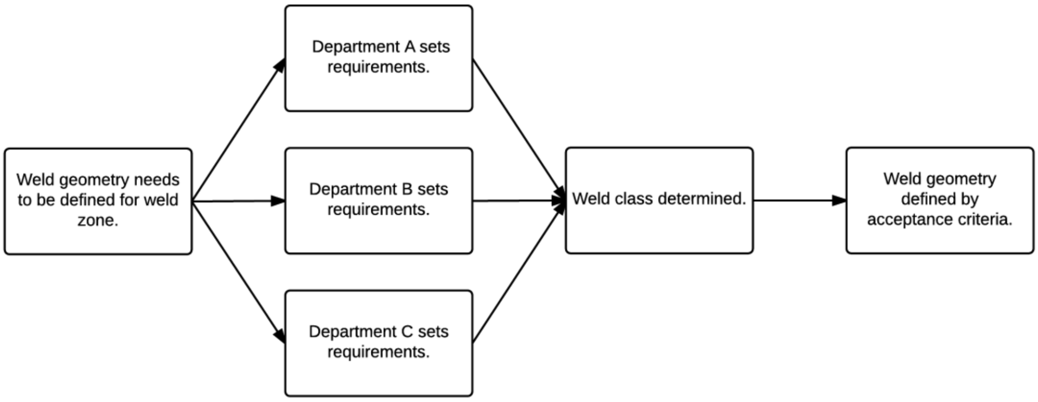


Figure 15. A simplified flow diagram that shows the process of how GAS defines weld geometry for a certain zone of TEC A

For example, the material thickness is an important feature that has to be revised by one department in order to ensure that expected life would be fulfilled. The weld geometry also needs to be revised by the aerodynamic department because depending on different zones of the product, such as inner or outer located weld joints, certain restrictions to metrics have to be done (Internal document). After that a weld class has been defined, the dimensions of the weld geometry can be calculated and engineering designers can assign this weld class to the weld zone in TEC A’s drawings and state in the specification why this weld class has been set. To illustrate this justification an example is given from the specification to why a zone in the drawings of TEC A has certain requirements:

“Requirement number 05003. Sheet zone 05/L8. Welding note of weld E01.Typical for welds E01 thru E10. Requirement set to GTAW method, Class B, Maximum X millimeters. Justification: Class B with restrictions in mismatch and weld geometry needed to comply with life requirement due to requirement 00007, that concerns weld penetration and weld bead radius. Aerodynamic department: weld bead restriction needed for aerodynamic performance due to requirement 00020, that concerns that the weld zone is sensitive to loads and airflow” (internal document).

As shown by the example, requirements on a specific zone (05/L8) are derived from certain disciplines (life and aerodynamics) where there is a method described (GTAW), which have to fulfill a requirement (Class B) with a certain tolerance (maximum X millimeters).

4.2.2 Findings of how to fulfill requirements on weld geometry

To ensure that a weld class will be fulfilled there are method-specialists in welding that explores appropriate welding methods. Engineers' goal at GAS is to develop methods that are robust, with parameters that can withstand certain variation (Design engineer 2 & Operation weld engineer, 2015-04-21). Weld methods for TEC A was based on projects that focused on development of a weld method's capability to weld material with certain properties. The purpose with the project was to provide both TEC A and another product with a weld method that later could be industrialized at GAS (Internal document).

During development there were certain requirements that had to be taken into consideration. First, process requirements for welding had to be fulfilled to ensure that GAS could establish both qualification and process control requirements (e.g. parameters) for fusion welding (Internal document). Secondly, technical requirements from GAS had to be fulfilled during the project to ensure that weld geometry could be achieved in accordance with defined weld classes (Internal document). Lastly, design practice requirements from GAS (Internal document) had to be revised to ensure that factors in a weld method (e.g. robustness, repeatability) were taken into consideration when developing the weld method. The weld method's robustness was verified by testing it with varying pre-conditions (Internal document). The verification of the weld method was then issued through a report consisting of recommendations and conclusions of the results from the project.

After that the weld method had been recommended from the results of the project, weld specialists might adjust the method to fit the products' unique design solution (e.g. geometrical features, fixture setup). This is when parameters' values are set to control that the weld geometry will be fulfilled. To find the right values there are different kind of simulations and trial and error experiments (Operation weld engineer, 2015-04-21). These steps of adjustments during development of a weld method are usually dependent on each product's own design solution and generalization is not common during product and production development.

For TEC A there has been different type of analysis on how the component will deform when it is manufactured with different parameter values (Internal document). These types of analyses should be considered as unique for each product and it is important to be careful when doing generalizations because of each component's geometrical properties has a big impact on how a component will deform (Senior manufacturing engineer, 2015-04-21). Development programs for a weld method are also dependent on surrounding environment of the workpiece (e.g. fixtures) during manufacturing because it is hard to predict how heat will be distributed. However, certain characteristics of a product are less complex than others. Product characteristics that define a product's weld geometry are easier to control because that associated parameters' impact are to a certain extent predictable. Because of this opportunity to generalize parameter settings to weld geometry, it would be a good idea to do further investigations in how parameters affect product characteristics, in order to increase efficiency in product and production development (Senior manufacturing engineer, 2015-04-21).

Lastly, before parameters for a weld method can be applied in production they need to be certified and after this it is not possible to change these unless re-certified. However, certain parameters for a weld method are allowed to be adjusted within a range during production in order to give the possibility to overcome small deviations during welding (Operation weld engineer, 2015-04-21).

4. 3 Fabrication process of TEC A

At GAS, a fabrication process produces the product TEC A where parts are joined together by welding them into a complete assy (Fig. 16). To simplify the design and to end up with a product that fulfill all customer requirements, TEC A was designed by making use of H-sector parts, where each sector acts as a slice of a cake. There are three parts that builds up each H-sector, the inner ring called hub, the outer ring case, and the vane, which connects the two parts. There are two types of H-sectors, mounts and regulars, where their case parts have different geometrical shapes and functionalities for TEC A. These H-sectors are afterwards welded together with case plates to form an assy.

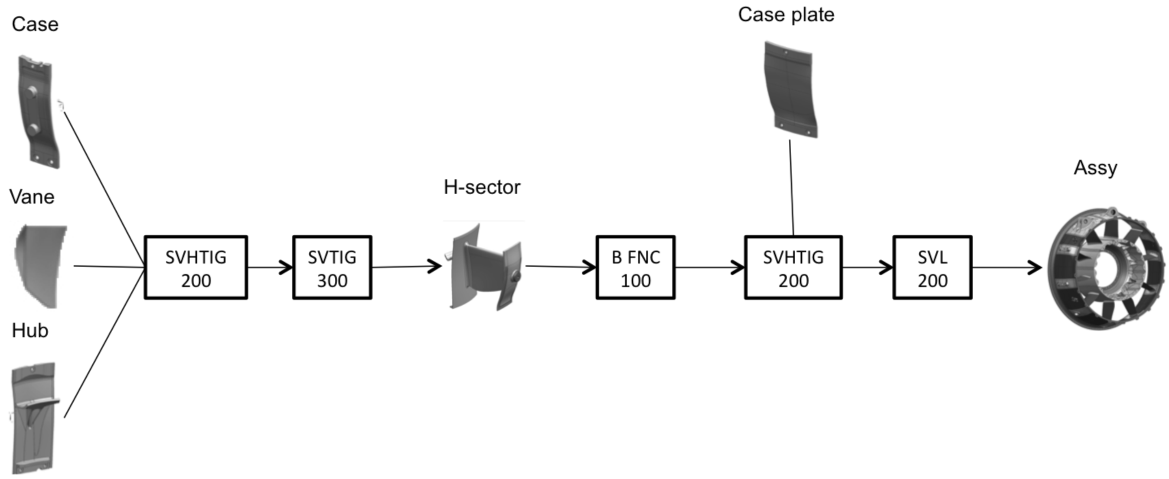


Figure 16. The fabrication process of TEC A including different manufacturing steps

The complexity behind the fabrication process of TEC A is that all parts have to be welded together. Due to deformations during welding this is not always an easy task because when one part deform, it will be difficult to use it in an assembly due that the part's geometrical features has changed. Another reason for the complexity has been crack propagation. During inspections in production of TEC A, components appear to contain porosity or cracks. Both deformation and cracks leads to rework and the development team tries to reduce these problems from occurring in production with efforts made in both manufacturing as well as changes in the design solution. For instance, in one of the weld methods in production there have been tests on how a weld's pulse factor will have an impact to crack propagation. Another improvement has been that from simulations, there have been compensations made in the design solution to avoid problems with deformations of the component. These types of improvements in how to overcome non conformances on TEC A's product characteristics are continuously executed by the development team to secure that production of TEC A has as low cost and high quality as possible. These changes are documented at GAS and results are followed up when inspection data is available. However, there is a trade-off between cost and improvements to increase automation. A requirement on one of TEC A's product characteristics is that no weld spatter is allowed. This is a common problem after welding but an easy task for an operator to remove afterwards. The reason for not investigating further in how to reduce weld spatter is because in order to make a method that robust is not cost-efficient when a problem is easy to overcome (Project engineer, 2015-02-16).

In each manufacturing step, parameters are set to secure that TEC A will be produced with fulfilled requirements on product characteristics. At GAS, there is a lot of knowledge and experience of parameters contribution to product characteristics similar to the pulse factor's impact to cracks. However, certain parameters' impacts to product characteristics are not always known. If there is no problem with a product characteristic, an investigation of how parameters affect a product characteristic is not always done (Technology and production engineer, 2015-04-23). What is of importance is that requirements are always fulfilled before a component is delivered from GAS and the solutions made for production to increase producibility has been developed by a long process of small continuous improvements with simulations and trial and error experiments. To capture these improvements and decisions on how to create a production that fulfill requirements and then apply same solutions for other products at GAS seems difficult. There are several years behind the product and production development of TEC A and to answer to all different demands for only TEC A are based on experience and skills on how to approach each problem (Project engineer, 2015-02-16).

Each manufacturing step presented below is a part of the fabrication process of TEC A and findings are based on observations, interviews and operation lists (internal document).

4.3.1 OP 200 SVHTIG – Manual TIG welding of a H-sector

The first operation is manual tack welding of three parts, hub, vane and case. These parts are delivered from suppliers and are not being treated in any way before this operation. The purpose of the operation is to tack the parts together by using the TIG welding method and the result aims to be without any misalignment and without gaps. The operation is performed with all three parts placed in a fixture. The vane is tack welded towards the hub and case, with a recommended weld sequence in order to spread out stress and to get as little deformation as possible and to get less part-to-part variation. The longer and deeper welds, the more heat input and this leads to more deformation of the component.

The hub and case are put in the fixtures and the vane is adjusted between them to have the best fit with hub and case. The fitting of vane is highly operator dependent and the operator needs to adjust several screws to fit the three parts together. By visual inspection and by using feeler gauges to measure the amount of flush, the operator decides when a good fit is achieved. These adjustments of the operation is an unwanted task that GAS wants to reduce to as large extend as possible in order to reduce operation time as well as variation. An issue is to find the right balance, between putting tight tolerance leading to higher cost versus loser tolerances, which is cheaper but requires more operator dependent work, in order to fulfill requirements on characteristics. Different areas of the vane have different requirements on characteristics such as flush requirements, which have to be tighter within certain areas in order for the product to fulfill customer demands. Since two main types of H-sectors are produced it also exist two different fixtures, one for the regular type and one for the mount type where the mount’s fixture is harder to handle.

4.3.2 OP 300 SVTIG – Robot TIG welding of a H-sector

The robot TIG welding operation aims to completely fuse hub, vane and case together to form an H-sector, which is shown in figure 17. The goal is to have a H-sector with as small deformations as possible and have complete penetration of the weld joints. Since the thickness of the material that is welded has a constant thickness, the weld joint has a narrow radius as well as the thickness is below a certain measure, TIG is the most proper weld method. Even though TIG welding is a low intensive weld method resulting in more heat input and therefore more weld shrinkage and deformation the benefits such as cost and robustness of weld method outweighed the disadvantages. In order to end up with the proper geometrical dimensions, there were simulations done to compensate for weld shrinkage.

Figure 17 A reg. H-sector completely welded

The first step of the operation is that the H-sector is placed in the fixture, using the locating scheme. The fixture is itself placed within a gas chamber to get an oxygen free weld environment. Due to weld shrinkage and deformation the weld sequence always starts from the outer weld joint, vane to case in order to know the exact position of the inner weld joint when that joint will be welded. Critical parts of the operation are the start and stop position at the trail edge as well as the leading edge due to its narrow radius. The trailing edge is after the robot operation welded by hand to get complete penetration and good weld joint shape.

The H-sector robot weld operation is performed by TIG welding, which is a robust weld method when it comes to geometrical variation in flush and gap. This is due to that TIG welding results in a wide weld joint, which leads to that the material will fuse together even if the parts have gap and flush deviations. However, TIG welding is sensitive when it comes to thickness variation, which also is the most common cause leading to weld defects of this operation. Thickness variation leads to that the temperature in the weld joint will be affected resulting in either incomplete penetration if the material is thicker, or an underfilled weld joint if the material is thinner. Furthermore another important aspect is the way the filler material is fed into the arc weld, which cause variation to the operation. The filling material feed is a critical parameter causing variation to the process.

4.3.3 OP 200 B FNC – Machining of a H-sector

Machining operation of the H-sector has the aim to get good geometrical fit in the next weld operation and to shape the sector edges to nominal value. Previous weld operations results in that H-sectors become deformed. By applying three-sided machining, one can locate the exact position of the product, which makes it easier to fit them together without flush and gap and to fulfill requirements. The operation performs a three-sided machining and also drills holes for new locating schemes for next manufacturing step. The operator put the H-sector in the fixture and there are different fixtures for regular and mount types. The H-sector is locked in its locating scheme and the rest of the part is carefully fixed by the operator in order to not force the sector in any direction. Mounting the sector in the fixture is very operator dependent when the part has to be fixed and it has to be remounted quite frequently to get in a good position. The operator needs to ensure that the part is not being forced in any direction when fitting it in the fixture, resulting in that the H-sector will be machined in the wrong way and therefore not fulfill nominal geometry requirements. Important for this operation in order to succeed is to ensure that both edges at the case part of the sector will be milled at all three sides to get the right measures and to increase the possibilities for the following weld operation to succeed.

4.3.4 OP 300 SVHTIG – Manual TIG welding of 360 assy

The purpose with this operation is to tack H-sectors together into one complete assy with as little gaps and flush as possible and to get a good geometrical fit (Fig. 18). This operation is done through manually TIG welding and is therefore operator dependent. Gap and flush is highly important to decrease as much as possible to ensure good preconditions for the following laser welding operation. Regular H-sectors and mount H-sectors are put together with case plates and are mounted into the 360 fixture.

Figure 18. Complete assy with H-sectors and case plates

Most critical part for this operation is the alignment procedure performed by the operator. Alignment is very operator dependent since all adjustments are done manually to ensure good alignment. If the fit between parts not are good and requirements on characteristics not are fulfilled, the operator will coldform the pieces into the right position. This tack weld operation takes several hours for an operator where adjustments and forcing the parts together takes a large amount of time. In order to optimize costs to as large extent as possible it has carefully been considered the best optimization of tolerances from suppliers together with the amount of working hours for an operator. To decrease tolerances on the case plate or to machine the parts at GAS would result in increased costs compared to wider tolerances and more operator work.

To receive an alignment between different parts an operator has to adjust screws until a good fit is received of the H-sector. For alignment between different parts the operator has to force parts to fulfill right flush requirements, which also is the most critical part for this operation to fulfill requirements on product characteristics to the following operation. A recommended weld sequence is followed. This is because GAS wants to avoid tensions to as large extent as possible.

4.3.5 OP 300 SVL – Robot laser welding of 360 assy

The complete welding of 360 assy is performed by laser robot welding with the purpose to completely fuse joints together. There is big thickness variation along the weld joints resulting in that certain weld methods (e.g. TIG welding method) is no longer an option. This makes laser beam welding to an optimal method. This is also due to its speed since long distance of weld joint will be performed within this weld operation. Disadvantages such as problems with pores in start and stop zones, due to opening and closing of keyhole is neither a problem because those areas will later be removed. The first step is to put the sector in its fixture and weld spatter protections are mounted on to the assy and then placed in a gas chamber to get an oxygen free weld environment in order to reduce oxidation on the weld joint. Start and stop position is critical during laser welding due to keyhole is created and closed. A certain weld sequence is performed in order to spread out stress to as large extent as possible and to avoid deformation but also to get a symmetric shape due to weld shrinkage. Important requirements on product characteristics are weld geometry and weld quality (e.g. no cracks) but also geometry where inner and outer diameter of the product is vital.

4.4 Findings on TEC A's product characteristics in the fabrication process

During the fabrication process of TEC A, each product that is being manufactured has to fulfill several requirements on product characteristics before it can proceed to next manufacturing step. If these requirements deviate from their target values or exceed their limits, it will lead to additional actions (e.g. rework). In this section all product characteristics that have a requirement will be presented. The characteristics are grouped into two different categories, weld quality and geometrical dimensions. Which characteristics that belong to which operation can be found in the process map (see appendix: 1). Several characteristics belong to more than one manufacturing step and therefore a general description of each characteristic is presented, followed by a more detailed description about characteristics in a certain operation, if it exists. The description will contain information of why a characteristic exists, what requirements (e.g. aerodynamics) it derives from and how it will be controlled during production.

4.4.1 Weld quality

All weld joints are inspected after each weld operation both by visual inspection as well as by geometric measures. Visually inspection occurs in order to determine surface defects of the weld joints and to assure that desired weld quality is achived. The inspection includes control of joints according to their weld geometry as well as other purposes (e.g. oxidation). Below is an explanation of the different product characteristics. Measurements of weld geometry will be done during or after each weld operation in order to ensure that the characteristics are fulfilled, regarding geometrical dimensions, before leaving that certain operation. The operator is controlling most of the measurements while some characteristics cannot be controlled during production and are therefore verified during product development phase to make sure they are fulfilled.

4.4.1.1 Oxidation

Welds are being visually inspected after each weld operation to see if they are oxidized, which is a negative characteristic. The purpose is to ensure that no oxidation exists on welds, which will be controlled by checking the color of the welds. Oxidized welds will appear colorful. If the welds are oxidized the melting temperature will be significant higher compared to if it is not oxidized. If the welds are being oxidized in the tack weld operation the following weld operation will then have problems to consume the tack and the material will therefore not melt completely. This can lead to incomplete fusion, which in turn results in that fatigue of the weld will increase as well as the life length of the weld will be significantly reduced. If oxidation occurs it has to be removed by grinding away oxides before entering the next weld operation. In order to work proactively with removing oxides an operator is always grinding weld joints after each weld operation to get rid of oxides. Decreasing the oxygen level in the weld environment can minimize oxidation. This is usually done by adding a gas mixture to the weld environment, which is done either in a gas chamber, or by a steady flow of gas on both the top and root side of the welds.

4.4.1.2 Smooth transition

After robot welding operations it is of high importance that the weld to the parent material is smooth and that there are no sharp edges or any notch in the weld (Fig. 19).

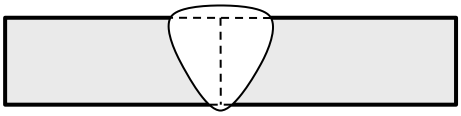


Figure 19. A weld joint with smooth transition

This is important due to that stress going through the material will be collected at those points where there are sharper edges which will result in bigger risk for crack propagation. If the transition is smooth, GAS will ensure that durability and life length of the weld is kept to meet requirements. The smoothness transition is controlled by visual inspection but could also be done through measuring the angle between the parent materials towards the weld joint. This angle is called weld bead angle and will be explained later in this chapter. The visual inspection occurs to detect if deviations from the natural weld joint geometry occurs and if so, further control inspections has to be performed. In the robot laser welding, a weld joint with sharp edges is created that can have a high peak in the center of the weld joint and with deeper valleys at the sides. To overcome this problem GAS performs an additional step in the operation to give the weld joint a more appropriate shape.

4.4.1.3 Weld spatter

After weld operations the component is visually inspected regarding weld spatters, which is a negative characteristic. Weld spatter are small metallic parts that are spattering around the weld joint when the metal is in liquid form. Weld spatter gets stacked besides the weld joint and is an unwanted characteristic due to that the weld spatter can break free during use of the engine as well as have negative impact on aerodynamics. By grinding the material after welding weld spatter will be removed. Weld spatters is not a critical characteristic in that sense that it will have significant contribution to decrease the durability of the product it will rather affect the aerodynamics in a negative way. Weld spatter is most common for weld methods resulting in keyhole welding such as laser welding which is used for 360 assy robot welding. Weld spatter rarely occurs when TIG welding is performed which is the case for tack welding and robot welding for H-sectors. For the robot 360 welding weld spatter protections are mounted on the assy to reduce the amount of weld spatter on the product. As mentioned earlier, weld spatter is not a critical issue and not under investigation of how to reduce or eliminate its occurrence.

4.4.1.4 Fusion

Full fusion of materials is vital in order to fulfill the right durability and life length requirements. The definition of full fusion according to GAS weld specification is that fusion shall be complete and uninterrupted at all facing surfaces along the complete weld length of the weld (Internal document). More specifically this means that both the edges of the parent material have to be covered by the weld and fully fused together. Incomplete fusion could occur in several ways, alter all if the root side of the weld is decentered and as a result of this the edges of the parent material are not fused together. This defect could be detected through visual inspection. However it is worse if incomplete fusion occurs internally in the weld. An example of this could be that the weld has a thinner waist compared to the top and root side of the weld and that the waist is decentralized resulting in that the weld joint does not fuse the two parts of the parent material together. An incomplete fusion of the two materials like this is impossible to detect through optical inspection and could only be detected through volumetric inspection methods or through laboratory cut up. Figure 20 shows an example of incomplete fusion.

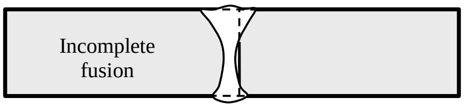


Figure 20. Incomplete fusion, internally

In order to ensure that incomplete fusion does not exist internally during production carefully studies has been carried out in a development phase where one can prove that the selected method and parameter settings will result in full fusion and fulfill specified requirements regarding depth of fusion. Because of those verifications done in the development state it becomes difficult to make any major changes in parameter setting due to that one does not exactly know how the weld joint geometry will be affected and one can neither inspect all characteristics of the weld joint.

Depth of fusion is defined as the smallest width from the centerline of the joint between the parent materials to the end of the weld joint and is a highly important measure when it comes to the durability of the weld joint. How depth of fusion is measured could be seen in figure 21 below.

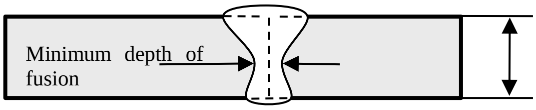


Figure 21. Measurement of minimum depth of fusion within the weld joint

The depth of fusion is one example of measures that is controlled in preproduction in order to ensure that the requirements are fulfilled. During development of parameter window GKN verifies that the specific parameter settings meets requirements on fusion since depth of fusion might be located in the middle of the weld joint and can there for not be inspected during production.

Parameters that affects full fusion of materials and depth of fusion are those parameters that are connected to heat input, where lower weld speed or higher weld effect will increase the depth of fusion as well as full fusion. However by increasing the heat input one will also increase the risk of pores as well as deformation and weld shrinkage will increase. Of highest relevance when it comes to production to get full fusion of materials, and especially for laser welding where the weld joint is thin, is to have a centralized hit of the joint. Centralized hit of the joint increases the possibility to get full fusion of materials and that the depth of fusion is equal into both parent materials.

4.4.1.5 Penetration

Complete penetration is vital in order to fulfill the requirements of durability and life length. Ending up with welds that has incomplete penetration is unacceptable and leads to that the piece has to be re-welded to meet requirements. By inspecting the root side of the welds, which is the most critical place when it comes to complete penetration, one can ensured that the weld has penetrated through the whole material thickness (Fig. 22). Variation in penetration will be shown on width and height of welds at the root side as well as on the height of the weld on top side where lower top side indicates better penetration.

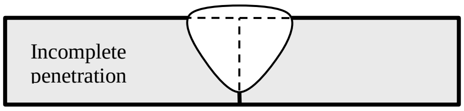


Figure 22. Weld joint with lack of penetration

There are several parameters leading to the degree of penetration. The most common parameter contributing to incomplete penetration is the variation of thickness in materials and this especially for TIG welding, which is sensitive to thickness variation. When the material becomes thicker it is harder to ensure complete penetration due to that the weld effect and weld speed is adjusted to give perfect penetration according to a certain thickness of the material. Furthermore another characteristic connected to thickness is the height of tack welds. Too high tack welds can lead to insufficient penetration and this especially when it comes to the areas where the material is thinner, which is more critical due to height variation. Variation of thickness of vanes occurs where the weld joint along the vane is placed. In order to have the same thickness along the vane surface between hub and vane parts and vane and case parts, the weld joint height on the inside of the vane is grinded away before tacking it together to an H-sector to ensure the same material thickness.

Parameters that will have impact on the degree of heat in the weld joint are also of high relevance when it comes to the degree of penetration such as higher weld effect and lower weld speed. Those will result in deeper penetration but this has to be weighed against the degree of underfill that will occur due to that the heat impact gets too big. Another parameter that also will have effect on the degree of heat in the weld but that is not as vital is the amount of filler material. Since the filling material will have a cooling effect on the weld joint, the more filler the lower temperature. For weld techniques such as TIG welding, which is used for tack welding and the H-sector robot welding the quality of the electrode will have impact on the heat. The quality is affected if it gets oxidized or if weld spatter will occur. For laser beam welding the focus of the laser beam can be adjusted which will have an effect on the intensity in the keyhole that is created by the laser beam.

Weld sequence is another parameter that to some extent has impact on the heat of the weld joint. The later into the weld operation, for example in a robot welding, the temperature of the product gets higher due to the heat from the previous weld joint that have been made at the product.

4.4.1.6 Cracks and porosity

Cracks and porosity are controlled through visual inspection of the surface of the weld joint after each weld operation. Cracks and pores are allowed to exist to some extent however they have requirements and are then allowed if they have smaller diameter than a specific measure as well as if they not are placed in close clusters with certain distance between each other. However pores are not allowed on the surface of the weld joint. One common cause resulting in pores and cracks is if the material is dirty and greasy. This will be prevented through cleaning of incoming parts. Pores are also much more common for laser welding compared to TIG welding. For laser welding pores are one of the key issues and a big part, of the parameter optimization, for this process is about to get a weld joint with as few pores as possible. The reason for that pores are existing for laser welding is that a keyhole is created through the material where the focus point of the laser is, which results in that pores are being created around the keyhole area. Especially critical when it comes to occurrence of pores is when the keyhole is being opened and closed at the start and stop of the weld joint. At the stop position small pores are being sucked within the material when the material goes from vaporized to solid state making those areas more sensitive to pores occurrence. Worth mention is that it is showed that pores will not have a significant effect on crack propagation if it has certain sizes and distance from each other. Cracks will have a big impact on the durability and life length of the weld joint and are mostly expanded and created by thermic loads.

Parameters that will have impact on the amount of pores in the laser welding operation are primarily the pulse factor, which means the difference between high and low power effect. The bigger difference between high and low effect results in fewer amounts of pores. Furthermore, if the material becomes thicker, then the pulse factor also has to increase in order to get rid of pores. However, higher pulse factor leads to a more aggressive weld joint geometry with higher peak and lower valleys making it less likely to meet requirements such as weld height and minimum radius of undercut as well as radius of underfill. Moreover, by cleaning the joint to remove grease and dirt before welding will reduce the risk of getting pores and cracks.

4.4.1.7 Undercut

Welds are controlled after each robot operation regarding if they have any undercut, which is a negative characteristic. Undercut is when the weld joint has a sharp edge towards the parent material as shown in figure 23.

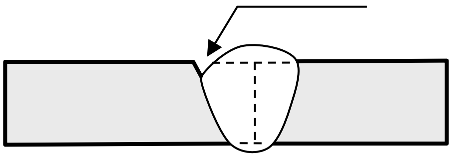


Figure 23. Weld joint with undercut

If the weld joint have an undercut, this will have significant impact on the life length and stress requirements as well as on fatigue and crack occurrence. An undercut weld joint will be more exposed for tensions and stress that goes through the material will be collected at those points and therefore much more likely that cracks will appear in those areas. Undercut appears besides the center of the weld joint next to the parent material edge and it is controlled through measuring the radius at the bottom of the undercut, which have to be above certain measures. Flush is a characteristic leading to that one will end up with undercut. Another cause for undercut is decentralized hit of the joint, both for manual as well as for robot welding. If the scanning is improperly done the weld joint will not be centralized over the two parent materials and therefore leading to undercut because of that the heat focus will not cover the both parent materials and be able to fuse both edges together. For the robot 360 weld operation undercut is allowed, however the radius that is created has to be above some specific metrics in order to ensure that the right requirements are meet regarding tension, durability and stress. Undercut is controlled by visual inspection firstly and if any undercut occurs machine measurements has to be done, by making a wax footprint. If the undercut is outside tolerance limits one has to adjust the undercut which is done by a manually operation.

Parameters that will have impact on undercut are those connected to heat input to the HAZ as well as variation in material thickness. For the H-sector robot TIG welding, the filler material speed is highly relevant due to that it is both affecting the heat input of the weld joint as well as the amount of material that is added to the joint. The less material added the bigger risk for undercut since it will be higher temperature and less material added.

4.4.1.8 Weld width

The widths of the tack welds are highly relevant to control in order to ensure that it not exceed the specified measure. If tack welds are too wide one will end up with that whole tack weld might not be consumed in the following robot weld which in turn leads to that the durability as well as life length will be significantly reduced. This due to that one will end up with an edge between the tack weld and the final weld joint, which will be exposed to stress and increase possibilities or crack propagation. The final weld should be able to completely consume and cover tack welds to ensure right weld quality. The control inspection of width should be performed by using feeler gauges as well as by visual inspection in the following weld operation to ensure that the whole tack weld is consumed. The width of tack welds is operator dependent and not really dependent by other parameters.

After the robot welding operations the width of the weld is controlled to ensure that all tack welds are completely consumed and that the weld fulfills minimum weld width, this in order to get good fatigue and life length performance.

The weld with on top side, depth of fusion and weld with of root side has a strong connection. By ensuring that the weld width of top side and weld width on root side fulfills specified requirements one can be sure that the depth of fusion also meets its requirements. Parameters that have influence on the width of the weld joints are first of all those that are affecting the heat in the weld joint such as speed and power, the higher temperature the wider weld joint. Moreover different weld methods will give different width of welds where high energy intensive methods such as laser beam welding will give low heat input and narrow weld joint.

4.4.1.9 Length of tacks

This characteristic has not significantly high relevance due to that the weld length will not have significant impact on the characteristics of the next operation. However the longer tack welds the more heat input to the material, which can lead to deformation if they are extremely long. However the length is not seen as a critical characteristic for achieving good results in the following operation. The inspection method for controlling the length of tacks is by using feeler gauges.

4.4.1.10 Weld height

Weld height is measured from the surface of the parent material to the top of the weld joint and should be below a certain value to fulfill requirements (Fig. 24).

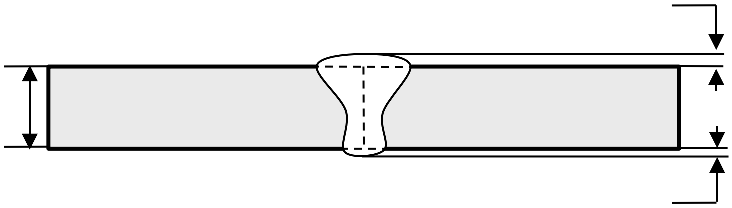


Figure 24. Height of weld joint, both top and root side

However if it is too low below the material surface it is being classified as underfilled. If the weld joint is too high this will have negative impact on aerodynamics as well as it leads to that the weld bead angle increases which leads to durability and life length will decrease. Too high welds are manually grinded away until weld height requirements are fulfilled. The weld height is highly correlated to several other characteristics such as the degree of complete penetration where uncompleted penetration results in higher welds. Gap is another characteristic that lead to decreased weld height since the gap requires more material to fill and therefore lower weld joints. Gaps also results in higher temperature of the weld joint due to that less material is within the HAZ. The inspection method for controlling the height is by feeler gauges.

One of the parameters that are influencing the weld height most is the speed of filling material to the weld joint. The more filling material added to the weld joint the lower temperature since the filling material will have a cooling effect. Other parameters that will have impact on the weld height are altering all those that are connected to heat input such as weld effect and weld speed. Heat of the weld joint is highly relevant since if the temperature do not get high enough his leads to insufficient penetration and more material will be located on the top side of the weld joint and not flow down to the root side of the weld joint. This since one is always welding with the material perpendicular to the gravity field. For the laser welding the parameter that affects the weld height most is the pulse effect. The bigger difference between high and low effect the more aggressive weld geometry resulting in higher weld peak.

4.4.1.11 Underfill

Weld joints are controlled regarding the degree of underfill which is a negative characteristic (Fig. 25). Usually weld joints are allowed to be underfilled with a height of 10 percent of the material thickness. Underfilled welds results in lack of durability and fatigue requirements due to that those areas will be more exposed to stress tension as well as the material will be thinner in those areas. Underfilled welds are not allowed at all in certain areas where the parent material already has minimum thickness due to durability requirements or if requirements are set to be tighter. Underfilled weld joints are only critical when it comes to complete welding and not for tack welding. In order to control whether or not the weld joint is within the requirements or not an operator measure this with feeler gauges.

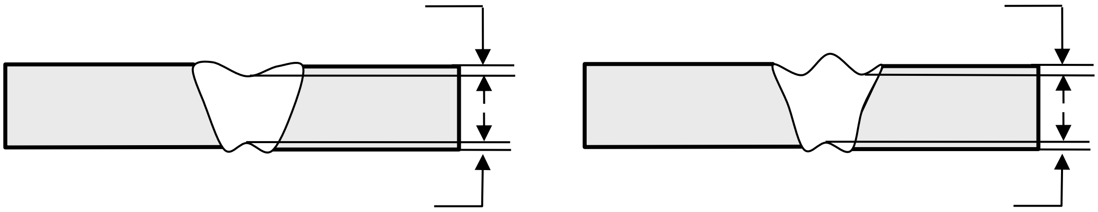


Figure 25. Underfilled weld joint on a TIG operation (left) respectively on a laser operation (right)

Underfilled welds can be caused by many different factors both other characteristics as well as by parameters. Gap is one important characteristic adjusting the degree of underfill. The bigger gap between the two parent materials the more material is missed to fuse the gap together, which leads to larger underfill. Furthermore larger gap also leads to less material will be exposed for the weld focus and therefore resulting in higher temperature in the HAZ.

Another characteristic having impact and leading to underfilled weld joints are flush between the two parent materials. Flush leads to that the piece of material located higher than the other will be exposed to more heat and the liquid metal at the center of the weld will therefore create an uninformed weld joint, which is underfilled.

Different parameters are also affecting the degree of underfill where heat input is the one that is most important. When the weld joint is welded this is done by the weld tool from above in a vertical plane. When more heat is applied to the weld joint this results in that the liquid metal will flow towards the root side of the weld joint by gravity and create underfill on the top side of the weld joint. Parameters leading to increased heat in direct sense are lower weld speed and increased weld effect. Both these parameters are steady during production but have impact on the degree of underfill. The most common parameter leading to underfilled welds during production are variation in material thickness. If the material is thinner at a certain point this leads to that the material will be penetrated completely quicker which in turn leads to that the liquid metal will flow to the root side of the weld. Other parameters that vary during production are quality of weld electrode and focus of laser beam. Weld electrode does only include TIG welding and laser focus only includes laser beam welding. Both of those parameters are however leading to that the concentration of heat input to the weld joint is affected leading to different degree of underfill. In which extend electrode quality and laser beam focus matter could be read below under the description of each parameter. Moreover for laser welding underfilled joints are more common since the weld shape of the top side is different where one ends up with one centralized peak and two valleys on the sides. Those valleys need to have a minimum diameter in order to achieve requirements regarding fatigue and crack propagation. By adding a cosmetic weld over the final weld joint one can smoothening out the aggressive weld geometry.

4.4.1.12 Flush

Flush is the offset between the two different parent materials surface and is shown in figure 26.

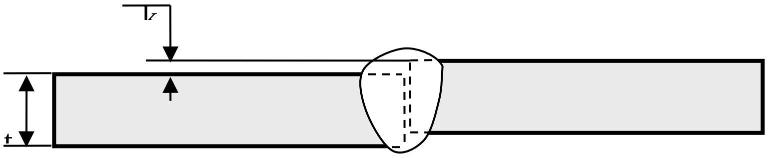


Figure 26. Flush on a but joint

Different flush requirements are set at different areas of the weld joints. Usually the more loads the part or weld joint is exposed to the tighter tolerances in order to ensure that the right requirements are meet due to durability. There are also different tolerances on flush when it comes to different thicknesses of the material. Thinner parts have tighter tolerances due to that the material has to fulfill load requirements and have enough weld area towards each other. Flush between the parts also has negative effect on the geometrical form of the weld joint, which can result in that the root side of the weld joint will end up with a geometry that is not smooth or that the weld bead angle is too small. Depending on which weld technique that is used one will be more or less sensitive to variation. TIG welding is fairly robust when it comes to flush variation however laser welding is more sensitive. This is due to that the shape of the weld is highly dependent on how the material will flow together after the keyhole of the weld. Flush results in an unsymmetrical shape of the weld joint.

4.4.1.13 Gap

Gap is the distance between the two edges of material that will be welded together. Gap requirements are controlled because of several reasons. If the gap becomes too wide this can result in several failures such as underfilled weld joints or that the weld does not end up within the specified geometrical requirements regarding depth of fusion and as well as other geometrical dimensions. Furthermore for certain weld methods, such as laser welding, gap requirements are more important in order to be able to achieve a good weld result. Since the weld joint is much thinner for laser compared to for example TIG welds the gap then has to be smaller to get enough fusion from both parent materials and to fulfill the requirements from depth of fusion. Within certain areas exposed to high loads, such as the weld joints at the mounts and front side of the vane, gap requirements are tighter in order to fulfill crack propagation and life length requirements (internal document).

Worth mentioning is however that the geometrical dimension change, caused by gap, that exists after tack welding is to some extent reduced when the weld joint is finished due to weld shrinkage. Weld shrinking exists because of that the molecular composition in the weld joint is much more compact leading to that the length or diameter of the product will be reduced after the complete weld joint is done compared to when just the tack welding is performed.

Gaps are however to some level making the work faster and easier when it comes to robot welding. During the robot welding the robot identifies the joint that is going to be welded before performing the weld joint. If the gap becomes too small and there for hard to see hard to see, this result in that the robot scanner might have problems identifying it. This in turns leads to that the joint has to be identified manually by the operator.

4.4.1.14 Weld bead angle

Weld bead angle is defined as the angle between the parent material and the weld joint (Fig. 27). This angle is critical when it comes to crack propagation. The smaller angle the bigger risk for cracks and this due to that material stress will be gathered in areas where there are sharp edges.

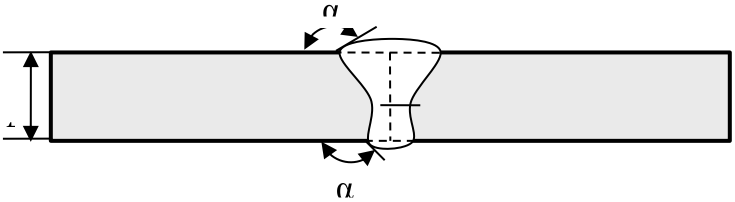


Figure 27. Weld bead angle on top and root side

The minimum weld bead angle that is allowed depends on the classification on that certain weld joint. The weld bead angle is hard to measure in production and is therefore usually controlled during development phases where one ensure that the weld setting can fulfill requirements when it comes to the weld bead angle.

The weld bead angle is closely connected to the height of the weld joint as well as to the degree of penetration. Therefore it is controlled by parameters that are affecting the temperature of the HAZ and where the filling material speed is of high importance since higher speed will lead to more material in the weld joint and there by higher joints.

4.4.1.15 Overlap

Overlap is when the weld joint becomes overfilled and the fluid metal flows out over the parent material and creating an overlap without full fusion of the complete weld width, which is shown in figure 28.

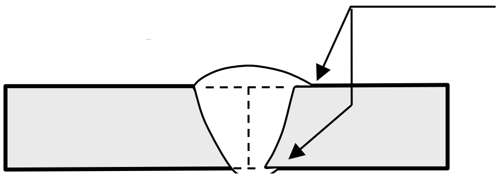


Figure 28. Overlaping weld joint on both top and root side

Overlap is usually not possible to detect by visual inspection on the component due to that the surface usually looks smooth. Due to this overlap is controlled by laboratory cut up and assessment of test pieces for the approval of welds. Because of this carefully studies are performed during the development phase where one can prove that the parameter settings will not result in overlap. After those test are performed and parameters are given specific values it becomes hard to make any major changes and adjust those parameters.

4.4.2 Geometrical dimensions

In order to end up with an assembly that will fit well together and that all interfacing parts are fitting together towards each other, geometrical dimensions have to be fulfilled on different parts. There are several different dimensions that are critical in order to ensure that the final assembly will end up with good conditions and that the expected output is created from the final operation. The machining operation has the purpose to getting back to a geometric dimension that is under control and knowing the exact position of the workpiece. Geometric dimensions or geometric characteristics and their change during each operation could be found in the process map (see appendix: 1).

4.5 Findings on TEC A's fabrication process' parameters

Below are parameters that influence the fabrication process' product characteristics. The parameters are being grouped into Man, Machine, Milieu, Method, Material and Design, which are different, groups of parameters that have effect on TEC A's product characteristics.

4.5.1 Man

Parameters that are man dependent are those that are being affected by the operator itself during production and are causing variation to the output, which means the product characteristics. Those parameters can be varying from operator to operator or even from part to part depending on the operator procedure. One want to decrease this variation to as large extend as possible to get as little variation as possible as well as if product defects will show up it is really hard to track this kind of variation caused by man. Below the man dependent parameters will be explained into more detail what they mean and how they will impact product characteristics.

4.5.1.1 Cold forming

Cold forming is when an operator forcing the material’s edges to fit towards each other’s surfaces until satisfactory result is achieved. Cold forming is mainly done when the operator is fitting parts' interfaces towards each other in the two different tack welding operations.

4.5.1.2 Manual centralization of tacks

Manual centralization of tacks means to which degree the tack welds are centralized over the interface between the different pieces of material. Good hit of the joint is important due to that if the tacks are not centralized one can risk that not the whole tack will be consumed in the following weld operation and therefore resulting in a product deviation.

4.5.1.3 Sequence of tacks

Sequence of tacks is varying between operators but also from part to part by the same operator resulting in variation. The heat input to the product will be different and due to this different products will have different tension but also be deformed in different ways. A recommended weld sequence has been developed in order to get as little deformation and internal tensions as possible in the material.

4.5.1.4 Amount of filler material

Amount of filler material will have effect on the following weld operation. Especially sensitive to thickness variation is the TIG robot welding and especially when it comes to thinner parts of the weld joint. Different amount of filler material can lead to different degree of penetration.

4.5.1.5 Amount of tacks

Amount of tacks the operator can freely decide the amount of tacks to some extent. Parts that have better fit needs fewer tacks and therefore they will also be exposed to less heat input. This leads to less deformation and stress tension in the product. The larger gap between the different pieces results in that the operator is adding more tacks.

4.5.1.6 Cleaning

Cleaning is done manually and by wiping the joint with acetone on a cotton cloth to get rid of grease and dirt. The cotton cloth is changed when it becomes dirty. If a greasy and dirty joint is welded one increase the risk of getting pores and cracks.

4.5.1.7 Height of weld tool

The operator can adjust the height of weld tool during the H-sector robot TIG welding in leading to variation. By increasing the height of the weld tool the arc length will also be changed leading to increased resistant and thereby also increased power. However, since the arc length is just changed with a small distance this have rather little impact on the power applied to the weld joint.

4.5.1.8 Cut filler material at start

Cut filler material at start is done by the operator at the H-sector robot weld to control that the edge of the feeding material have the same shape each time since the ending of the previous weld operation can lead to that the filler material edge will end up with drop shape leading to more material at the start of the following operation.

4.5.1.9 Manual welding on trailing edge

Manual welding on trailing edge is done after the robot welding of the H-sector since this zone is not possible to weld by robot. This results in variation of both joint shape and amount of filler material.

4.5.1.10 Fitting in fixture

Fitting in fixture is done at all five different operations and more dependent on the operator at some operations. It is vital that the part is fitted in the fixture correct for all operations in order to get the right results out from each operation. For the two tack weld operations fitting the different parts in to the fixture are vital in order to be able to perform the tack welding and fulfill requirements such as flush and it is also totally dependent on the operator to get a good fit since some parts lacking locating schemes. Fitting in fixture is also of high relevance when it comes to fix the workpiece in the machining fixture and is difficult due to it has to be fixed at several positions without locating schemes and not forced in any direction. More information about how fitting in fixture is done could be found in the different operation descriptions.

4.5.1.11 Manual identification of weld joint

The operator at the 360 assy laser welding operation sometimes does manual identification of joint. The robot is scanning the weld joint before performing the weld each time but if the gap is so small that it cannot be seen at the scanning, the operator has to perform the scanning oneself to identify the weld joint.

4.5.2 Machine

Parameters that are machine dependent are those parameters, which will be defined during the programing of the machine. Those parameters are usually carefully selected from experiments in order to achieve the best results for the operation leading to fulfill the desired output of characteristics. Furthermore, those parameters are usually locked and are not allowed to modify. However some parameters could be modified within tight tolerances to achieve desired product characteristics.

4.5.2.1 Weld speed

Weld speed is defined as the speed that the tool or robot weld tool is moving above the surface of the weld joint. Weld speed is a vital parameter controlling more or less all weld joint characteristics. Lower speed leads to higher temperature in the weld joint and bigger HAZ. By reducing the weld speed more power will be applied per measure unit resulting in higher temperature in the weld joint. However, decreased speed results in some negative effects on the material, namely geometrical deformation. The more heat input to the material the more geometrical deformation, which also leads to residual stress in the material.

4.5.2.2 Weld power

Weld power is the power that the robot or operator adds to the welding operation. Higher power will lead to higher temperature in the weld joint and a therefore bigger HAZ. For manual welding the current is adjusted by a foot control up to a certain limit, which has been set at the machine. Weld power is a vital parameter and controls many of the weld joint characteristics. The arc length has a direct impact to what power that is distributed to the workpiece because increased arc length leads to increased resistance and higher power. There are only small adjustments made during TIG welding regarding the arc length, which results in small power adjustments. However the main purpose is to ensure that the feeding material is fed at a good height above the material surface.

4.5.2.3 Angle of weld tool

Angle of weld tool is usually perpendicular towards the surface that is welded. However, for the robot laser welding the optics in the laser equipment is sensitive and reflections of the laser beam can damage the equipment. Therefore during the start when one lacking the keyhole, one start with the weld tool tilted to not damage the optics.

4.5.2.4 Joint scanning

Joint scanning is performed by the robot in front of each weld joint operation in order to know the exact position of the joint. If the joints real position differs compared to the programed joint, adjustments are done in order to get perfect joint centralization.

4.5.2.5 Centralization of joint

Centralization of joint means to which degree the weld joint is centralized between the different pieces of material. A good hit of the joint is vital in order to get a good depth of fusion into the different pieces of material as well as to reduce the risk of getting undercut where decentralized hit of the joint is the main reason for undercut.

4.5.2.6 Filling material feed

Filling material feed is the speed the filling material string is fed towards the weld joint. Feeding material is used at the H-sector TIG robot operation and will adjust the height of the joint. Filler material has a chilling effect to the weld joint center.

4.5.2.7 Electrode quality

Electrode quality means how clean the electrode is. A clean electrode has a centralized arc weld towards the weld joint center, which is crucial to get the right temperature in the weld joint during welding. The electrode can be contaminated by weld spatter or vaporized metal from the weld joint. Furthermore if the electrode comes in contact with the liquid metal in the weld joint this lead to contaminated electrode. A contaminated electrode will have a much more spread out arc beam leading to lower temperature in the weld joint.

4.5.2.8 Machine accuracy

Machine accuracy is how accurate the machine position is towards nominal value and how accurate the machine can move along a pre-defined weld joint.

4.5.2.9 Milling and drilling tools

Milling and drilling tools are chosen depending on the precision that is required from the manufacturing method.

4.5.2.10 Depth of cutting

Depth of cutting is the depth the tool is cutting into the workpiece, the bigger cutting depth the rougher surface. If the cutting depth becomes to big one will risk destroying the cutting tool.

4.5.2.11 Cutting velocity

Cutting velocity is the speed the cutting tool is rotating around its own axis. Depending on material hardness one has to adjust the cutting tool velocity.

4.5.2.12 Coolant

Coolant is the cooling system that controls the temperature of the workpiece. This parameter ensures that the workpiece does not get too warm during machining operations such as milling and drilling.

4.5.2.13 Feed rate

Feed rate is the speed that the tool is moving along the surface of the workpiece. When the feed rate increases there is a possibility that the components surface becomes rough and that the metrics alter.

4.5.2.14 Pulse factor

Pulse factor is the factor between high and low effect. When conducting laser beam welding the effect is adjusted in short pulses, usually with X milliseconds of high effect respectively low effect. The purpose with this is to get rid of the amounts of pores in the weld joint. Usually the higher pulse factor, the less pores. However, higher pulse factor results in more aggressive weld bead geometry, which is an unwanted characteristic. The thicker material that is welded the higher pulse factor is needed to get a weld joint without pores. When welding in material thickness below three millimeters continuous wave is used which means that pulse factor is not required to get good weld geometry without any pores.

4.5.2.15 Focus length

Focus length is the distance between the focal lens and the focal point. The focal point will vary depending on different lenses used in different weld tools. Important regarding focus length is that one can perform the weld joint both in focus as well as off focus. Off focus welding results in that one will not get a keyhole and just a melt joint, which is used when performing cosmetic joint leading to that just the top of the joint is melted and becomes smoother.

4.5.2.16 Frequency

Frequency is the number of occurrences per second and is relevant for the laser welding during pulse welding. Usually for laser beam welding one are making the weld with pulses of high and low power and then the frequency will be dependent on the pulse time of high and low power. The frequency will have effect on the amount of pores as well as the weld bead geometry.

4.4.2.17 Focal spot diameter

Focal spot diameter is the diameter on the laser spot hitting the material that will be welded. The larger spot diameter the less aggressive weld joint and the less amount of weld spatter. Since the smaller spot diameter the more intensive laser beam which also leads to that the whole weld joint geometry will be slightly different regarding height and width.

4.5.3 Milieu

Milieu parameters are those parameters, which will affect the environment around the workpiece or having an impact on the workpiece.

4.5.3.1 Oxygen level

Oxygen level is being controlled during all weld operations in order to minimize the degree of oxidation and defects on the weld joint. In order to control the level of oxygen the parts are placed in gas chambers, which later on are filled with a mixture of argon gas and hydrogen gas. Usually the weld operation does not start before a certain level of oxygen is reached. A steady flow of gas is added during the weld operation to ensure that one not exceed the maximum oxygen level.

4.5.3.2 Temperature in workpiece

Temperature in workpiece and tool changes during the operation and will lead to a significant impact on how the weld joint geometry will be as well as size of the piece during the operation.

4.5.4 Method

Method parameters refer to the work method which the operator or machine is using to do a certain operation. For all manual operations a work method is developed and should be followed by the operator to get the same result each time. Method parameters are those that are developed or decided during the development phase of the product and will be fixed if no drastically improvements will be achieved.

4.5.4.1 Weld sequence and direction

Weld sequence and direction is in which orders all the different weld joints should be welded and in which direction. This is done both for tack welding and for robot welding. Sequence and direction are pre-defined and should be followed for all weld operations. Simulations have been made according to sequence and direction and are suggested to create as little deformation as possible as well as minimize tensions in the material. On the operation lists a recommended weld sequence is described.

4.5.4.2 Three-sided machining

Three-sided machining is preferred when performing machining because it gives the opportunity to control the part regarding gap, flush and parallelism while one-sided machining only can control parallelism.

4.5.5 Material

Material parameters mean that the incoming material will vary and create variation on the output of characteristics. Every operation has incoming material and material parameters are in GAS’ case dependent on suppliers and how they are fulfilling their requirements.

4.5.5.1 Thickness variation

Thickness variation is the deviation from nominal thickness value of the material from suppliers. The variation that occurs is due to part-to-part variation and leads to that the results from the weld operations differ which means that product characteristics are varying (e.g. penetration). The weld thickness is also creating problems for the operators to fit parts into fixtures and leads to that the operator has to force the part into the correct position by coldforming.

4.5.6 Design

Design parameters are those that can be found in the drawings or which design will have an impact on the product characteristics.

4.5.6.1 Tolerances

Tolerance is the allowed variation from target value. In order to make it as cost efficient as possible one strive to have as wide tolerances as possible and at the same time meet requirements. In order to have as wide tolerances as possible and at the same time meet requirements one divide joints into zones to only sett tighter tolerances where it is needed. Examples of different requirements of tolerances are weld joint classification A, B or C.

4.5.6.2 Fixture

Fixture is the system that assures that the workpiece is in the correct position to be manufactured. The fixture system should reduce movements and vibrations to as large extent as possible. Depending on the fixture design and how the workpiece is locked in the fixture system more or less variation could occur when the operator is fitting the workpiece in the fixture. Due to wear, a fixture system’s robustness can be reduced, which can lead to increased movement and vibrations in the workpiece.

4.5.6.3 Locating scheme

Locating scheme is the 3-2-1 principles that lock the workpiece's motions in three non-parallel planes. The target systems purpose is to create a robust solution in manufacturing that increase accuracy by decreasing motions of the workpiece. A robust locating scheme is vital in order to get a robust manufacturing process. By locating the locating scheme’s points at positions where the workpiece will not vary geometrically one will end up with better and more robust results after each operation.

4.5.6.4 Deformation compensation

Deformation compensation is the geometrical compensation that is done to the workpiece due to that it will deform in the same way each time and therefore it is possible to make compensation for those deformations. Deformations occur due to heat input to the material when it is being welded and the deformation pattern is more or less the same each time. It is very difficult to estimate how the workpiece will deform during welding, which results in that deformation compensations are made during the ramp up period when one conducting optical measurement techniques on the workpieces. How the workpiece will deform depends on several characteristics such as material, geometry of the workpiece, thickness, interfacing areas such as flanges or vanes, and fixtures. Furthermore it is very difficult to predict how a workpiece will deform from project to project due to differences in previously mentioned characteristics.

4.5.6.5 Radius of front side of vane

Radius of front side vane is the geometrical requirement that is defined by design in an early phase of the product development. The radius has a significant impact to the producibility because of the complexity of welding areas with narrow radius. The radius is important for the aerodynamic department because of the possibilities to adjust airflow by adjusting this radius.

4.5.6.6 Weld shrinkage

Weld shrinkage is the amount of retraction in the workpiece after a weld operation. The weld shrinkage's magnitude is dependent on the materials thickness but in particular it depends on the weld method and heat applied to the weld joint. The shrinkage is moving in longitudinal direction.

4.5.6.7 Start and stop zone of weld joint

Start and stop zone is the start and stop place of the weld joint. These points are critical and are usually creating quality problems, especially when it comes to keyhole welding methods such as laser welding where pores are frequently occurring in those areas. Therefore it is recommended if possible to locate those points in areas that later on will be removed.

4.5.6.8 Stabilization points

Stabilization points on case and vane parts are points, which are being locked in the machining operation in order to be able to mill and drill the workpiece without any motions and vibrations. Those stabilization points should not force the workpiece from its nominal position which it has when fitted into fixture. This work procedure is highly operator dependent and rework is frequently occurring due to that the workpiece is forced into a new position.

4.6 Fabrication process presented through conceptual framework

TEC A's fabrication process has been presented in a process map (see appendix: 1) to get a good overview and visualization of all steps in the process. The process map presents how the conceptual framework has been applied on five manufacturing steps that together ensure that final product characteristics of TEC A are met. Two transformation processes of two subsequent operations are presented in figure 29 to visualize the interplay that is required by TEC A's fabrication process.

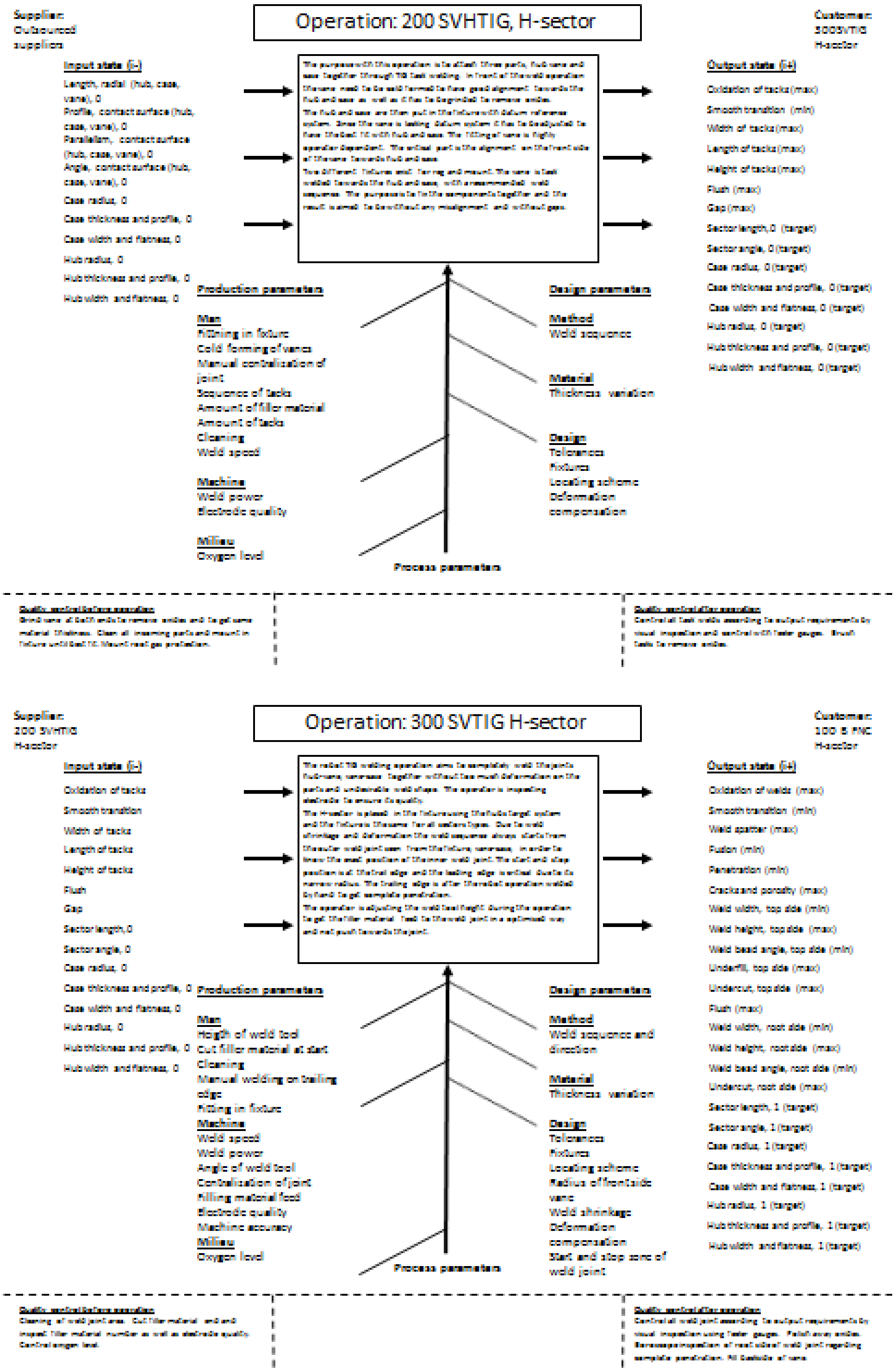


Figure 29. The conceptual framework with the transformation process of the H-sector tack welding and robot welding

4.6.1 Transformation process description

The requirements on product characteristics for the TIG robot welding are listed as outputs of the transformation process. In order to fulfill those requirements after the operation has been performed it put certain requirements on the input to the operation. This has been demonstrated in the conceptual framework and also for the two operations in figure 29. With the right input requirements to the process one have the start for succeeding with the transformation that will occur in the operation. At the bottom side of the transformation box all parameters that are of significant relevance are listed in order to get a good picture of what process parameters that contributes to variation to the output characteristics.

In this case of the H-sector, the purpose is to transform all three incoming parts from suppliers into one H-sector with a defined length and angles. The incoming parts have all the value 0, which defines that they have not been changed or transformed into a new shape. The radial length of the three incoming parts, hub, vane and case are all transformed into a new length, namely sector length. Since the sector length is created within this process it gets a value of 0. Furthermore they then get a value of 1 that indicates that the have changed to a new value. Moreover, the characteristics indicating weld shape are marked with a maximum or minimum that indicates that a characteristic should have a maximum or minimum value, whereas geometrical characteristics have target values that should be met. At the bottom of each transformation process a quality control is located to indicate which quality controls that are performed both before and after each operation to ensure that the characteristics are fulfilled.

4.6.2 Interrelationship matrix description

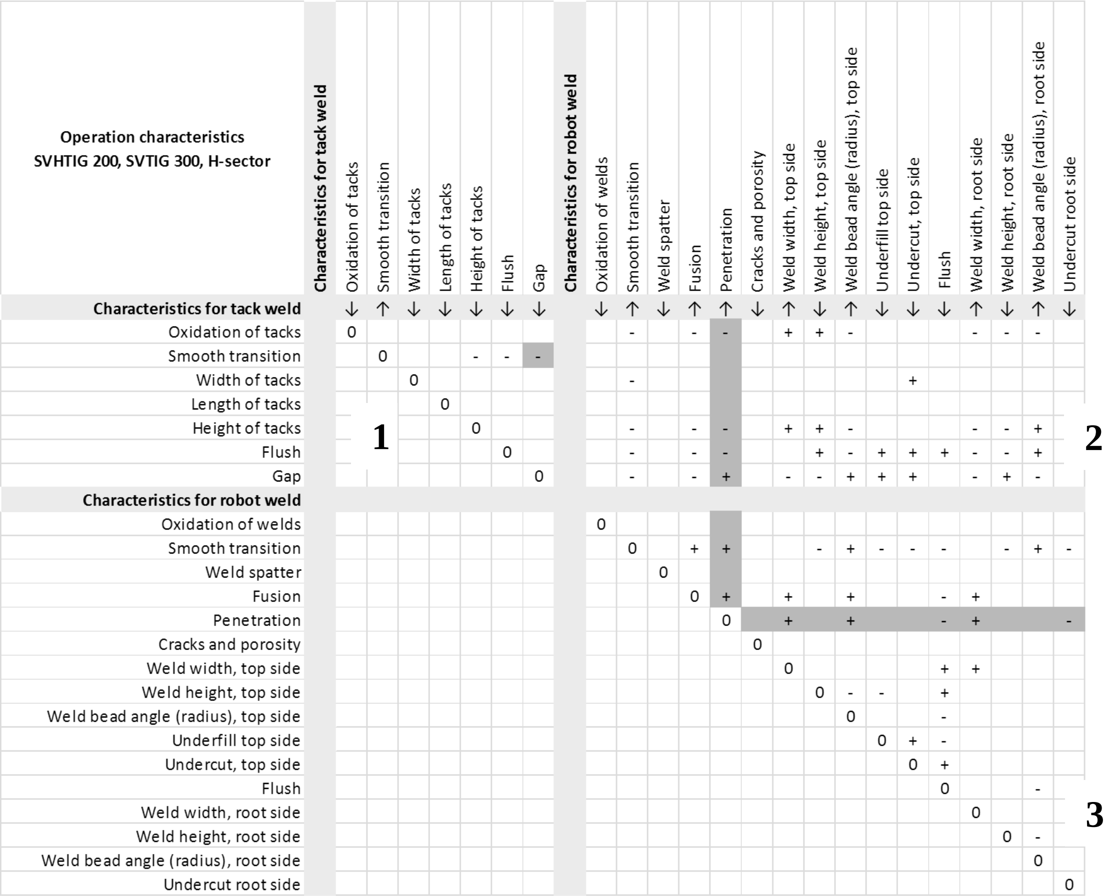
In order to get a more deeply and detailed understanding of how different characteristics are affecting each other as well as what characteristics are affecting characteristics for the following operation, an IRM was developed (see appendix: 2). The purpose with the IRM is to in a detailed way explain how variation of characteristics has positive or negative correlation with other characteristics. The process of the TEC A with five manufacturing steps was decomposed into three different sub groups where tack welding and robot welding of H-sector was the first part, machining and tack welding for assy the second part and lastly tack welding and robot welding of assy as the last part. The purpose with this was to track how characteristics from one operation impacts characteristics of the following operation to get a better understanding of how the different operations are dependent on each other or more correctly how product characteristics will affect the following operation’s characteristics. Furthermore the purpose was also to track how variation of characteristics within one operation will lead to variation of other characteristics within the same operation, this to identify their interrelation with each other and what causes this will lead to in the following operation.

Moreover each of the five different operations has certain parameters that will control the process. By different parameter settings these characteristics will obtain different values or measures resulting in fulfilling or not fulfilling their requirements. Most commonly will an adjustment of a parameter value contribute with that several product characteristics are affected. Findings also show, while one characteristic will obtain a better output from an adjustment in a parameter, another characteristic could change in a negative way. This results in that setting parameter values is a difficult process with lots of compromises in order to make sure that all characteristics fulfill their requirements. How parameters are affecting characteristics in a positive or negative way is shown in the IRMs (see appendix: 2).

The IRMs also explain in which direction characteristics will change to the better and is indicated in the IRM by arrows pointing up or down. An arrow that points up means that GAS wants a product characteristic to increase (e.g. increased penetration) and an arrow that points down, then GAS wants a product characteristic to decrease (e.g. less cracks). Furthermore the different signs, a plus or a minus sign in the boxes, indicates if there is a positive or a negative correlation between the different characteristics or parameters and characteristics. A positive correlation means that for example if one characteristic increase the other characteristic will also increase where as a negative correlation means that if one will increase the other one will decrease. Next section will present an example of characteristics and parameters impact on different characteristics.

4.6.3 Example of interrelationship matrix

To describe the IRM in an easy way the characteristic penetration will be followed through two different operation steps, tack welding and TIG robot welding, and how other characteristics will have impact on penetration (Fig. 30) as well as which parameters that will impact the degree of penetration (Fig 31).



Operation characteristics SVHTIG 200, SVTIG 300, H-sector	Characteristics for tack weld	Oxidation of tacks	Smooth transition	Width of tacks	Length of tacks	Height of tacks	Flush	Gap	Characteristics for robot weld	Oxidation of welds	Smooth transition	Weld spatter	Fusion	Penetration	Cracks and porosity	Weld width, top side	Weld height, top side	Weld bead angle (radius), top side	Underfill top side	Undercut, top side	Flush	Weld width, root side	Weld height, root side	Weld bead angle (radius), root side	Undercut root side
Characteristics for tack weld		↓	↑	↓	↓	↓	↓	↓		↓	↑	↓	↑	↑	↓	↑	↓	↑	↓	↓	↓	↑	↓	↑	↓
Oxidation of tacks		0									-		-	-		+	+	-				-	-	-	
Smooth transition			0			-	-	-																	
Width of tacks				0							-									+					
Length of tacks					0																				
Height of tacks						0					-		-	-		+	+	-				-	-	+	
Flush							0				-		-	-			+	-	+	+	+	-	-	+	
Gap								0			-		-	+		-	-	+	+	+		-	+	-	
Characteristics for robot weld																									
Oxidation of welds										0															
Smooth transition											0		+	+			-	+	-	-	-		-	+	-
Weld spatter												0													
Fusion													0	+		+		+			-	+			
Penetration														0		+		+			-	+			-
Cracks and porosity															0										
Weld width, top side																0					+	+			
Weld height, top side																	0	-	-		+				
Weld bead angle (radius), top side																		0			-				
Underfill top side																			0	+	-				
Undercut, top side																				0	+				
Flush																					0			-	
Weld width, root side																						0			
Weld height, root side																							0	-	
Weld bead angle (radius), root side																								0	
Undercut root side																									0

Figure 30. Interrelationship matrix of characteristics for H-sector operations

The first box, upper left, in the IRM explains how characteristics of the tack welding affect other characteristics within that operation. As could be seen there are not many interrelations within this operation and penetration is not even a characteristic in this operation. However an example from this box is that if the gap increase, which is negative, smooth transition will decrease, which also is negative. The following box to the right explains how characteristics from tack welding have impact on characteristics in the main TIG robot weld operation. Penetration is one product characteristic for this operation and as could be seen in the IRM it has an arrow upwards meaning that more penetration is better and critical in this operation is to fulfill the minimum amount of penetration. By looking in the column of penetration it could be seen that oxidation of tacks from previous operation have a negative impact on penetration. This means that the more oxidation from previous operation the less penetration in the main weld operation. An explanation why it is like this could be found in section 4.4. Furthermore, the height of tacks and flush will also have negative impact on the degree of penetration, meaning higher tacks and more flush will decrease the degree of penetration. Lastly, it could be seen that a gap between parts will have a positive relationship with penetration and lead to that when a gap increase, the penetration increase. However one should be careful here, even though more gap results in better penetration, more gap is a negative characteristic and unwanted and therefore not a good way to create better penetration.

In the third box information on how characteristics within the main robot weld operation affect other characteristics within this operation are explained. By increasing the fusion, which basically is the width of the weld joint inside the material, one receives more penetration as well as the weld width on both top side and root side will increase. Furthermore increased penetration will result in decreased weld height on the top side leading to increased angle of top side and also increase the chance of getting undercut. Almost the opposite will happen with the weld geometry at the root side where the height will increase and the weld bead angle will decrease.

Information about how different parameters influence the characteristic penetration can be seen in figure 31. In this column it could be seen that the man dependent parameter manual welding on root side have impact but the impact is not specified. It means that it could both have a negative or positive impact on the penetration but that it depends on the man or operator. For the machine dependent parameters there are several parameters, which will impact the amount of penetration. The speed has negative effect. By this it means by keeping all the other parameters constant one and decreasing the speed this will result in increased penetration. The opposite relation exists for weld power. More detailed explanation on how this relationship works and why it is as it is could be found in section 4.5. The amount of filling material added to the weld joint will have negative impact on penetration, the more filling material, the less penetration. Lastly decreased electrode quality will have negative impact on penetration.

Parameters influencing H-sector weld	Charachteristics for robot weld H-sector	Oxidation of welds	Smooth transitions	Weld spatter	Fusion	Penetration	Cracks and porosity	Weld width, top side	Weld height, top side	Weld bead angle, top side	Underfill top side	Undercut, top side	Flush	Weld width, root side	Weld height, root side	Weld bead angle, root side	Undercut root side
Man		↓	↑	↓	↑	↑	↓	↑	↓	↑	↓	↓	↓	↑	↓	↑	↓
Heigth of weld tool			●		●			●	●	●	●	●		●	●	●	
Cut filler material at start			+					●			●						
Cleaning		-					-										
Manual welding on trailing edge			●		●	●					●			●	●		
Fitting in fixture																	
Machine																	
Weld speed			●		-	-		-	-	●	-	-		-	-	●	
Weld power			●		+	+		+	-	●	+	+		+	+	●	
Angle of weld tool					●									●			
Centralization of joint			+		+							-					-
Filling material feed			●		-	-		+	+	-	-	-		-	-	-	
Electrode quality		-	+		+	+		-	-	+				-	-	●	
Machine accuracy												●					

Figure 31. Interrelationship diagram showing machine parameters effect on characteristics where penetration is followed

By carefully study this parameter IRM one can get a good understanding of what different characteristics that will be changed by changing the value of one parameter, which is shown in figure 31. Furthermore it could also be seen if it will have a positive or negative impact on other characteristics, which is the most complex part when it comes to parameter settings. By example given, increasing a parameter will have a desired positive effect on a characteristic that one would like to change, however by increasing this parameter this will lead to negative results on other characteristics. By following a row in the IRM one can see which characteristics that a parameter will control and have an impact on.

By looking further into the row of weld speed it could be seen that changing the parameter weld speed will have impact on almost all characteristics in the H-sector main weld operation. This results in that the parameter setting is an extremely complex process requiring lots of knowledge and skills as well as trial and error testing to achieve desired weld bead geometry and fulfilling all characteristics defined for the weld joint.

5. Discussion

This chapter provides a discussion of the thesis where the conceptual framework's systematic approach is discussed together with that the three research questions are recaptured and answered.

5.1 Answers to research questions

The purpose of this thesis was to create more knowledge of how GAS control that TEC A's fabrication process fulfill final requirements. These efforts have been achieved by using the conceptual framework to systematically decompose product characteristics and identify process parameters. The conceptual framework worked as a basis throughout the entire thesis and findings should support GAS to develop methods for how to predict producibility. Three research questions were developed to support in this thesis' work and are below recaptured from section 1.3 together with answers.

RQ 1. How can better knowledge of the product's characteristics and its fabrication process' parameters lead to increased quality and efficiency?

To assure that a product meet customer expectations, GAS wants to achieve a robust design of their TEC A with process parameters that are insensitive to variation (Design engineer 2 & Operation weld engineer, 2015-04-21). To reach this goal it has been claimed by Bergman and Klefsjö (2010) that it is important to understand how variation affects the system (i.e. a product or process). Today at GAS there is a lot of knowledge and experience about how to develop a product. However, there are still certain gaps of information in product and production development that can lead to rework and reduced automation in production.

The conceptual framework should support in systematically derive how final requirements of a product are fulfilled through decomposing these requirements into product characteristics for each manufacturing step and identify how manufacturing steps generate variation. Parameters should furthermore be identified for each manufacturing step to know how a company control that requirements on product characteristics are fulfilled (Madrid et al, 2015). By systematically identifying how GAS controlled their fabrication process of TEC A, product characteristics of each manufacturing steps were identified and visualized by the framework (see appendix: 1). Each manufacturing step's process parameters were also identified and led to further investigations about their impact to TEC A's product characteristics. This information was collected from several sources that were spread out at GAS. The conceptual framework centralized a lot of this information and increased the possibility to get a comprehensive picture of the complexity within the fabrication process of TEC A.

The conceptual framework should in a long-term perspective support in product and production development by creating a platform of how to control product characteristics within different manufacturing steps by re-using knowledge (Madrid et al, 2015). These kinds of generalizations are according to certain employees at GAS, as well as Ion (2005) very difficult due that there are a lot of aspects to consider during product and production development. However, findings from this case study can work as a basis to start understanding relationships between product characteristics and parameters better and give GAS input in how to control weld joint geometry, which will increase efficiency according to employees. Today at GAS there are already to some extent analysis made in terms of how a product deviates from target values. These analyzes are however limited to only look at certain parameters as well as certain characteristics of the product and only explain in general ways what effect a parameter adjustment will lead to. The IRMs that has been introduced to explain this interplay are a good start to investigate relationships in the fabrication process but must be further developed to discover to what degree parameters variation will affect a product characteristic. Furthermore, as stated by Karlsson et al. (2010) an IRM is a good tool in order to capture and explain a complex situation in a systematically and graphical way that entails knowledge transferring between different projects.

To conclude, the conceptual framework can work as a supportive tool in product and production development to centralize information and visualize variation between manufacturing steps. The conceptual framework can also become a basis to know what product characteristics is being affected and open up for further investigations into how a system can be optimized.

RQ 2. What product characteristics and associated parameters from the process steps have significant impact on the quality of the product?

In order to identify what product characteristics and associated parameters that have a significant impact on product quality, a detailed mapping of product characteristics for the different manufacturing steps was created. To get a deeper understanding of the requirement breakdown as well as what departments that had specific requirements on TEC A, there was a tracking of all the identified characteristics. In the conceptual framework that has been used during this thesis, the product characteristics that impact the product quality are mapped together with their associated parameters, in order to visualize it in an easy way (see appendix: 1). Product characteristics and associated parameters are also described in previous chapter to bring a better understanding to why they exist, and what their impacts to final requirements are.

The conceptual framework captures the relationship of what requirements on product characteristics that has to be fulfilled before an operation, and what parameters that control the process. However, to get a better understanding of the complexity of how different characteristics affect each other within one operation as well as how characteristics from one operation affect characteristics of the following operation, IRMs was developed (see appendix: 2). This additional information complements the conceptual framework in two ways. First, the IRMs capture the complexity of many-to-many relationships between characteristics and parameters and if a product characteristic is affected in a positive or a negative way. Second, the relationships that exist between characteristics in the same operation as well as for the following operation are currently not possible to describe in the conceptual framework that exist today. With the IRMs it is possible to capture what happens when variation occurs of one product characteristic and what consequences this leads to.

Three different matrices were developed to describe the different operation sections of the production line. The first section is manual tack welding and robot weld of H-sector, the second is machining of H-sector to manual tack welding of assy and the last one is manual tack welding of assy to robot weld of assy. By dividing the operations into these sections it becomes easier to grasp why each characteristics needs to be fulfilled and what purpose they have for the following operation. In the IRM, data could be found in which way different characteristics are influencing each other and if a positive or negative correlation occurs.

To show which parameters that have influence on different product characteristics an interrelationship diagram similar to the previously described was developed. This diagram describes how changes of one parameter will impact different characteristics. During the time this thesis has been going on the researchers has realized the complexity that exists between different parameter settings. To find the right parameter setting one has to compromise between different characteristics to get a good output.

To conclude, the decomposition of these requirements has been described throughout the conceptual framework (see appendix: 1). The manufacturing steps together ensure that final requirements are fulfilled in means of product characteristics and parameters. The conceptual framework brings an overview of how TEC A's system behaves and what it is that affects the system during the fabrication process. To bring a more detailed overview of how product characteristics and parameters affect each other, interrelationship diagrams were created (see appendix: 2) in order to capture the complexity that exists within each operation between different characteristics.

RQ 3. How can a conceptual framework that describes the relation between significant process parameters and resulting product quality support in product and production development at GAS?

The conceptual framework can be helpful and contribute to an improved product and production development if it will be used in the right way and if it can re-use knowledge from previous projects (Madrid et al, 2015). By capturing one product’s fabrication process and identify how it works, it could lead to that future projects can use this knowledge when developing manufacturing methods. What is important is to have a strategy in product and production development and to have the right information from the start of the project without any gaps of information. A decomposition of customer demands with a proper key characteristic breakdown can ensure that critical characteristics will be highlighted early in the project as well as one will keep the cost down by not putting too much effort on inefficient work that do not bring value to the final customer.

The conceptual framework can also contribute with that GAS can systematically identify how they control their fabrication processes and put effort to the improvements that matters the most in order to reduce variation and eliminate weak points in the total product and production development. To do this, a lot of knowledge and experience is needed with more analysis on dependencies. However, with a conceptual framework as the one that has been developed, GAS can start to map dependencies and get an extremely complex context to be easier to follow and understand by visualizing the requirements on product characteristics together with parameters that control those characteristics. Because if it is possible to identify parameter combinations that are more sensitive to variation than others, it could lead to that it is possible to optimize parameter settings and create a robust design (Bergman & Klefsjö, 2010).

The result in chapter 5 also show that compromises are necessary in product and production development and the IRMs describe what compromises that has to be done for each product characteristic. These compromises can be useful information both in an early phase of product and production development as well as on-going improvement work to ensure that another characteristic will be changed in an unexpected way which will reduce performance of the product. It is also important to understand that a fabrication process increases the amount of manufacturing steps and thereby also the sources of variation where geometrical variation has been identified as the most complex. Employees with several years of knowledge highlights the complexity when it comes to predict how a workpiece will behave during different process steps because of material thickness, different materials, interfacing geometry and differences in fixtures. To investigate this, GAS currently has to make full production tests to certainly know how a workpiece will behave during production and even though this becomes costly it is necessary. However, a re-use of manufacturing knowledge within the platform base will be helpful since it can support in creating more efficient estimations on deformations and needed compensation where it is today very costly to arrive at these results.

Having said that, the conceptual framework can support and structure the work of mapping and understanding how variation is created and in which way characteristics are affected by this. It can also support in developing further understanding about product characteristics and their controlling parameters which will be helpful and contribute with increasing the speed of the product development since it is possible to generalize how those correlates and how the weld joint geometry could be controlled. Furthermore it can serve as a basis for both product and production development in an early phase as well as current improvement work. Lastly, by re-using technology and knowledge, GAS could have the opportunity to predict producibility and reduce number of tests that currently has to be done.

6. Recommendations and future work

As stated from the discussion, certain gaps of knowledge in how to control TEC As fabrication process have been identified and there are opportunities for improvement in the work with product and production development. Recommendations to GAS are provided in this chapter to answer to these gaps and opportunities.

6.1 Continue to analyze how parameters affect weld geometry

Weld geometry quality has been identified as critical in manufacturing in order to ensure that TEC A fulfills requirements. During the thesis work it has been identified that there is a gap of knowledge of how different parameters affect characteristics of the weld geometry of product TEC A. This information could be valuable in order to know what effect variation of a parameter will have on a specific characteristic as well as which other characteristics that will be affected when this parameter change in a manufacturing method. It has also been stated by employees at GAS, that this information will be useful and bring value to the product development process if it could be generalized to future projects. Recommendations are therefore to continue to analyze how parameters affect weld geometry through the two following steps.

6.1.1 Centralize information

First, GAS has to collect what they already know about process parameters impact to weld geometry and store this in one common database. This thesis' findings can be seen as a basis to this summary because it has captured data from both experienced employees as well as it has included results from internal documents. However, there is probably more knowledge within GAS that still has not been collected because of the difficulty to find it. There is a need to increase collaboration and centralize information within GAS to make it easier for this data to be available for improvement projects. Data that was collected in this thesis came from several sources because information was spread out between people and databases, which were not communicating with each other. When data is centralized and summarized, gaps in the findings should be identified and GAS should then decide how to fill this lack of knowledge (see section 6.2).

6.1.2 Ranking system of product characteristics

As been stated before, to decide appropriate parameter settings that fulfill all weld joint requirements is a complex process due to many-to-many relationships where compromises has to be done. By changing one parameter will affect several characteristics and in most cases in different ways meaning that improving the output for one characteristic another characteristic will be affected in a negative way. For the development of TEC A, these compromises are made with considerations taken to cost and quality in order to find optimal parameter settings. However, these compromises should be made in a systematic way in order to ensure that GAS always has the same focus. By introducing a ranking system and work procedure similar to a Failure Mode and Effect Analysis (FMEA), characteristics can be ranked and prioritized with the purpose to focus on fulfilling the most critical characteristics.

To ensure that the ranking system's purpose is in line with product and production developments focus, each aspect of the rank system should first be identified. A recommendation would be to rank characteristics on two different criteria. One criterion could be probability of failure or sensitivity to variation where a second criterion could be the degree of severity or the cost by not fulfilling a characteristic’s requirements. By multiplying two of these values, a total risk priority number (RPN) can indicate which characteristic that is most important and should be prioritized when it comes to parameter setting design.

6.2 Future work with analyzing parameters

To completely map how parameters affect product characteristics and have the opportunity to point out what parameter combinations that are less sensitive to variation, further analysis have to be done. From the conceptual framework and IRMs it has been found that there are many-to-many relationships between product characteristics and parameters. A suggestion is to use findings from this thesis to use for further experiments such as Design of Experiments and Multiply Criteria Optimization. By doing these types of experiments it would increase the confidence of this thesis findings in how product characteristics and parameters interplay and result in that GAS can base their decisions on fact when determining parameter settings. Furthermore results on how different characteristics are correlating and affecting a third characteristic could be shown which will capture the complex situation in a better way.

6. 3 Future work with the conceptual framework

Since input to the conceptual framework could be dependent on several employees with different expertise it is important to reduce the risk for confusion or misunderstandings. One suggestion is to keep the conceptual framework easy to interpret by using a simple design. It is also important to give the company the right expectations of the framework by explaining the purpose and how it can contribute in a larger context for a company's product and production development and that short-term gains can lead to a more systematic work.

During this thesis it has also been discussed how to improve the conceptual framework’s clarity to describe variation that occurs during manufacturing. IRMs was developed to bring both clarity and deeper understanding in how characteristics and parameters affected each other, a feature that the two researchers thought were missing in the conceptual framework's layout. Future work should include how to bring this missing part of valuable information into the conceptual framework's layout, in order to reduce number of tools to explain the complexity. One suggestion is to give the conceptual framework an increased digital presentation. An example would be that if a product characteristic were marked, then those product characteristics that will be affected together with controlling parameters would be highlighted. By developing this kind of digital presentation, the conceptual framework can both describe a transformation process clearer, and it would have a modern touch.

7. Conclusion

Variation is a normally occurring problem that makes it difficult to completely control manufacturing. The complexity increases with the number of manufacturing steps in the process that has to interplay in order to fulfill requirements on a product. Requirements on the jet engine component TEC A is developed together with the customer and thereafter by a long iterative process between different departments at GAS to ensure both high quality and producibility. At GAS there are continuous efforts made to improve TEC A’s fabrication process to reduce cost and increase quality.

This thesis used a conceptual framework to systematically decompose TEC A’s fabrication process in order to do deeper analysis of its manufacturing methods. Findings capture how GAS control TEC A’s fabrication process in means of product characteristics and process parameters, where each manufacturing step have to fulfill certain requirements in order for the next to be successful. The goal with this thesis has been to provide GAS with more knowledge in how they are controlling one of their fabrication processes and with this information support in future work of how to predict producibility. Even though generalizations are seen as very difficult due to each product’s own design solution, employees at GAS are positive towards creating a model with information about how parameters are affecting weld geometry’s product characteristics because it is not as dependent on a product’s design solution. It has been raised that better knowledge about these characteristics and their associated parameters would bring efficiency to product and production development and optimize parameter design in manufacturing.

For short-term gains, by including the recommended ranking system, GAS could capture the criticality of different product characteristics and be able to work systematically in product and production development when prioritizing in what improvement projects they should invest their resources. To proceed with developing knowledge of how to control weld geometry, GAS first have to identify what information that already exists and then complement with additional tests to completely understand the complexity that exist between product characteristics and process parameters. This should in a long-term perspective lead to that it should be possible to re-use manufacturing methods and reduce number of expensive trial and error tests. The conceptual framework and IRMs in this thesis can be seen as a basis that have captured how variation occurs through a fabrication process and what product characteristics’ and parameters’ that interplay with each other.

References

Arvidsson, M. and Gremyr, I. (2008) Principles of Robust Design Methodology. *Quality and Reliability Engineering International*, vol. 24(1), pp. 23-35.

Assuncao, E. and Williams, S. (2013) Comparison of continuous wave and pulsed wave laser welding effects. *Optics and Lasers in Engineering*, vol. 51(6), pp. 674.

Bell, J. (2010) *Doing your research project*. Maidenhead: Open University Press.

Bergman, B. and Klefsjö, B. (2010) *Quality - From Customer Needs to Customer Satisfaction*. 3rd ed. Lund: Studentliteratur AB

Bergman,B. (ed.), de Maré, J. (ed.), Lorén,S. (ed.) and Svensson,T. (ed.) (2009) *Robust Design Methodology for Reliability: Exploring the Effects of Variation and Uncertainty.* West Sussex: John Wiley &Sons, Ltd.

Bryman, A. and Bell, E. (2011) *Business Research Methods.* 3rd edition. New York: Oxford University Press.

Colosimo, B. M. and Senin, N. (2010) *Geometric tolerances: Product design, manufacturing, quality inspection and monitoring*. London: Springer-Verlag London Limited.

Doggett, A. M. (2005). Root cause analysis: A framework for tool selection. *Quality Management Journal*, vol. *12*(4), pp. 34

Dubois, A., and Gadde, L. (2002) Systematic combining: An abductive approach to case research. *Journal of Business Research*, vol. 55(7), pp. 553-560.

Ejvegård, R. (2003) *Vetenskaplig metod.* Lund: Studentlitteratur.

Forslund, A., Söderberg, R. and Lööf, J. (2011) Multidisciplinary Robustness Evaluations of Aero Engine Structures, *in 20th ISABE proceedings*.

George, M.L., Rowlands, D., Price, M. and Maxey, J.. (2005) *The Lean Six Sigma Pocket Toolbook.* United States of America: McGraw-Hill.

Ghauri G. and Grønhaug, K. (2005) *Research methods in business studies A Practical Guide*. 3rd edition. Harlow: Pearson Education Limited.

Gillham, B. (2010) *Case study research methods*. Great Britain: Bloomsbury UK.

GKN (2015) *About us – GKN PLC.* Available at http://www.gkn.com/aboutus/Pages/default.aspx [Accessed: 2015-03-02].

Haig, B D. (2005) An abductive theory of scientific method. *Psychologial methods*, vol. 10 (4), pp. 271-388.

Hasenkamp, T., Arvidsson, M. and Gremyr, I. (2009) A Review of Practices for Robust Design Methodology. *Journal of Engineering Design*, vol. 20(6), pp. 645 – 657.

Heinze, C., Schwenk, C. and Rethmeier, M. (2012) The effect of tack welding on numerically calculated welding-induced distortion. *Journal of Materials Processing Technology*, vol. 212 (1), pp. 308-314.

Hennink, M., Hutter,I., and Bailey, A. (2011) *Qualitative Research Methods*. London: SAGE Publications Ltd.

Ion, J. C. (2005) *Laser processing of engineering materials: Principles, practice and industrial application.* Amsterdam: Elsevier Butterworth-Heinemann.

Jacobsen, K., Sigurjónsson, J., and Jakobsen, Ø. (1991) Formalized specification of functional requirements. *Design Studies*, vol. 12(4), pp. 221-224.

Jareteg, C., Wärmefjord, K., Söderberg, R., Lindkvist, L., Carlson, J., Cromvik, C. and Edelvik, F. (2014). Variation simulation for composite parts and assemblies including variation in fiber orientation and thickness. *Procedia CIRP*, vol. 23, pp. 235-240.

Jarfors, A. E. W. et al (2006) *Tillverkningsteknologi*. 3rd edition. Lund: Studentlitteratur

Johansson, P., Hasenkamp, T., Chakhunashvili, A. and Arvidsson, M. (2005) Using VMEA to Facilitate the Preparation of Robust Design Experimentation, *in 8th QMOD proceedings*, vol. Palermo, June 29- July 1, 2005, pp. 635-640.

Kalpakjian, S. and Schmid, S.R. (2008) *Manufacturing Processes for Engineering Materials*. 4rd edition. United States of America: Pearson Education.

Karlsson, J., Markmann, C., Minhaj Alam, M. and Kaplan, A.F.H. (2010) Parameter influence on the laser weld geometry documented by the matrix flow chart. *Physics Procedia*, vol. 5(2), pp. 183-192.

Katayama, S. (2013) *Handbook of laser welding technologies*. Philadelphia, PA: Woodhead Pub.

Kou, S. (2003) *Welding Metallurgy.* New Jersey: John Wiley & Sons.

Larsson, C. and Sagar, V. (2014) *Quality Parameter analysis at GKN Aerospace Sweden.* Gothenburg: Chalmers University of Technology. Master thesis in Department of Product and Production Development. Division of Product Development.

Ljungström, M. (2005) A model for starting up and implementing continuous improvements and work development in practice. *The TQM Magazine*, vol. 17(5), pp. 385 – 405.

Lööf, J. (2010) *Managing Geometrical Variation Through Optimization and Visualization.* Gothenburg: Chalmers University of Technology. Thesis for degree of doctor of philosophy in Department of Product and Production Development. Division of Product Development.

Maddox, S. J. (1991) *Fatigue strength of welded structures*. Cambridge: Abington Pub.

Madrid, J., Söderberg, R., Vallhagen, J., and Wärmefjord, K. (2015) Development of a conceptual framework to assess producibility for fabricated aerospace components. *Procedia CIRP*, in press.

Mohapatra, S., Anusree, M. R., and Sreejesh, S. (2014) *Business research methods: An applied orientation.* Cham: Springer International Publishing.

Mukerjee, R., and Wu, C. F. J. (2006). *A modern theory of factorial design*. New York: Springer Science + Business Media, Inc.

Nee, A.Y.C. (ed.) (2014) *Handbook of manufacturing engineering and technology*. London: Springer-Verlag London Limited.

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K. (2007). *Engineering design: A systematic approach.* London: Springer-Verlag London Limited.

Pantazopoulos, G., & Tsinopoulos, G. (2005) Process failure modes and effects analysis (PFMEA): A structured approach for quality improvement in the metal forming industry. *Journal of Failure Analysis and Prevention*, vol. 5(2), pp. 5-10.

Patel, R., and Davidson, B. (2003) *Forskninsmetodikens grunder*. 3rd edition. Lund: Studentlitteratur

Pettersson, F. and Rasmussen, R. (2002) Towards an Improved and Expanded FMEA Usage. Gothenburg: Chalmers University of Technology

Poli, C. (2001) *Design for manufacturing: A structured approach.* Boston: Butterworth-Heinemann.

Prakash, R. (2009) *Non-Destructive Testing Techniques*. New Academic Science Limited.

Qu, S. Q. and Dumay, J. (2011) The qualitative research interview. *Qualitative Research in Accounting & Management*, vol. 8(3), pp. 238-264.

Remenyi, D. (1998) *Doing research in business and management: An introduction to process and method*. London: SAGE.

Robinson, T. J., Borror, C. M. and Myers, R. H. (2004) Robust parameter design: A review. *Quality and Reliability Engineering International*, vol. 20(1), pp. 81-101.

Scheinberg, S. *Qualitative Research Methods Curiosity & Interviewing, lecture slides p. 33*. Göteborg: Chalmers University of Technology (2014-05-08).

Söderberg, R. (1998) Robust design by support of CAT tools. In *proceedings of the ASME Design Automation Conference*, Atlanta, GA.

Tang, Wenbin., Li,Yuan., Yu, Jianfeng., Zhang, Jie. and Yu, Lin. (2014) A systematic top-down approach for the identification and decomposition of product key characteristics. *Journal of engineering Manufacture*, vol. 228 (10), pp. 1305-1313.

Thornton, A C. (2004) *Variation risk management: Focusing Quality Improvements in Product Development and production*. New Jersey: John Wiley & Sons, Inc.

Thornton, A. C., Donnelly, S. and Ertan, B. (2000). More than just robust design: Why product development organizations still contend with variation and its impact on quality. *Research in Engineering Design*, vol. 12(3), pp. 127-143.

Ueda, Y., Murakawa, H. and Ma, N. (2012) *Welding deformation and residual stress prevention.* Waltham: Elsevier/Butterworth-Heineman.

Vallhagen, J., Lööf, J., Söderberg, R. och Wärmefjord, K. (2011) Robustness in aerospace components manufacturing and fabrication – a case study, *in 20th ISABE proceedings.*

Wheelwright, S. and Clark, K. (1992) *Revolutionizing product development: Quantum leaps in speed, efficiency, and quality*. New York: Free Press.

Whitney, D. E. (2006) The role of key characteristics in the design of mechanical assemblies. *Assembly Automation*, vol. 26(4), pp. 315-322.

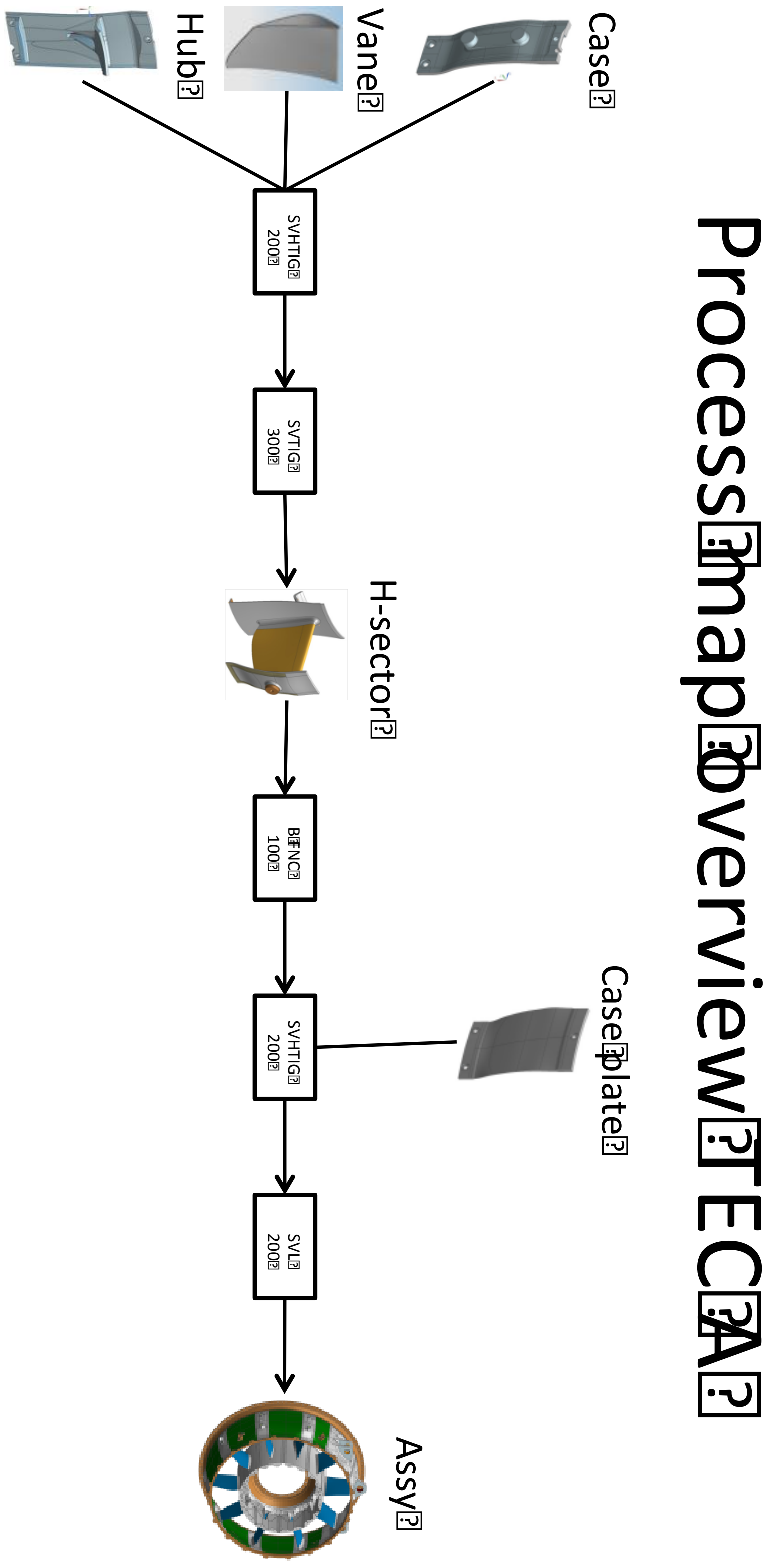
Wu, C. and Hamada, M. (2000) *Experiments: Planning, analysis, and parameter design optimization.* New York: Wiley.

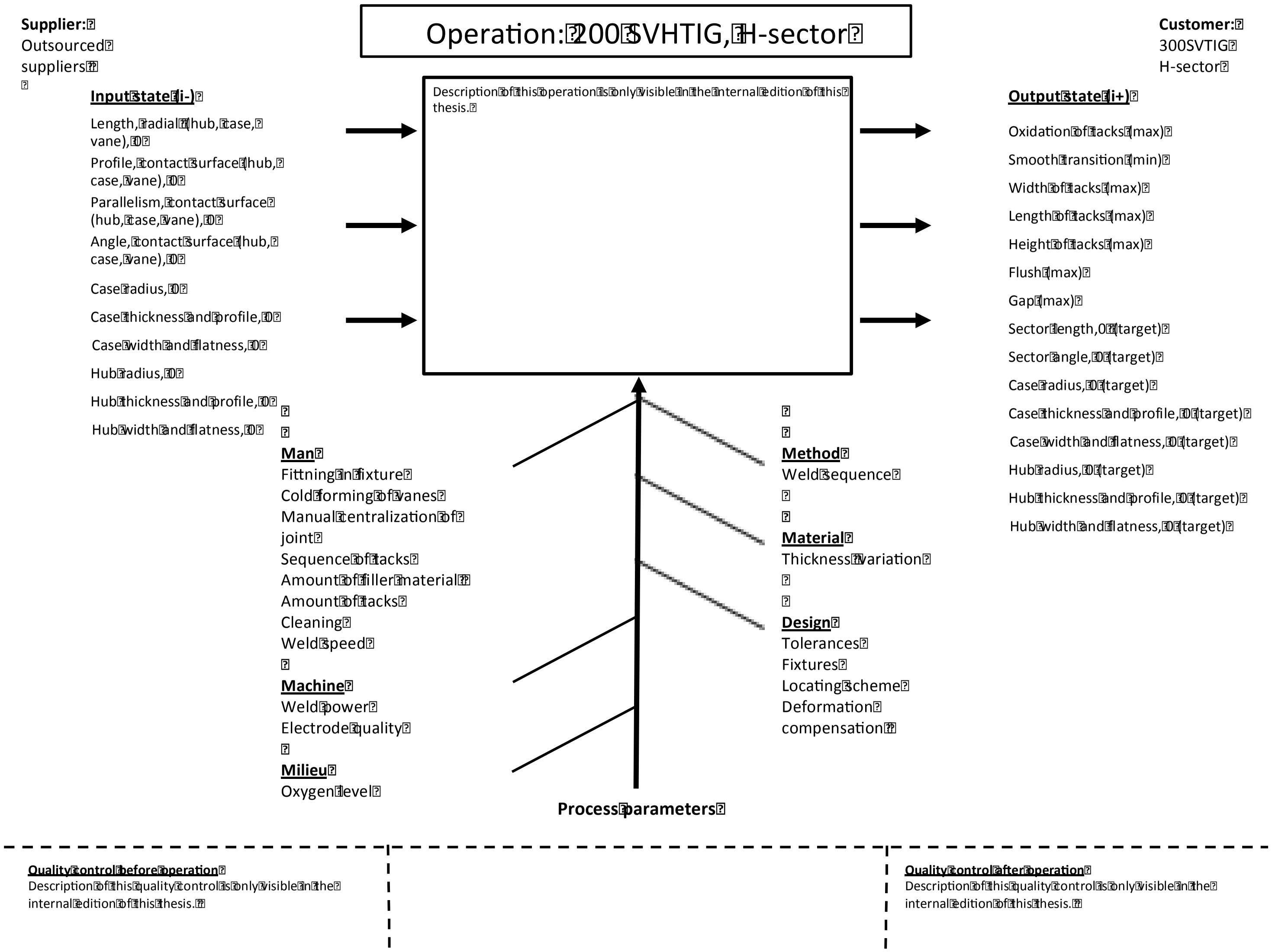
Xiong, L., Molfino, R. and Zoppi, M. (2013) Fixture layout optimization for flexible aerospace parts based on self-reconfigurable swarm intelligent fixture system. *The International Journal of Advanced Manufacturing Technology*, vol. 66(9), pp. 1305-1313.

Yin, R. K. (2003) *Case Study Research: Design and Methods.* 3rd edition. California: Sage Publication.

Zheng, L. Y., McMahon, C. A., Li, L., Ding, L. and Jamshidi, J. (2008) Key characteristics management in product lifecycle management: A survey of methodologies and practices. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 222(8), pp. 989-1008.

Appendix 1 – The process map





Operation: 200 SVHTIG, H-sector

Supplier:
Outsourced
suppliers

Input state (i-)

Length, radial (hub, case, vane), 0

Profile, contact surface (hub, case, vane), 0

Parallelism, contact surface (hub, case, vane), 0

Angle, contact surface (hub, case, vane), 0

Case radius, 0

Case thickness and profile, 0

Case width and flatness, 0

Hub radius, 0

Hub thickness and profile, 0

Hub width and flatness, 0

Description of this operation is only visible in the internal edition of this thesis.

Customer:
300SVTIG
H-sector

Output state (i+)

Oxidation of tacks (max)

Smooth transition (min)

Width of tacks (max)

Length of tacks (max)

Height of tacks (max)

Flush (max)

Gap (max)

Sector length, 0 (target)

Sector angle, 0 (target)

Case radius, 0 (target)

Case thickness and profile, 0 (target)

Case width and flatness, 0 (target)

Hub radius, 0 (target)

Hub thickness and profile, 0 (target)

Hub width and flatness, 0 (target)

Man
Fittning in fixture
Cold forming of vanes
Manual centralization of joint
Sequence of tacks
Amount of filler material
Amount of tacks
Cleaning
Weld speed

Machine
Weld power
Electrode quality

Milieu
Oxygen level

Method
Weld sequence

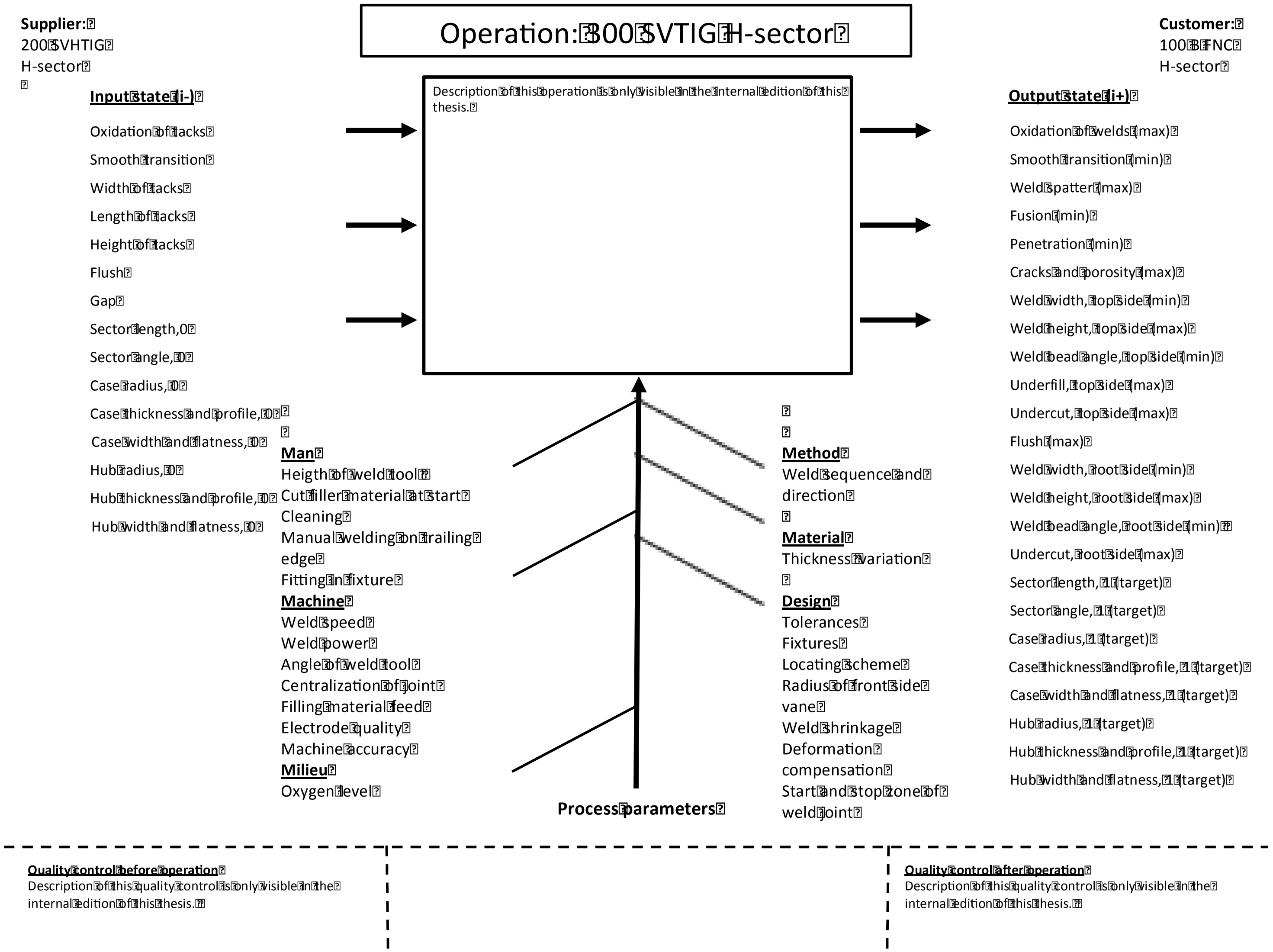
Material
Thickness variation

Design
Tolerances
Fixtures
Locating scheme
Deformation compensation

Process parameters

Quality control before operation
Description of this quality control is only visible in the internal edition of this thesis.

Quality control after operation
Description of this quality control is only visible in the internal edition of this thesis.



Supplier:
200 SVHTIG
H-sector

Operation: 300 SVTIG H-sector

Customer:
100 B FNC
H-sector

Input state (i-)

Oxidation of tacks
Smooth transition
Width of tacks
Length of tacks
Height of tacks
Flush
Gap
Sector length, 0
Sector angle, 0
Case radius, 0
Case thickness and profile, 0
Case width and flatness, 0
Hub radius, 0
Hub thickness and profile, 0
Hub width and flatness, 0

Description of this operation is only visible in the internal edition of this thesis.

Output state (i+)

Oxidation of welds (max)
Smooth transition (min)
Weld spatter (max)
Fusion (min)
Penetration (min)
Cracks and porosity (max)
Weld width, top side (min)
Weld height, top side (max)
Weld bead angle, top side (min)
Underfill, top side (max)
Undercut, top side (max)
Flush (max)
Weld width, root side (min)
Weld height, root side (max)
Weld bead angle, root side (min)
Undercut, root side (max)
Sector length, 1 (target)
Sector angle, 1 (target)
Case radius, 1 (target)
Case thickness and profile, 1 (target)
Case width and flatness, 1 (target)
Hub radius, 1 (target)
Hub thickness and profile, 1 (target)
Hub width and flatness, 1 (target)

Man
Heigth of weld tool
Cut filler material at start
Cleaning
Manual welding on trailing edge
Fitting in fixture

Machine
Weld speed
Weld power
Angle of weld tool
Centralization of joint
Filling material feed
Electrode quality
Machine accuracy

Milieu
Oxygen level

Method
Weld sequence and direction

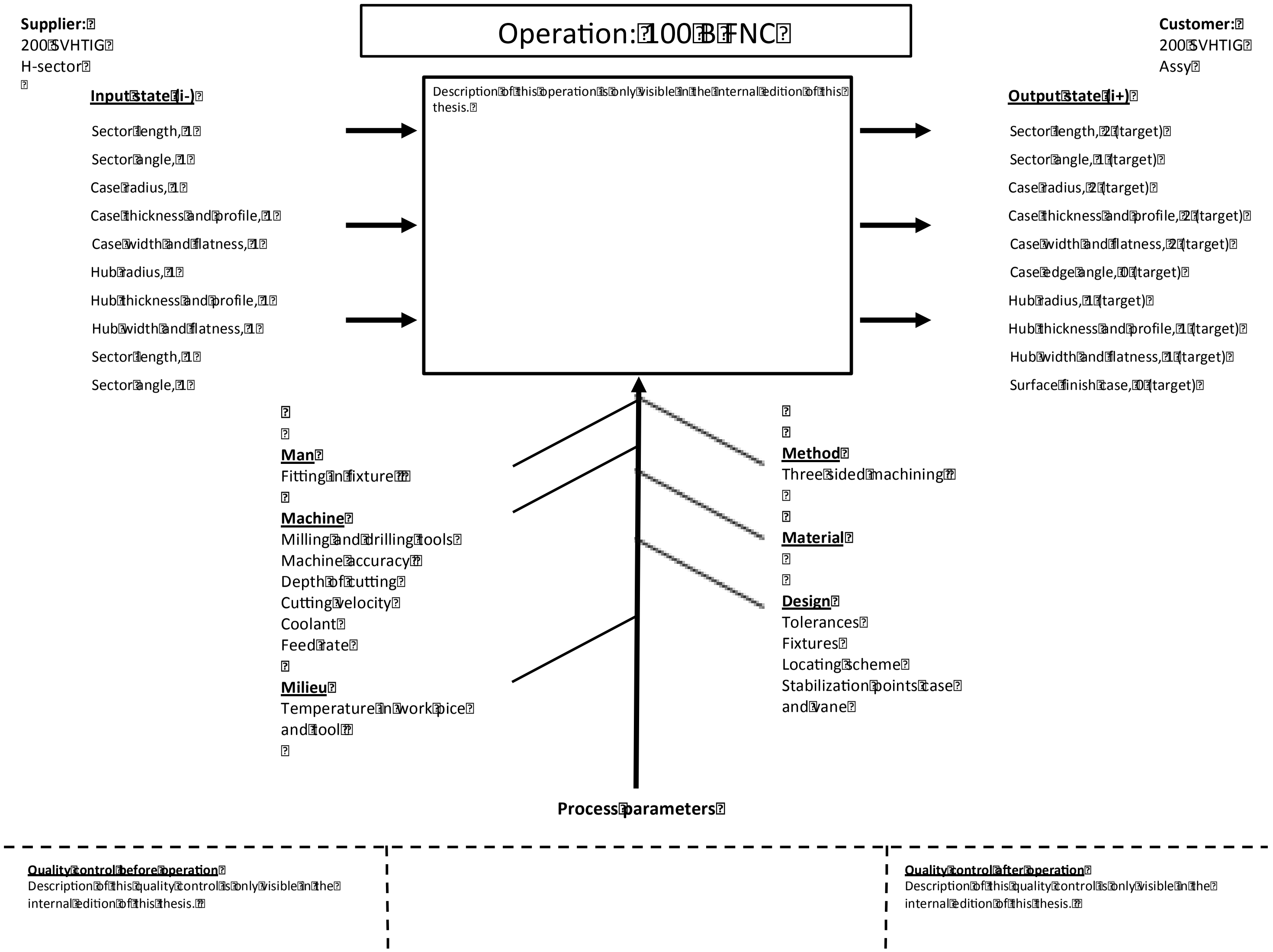
Material
Thickness variation

Design
Tolerances
Fixtures
Locating scheme
Radius of front side vane
Weld shrinkage
Deformation compensation
Start and stop zone of weld joint

Process parameters

Quality control before operation
Description of this quality control is only visible in the internal edition of this thesis.

Quality control after operation
Description of this quality control is only visible in the internal edition of this thesis.



Operation: 100 B FNC

Supplier:
200 SVHTIG
H-sector

Input state (i-)

Sector length, 1
Sector angle, 1
Case radius, 1
Case thickness and profile, 1
Case width and flatness, 1
Hub radius, 1
Hub thickness and profile, 1
Hub width and flatness, 1
Sector length, 1
Sector angle, 1

Description of this operation is only visible in the internal edition of this thesis.

Customer:
200 SVHTIG
Assy

Output state (i+)

Sector length, 2 (target)
Sector angle, 1 (target)
Case radius, 2 (target)
Case thickness and profile, 2 (target)
Case width and flatness, 2 (target)
Case edge angle, 0 (target)
Hub radius, 1 (target)
Hub thickness and profile, 1 (target)
Hub width and flatness, 1 (target)
Surface finish case, 0 (target)

Man
Fitting in fixture

Machine
Milling and drilling tools
Machine accuracy
Depth of cutting
Cutting velocity
Coolant
Feed rate

Milieu
Temperature in work pice
and tool

Method
Three sided machining

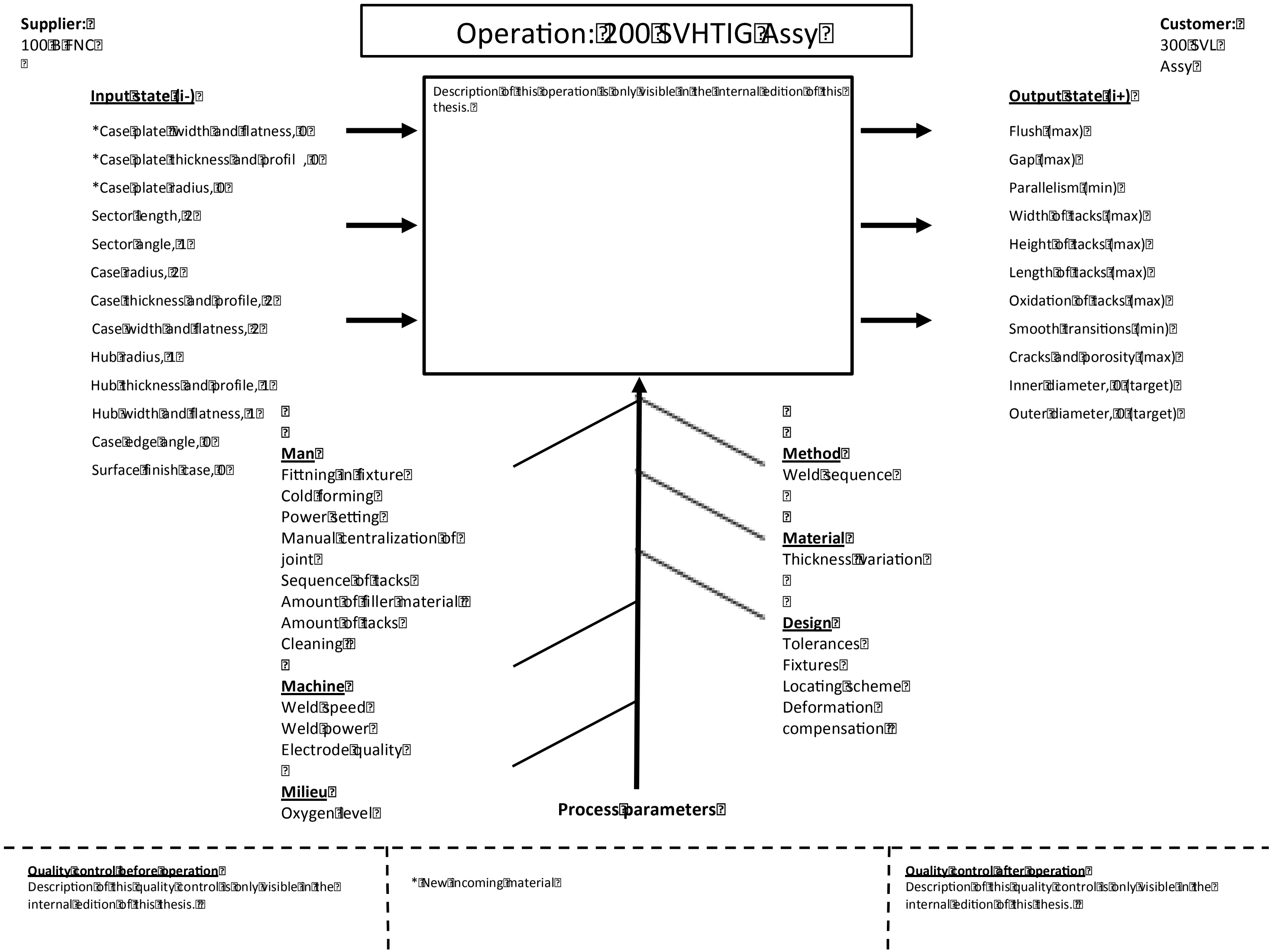
Material

Design
Tolerances
Fixtures
Locating scheme
Stabilization points case
and vane

Process parameters

Quality control before operation
Description of this quality control is only visible in the internal edition of this thesis.

Quality control after operation
Description of this quality control is only visible in the internal edition of this thesis.



Operation: 200 SVHTIG Assy

Supplier:
100 B FNC

Customer:
300 SVL
Assy

Input state (i-)

*Case plate width and flatness, 0
*Case plate thickness and profil , 0
*Case plate radius, 0
Sector length, 2
Sector angle, 1
Case radius, 2
Case thickness and profile, 2
Case width and flatness, 2
Hub radius, 1
Hub thickness and profile, 1
Hub width and flatness, 1
Case edge angle, 0
Surface finish case, 0

Description of this operation is only visible in the internal edition of this thesis.

Output state (i+)

Flush (max)
Gap (max)
Parallelism (min)
Width of tacks (max)
Height of tacks (max)
Length of tacks (max)
Oxidation of tacks (max)
Smooth transitions (min)
Cracks and porosity (max)
Inner diameter, 0 (target)
Outer diameter, 0 (target)

Man
Fittning in fixture
Cold forming
Power setting
Manual centralization of joint
Sequence of tacks
Amount of filler material
Amount of tacks
Cleaning

Machine
Weld speed
Weld power
Electrode quality

Milieu
Oxygen level

Method
Weld sequence

Material
Thickness variation

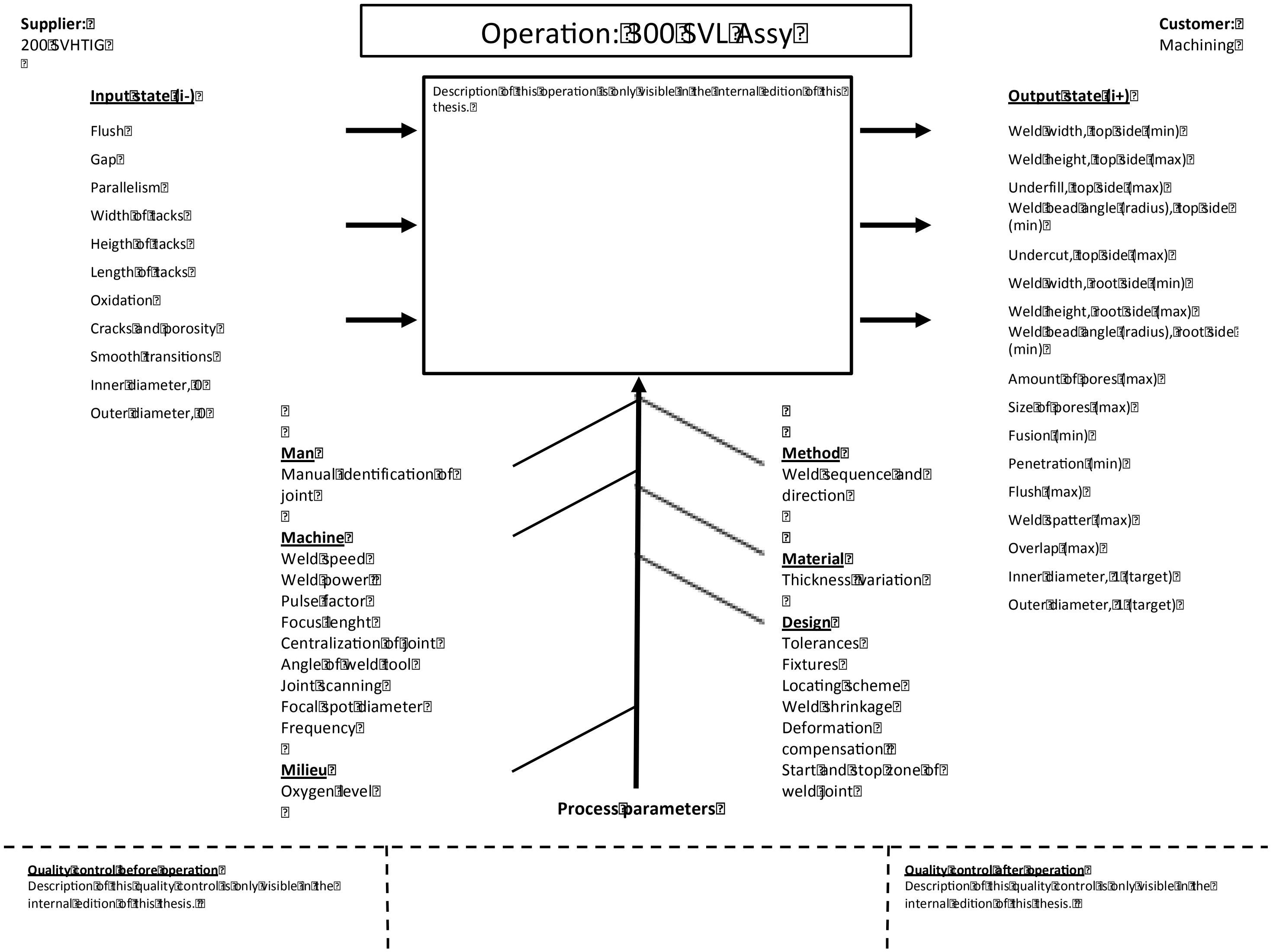
Design
Tolerances
Fixtures
Locating scheme
Deformation compensation

Process parameters

Quality control before operation
Description of this quality control is only visible in the internal edition of this thesis.

* New incoming material

Quality control after operation
Description of this quality control is only visible in the internal edition of this thesis.



Supplier:
200 SVHTIG

Operation: 300 SVL Assy

Customer:
Machining

<u>Input state (i-)</u>

- Flush
- Gap
- Parallelism
- Width of tacks
- Heigth of tacks
- Length of tacks
- Oxidation
- Cracks and porosity
- Smooth transitions
- Inner diameter, 0
- Outer diameter, 0

Description of this operation is only visible in the internal edition of this thesis.

<u>Output state (i+)</u>

- Weld width, top side (min)
- Weld height, top side (max)
- Underfill, top side (max)
- Weld bead angle (radius), top side (min)
- Undercut, top side (max)
- Weld width, root side (min)
- Weld height, root side (max)
- Weld bead angle (radius), root side (min)
- Amount of pores (max)
- Size of pores (max)
- Fusion (min)
- Penetration (min)
- Flush (max)
- Weld spatter (max)
- Overlap (max)
- Inner diameter, 1 (target)
- Outer diameter, 1 (target)

<u>Man</u>
Manual identification of joint

<u>Machine</u>
Weld speed
Weld power
Pulse factor
Focus lenght
Centralization of joint
Angle of weld tool
Joint scanning
Focal spot diameter
Frequency

<u>Milieu</u>
Oxygen level

<u>Method</u>
Weld sequence and direction

<u>Material</u>
Thickness variation

<u>Design</u>
Tolerances
Fixtures
Locating scheme
Weld shrinkage
Deformation compensation
Start and stop zone of weld joint

Process parameters

<u>Quality control before operation</u>
Description of this quality control is only visible in the internal edition of this thesis.

<u>Quality control after operation</u>
Description of this quality control is only visible in the internal edition of this thesis.

Appendix 2 – Interrelationship diagram

Explanation of the interrelationship diagrams

The first three matrices describe how product characteristics are affecting each other within each operation as well as how one operations product characteristics affects next operation.

First matrix describes the manual tack welding operation and the TIG robot welding operation of H-sectors.

Second matrix describes the machining operation and the tack welding operation of the assy.

Third matrix describes the tack welding operation and laser beam welding of the complete assy.

The last three matrices describe how process parameters affect product characteristics in the TIG robot welding operation, machining operation and laser beam welding operation.

+	Indicates that there is a positive correlation between product characteristics or a product characteristic and a parameter.
-	Indicates that there is a negative correlation between product characteristics or a product characteristic and a parameter.
●	Both an increase or decrease of a product characteristic's value or a parameter's value will lead to that the product characteristic will deviate from nominal value.
↑	Indicates that this product characteristic's value has a minimum requirement.
↓	Indicates that this product characteristic's value has a maximum requirement.

Operation characteristics **SVHTIG 200, SVTIG 300, H-sector**	**Characteristics for tack weld**	Oxidation of tacks	Smooth transition	Width of tacks	Length of tacks	Height of tacks	Flush	Gap	**Characteristics for robot weld**	Oxidation of welds	Smooth transition	Weld spatter	Fusion	Penetration	Cracks and porosity	Weld width, top side	Weld height, top side	Weld bead angle (radius), top side	Underfill top side	Undercut, top side	Flush	Weld width, root side	Weld height, root side	Weld bead angle (radius), root side	Undercut root side
Characteristics for tack weld		↓	↑	↓	↓	↓	↓	↓		↓	↑	↓	↑	↑	↓	↑	↓	↑	↓	↓	↓	↑	↓	↑	↓
Oxidation of tacks		0									-		-	-	+	+	+	-				-	-	-	
Smooth transition			0			-	-	-																	
Width of tacks				0							-									+					
Length of tacks					0																				
Height of tacks						0					-		-	-		+	+	-				-	-	+	
Flush							0				-		-	-			+	-	+	+	+	-	-	+	+
Gap								0			-		-	+		-	-	+	+	+		-	+	-	
Characteristics for robot weld																									
Oxidation of welds										0															
Smooth transition											0		+	+			-	+	-	-	-		-	+	-
Weld spatter												0													
Fusion													0	+		+		+			-	+			
Penetration														0		+		+			-	+			-
Cracks and porosity															0										
Weld width, top side																0					+	+			
Weld height, top side																	0	-	-		+				
Weld bead angle (radius), top side																		0			-				
Underfill top side																			0	+	-				
Undercut, top side																				0	+				
Flush																					0			-	
Weld width, root side																						0			
Weld height, root side																							0	-	
Weld bead angle (radius), root side																								0	
Undercut root side																									0

Operation characteristics BFNC 200, SVHTIG 200 Assy	**Characteristics for machining**	Sector length	Sector angle	Case raduis	Case thickness and profile	Case width and flatness	Case edge angle	Hub radius	Hub thickness and profile	Hub width and flatness	Surface finish case	**Characteristics for tack welding**	Flush	Gap	Parallelism	Width of tacks	Heigth of tacks	Length of tacks	Oxidation	Pores and cracks	Smooth transitions
Characteristics for machining		●	●	●	●	●	●	●	●	●	↑		↓	↓	↑	↓	↓	↓	↓	↓	↑
Sector length		0	●		●								●								●
Sector angle			0										●								●
Case raduis				0				●					●								●
Case thickness and profile					0		●						●			●					●
Case width and flatness						0	●							●	●	●					●
Case edge angle							0							●							●
Hub radius								0													●
Hub thickness and profile									0				●			●					●
Hub width and flatness										0				●	●	●					●
Surface finish case											0										

Operation characteristics SVHTIG 200, SVL 300	**Charachteristics for tack weld**	Flush	Gap	Parallelism	Width of tacks	Hight of tacks	Length of tacks	Oxidation of tacks	Smooth transition	Cracks and porosity	Inner diameter	Outer diameter	**Characteristics for laser welding**	Weld width top side	Weld height top side	Underfill top side	Weld bead angle (radius) top side	Undercut top side	Weld width root side	Weld height root side	Weld bead angle (radius) root side	Amount of pores	Size of pores	Fusion	Penetration	Flush	Weld spatter	Overlap of weld joint
Charachteristics for tack weld		↓	↓	↑	↓	↓	↓	↓	↑	↓	●	●		↑	↓	↓	↑	↓	↑	↓	↑	↓	↓	↑	↑	↓	↓	↓
Flush		0					●		-		●	●				+		+			+							
Gap			0		+	+					●	●		-	-	+	+	+	-	+	+			-	+			
Parallelism				0	-				+		●	●																
Width of tacks					0																							
Height of tacks						0			-						+		-		-	-	+			-	-			
Length of tacks							0																					
Oxidation of tacks								0						+	+	-	-		-	-	-			-	-			+
Smooth transition									0																			
Cracks and porosity										0																		
Inner diameter											0	+														●		
Outer diameter												0														●		
Characteristics for laser welding																												
Weld width top side														0	-				+					+	+		●	
Weld height top side															0	+	-		-	-	+			-	-			
Underfill top side																0	+	+	+	+	-			+	+			
Weld bead angle (radius) top side																	0		+	+	-			+	+			
Undercut top side																		0										
Weld width root side																			0	+	-			+	+		●	
Weld height root side																				0	-			+	+			
Weld bead angle (radius) root side																					0			+	+			
Amount of pores																						0					●	
Size of pores																							0					
Fusion																								0	+			
Penetration																									0			
Flush																										0		
Weld spatter																											0	
Overlap of weld joint																												0

Parameters influencing H-sector weld	**Charachteristics for robot weld H-sector**	Oxidation of welds	Smooth transitions	Weld spatter	Fusion	Penetration	Cracks and porosity	Weld width, top side	Weld height, top side	Weld bead angle, top side	Underfill top side	Undercut, top side	Flush	Weld width, root side	Weld height, root side	Weld bead angle, root side	Undercut root side
Man		↓	↑	↓	↑	↑	↓	↑	↓	↑	↓	↓	↓	↑	↓	↑	↓
Heigth of weld tool			●		●			●	●	●	●	●		●	●	●	
Cut filler material at start			+					●			●						
Cleaning		-					-										
Manual welding on trailing edge			●		●	●					●			●	●		
Fitting in fixture																	
Machine																	
Weld speed			●		-	-		-	-	-	-	-		-	-	●	
Weld power			●		+	+		+	-	+	+	+		+	+	●	
Angle of weld tool					●									●			
Centralization of joint			+		+							-					-
Filling material feed			●		-	-		+	+	-	-	-		-	-	-	
Electrode quality		-	+		+	+		-	-	+				-	-	●	
Machine accuracy												●					
Milieu																	
Oxygen level		+															
Method																	
Weld sequence and direction						●			●						●		
Material																	
Thickness variation			●		●	●		●	●	●	●	●		●	●	●	●
Design																	
Tolerances					●	●			●	●	●	●	●	●	●		
Fixtures																	
Locating scheme																	
Radius of front side vane			●		●	●								●			
Weld shrinkage									●	●	●						
Deformation compensation																	
Start and stop zone of weld joint			●				●										

Parameters influencing machining	**Characteristics for machining**	Sector length	Sector angle	Case raduis	Case thickness and profile	Case width and flatness	Case edge angle	Hub raduis	Hub thickness and profile	Hub width and flatness	Surface finish case
Man		●	●	●	●	●	●	●	●	●	↑
Fitting in fixture		●	●	●	●	●	●				●
Machine											
Milling and drilling tools											●
Machine accuracy		●	●	●	●	●	●	●	●	●	●
Depth of cutting											●
Cutting velocity											●
Coolant											●
Feed rate											●
Milieu											
Temperature in work pice and tool		●	●	●	●	●	●				●
Method											
Three sided machining		●	●	●	●	●	●				
Material											
Design											
Tolerances		●	●	●	●	●	●	●	●	●	●
Fixtures		●	●	●	●	●	●				●
Locating scheme											●
Stabilization points case and vane		●	●	●	●	●	●				●

Parameters influencing laser weld	**Characteristics for laser welding**	Weld width top side	Weld height top side	Underfilled top side	Weld bead angle (radius) top side	Undercut top side	Weld width root side	Weld height root side	Weld bead angle root side	Amount of pores	Size of pores	Fusion	Penetration	Flush	Weld spatter	Overlap of weld joint
Man		↑	↓	↓	↑	↓	↑	↓	↑	↓	↓	↑	↑	↓	↓	↓
Manual identification of joint						●						●				
Machine																
Weld speed		-	-	-	-	-	-	-	+	+	●	-	-		+	
Weld power		+	-	+	+	+	+	+	-	●		+	+		+	
Pulse factor			+	+	-	+	-	+	-	-	-	-			+	
Focus lenght		●	●	●	●	●	●	●	●	●		●	●		●	
Centralization of joint						-						+				
Angle of weld tool												●			●	
Joint scanning						●						●				
Focal spot diameter		+	-		+		+		+	-		+	-		-	
Frequency		●	●	●	●	●	●	●	●	●		●	●			
Milieu																
Oxygen level																
Method																
Weld sequence and direction																
Material																
Thickness variation							●	●	●			●	●	●		
Design																
Tolerances							●	●	●				●			
Fixtures														●		
Locating scheme												●		●		
Weld shrinking		●	+		-	-		+	-							
Deformation compensation																
Start and stop zone of weld joint										●	●					

Appendix 3 – Internal references

Internal documents at GAS

Internal documents at GAS are only visible in the internal edition of this thesis.

Interviewees at GAS

Interviewees at GAS are only visible in the internal edition of this thesis.