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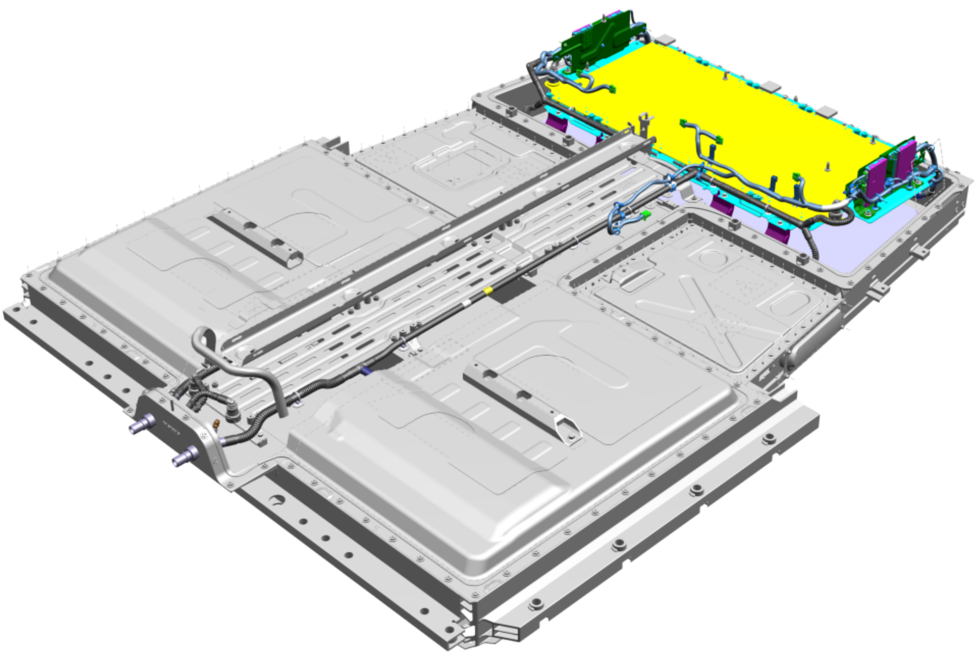

Battery Cooling Function in Structural Brackets

Master's thesis in Product Development

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2022

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Cover: CMA platform Battery Pack of Volvo Cars.

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Abstract

In the current production of battery packs at Volvo Cars, there are separate cooling plates for thermal management of the battery modules and cells. To hold the cooling plates and the modules in place, separate support bracket with load carrying and crash withstanding capability is used. The two component design of cooling plate and bracket causes issues in the rigidity of the assembly due to tolerance stack up as well as being a complex and bulky solution. The objective of the thesis work was to find an integrated solution that would provide both the required cooling functionality and rigidity to hold the parts in place.

Since the battery pack is already in production, the development task was perceived as an incremental product of the existing part and thus the scope was set to keep the changes as minimal as possible from the existing design. The current design was benchmarked thoroughly, the performance was understood and the key requirements from the product were noted down in a requirements list. A functional analysis for the system was done to note down the important functions of the system.

Based on the functions of the system, solution principles were brainstormed and developed. The solution principles or concept combinations were screened and evaluated using normative assessment methods like Elimination Matrix and Pugh Matrix.

A concept involving aluminium die casting of the part was the winning concept and embodiment of design was carried out following the concept screening. During the embodiment design stage, focus was towards manufacturing feasibility, joining techniques, assembly techniques and feasibility.

Finally, a cost, assembly tolerance and weight comparison between the current design and proposed design was carried out and scope for further work is recommended to Volvo Cars.

Keywords: Thermal management, Structural rigidity, Current production, Die Casting

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Anand Srinivas Rajamani, Gothenburg, June 2022

Contents

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BLT	Bond Line Thickness
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CMA	Compact Modular Architecture
CVTN	Cell Voltage Temperature Node
DFMA	Design For Manufacturing and Assembly
EV	Electric Vehicles
FSW	Friction Stir Welding
HPDC	High Pressure Die Casting
LPDC	Low Pressure Die Casting
OEM	Original Equipment Manufacturer
PD	Product Development
TIM	Thermal Interface Material

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1
Introduction

This chapter consists the company background and project background. It also discusses the aim, objective, scope of the work, limitations, research questions and outline of the report.

1.1 Company Background

Volvo Cars is one of the leading OEM in the automotive industry, headquartered in Gothenburg,Sweden. Volvo Cars has presence across the world in different continents and is currently owned by Zhejiang Geely Holding of China [1].

Currently, Volvo Cars sells premium-segment car models in three segments: sedans (S60, S90), versatile estates (V60, V90) and SUVs (XC40, XC60, XC90).In 2020, Volvo Cars sold 661,713 cars. The largest market was China with nearly 25% of the total sales volume in 2020, followed by the United States (17%), Sweden (8%), Germany (7%) and the United Kingdom (7%)[2].

Volvo cars are a pioneer and torch bearer to drive a change towards sustainability and and the entire organization is structured to lead the change for the environment. The mid-decade (2025) business ambitions of the organization is to sell 1.2 million cars of which fully electric vehicles should constitute atleast 50% of the sales. Volvo Cars also aim to sell only fully electric car models by 2030 and be the first climate neutral company by the year 2040[1].

1.2 Project Background

The CMA (Compact Modular Architecture) platform battery packs are currently used in the XC40, C40 model of Volvo Cars and Polestar 2. The battery pack weighs close to 500kg with an energy capacity of 78kWh for an estimated range of 400km. In the current production of CMA battery pack at Volvo Cars, separate cooling plates are used for thermal management of the battery modules and cells. Separate support brackets with load carrying and crash withstanding capability are used as well to ensure stability of the cooling plates and the module. This separate components for separate functions increases number of parts causes issues in the assembly due to tolerance stack up as well as being a complex and heavy solution.

1.3 Objective

The objective of the thesis work is to find an integrated solution that provides the structural function as well as the cooling function in an integrated single part design, which is now provided by two parts. The part developed should be able to provide ideal cooling capabilities as well as the required structural rigidity and reduced weight.

1.4 Limitations

Since the battery pack has multiple cooling plates and support brackets, in the time period of 20 weeks, not every cooling plate and supporting bracket was considered. To begin the work, only the rear side cooling plate and support brackets have been considered. Sufficient time was not available to build prototypes to check and validate the results. Hence, majority of the work was carried out and validated only using digital tools like CAD/CAE. If the concept is found to be successful,cooling plates in other regions can be investigated.

1.5 Research Questions

The work carried out during the thesis time period sought answers for the following research questions within the scope of the project.

1. How has the current product been designed? What are the critical attributes of the product?

2. Are there worthy alternative materials and manufacturing processes to integrate the parts to provide cooling as well as structural rigidity functions with minimal changes to current design?

3. What are the benefits that could be leveraged if the cooling plate and brackets are combined together?

1.6 Report Outline

This report begins with a brief introduction of the thesis work as well as the basic theory for the reader to be able to understand. The research methodology has been briefly explained in Chapter 3. In Chapter 4, the work is then presented in chronological order of how the work was carried out, beginning with benchmarking and literature study, to materials selection, concept design and finally the presentation of the embodiment design along with conclusions. Potential future work and opportunities for the company have also been listed at the end of the report.

2

Theory

In the following sections, theory for the concepts and principles which have been discussed in later chapters have been discussed. As the main scope of the thesis focuses on the cooling plate and fixing parts of the battery pack, this chapter deals with the most relevant topics of the thesis to provide context for different aspects.

2.1 Types of Product Development Projects

The product development projects can be classified into different types.

1. **Advanced Development Projects:** The focus in advance development projects is the creation of knowledge(know-how and know-why) as a precursor to commercial development. Generally, firms conduct advanced development in a separate group of experts,engineers and equipment compared to commercial development.[3]

2. **Alliance or Partnered Projects:** An organization forms an alliance or partnership with another organization to conduct research, to pursue a new concept, or to develop a simple line extension. The advantage of such projects is that instead of using the organization's resources, the partner firm often provides unique and/or significant resources (and sometimes all of the resources) and may manage the project execution.[3]

3. **Incremental or Derivative Projects:** Derivative products can be anything from cost reduced versions of platform products to enhanced and even hybrid version of the same. Derivative projects generally include incremental product changes with little or no process change. The incremental projects require substantially fewer resources than other projects, because the project leverages existing products or processes by extending their applicability. Generally on such projects cost of change is also a driving factor.[3]

4. **Breakthrough or radical Projects:** The focus is on the product, representing a new application or function. Breakthrough projects also involve huge resources for process development as the process is likely to be critical to the success of the product upon launch.[3]

5. **Platform or Next Gen Projects:** Platform projects represent a new sys-

tem solutions for customers involving huge changes on either the manufacturing process, the product itself, or both. Platform projects provide a base for a product and processes that can be leveraged in the upcoming years and would require significantly high resources compared to derivative or incremental developments.[3]

Derivative products are often times the more optimised product in terms of cost, performance, weight etc [3]. The thesis can be treated as development of derivative product to the existing product as the cars with these battery packs are already running in the market and have been performing well. The need for the improvement in the product has arose through internal stakeholders as integrating the two parts will make the assembly easier and reduce the weight.

2.2 Product Development Process

Product Development (PD) process is a very versatile and dynamic process. A structured approach is essential during the development process for the success of product. A general PD process is shown in Figure 2.1.

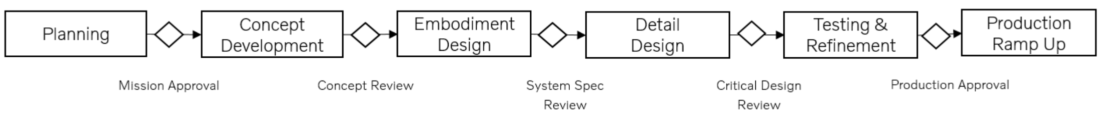

Figure 2.1: General Product Development Process [4]

The association of German engineers have come up with a guideline for design and is often referred as VDI 2221 (Refer Figure 2.2). According to the guideline, there are 4 main phases:

1. Planning and task clarification
2. Conceptual Design
3. Embodiment Design
4. Detail Design

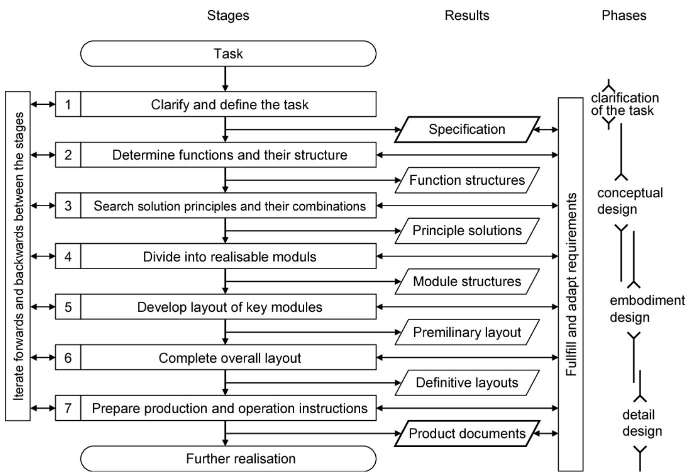

Figure 2.2: General Approach to Design [5]

"Iterate back and forth between the stages" is particularly an important step as concept evaluation and refinement results in iterations. As the number of iterations increases, new requirements are found and knowledge of the problem also enhances. The overlap between the every subsequent phase in the guideline should be noticed. Embodiment design can begin concurrently at a later stage of conceptual design helping in refining and enhancing the concepts. The guidelines were followed as methods for the thesis work and have been discussed in chapter 3.

2.3 Battery Thermal Management

The optimal temperature for best performance of Lithium-ion batteries is between 20°C and 25°C[6]. In temperate climate regions, thermal management is easier to maintain but is more challenging in regions of the world that experience extremes of temperature. For example, Sweden is a cold country and requires far more thermal management control. Although the external temperature is a factor for the cooling system but is not the most challenging or limiting factor. The more extreme conditions are when cars are plugged to fast charging or when there is an onset of thermal runaway[6]. Thermal runaway can be described as an event of an exothermic process, triggering other processes and resulting in uncontrollable situation. The functioning of Li-ion batteries are as such exothermic, hence thermal runaway becomes an important criteria to monitor as well.

During charging, there is a buildup of heat in the lithium-ion cells. The temperature in the cells needs to be regulated to stay in their optimum range, with a maximum of 45°C. To ensure batteries does not exceed the temperature zone, liquid cold plates on the module cooling interface are used. A coolant flows between two plates and effective heat transfer is ensured between the module and coolant. The coolant system is usually coupled with high-end refrigerant system.By using liquid cold plates on the module cooling interface this heat is transferred to the cooling liquid. Coupling this coolant system with a high-end refrigerant system, the battery temperature can be properly managed, even during Electric Refueling and racing at high speeds.[7]

2.3.1 Thermal Interface materials

Good heat transfer between two parts requires intimate contact between two surfaces. In reality, the surfaces of parts aren't perfectly smooth and there exists roughness in them. The point to point contact between two parts drives the heat transfer. The other places are filled with air gaps. A schematic representation of contact between two surfaces is shown in Figure 2.3.

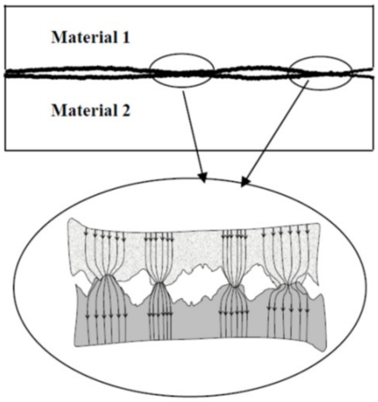

Figure 2.3: Schematic representation of two materials in contact [8]

Air is a poor conductor of heat and limits the heat transfer. In the case of Lithium ion batteries, when heat transfer is not smooth, batteries can get heated up which is not desirable. To eliminate air gaps, Thermal Interface Materials (TIM) are used. A schematic representation of contact between two surfaces when TIM is applied is shown in Figure 2.4. BLT refers to the bond line thickness of TIM. Bondline refers to structure including the adhesive between the two materials. $R_{C1}$and R_{C2} refers to the contact resistances of TIM at the two surfaces.[8]

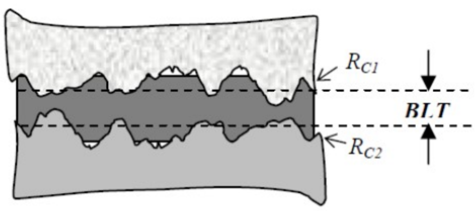

Figure 2.4: Schematic representation when TIM is inserted between two materials [8]

The combination of interface resistance and thermal resistance of TIM together is called as the thermal contact resistance. Thermal resistance is property which indicates the materials ability to resist or allow heat flow through the material. Lower the thermal resistance, the material allows heat to pass through more easily. Thus, the goal when applying TIM is to have the least possible thermal resistance path. The ideal thermal resistance part between two parts and TIM is shown in Figure 2.5. The thermal resistance depends on BLT, $R_{C1}$and R_{C2}.[9]

Surface roughness also affects the thermal contact resistance between two materials. Increase in surface roughness, increases the thermal contact resistance between two surfaces. [10]

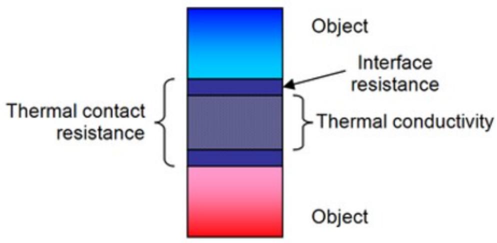

Figure 2.5: Ideal thermal resistance path between two parts [9]

2.4 Crash Test Simulation

During car crash, high shock loads are experienced from the impact.Shock loads can be defined as high transient loads that act for very short duration. During crash, shock loads act on the various members of car. During crash tests of car, accelerometers are connected with various parts of vehicle and shock load acting on various regions of car are then studied. These data aid in defining the boundary conditions for the safety requirements.

Full functional shock and Destructive shock are the two types of shock load tests performed in Volvo cars during the development phase of a project. In a full functional shock, the requirement is that the battery pack as a whole should function properly after the crash. In a destructive shock load case, the battery pack can fail as the boundary conditions are extreme but the failure should be safe, without causing any fire or gas leakage etc.

2.5 Manufacturing and Joining Techniques

There are variety of manufacturing and joining techniques for metallic components. The techniques/process which are very relevant to the project are only discussed here.

2.5.1 Stamping

Stamping is a metal forming process where a flat sheet metal in blank or roll form is fed into a stamping press. The press consists of a punch and die and the punch stamps on the metal to get a near net shape of the part.Stamping process is highly suitable for large volume production and usually thickness of material can be up to 6mm. The dimensional accuracy of the stamped parts is not significantly great but stamping is cheaper manufacturing process, often times the design of parts are developed considering the large variation. Stamping is the most common manufacturing process across industries[11]. In Figure 2.6, a simple layout of a punch and die in a stamping operation can be seen.

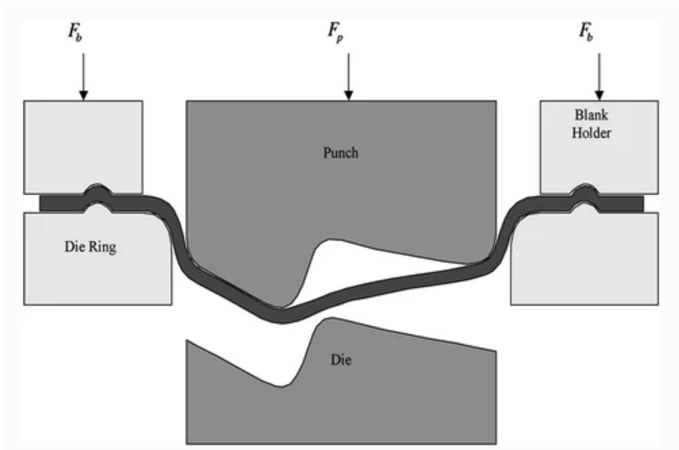

Figure 2.6: Metal Stamping Process [11]

2.5.2 Metal Casting

Casting is a manufacturing process where a metallic object is obtained from solidification of molten metal in a mold cavity. The process involves pouring or feeding of molten metal into a mold cavity, solidification and then ejection of part. The mold cavity is usually close to the final dimension of the part. There are many different types of casting processes, like die casting, sand casting, lost foam casting, investment casting etc. Metal castings have widespread applications across industries like automotive, aerospace, mining etc. By volume and value in terms of application, metal castings are second most common after sheet metal parts. [12]

Since Die casting is more relevant and discussed more in the later chapter, Die casting process is discussed in detail.

2.5.2.1 Die Casting

This type of process can be characterised as the most direct of all casting processes as a molten metal is directly introduced into the permanent tooling. The process involves large investment costs but offer really low part costs for compatible materials and high production rates as well. The mold cavity is made of 2 halves and they close and exert pressure once the molten metal has been flown into the cavities[13].

In Figure 2.7, the setup of a die cast operation is shown for better clarity.

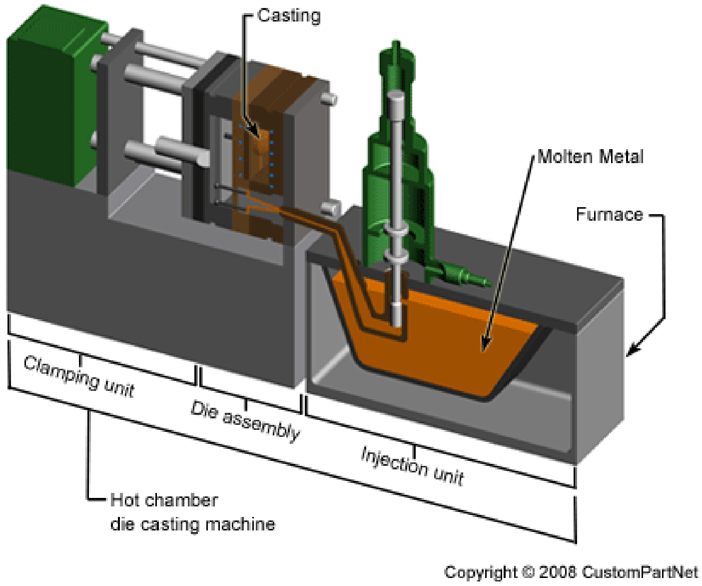

Figure 2.7: Die Casting setup [14]

There are two types of Die Casting process (High Pressure Die Castings and Low Pressure Die Castings) and in Table 2.1, some of the differences has been listed.

Low Pressure Die Casting (LPDC)	High Pressure Die Casting (HPDC)
The pressure exerted by the two halves is lower and is generally less than 0.08MPa	Pressure is higher usually 30-70MPa
Surface smoothness is poor	Very smooth surface can be obtained
No porosity inside the casting	Porosity chances are high
Low operating cost	High setup cost, suitable for large volume production

Table 2.1: Die Casting Processes [15]

2.5.3 Metal Joining Methods

In the following section, some of the joining techniques which are relevant to the scope of work has been discussed.

2.5.3.1 Spot Welding

Welding can be defined as the process where two or more parts are joined together by fusing the work pieces with heat,pressure or both. Welding has widespread application as welding is one of the cheapest method to join metals, especially ferrous metals [16].
Spot Welding is the process of welding two or more sheets of metal by applying pressure and heat from electric current. The current is generated by copper alloy electrodes at the surfaces of metal [17].

2.5.3.2 Friction Stir Welding

Friction Stir Welding (FSW) is a solid state joining process where heat generated by friction between a rotating tool and work pieces are used to join materials. The tool while traversing along the line of desired joint, intermixes the two metal pieces mechanically. The tool then forges the hot softened metal by the mechanical pressure. Aluminum alloys of all grades can be friction stir welded. FSW has been used for a variety of applications across industries ranging from aerospace to shipbuilding and rail to electronics, including EV battery trays [18]. The FSW tool and the work piece setup can be seen in figure 2.8.

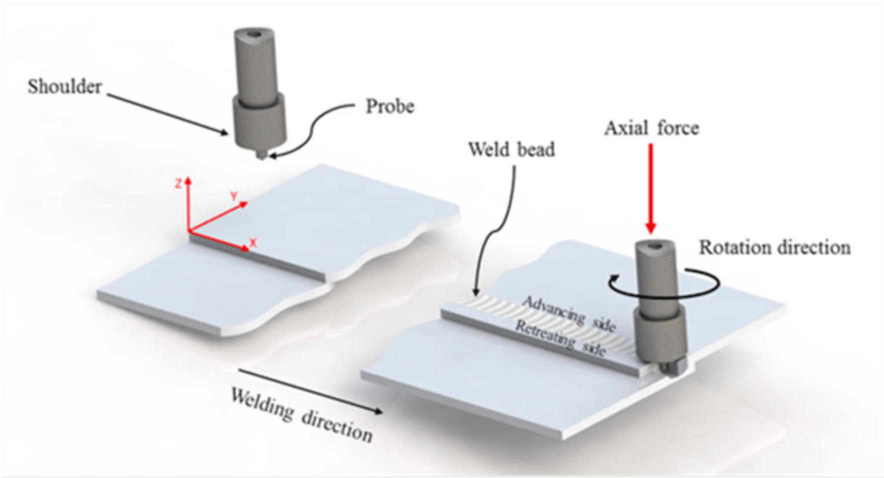

Figure 2.8: FSW tool and work piece setup [19]

The process can be described in following steps as per the same order and has been listed below [20].

1. Clamping of work piece
2. Tool Plunges into work piece
3. Tool traverses along the desired path
4. Tool rises from the work piece creating an exit hole

In Figure 2.9, a typical exit hole from a FSW is shown. The exit hole formed when the tool rises out can be a critical issue based on the application and operation conditions of the part. If the part is subjected to conditions where leakage and pressure drop is a critical issue, the exit holes can be refilled.

Figure 2.9: Exit hole in a FSW process [21]

There are 4 important parameters to consider when designing parts that are to be friction stir welded [20]:

1. **Weld length and path**
2. **Depth of the weld**
3. **Material of the parts to be welded**
4. **Tool geometry**

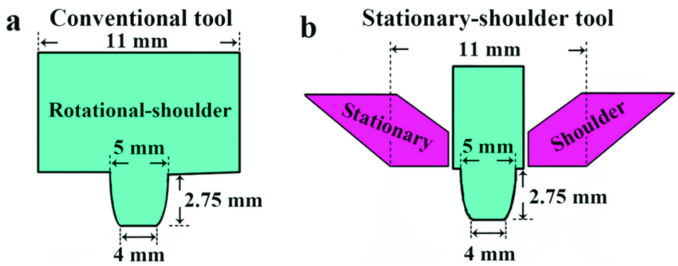

Figure 2.10: FSW tool geometry [22]

There are two types of FSW process called as the rotational shoulder and the stationary shoulder FSW. As the name suggests, the naming is given from the motion of the shoulder of the tool. The tool geometry for the shoulders can be seen in Figure 2.10.

2.5.4 Laser Welding

Laser welding is a technique to join metals or thermoplastics using a laser source. Since the heat source is very concentrated on a spot, laser welding can be used to carry out production with high welding speeds in thinner metals. When developing parts with laser welding as process,fatigue requirements of the part needs to be considered, as welding is prone to fatigue failure. In Figure 2.11, a schematic setup for a laser welding process can be seen.

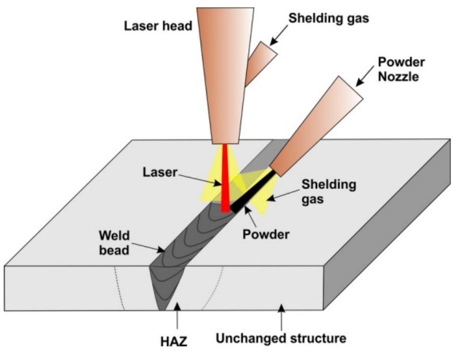

Figure 2.11: Schematic diagram for Laser Welding Process [23]

2.5.5 Brazing

Brazing is a metal joining process where two or more materials are joined by melting and flowing a filler material into the joint.Unlike welding the work pieces are not melted in brazing. A filler metal with much lower melting temperature than the parent materials, melts and fills the pores of parent materials through capillary action. A capillary action can be defined as flow of fluid into narrow spaces without influence of external force. Mercury filled thermometers is an example for capillary action. To achieve a good brazed joint, uniform gap and clean surfaces are required. Cleanliness of surface affects the capillary action. To ensure the cleanliness and surface purity of the parts, a flux is often used before brazing components.[24]

2.5.5.1 Vacuum Brazing

In vacuum brazing the components are placed inside a furnace. The furnace has a vacuum environment thus eliminating the risk of oxidation and the demand of flux. To speed up the assembly process, braze-clad components can be used to remove the braze alloy application step. Assemblies are placed inside a vacuum furnace that is heated to brazing temperature range, a level that will melt the braze alloy but not the main material. The molten braze alloy fills in gaps between components through capillary action and joins the components while cooling, thus forming a permanent joint. [25]

2.6 Fastening Methods

Screw Joints and Rivet Joint are the fastening methods discussed a bit more in the following sections.

2.6.1 Screw Joints

Screw joints are one of the widely used fastening solution. The joint area is usually a pre-threaded hole that is used for the assembly. The hole is used to attach two pieces of material. A joint design facilitates the screw to be tightened to the calculated depth of the pre-threaded joint hole. There are also thread forming screws available. These screws doesn't require pre-threaded hole, will deform the material in the holes and create threads while tightening.

2.6.2 Rivet Joints

A rivet, consisting a cylindrical shaft with a head on one end and tail on other end is a type of mechanical fastener to join two parts.During installation, the rivet is placed on a hole, axial force is applied and the tail is disturbed. The tail deforms by compression, holding the two parts together. The rivet joints are permanent joints and dis-assembly of parts is not possible once the parts are riveted.

2.7 Design for Manufacturing and Assembly

When designing parts for die casting, there are some design considerations and guidelines which can help to reduce the development time of the part and help the organization to launch the product at the earliest.

Thus, incorporating design for manufacture and assembly in the early stages of product development can help reduce lead time as well as costs.

Design Guidelines for Die Casting is mainly discussed here. The guidelines mentioned here are summarised from North American Die Casting Association (NADCA) manual and discussions from Die Casting experts within Volvo Cars. A short and summarised version is shown in Figure 2.12.[26]

S.No	Guidelines	Action for Designer
1	Through hole is not possible in die casting and requires secondary operation.	Consider secondary operations and cost implications
2	Min Draft of 1-2 degrees needs to provided for surfaces. More draft is required if depth of surface is more.	Draft Analysis
3	Wall thickness must be uniform. In case of varying wall thickness, transition must be smooth. Min wall thickness for casting is 2.5mm.	Thickness analysis
4	Ample fillets and ribs must be utlised in bosses to facilitate smooth flow of molten metal.	Use fillets in corners
5	All corners should be rounded by generous fillet both on outer and inner surfaces.	Use fillets in corners
6	Height to outer diameter ratio less than 3 is preferred for hollow bosses.	Consider surrounding parts and make suitable decisions

Figure 2.12: Some guidelines for Die Cast products

Assembly of parts must also be considered. The designers are advised to consider the assembly sequence to make right choices. The designers must also consider accessibility of tools based on the operations involved. For example, when a screw is used, sufficient clearances for the screw gun to apply torque must be ensured. Socket Clearance reference is available within organizations to consider the accessibility of tool. Likewise, for friction stir welding, the tool must be accessible to the desired surface.

2.7.1 Tolerance Stack up

Every dimension on a part is subject to variation. The allowable variation of dimensions is usually specified by the designer through tolerances associated with each dimension. The effects of variations on the assembly and assigning the right tolerances to dimensions arises the need for performing tolerance stack-ups. Stack up analysis bring together the knowledge of manufacturing process and dimension standards to meet the functional requirements of assembly.[27]

Stricter tolerances demand precision manufacturing methods. More precise control of the manufacturing process, higher are the costs involved. Hence, good designers allow the largest possible tolerances to achieve the functional requirements.[27]

Tolerance stack up calculations are generally carried out during the design phase to understand the sources of variation within an assembly. By performing stack up analysis, designers can assign tolerances based on manufacturing capability, assembly capability, and implement process control. [27]

The first step in stack up is to define the chain of dimensions contributing to the stack-up. The stack-up equation must be created before calculations can be carried out. There are different methods of calculation for the stack up.

1. **Worst Case method** - The worst case method is relatively simpler compared to the statistical method. The analysis is carried out twice. One analysis for the maximum assembly dimension and another for the minimum assembly dimension is done. Benefits of worst case method are simplicity and easier calculations. [27]
2. **Statistical method** - In the statistical analysis method, the focus is not on the possible deviations but rather on the probable deviations. The resulting tolerances of assembly are realistic provided the data and assumptions are more realistic. The analysis provides likely values and ranges depending on the confidence intervals. A confidence interval can be defined as the mean of estimate and variation in the estimate. Statistical stack up calculations are more reliable if the dimensions follow a normal distribution. [27]

2.7.2 Design for Sustainability

Design for sustainability is an important strategy in product development focusing on the reducing the carbon footprint of the part by using recyclable materials, avoiding manufacturing processes which generate huge scrap, reduce the number of parts etc. [28]

3

Methods

VDI 2221, General approach to design were followed as a guideline to drive the design work of the thesis. The methods followed to carry out the thesis work has been discussed in this chapter. Figure 3.1 has the sequential steps followed in the thesis. Based on the different phases shown in the picture, methods involved in the phases are discussed more elaborately below.

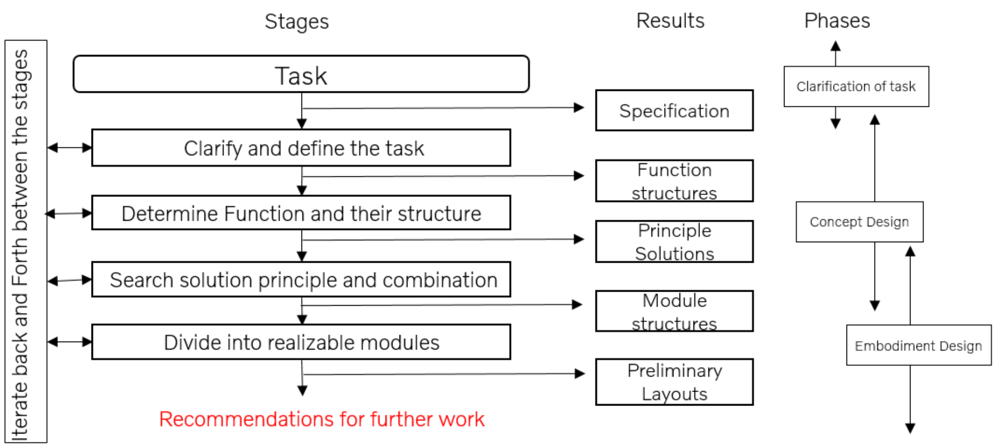

Figure 3.1: Project Approach[5]

3.1 Clarification of Task

Literature Study and Benchmarking of the current product was one of the first step of the thesis work in clarifying and defining the task. Thorough understanding of the current product, the functioning, strength, limitations, production and assembly were needed [5].

The mentioned knowledge gaps were closed by studying research papers,article and books on the internet, discussing and collecting data from different stakeholders. As discussed in chapter 2, the project was treated as an increment product for the reasons stated. This scope setting was particularly important in evaluating concepts.

Since the product is already in production, one of the main requirements while fixing the scope was that the changes due to the development of this proposed product must be as minimal as possible. A mission statement and requirement specification was formulated based on clarification of task and can be seen in Appendix A.

3.2 Concept Design

In the concept design phase, function decomposition, concept generation, material selection and concept evaluation were some of the major activities. The methods of each activity is described in following subsections.

3.2.1 Function Decomposition

Function decomposition in product development helps in analyzing/improving the products, better understanding of the products and support in design and development activities. Function decomposition refers to breaking down the purpose of product under consideration to what the product does or needs to do. Based on the understanding of the problem, a function tree was formulated. [29]

3.2.2 Concept Generation

During the concept generation phase, methods such as external search and internal search was used to generate concepts to solve the problem. External search refers to activities such as consulting experts, searching patents,literature and benchmarking related products. Internal search refers to activities that were carried out individually. The guideline for material selection in design process was quite useful.

3.2.2.1 Materials Selection in Design Process

The material selection process can be broken down to simpler steps [30]:

1. **Translate demands of component to demands of material**
2. **Screen**
3. **Optimize**
4. **Find Documentation**
5. **Iterate**

As the progress from concept to embodiment to detail design occurs, the materials selection narrows down from the choice of material family to material class and finally one single material.

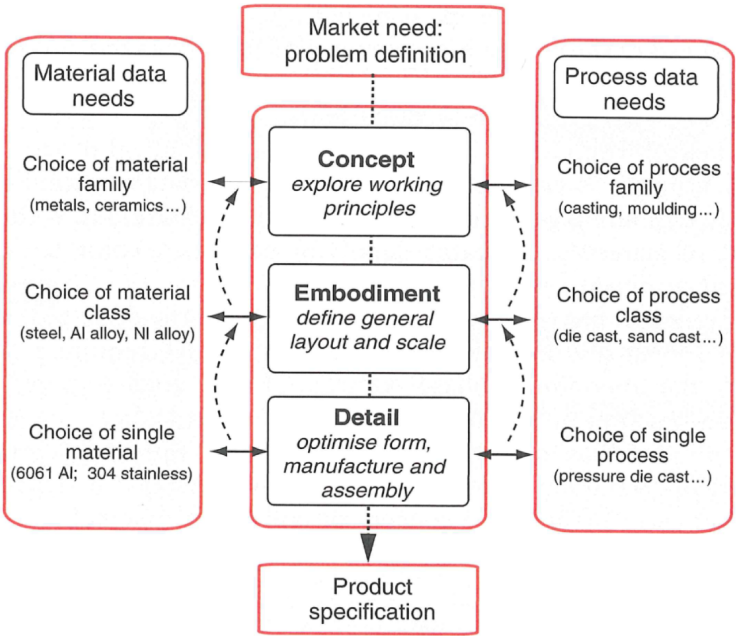

Figure 3.2: Design Process and Material Selection [30]

3.2.3 Concept Evaluation

Concepts generated based on material choices and manufacturing process choices were needed to be filtered. Summative evaluation to identify strength, weakness and potential of the concepts was followed by formative evaluation to improve the concepts further. The concepts evaluation was carried out by scheduling meetings with different stakeholders and Engineering assessment.[31]

Concepts were evaluated using combination of normative, performance/cost assessment, reflective methods.

Normative methods refers to the evaluation of the concepts with typically predefined criteria (requirements, targets etc.). Elimination Matrix and Pugh Matrix for concept evaluation were used in the thesis work.[31]

Elimination Matrix was understood and modified to suit the thesis scope, was useful in filtering the bad concepts. Elimination matrix is considered to be a strong filter in filtering the concepts which are completely random and inappropriate.[31]

Pugh Matrix was more suited and beneficial to the thesis work as the product is already in production. Current design was set as datum and remaining concepts from the elimination matrix was compared with the current design.[31]

Performance/ Cost assessment for the concepts , a cost assessment was done to compare the cost of current product and estimated cost if the concept is developed more in detail and produced.[31] Performance assessment was done in collaboration with CAE team to evaluate the rigidity and deformation of the concept.

Reflective methods like listing the drawbacks/ benefits and having expert/peer reviews were done to assess the solution potential and further development plans. [31]

3.3 Embodiment Design

Embodiment Design refers to the process of going from an idea to realization. During this process, Design for Manufacturing and Assembly guidelines were applied to the winning concept to make it better. An embodiment design is an attempt to fulfil a given function with definite layout, shape and material choices [32].

4
Project Work

The different phases of the project are discussed in this project more elaborately.

4.1 Clarifying the task

In this chapter, the benchmarking of current product is explained.

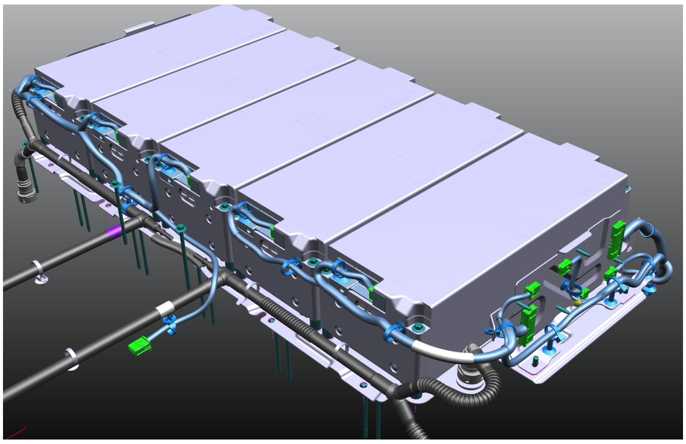

Figure 4.1: Rear Upper Side of CMA Battery pack

The battery pack as such is a very big system and contains various sub-systems. In Figure 4.1, only the rear upper side of the CMA battery pack is shown as these parts are the most relevant parts of the thesis work. The different components in the picture will be elaborated subsequently.

4.1.1 Cooling Plate

In Figure 4.2, the cooling plate and coolant flow pipe are seen. A section view of cooling plate is also shown in Figure 4.2. The cooling plate has 2 ports to control the inlet and outlet of the coolant flow.

As shown in the view, there are 2 plates. The flat upper plate is referred as cover plate and the lower plate with pockets (in desired flow channel shape) is referred as the channel plate. The two plates are vacuum brazed to achieve a permanent joint and the coolant flows in between two plates. Heat transfer occurs between the cover plate and battery modules which come above the cover plate.

The two plates are Al3003 alloy plates. Thermal Interface Material (TIM) is applied on the top side of cover plate to ensure there is no air gap between the battery modules and cooling plate.

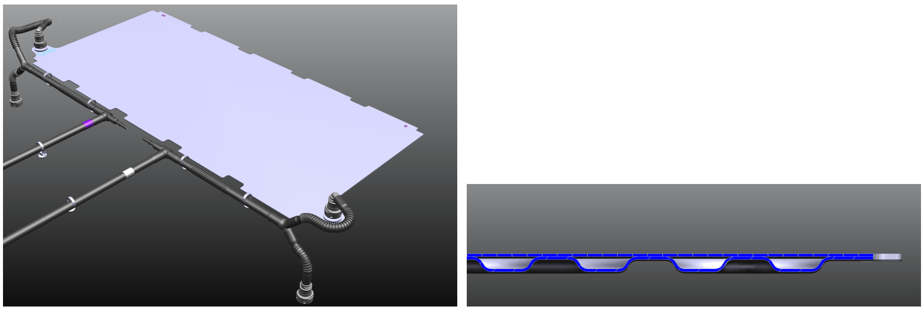

Figure 4.2: Cooling Plate

The coolant used is 50 percent mixture of Ethylene Glycol and 50 percent water.A spigot controls the entry and exit of the coolant. The spigot is also placed inside the vacuum furnace and is brazed to join with the plates.

4.1.2 Rear Bracket Assembly

In Figure 4.3, the rear bracket sub-assembly is shown. The sub-assembly consists of a steel bracket, 20 weld nuts and 20 spacers. The bracket is stamped and weld nuts are welded in the brackets. The spacers are riveted with the bracket. A surface coating process is carried out after welding and rivet operations.

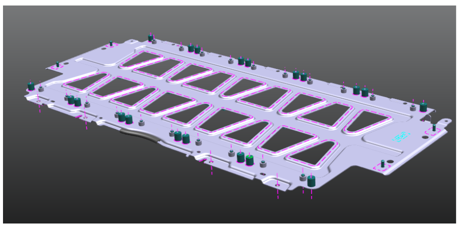

Figure 4.3: Rear Bracket Assembly

The weld nuts are used to fasten the battery modules using screws. The geometry and alignment of the bracket,weld nut, spacers, battery module and screw can be seen in Figure 4.4. The height of weld nut is 15 ± 0.5 mm. The stamped parts have a flatness tolerance of ±1mm. Hence, on assembly level the allowable variation was ± 1.5mm.

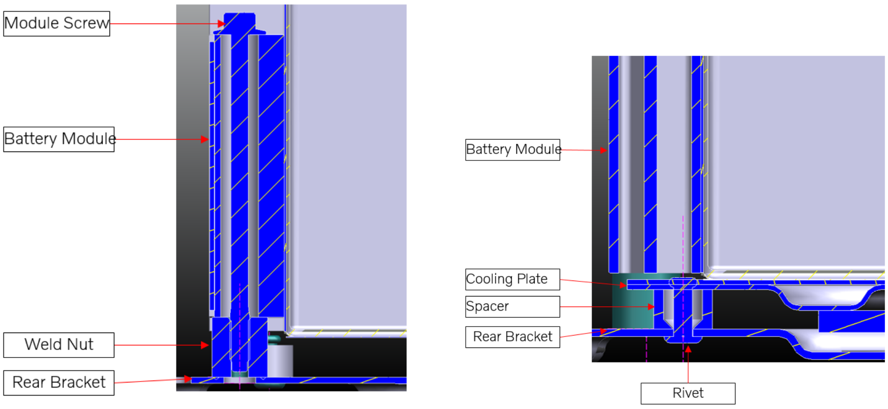

Figure 4.4: Section view

4.1.3 Wiring Harness

In Figure 4.5, the wiring harness in the rear upper side is shown. Wiring harness in this context refers to the electric cables which are connected to the temperature sensors in the battery pack to monitor the temperature of the battery modules.

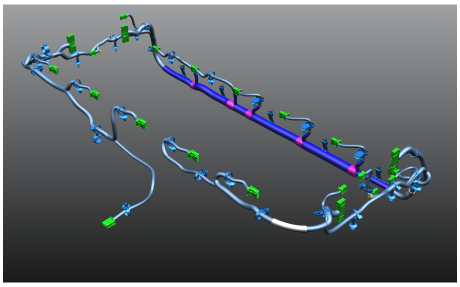

Figure 4.5: Wiring Harness

4.1.4 CVTN Bracket

CVTN (Cell Voltage Temperature Node) bracket is a sheet metal stamped part which is used to house the CVTN temperature nodes. The CVTN bracket is assembled with the rear bracket using a nut and weld screw. As seen in Figure 4.6, there are two brackets on the Left and Right hand side. CVTN temperature nodes are used to monitor the temperature within the battery packs.

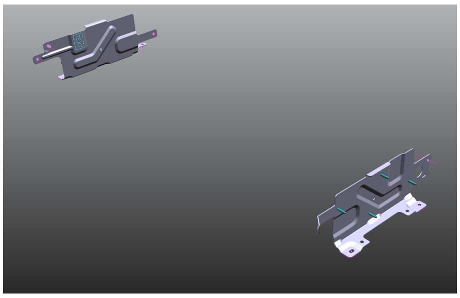

Figure 4.6: CVTN bracket

4.1.5 Fixation Bracket

Fixation Bracket is an Aluminum extruded part which is used to support the rear bracket. The fixation bracket and the rear bracket are screwed together using a M6 Flange screw. The orientation of the mentioned parts can be seen in Figure 4.7. There are 9 fixation brackets on which the rear bracket rests upon. The fixation brackets are welded with the cross beam in the battery pack.

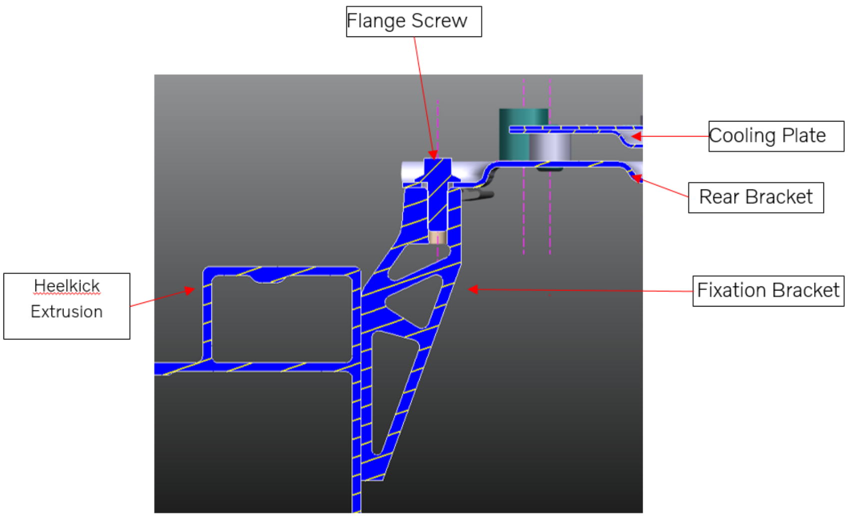

Figure 4.7: Fixation Bracket and rear bracket fastening

4.1.6 Assembly Sequence

The Assembly Sequence of the parts in the main assembly line is shown in Figure 4.8. The CVTN bracket is assembled in a different station, hence has been indicated in a different level.

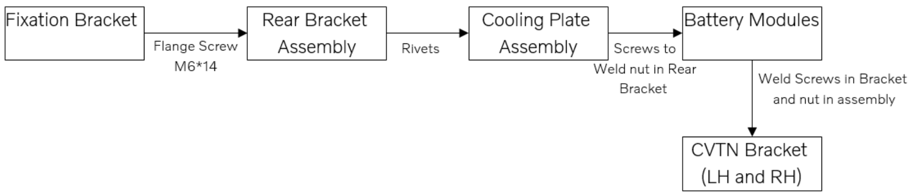

Figure 4.8: Assembly sequence of the parts

4.1.7 Boundary Conditions for Destructive Shock testing

Destructive shock analysis is a dynamic CAE test to simulate the crash. Based on previous crash tests and analysis, Volvo Cars has defined the boundary conditions for destructive shock. The destructive shock is the worst crash scenario. The load acting are as following:
1. X direction - 55g for 66ms
2. Y Direction - 100g for 20ms
3. Z Direction - 50g for 44ms

The cooling plate and brackets are allowed to deform or fail in a destructive shock load case but the failure must be safe and shall not induce any fire or risk with the battery modules.

A comprehensive understanding of the product and requirements were obtained and was used in formulating a requirement specification.

4.2 Concept Design

Function analysis, material selection choices and concept evaluation are discussed here. Preliminary concept design and evaluation were done using normative methods and CAE based assessment.

4.2.1 Function Analysis

Once initial product specification was created, Functional Decomposition was carried out for the scope of the task and is shown in Figure 4.9.

The main functions identified were to ensure heat transfer and rigidity; prevent coolant leak. To identify means to achieve the function, ideas were searched for externally and internally. With the ideas gathered, a morphological matrix was created to generate different potential solution concepts.

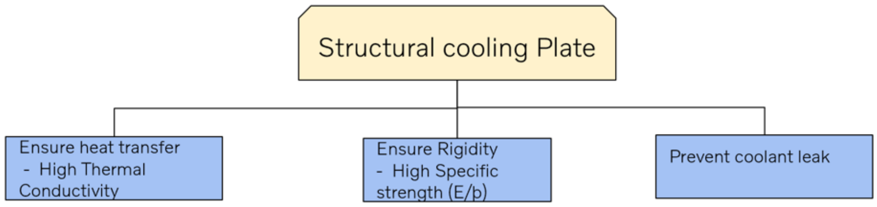

Figure 4.9: Function Means tree for the task

4.2.2 Material Selection and Concept Generation

The material selection was done in a methodical approach as discussed in Chapter 3.

Translate demands of product: The functional analysis aided in translating the demands. The product has to conduct heat at the same time needs to be stiffer. The objective is to minimize the cost. Higher the thermal conductivity, materials conducts heat better facilitating efficient heat transfer. Higher the stiffness, the material is immune to large deformations when loads are applied. Thus, materials were screened based on thermal conductivity and specific strength.

Based on the demands, material choices were explored. Copper alloys and Aluminum alloys were the material choices which satisfied the criteria for high thermal conductivity and aluminum alloys, copper alloys, steel and plastic satisfied the high specific strength.

Morphological Matrix								
Subfunctions		Subsolutions						
		1	2	3	4	5	6	7
A	Ensure Heat transfer	Aluminum Flat Plate (Stamped)	Copper Cooling plate	Aluminum Extrusion	Aluminum plate and cooper tube			
B	Ensure rigidity	Aluminum Channel plate (Stamped)	Copper channel plate		Aluminum Channel plate (Casted)	Steel Channel plate	Plastic Channel plate	
C	Prevent coolant leak	Brazing	Welding (FSW/laser)		Adhesives			

Figure 4.10: Morphological matrix for material/design choices

Screen: An Elimination Matrix as shown in Figure 4.11 was constructed for initial screening.

1. Concept Copper refers to the concept using copper alloy based cover plate and channel plate, joined by brazing process. Since Copper alloys are more expensive than the Aluminum alloys, Copper alloys were not considered further.

2. Concept Hybrid refers to using Aluminum alloy based cover plate and joined with a polymer based channel plate using Adhesives. Concept Adhesive is similar as well, instead of polymer based channel plate, the material of channel plate is Steel.The drawback of these 2 concepts were that using adhesives to join aluminum with dissimilar materials (Steel, plastics etc.) is still in very early stages of development and can not be industrialized yet.

3. Concept Extrude refers to using an Aluminum extruded cold plate. The concept was filtered because the changes with the surrounding parts were very high to realize. Hence, had a large cost impact and didn't fit the portfolio of a derivative product.

4. Concept Cast and Stamp refers to using existing Aluminum cover plates and joined with Al cast alloy and wrought alloy respectively. Both these concepts were found to be the promising after the first screening using Elimination matrix.

Elimination Matrix

(+) Fulfills criteria
(-) Do not fulfill criteria
(?) More info needed

Continue
Remove
Test

Solution alternative	Solves main problem	Fulfills all demands	Realizable	Reasonable cost	Fits Portfolio	Safe	Enough information	Comment	Decision
Concepts									
Copper (2-2-1)	+	+	+	-				Copper is expensive	
Hybrid (1-6-5)	+	+	+	+	-			Very few suppliers. Nascent Technology	
Cast (1-4-2)	+	+	+	+	+	+	+	Die Cast Cold Plates are proven and existing	
Adhesive (1-5-5)	+	+	+	+	-			Very few suppliers. Nascent Technology	
Stamp (1-1-1)	+	+	+	+	+	+	+	Proven and Existing in market	
Extrude (3)	+	+	+	+	-			Requires many changes in the surrounding parts	

Figure 4.11: Elimination Matrix for Concept Screening

The design considerations were more abstract during the stage of concept screening. Elimination matrix was mainly used to filter out the worst concepts from the generated concepts.

Optimize: During later stages of concept design and embodiment design material choices were more optimised to the product requirements.

To begin the work and initial design iterations, the flow channels and fastening method of fixation bracket were not modified, and layout was developed considering the existing layout.

Find Documentation: External search and internal search were done to find relevant literature, documents etc. Few of the noteworthy findings have been discussed below.

1. **Brazed Cold Plate:** Inspired from the current design, Channel plate with increased thickness (to increase stiffness) brazed with cover plate was decided to explore further.

2. **Welded Cold Plate** - Cold plates with cast Aluminum alloy and wrought Al alloy joined either by FSW or laser welding process was found to be available in market. Hence, a concept with Welding the cold plate was created.[33][34]

4.2.3 Concept Evaluation

The remaining concepts from the elimination matrix were 2 concepts which were the concepts cast and stamp . The concepts where developed further before evaluation using Pugh Matrix.

The concept Cast consists of a cover plate of Al3003 and an integrated channel plate and bracket with Cast Al alloy. The fixings to Battery modules will be integrated in the part as screw bosses.

The concept Stamp consists of a cover plate of Al3003 and integrated channel plate and bracket with Al3003 alloy. The fixings for battery modules will be welded on the part.

Before evaluation, destructive shock CAE simulation test was carried out for the cast concept. The CAE simulation was performed by the CAE experts. The main objective of the CAE simulation was to identify the thickness of Aluminum which satisfies the criteria.

The CAD model developed was very basic and DFMA guidelines,interference with other parts were not taken into consideration. The justification of choosing cast concept over stamp concept is that the cast Al alloys are weaker than wrought Al alloys. If cast alloys meet the structural requirement, wrought alloys will also satisfy.The CAD model developed can be seen in Figure 4.12.

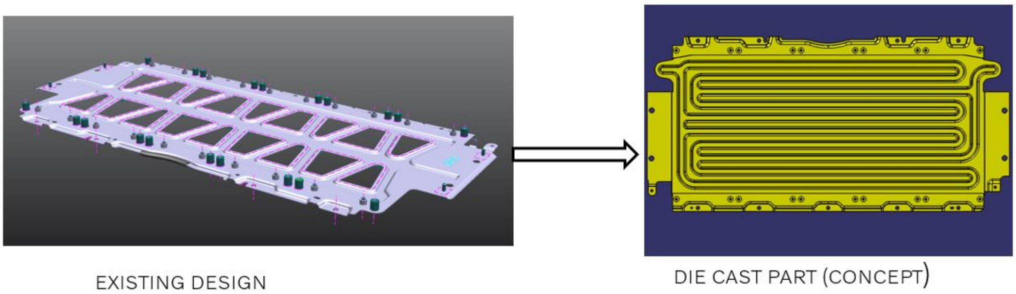

Figure 4.12: CAD model developed for CAE simulation

The model was shared to CAE teams at Volvo Cars and simulation was performed by CAE team.The results indicated that the CAD model developed was stiffer than the current design. Thus, the CAE assessment was one of the basis for concept evaluation. The results of CAE analysis can be seen in Appendix B.

A Pugh matrix for concept comparison was very useful. The concepts were compared with the current design for different criteria. The concept Stamp involved more changes with the surrounding parts and also required welding. Welding of aluminum is a challenge, is better avoided unless welding is the only option. Hence concept Cast is the only remaining concept and was considered for more further development. The Pugh matrix can be seen in Figure 4.13.

Embodiment design was carried out with concept Cast to take the idea a step closer to realization.During the embodiment design, the interference with CVTN bracket, joining method with cover plate and thread engagement study was carried out. The final embodiment design is discussed in the subsequent chapter.

Criteria	Current Design	Cast	Stamp
Weight	DATUM	+	+
Rigidity		+	+
Heat Transfer		0	0
Impact on other parts		-	-
Sustainability (based on mfg process)		+	0
Ease of manufacture/assembly		+	-
Tolerance stack up		+	-
Σ +		5	2
Σ −		1	3
Σ 0		1	2
Total		4	-1
Further Development		YES	NO

Figure 4.13: Pugh Matrix

4.3 Embodiment Design

The Cast concept was the winning concept and hence more time, effort was put in developing the concept more. In this chapter, embodiment design of the concept is presented.

4.3.1 Design of Die Cast Part

The primary operation of the part is die casting and the part requires machining as secondary operation for better tolerance control. The machining operation will also be briefly touched upon later in this section.

Design guidelines like smooth parting lines, avoiding sharp corners, adding ribs to increase the stiffness, providing sufficient draft for the surfaces, adding ribs to bosses and radii for the corners of the bosses were some of the guidelines followed while developing the integrated part (channel plate and rear bracket).

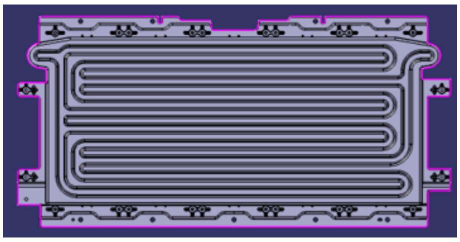

Figure 4.14: Proposed parting line for the part

In Figure 4.14, the part is oriented along the tool view. The tooling direction considered for the part is normal to the tool view (Z direction). The Parting line has been highlighted with magenta colored lines.

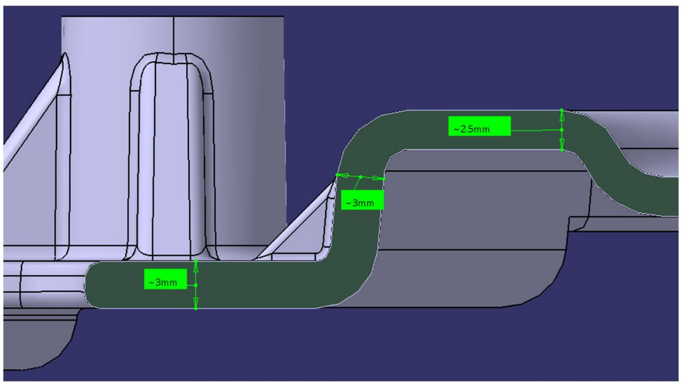

Figure 4.15: Variable thickness of the part

The inference from the destructive shock testing and from discussions with CAE team was that loads don't act as much in the cooling channel area as in the screw boss region.

Die casting also facilitates variable thickness in parts. The design criteria is that the transition region between two varying thickness regions must be smooth and not sudden. As can be seen in Figure 4.15, there is a transition between 2.5 mm and 3mm which was carried out by adding smooth radii on the outer and inner surfaces. The advantage of such a design is weight can be reduced even more.

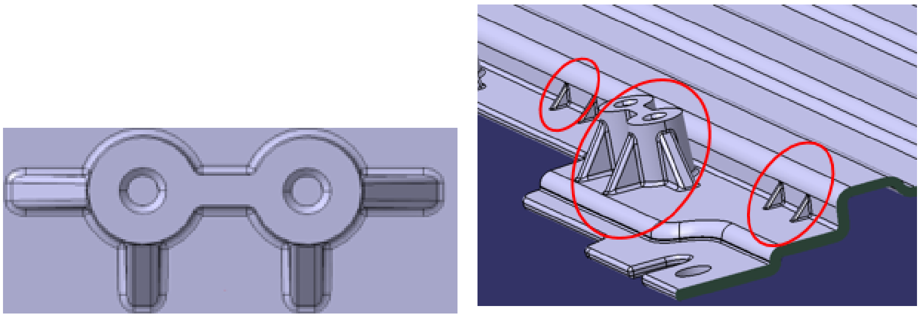

Figure 4.16: Ribs added to increase stiffness and facilitate molten material flow

Ribs were added on the parts as well as on the screw bosses to increase the stiffness of the parts. Ribs also serve another function by helping the flow of molten material. Triangular ribs aid better in regulating the flow of molten material,hence ribs with triangular profile have been added.

Note, the above discussed guidelines are only few and contact with a casting part supplier must be established for further detailed development of the part considering the shrinkage allowances and material properties. The work carried out is in the scope of embodiment design, which precedes the detail design of parts and components.

4.3.2 Secondary Operation

The part requires two secondary operations: trimming process and machining of screw boss. The details and justification for both the process have been discussed briefly below.

Through hole is not feasible in the die casting process. If through holes are required in the part, a trimming operation is performed using a separate trim press soon after casting process.

The integrated part requires through hole in the regions where the part is fastened with fixation brackets using flange screws. Hence, a trimming operation is proposed for the part. Usually, 0.5mm material is added to the area where through hole is required and is then trimmed. The as cast and after trimming representation is shown in Figure 4.17.

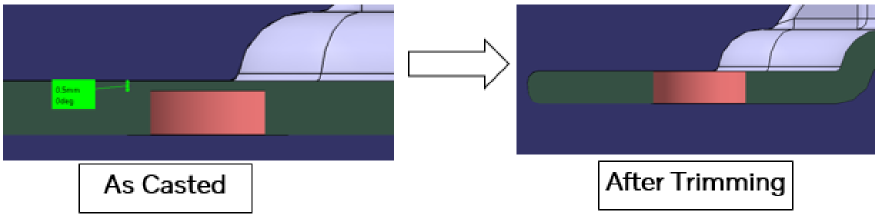

Figure 4.17: As cast and post trimming operation of the part

Machining is required for two purposes:

1. In cast part, the screw boss inner diameter will be drafted for the ejection of tool. The battery module screw that fastens the battery module and the integrated part is not a thread forming screw, hence the inside faces of screw bosses need to be drilled to uniform 5mm diameter and then threading operation is required to engage the screws.

2. A facing operation is also proposed on the top face of the screw boss to ensure better control of tolerance on the height of bosses. In chapter 4.1, the tolerance for the current design was discussed and the worst case tolerance of current design is 1.5mm. The tolerance of machining is ± 0.3mm and tolerance on wall thickness of a die-cast part is +0.5mm / -0.1mm. Hence the worst case tolerance is 0.8mm (better than the current design).

A tighter tolerance will aid in more efficient heat transfer between the battery module and cooling plate by reducing the air gap and more even spread of TIM material. However, Volvo Cars is recommended to carry out a probability based statistical analysis to find out how often the worst case tolerance would occur on the parts. For better understanding, a zoomed in picture of screw boss is shown in Figure 4.18.

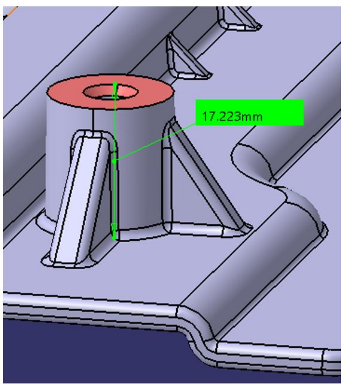

Figure 4.18: Machining of screw boss

4.3.3 Joining Cover plate and Die Cast Part

In Figure 4.19, the different techniques possible to join cover plate and die cast part are shown. Tool from top refers to the access of tool from the cover plate side while the tool from bottom refers to the access of tool from the integrated cast part.

	Tool From Top	Tool From Bottom
Friction Stir Welding (FSW)	Surface roughness for TIM Refill spots	Tool accessibility Refill spots
Laser Welding	Surface roughness for TIM Fatigue	Not Feasible (Material thickness to melt is high)
Brazing	Not Feasible (Cast alloy not suitable)	

Figure 4.19: Feasibility/ Constraint Matrix for different joining process

Laser welding from bottom is not feasible because the material thickness to be melted is thick while brazing of cast alloys are not feasible as cast alloys have much lower melting temperature than wrought alloys.

Friction stir welding from bottom is not feasible for the current profile of the coolant channel as the width is less than the diameter of the FSW tool.

FSW and Laser welding from the cover plate side is feasible but there are some constraints that need to be addressed. In laser welding, the chances of cracking is more and hence part might fail due to fatigue, hence fatigue test of part need to be carried comprehensively. In Figure 4.20, the possible tool path for the laser welding and FSW process is shown. For FSW process, with the current coolant channel profile, exit holes are formed and encircled in the picture. Hence, a refill FSW process can be considered but cost could increase.

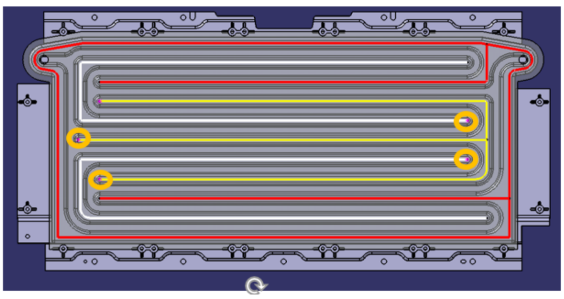

Figure 4.20: Tool path for FSW and laser welding process

The surface roughness of cover plate would change if the welding is done on the cover plate side. As discussed in chapter 2, the surface roughness increases the contact resistance between TIM and surfaces. Since the part will be machined to attain better tolerance, Bond Line thickness will reduce. Volvo Cars is recommended to investigate the discussed aspect about surface roughness and BLT further.

4.3.4 Changes in surrounding parts

CVTN brackets need to modified as well to accommodate the proposed integration of the bracket and channel plate. In Figure 4.21, the interference with the current CVTN bracket and the proposed change is shown. The proposed change includes having a screw boss and a locator in the integrated part instead of earlier design with weld screws and nut. The locator aids in the aligning the parts before fastening using torque in the main assembly line.

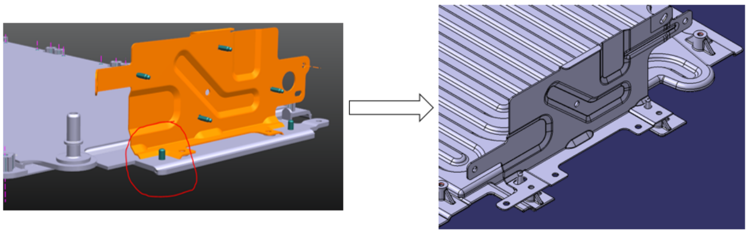

Figure 4.21: Clash with CVTN bracket and proposed changes to CVTN bracket

Modifying the fastening method also has an impact on the wiring harness connecting the CVTN sensors as the clearances were less. In Figure 4.22, the clip marked as 1 can also be used in position 2, to increase the clearance and this change in harness is very minor and will not have a significant cost impact.

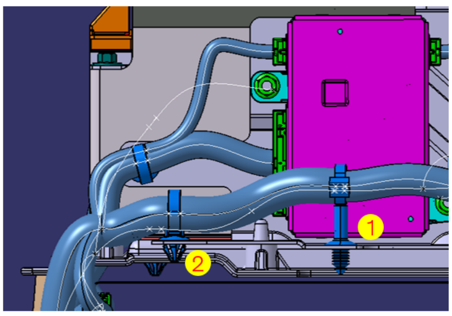

Figure 4.22: Changes required in wiring harness

5
Results

In this chapter, comparison between the current design and the proposed design for certain key aspects like cost,weight and ease of assembly are discussed.

5.1 Tolerance Chain

The desire is to have a 0mm gap between the battery module and cover plate. However, due to the variations associated with manufacturing processes , achieving 0mm always is practically impossible. In Figure 5.1, the comparison between the worst case tolerance for the current design and the proposed design is shown.

The proposed design is better than the current design. The casting tolerances and machining tolerances were added as per discussions with Design Engineers within Volvo Cars while the tolerances for current design were obtained from the drawings of the respective parts.

Current Design	Tolerance	Thesis Proposal	Tolerance
Stamping (Rear Bracket)	±1mm	Casting (Wall thickness variation)	+0.5/-0.1 mm
Weld Nut	±0.25 mm	Machining (Screw boss resting face)	±0.3 mm
Spacer	±0.25 mm		
Worst Case Tolerance	1.5mm	Worst Case Tolerance	0.8 mm

Figure 5.1: Comparison between worst case tolerance for the existing design and current design

5.2 Ease of assembly

If the proposed product can be realized, the assembly sequence in the main line of assembly would be as shown in Figure 5.2. The need for rivets has been eliminated completely and once the integrated part arrives at the assembly station, TIM can be applied and battery modules can then be fastened directly, thus reducing the assembly time.

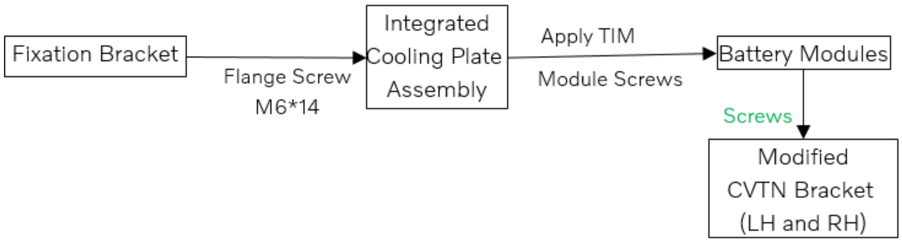

Figure 5.2: Ease of assembly if the concept can be realized

5.3 Design for Sustainability

The winning concept involves using Aluminium alloys, die casting manufacturing process and reduces the number of components. Aluminum alloys are recyclable, die casting is a manufacturing process with minimal scrap and reducing the number of components reduces the weight of car, which reduces the utilization of energy in use phase.Thus, the proposed concept has potential to be more sustainable than the current design.

5.4 Weight and Cost Comparison

The weight and cost comparison was carried out between the proposed part and the parts, the new design replaces in the current design. Due to confidential reasons, the exact values have not been added in the picture but the layout of comparison tables is shown in Figure 5.3.

The weight data was obtained using the CAD tools. The cost estimation for the proposed design was done by coordinating with a Cost Engineer within Volvo cars. For the cost estimation, the production region was considered to be Sweden and production volume to be 100,000 parts/year. There was a reduction in weight and cost in the range of 20-40%.

Current Design	Weight	Thesis Proposal	Weight
Rear Bracket	CONFIDENTIAL	Casted Part	CONFIDENTIAL
Weld Nut (20No.s)			
Spacer (20 No.s)			
Channel Plate			
Total		Total	

Current Design	Cost (in €)	Thesis Proposal	Cost (in €)
Rear Bracket Assy*	CONFIDENTIAL	Casted Part	CONFIDENTIAL
Cover Plate**		Cover plate	
Channel Plate**		Laser Welding (Spigot costs not included)	
Brazing			
Total		Total	

Figure 5.3: Comparison between weight for the existing design and current design

6
Conclusion

The research questions have been recalled, answered and some recommendations for further work has been discussed in this chapter.

6.1 Research Questions

1. **How has the current product been designed? What are the critical attributes of the product?**

As discussed in the chapter 4.1, the current design has many parts and stack up involved are too many dimensions. Due to the tolerance chain (spacers, weld nut and bracket), there is a possibility of poor spread of TIM on the cover plate which would prevent efficient heat transfer. The surrounding parts such as the wire harness and CVTN bracket have effects if bracket and cooling plate needs to be integrated.

2. **Are there worthy alternative materials and manufacturing processes to integrate the parts to provide cooling as well as structural rigidity functions with minimal changes to current design?**

Aluminium alloys are the choice of material for the integrated part as aluminum has high thermal conductivity as well as high specific strength. The choice available was between wrought alloys and cast alloys. Aluminum cast alloys were chosen as casting process offered much more advantages compared to wrought alloys.The Cast alloy part can be welded with the current wrought alloy part (Cover Plate) to achieve the functional requirements.

3. **What are the benefits that could be leveraged if the cooling plate and brackets are combined together?**

The integrated cooling plate promises to offer many benefits such as lower weight,lesser carbon footprint than the current design due to choice of material and manufacturing process, good spread of TIM ensuring efficient heat transfer, faster assembly of battery modules in the main line.

6.2 Recommendations for further work

Since the results obtained thus far is promising, the work is recommended to investigate further. The following are the immediate courses of action recommended for Volvo Cars in the scope of the work.

1. Carry an actual thermal test of CMA Battery Pack with cooling plates either friction stir welded or laser welded and compare the performance with brazed cold plate.

2. Establish contact with die-casting supplier and receive feedback for the manufacturing feasibility, shrinkage allowance and tolerances.

If the results are found to be satisfactory,

3. Carry a variation analysis and tolerance stack up calculation for the entire pack with the integrated part.

4. Cost of change and impact of change calculation for the CVTN bracket assembly and harness.

If the cost of change is not significantly high considering all the changes, Volvo Cars can proceed and focus extensively on detailed design.

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A

Appendix 1

MISSION STATEMENT	
Product Description	Integrated cooling plate and structural bracket
Benefit Proposition	Lesser weight of the battery pack Better tolerance chain in the assembly level Easier assembly in the main line
Key Business Goals	Reduce the cost and weight per part.
Primary Market	Assembly technicians, Procurement and Buyers.
Assumptions and Constraints	Current coolant flow profile is assumed to be good.Only if mandatory, changes in profile will be carried out.
Stakeholders	CAE (Structural and thermal) Manufacturing Engineering Electrical Harness Part Suppliers

Table A.1: Mission statement for the thesis work

Criteria	Target value	Evaluation /Verification	Requirement /Desire	Notes
1. Mechanical				
Weight	Less than X Kg	CAD, Material Choice	R1	Weight of the proposal is lower
Destructive Shock Dynamic CAE	Similar or better than current product	CAE dynamic test of crash	R2	Thr proposed concept is stiffer.
Screw Joints must satisfy thread engagement standards	Volvo Cars Internal standards	CAD, Internal standards	R3	The screw thread engagement satisifies the standards.
Tolerance stack up	Assembly tolerance less than 1.5mm	CAD, Geometric Assurance	R4	Proposed concept assembly tolerance is 0.8mm
Fatigue life	Similar or better than current product	Physical Test	R5	Physical tests need to be carried out.
2. Thermal and Material				
Surface area for TIM and heat transfer	Same as current design	CAD	R6	No change to Cover plate
Thermal Conductivity of cooling plate	Similar or better than current product (Al 3003)	Material Choice	R7	No change to Cover plate
Pressure Tests performance	Similar or better than current product	Documents, Engineering assessment	R8	Further work
3. Manufacturing and Assembly				
Assembly friendly design (Self aligning parts)	(Self aligning parts), Socket Clearance (Power Tool Standard PTF-6)	CAD, physical test	R8	Separate locators used in CVTN to facilitate easy assembly
4. Cost and Cost Effectiveness				
High performance/cost ratio	As high as possible	Engineering Assessment	D1	
Product Cost	Less than the sum of current parts (Relevant Parts)	Cost Analysis	R9	Cost of the proposal is lower.
5. Development Requirements				
Derivative product.	Cost/Impact of change as low as possible	Minimal changes of parts and processes involved.	D2	Changes in CVTN and harness unavoidable. Investment cost analysis should also be carried out.

Figure A.1: Requirement Lists for the thesis work

B

Appendix 2

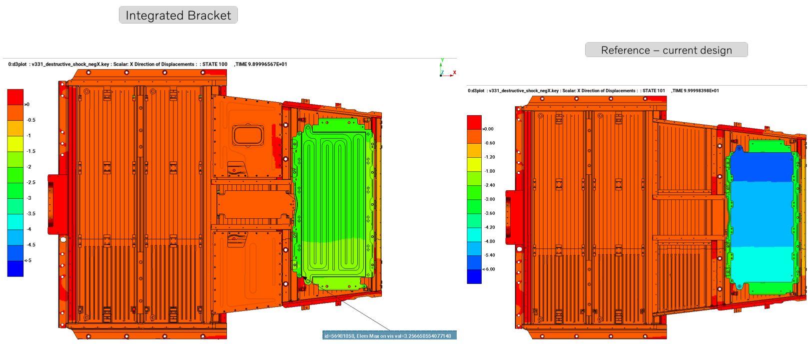

Figure B.1: Negative X–residual displacement after pulse

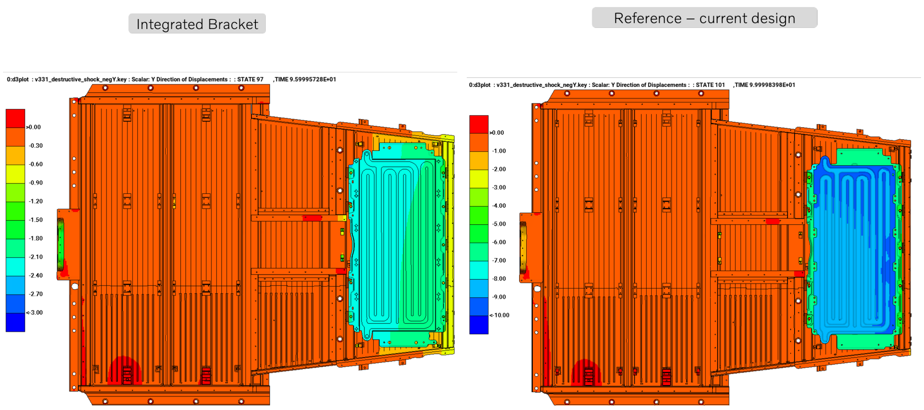

Figure B.2: Negative Y–residual displacement after pulse

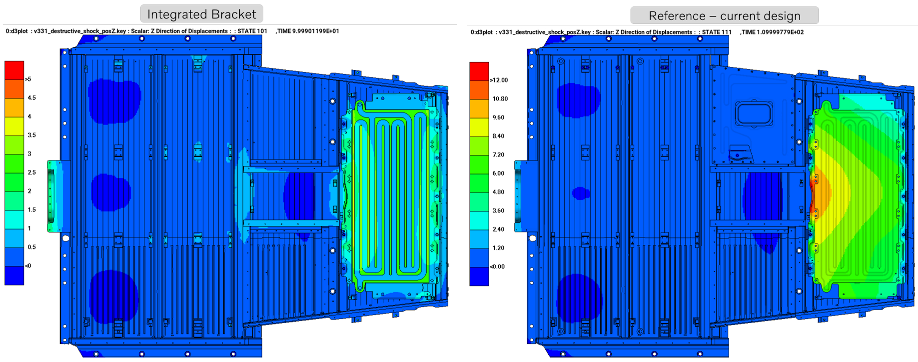

Figure B.3: Positive Z–residual displacement after pulse

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