CHALMERS
UNIVERSITY OF TECHNOLOGY

Remanufacturability of used pistons

Investigation of remanufacturing processes of used pistons for heavy duty engines

Master's thesis in Mobility Engineering

ALEXANDRA LUND
DENNIS SÖDERLUND

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Master's thesis 2024

Investigation of remanfucturability processes of used pistons for heavy duty engines

ALEXANDRA LUND
DENNIS SÖDERLUND

Department of Mechanics and Maritime Sciences
Division of Energy Conversion and Propulsion Systems
Chalmers University of Technology
Gothenburg, Sweden 2024

Investigation of remanufacturing processes of used pistons for heavy duty engines
ALEXANDRA LUND
DENNIS SÖDERLUND

Supervisor: Cleyton Castro, Volvo Technology AB
Examiner: Petter Dahlander, Department of Mechanics and Maritime Sciences

Master's Thesis 2024
Department of Mechanics and Maritime Sciences
Division of Energy Conversion and Propulsion Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Piston from a heavy duty engine (change later)

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

Investigation of remanufacturing processes of used pistons for heavy duty engines
ALEXANDRA LUND
DENNIS SÖDERLUND
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

In today's society circular economy and sustainability are becoming increasingly more important as the European Union and industries are working towards the EU's 2050 climate neutrality target. Circular economy is based on the foundation that the life of a product never reaches the end of life and is instead either repaired, refurbished, remanufactured or recycled. Volvo Group has been working with remanufacturing since the 1960's, where old parts and components, also called *cores*, are received and exchanged to a fully remanufactured part with the latest engineering and technical specifications. Currently Volvo Group has no viable process for remanufacturing pistons in heavy duty engines. Therefore, the need to investigate and evaluate the possibility of remanufacturing used pistons is of importance not only from a sustainability perspective but also of concern when adapting towards a more circular economy.

This thesis has mainly focused on investigating and evaluating early stages of remanufacturing where a cleaning test has been performed in order to remove carbon build up that commonly occurs in the combustion chamber of an engine, where the oil cooling gallery and upper compression groove has been of interest. Cleaning is also needed in order to prepares the piston for additive manufacturing as well as machining. By cleaning the pistons in a warm water and a ultrasonic cleaner it was found that initial debris and contamination was successfully removed. However, for the main focus areas, *the oil cooling gallery and upper compression groove*, a reasonable amount of carbon build up still remained.

It was found from the outcome of the cleaning test that the remanufacturing process heavily relies on further machining in order to fully remove the carbon build up and that future research is needed to fully determine if remanufacturing used forged steel pistons is of benefit for Volvo Group. Further research and testing is also needed in order to choose a appropriate additive manufacturing method that will provide the desired mechanical properties.

Keywords: Additive manufacturing, Circular economy, Heavy duty engines, Internal combustion engines, Remanufacturing, Piston.

Acknowledgements

First and foremost we would like to express our gratitude to our advisors at Volvo Technology, Cleyton Castro and Linda Rydén, for their continued support and trust throughout this thesis.

We would also like to extend our appreciation to the following people for their shared knowledge and help:

- Freddie Nilsson, Volvo Technology,
- Frank Löfskog, Volvo Technology,
- Conny Nilsson, Volvo Technology.

Lastly, we would like to thank our examiner Petter Dahlander for the collaboration during this thesis.

Alexandra Lund
Dennis Söderlund
Gothenburg, May 2024

List of Acronyms

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

AM	Additive manufacturing
CAD	Computer-aided design
GTT	Group Trucks Technology
HVAF	High velocity air-fuel
HVOF	High velocity oxygen-fuel
LCA	Life cycle assessment
REMAN	Remanufacture
TR	Technical Requirement

Contents

List of Figures

List of Tables

1 Introduction

In today's society circular economy and sustainability are becoming increasingly more important as the European Union and industries are working towards EU's 2050 climate neutrality target [1]. Sustainability and efficiency play essential roles in the automotive industry, and an approach that can increase these factors is circular economy. Circular economy is a framework for re-circulating products or materials to prolong the lifetime through different processes. The processes can be grouped into two main different cycles, biological or technical [2]. The biological cycle mainly focuses on biodegradable material whilst the technical cycle focuses on reuse, refurbish and remanufacturing (REMAN). What differentiates remanufacturing from reuse and refurbish is that a remanufactured product needs to be equal to or exceed the standard of a brand new component. Having the ability to remanufacture parts will not only allow for a potential reduction of environmental impact but also provide a more sustainable business model. The butterfly diagram, including the biological and technical cycle, described by the Ellen MacArthur foundation [2] also includes recycling of material, where for example 70% of all produced steel up until today are still in use [3] and is the most recycled material in the entire world [4].

Currently at Volvo Group there is no viable process for remanufacturing pistons in heavy duty engines. Every month the Volvo REMAN plant in Flen, Sweden, receives around 1500 engines where the pistons are taken out and sent for material recycling. Therefore, the need to investigate and evaluate the possibility of remanufacturing used pistons is of importance not only from a sustainability aspect but also of economic concern. Offering REMAN engines and components is also of customer interest since the remanufactured product follows the latest technical requirements and a "same as new" warranty to a reduced price.

1.1 Aim

The aim of this thesis is to investigate and evaluate possible solutions for remanufacturing of used pistons in heavy duty engines. The thesis will mainly focus on two different areas of the piston, cleaning of the oil cooling gallery and the upper compression groove as well as additive manufacturing of the upper compression groove. This thesis also aims to present a viable process on how piston should be remanufactured at the different Volvo REMAN sites.

1.2 Limitations

This thesis will be done during the spring of 2024 and covers 30 ECTS per person (total 60 ECTS). The scope of the thesis will be limited by the following factors:

- The pistons that will be analyzed is restricted to Monotherm and Monoweld forged steel pistons for heavy duty truck engines.
- The remanufacturing process will only consider the wear and cleaning of the upper compression groove and cleaning of the oil cooling gallery.
- Only available processes, e.g. machining equipment and methods at the Volvo REMAN sites will be considered.
- Manufacturing costs will only be considered if time allows.

1.3 Objectives

- Which is the most suitable method for removal of the carbon build-up in the oil cooling gallery?
- What type of cleaning method is most applicable for the upper compression groove?
- What type of additive manufacturing processes are needed for remanufacturing of the upper compression groove?
- Find sufficient requirements for cleaning of the compression groove and oil cooling gallery.
- Find sufficient requirements for additive manufacturing of the upper compression groove.

2
Theory

In the following chapter the theory required in order to understand the methodology and results of this thesis are presented. The chapter begins with the concept of remanufacturing and the theory behind the relevant pistons types, followed by a description of the current remanufacturing process used for other engine components at Volvo Group. Furthermore, relevant additive manufacturing and cleaning methods are also described.

2.1 Remanufacturing from a business perspective

The philosophy behind the exchange and remanufacturing processes at Volvo Group can be seen in Figure 2.1. The process is based on that the customer can buy a remanufactured part on the condition that the old or faulty one is returned. The dealer will install a remanufactured part and then send the old component to the core hub. Core is the term used for a previously sold, worn out or faulty part/component, e.g. an engine. The core will later be sent to the remanufacturing plant for REMAN. In order for the core to be considered a fully remanufactured part it has to meet a list of specific requirements, e.g. technical, engineering, quality and testing standards. The part will then have the latest engineering specification and a same as new warranty. The remanufactured product will then be sent to the distribution center ready to be installed once ordered from the dealer. Today the purchase price for a completely new piston ranges between 50-55 euro depending on the type and design.

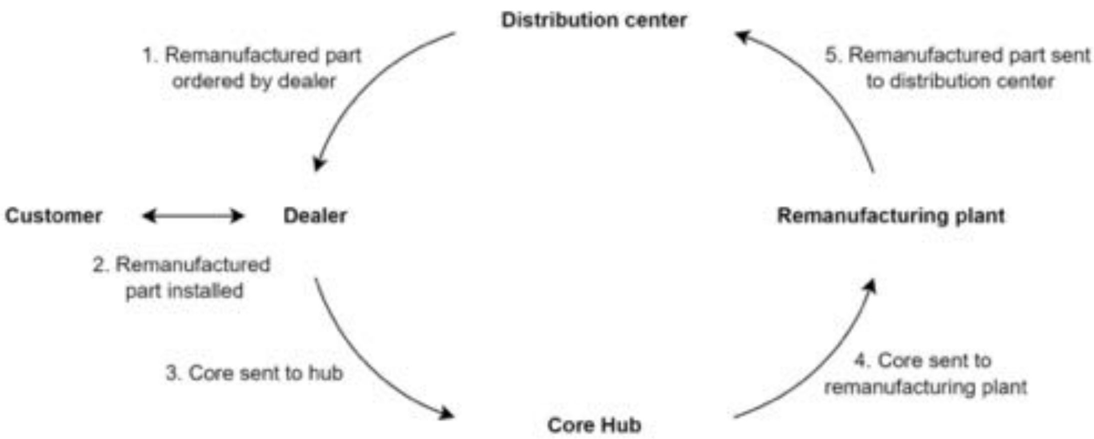


Figure 2.1: The business principle of the exchange system and remanufacturing process.

2.2 Piston function and types

In an internal combustion engine the piston is located inside the cylinder. By a reciprocating motion the piston transmits the pressure force in the combustion chamber into mechanical work in the crankshaft [5]. The piston design varies depending on the design targets, e.g. peak cylinder pressure or thermal expansion, and are usually made out of aluminium or steel.

2.2.1 Monotherm piston

The Monotherm piston is made out of forged steel and was introduced to the market by Mahle in 2000. An advantage of using steel instead of aluminium in this type of application is a lower thermal expansion coefficient [6]. The thermal expansion coefficient can be described as the expansion (also called *strain*) of a material in relation to a change of temperature. Steel is also significantly stiffer than aluminium which allows for heavy load operations. The Monotherm piston features a phosphate coated bore, eliminating the use for a pin bore bushing. The cooling gallery is closed off by a removable two-piece cover plate. The design of the piston also allows it to have an equivalent weight to a heavy duty piston made out of aluminium [6]. The Monotherm piston and the part names can be seen in figure 2.2.

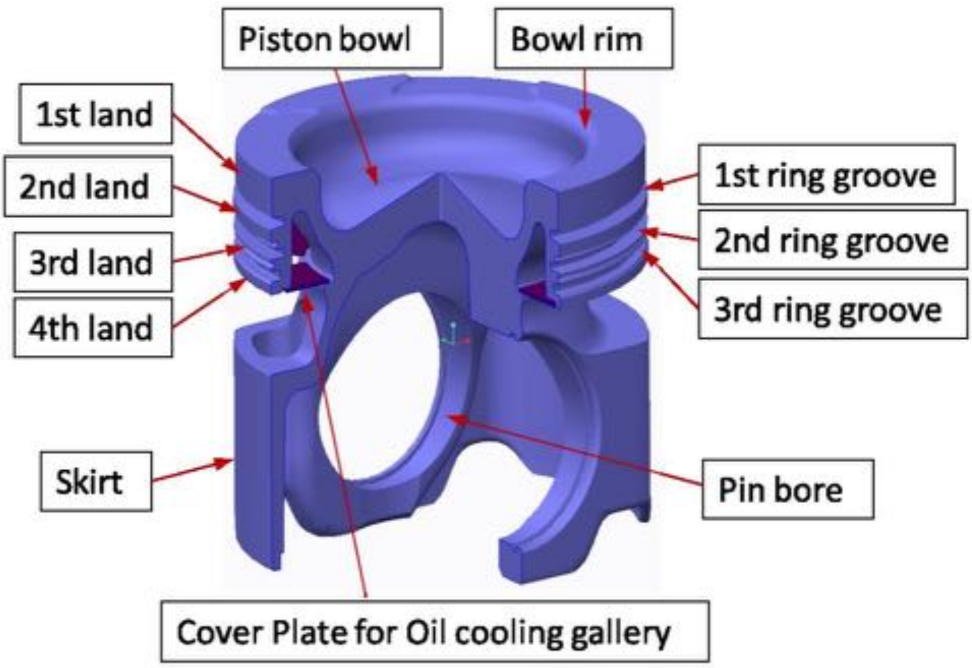


Figure 2.2: The Monotherm piston and part names.

2.2.2 Monoweld piston

The Monoweld piston geometry is achieved by using friction welding where two parts are bonded together due to frictional heat between the interface. Frictional heat is achieved due to two reasons: relative motion and high compressive load.

The relative motion can be achieved in different ways, either by rotational or linear motion [7]. The structure of the Monoweld piston is stiffer than the Monotherm piston and thus allows for a higher peak cylinder pressure [8]. Due to the process of friction welding the cooling gallery is completely closed off with a small access channel. The Monoweld piston and the part names can be seen in figure 2.3.

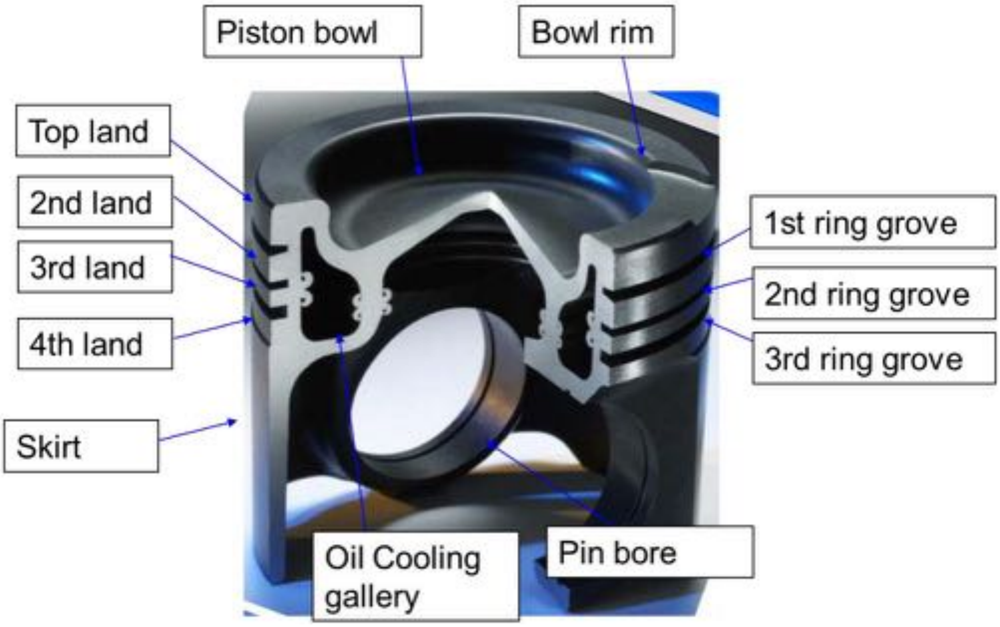


Figure 2.3: The Monoweld piston and the part names.

2.3 Remanufacturing processes

Remanufacturing is the process where an old worn part are repaired and restored to the same specification as a new component. Volvo Group has been working with remanufacturing since the 1960's and have REMAN sites spread all across the globe. One of Volvo Groups biggest REMAN sites are located in Flen, Sweden, where remanufacturing is carried out on over 500 different variants and models. Today Flen's REMAN plan mainly focuses on engines and transmissions. To achieve equivalent quality or better the REMAN process needs to be detailed and in line with the latest technical specifications including engineering, testing and quality standards. The following sections will further explain the working methods for the REMAN process for engines at Volvo Group.

2.3.1 Initial core inspection

Core is what Volvo Group calls a previously sold, worn or non-functional product or part and in this specific case it's the entire engine assembly. An example of a core can be seen in Figure 2.4. The first step is careful inspection and quality assessment of the core to make sure that it is suitable for remanufacturing. After inspection, the core is entered in the management system described in 2.1 and sent to the proper Volvo REMAN site.

Figure 2.4: Example of a received core.

2.3.2 Pre-cleaning and disassembly

The next step in the process is pre-cleaning of the core, this is done in order to remove excess oil and contamination's that might appear initially on the core. Once the pre-cleaning is done the disassembly process begins by stripping the core of its individual parts. The majority of parts will be sent to the next step, but components like gaskets, seals and defined wear parts are automatically scrapped for safety reasons. Currently during this stage, the pistons are directly scrapped and sent for material recycling. Recycling steel is a well established process since steel can be indefinitely recycled [9].

2.3.3 Cleaning

After disassembly the individual parts are sent to their own suitable cleaning process depending on the parts dirtiness and what types of contamination that exists. The most common cleaning processes that Volvo Group uses are warm water cleaning, ultrasonic and different levels of sandblasting. The purpose of this process is to make sure that there is no contamination's left so the part can be inspected correctly and machined if necessary.

2.3.4 Inspection

Subsequent to the cleaning process the parts will go through an additional inspection. The inspections rely on supporting documents, e.g. technical reports and original part documents in order to thoroughly inspect each component.
This implies taking specific measurements in order to determine if the component still is within approved or pre-determined tolerances.

2.3.5 Machining

The machining step of the remanufacturing process contains a variety of different machining methods, e.g. turning, milling, boring and thread repair. Different types of additive manufacturing methods also exists and are used within Volvo Groups REMAN facilities, e.g. thermal and cold spray. Once the machining process is completed the operator will once again verify that the component is according to the desired specification.

2.3.6 Assembly

After completing the verification all required parts are marked as complete in the internal management system and sent for final assembly. Similar to the inspection station, all required documentation are on hand for the operators so that the engine will be assembled in the correct order and all fasteners are torqued to desired specification.

2.3.7 Test and validation

Lastly, the REMAN engine will require testing and validation. This is done by connecting the engine to a jig where a magnitude of tests are performed while monitoring sensors and measuring different parameters. The running conditions during the validation tests are set to simulate the toughest conditions in order to establish that the engine will perform as intended. Once the tests are completed and approved the core engine is sent for painting to prevent corrosion and are then considered a fully REMAN engine.

2.4 Additive manufacturing processes

Additive manufacturing (AM) is a manufacturing method that utilizes the use of adding material instead of removing material which is present in more traditional manufacturing such as milling, turning and drilling. The basic principle behind AM is adding material layer by layer while creating the part. This opens up multiple possibilities for higher design freedom, e.g. creating more complex geometries or internal channels. Therefore AM is very suitable to create a complex component directly from a computer aided design (CAD) model [10]. When it comes to remanufacturing the process can be difficult since material is added to an already existing part. The current condition and wear will also be completely unique for each part.

The following sections will present the current AM methods used at Volvo Groups REMAN sites more in depth.

2.4.1 Thermal spray

Thermal spray describes a group of different coating processes where a stream of particles are deposited on a substrate, where the particles are either in a molted or semi-molted state. Due to the high velocity and temperature it forms a bond upon impact [11]. This type of AM method has multiple applications and is often used to offer resistance against erosion, corrosion, wear and cavitation etc. but it's also used within the industry to repair or restore worn components [12].

An important component for a general thermal spray system is a torch. The torch purpose is to convert energy into a stream of heated gases and the source of energy can either be electrical (discharge) or chemical (combustion). The heated gas stream accelerates and eventually melts the material, forming droplets of the molted/semi-molted material on the substrate [11]. A schematic overview of a general thermal spray process can be seen in Figure 2.5.

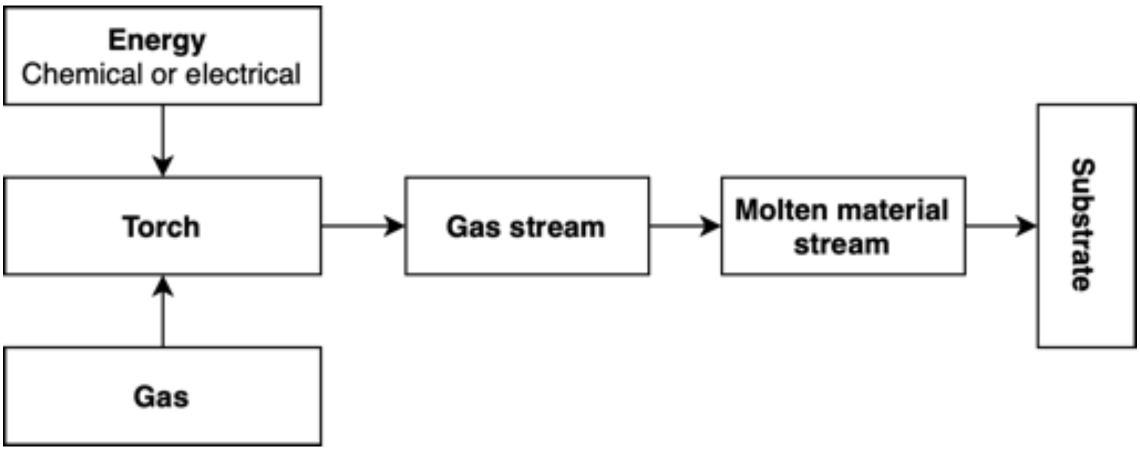


Figure 2.5: Schematic overview of a general thermal spray process.

Two common processes within thermal spray when using combustion are High velocity oxygen-fuel (HVOF) and High velocity air-fuel (HVAF). The main difference is the use of fuel type, HVOF uses oxygen-fuels e.g. acetylene or hydrogen where as HVAF uses air-fuels e.g. propane or natural gas [13]. HVAF is often called warm spray, but operates on a lower temperature than HVOF but higher than cold spray and offer some advantages in comparison to HVOF such as higher wear resistance in certain types of coating alloys [14].

2.4.2 Cold spray

The cold spray process is quite similar to thermal spray but there are a few key differences. Firstly, as the name suggests, cold spray does not rely on melting the deposited powder but instead it utilizes kinetic energy by high velocity in order to deform the powdered material and adhere it to the component, where the speed of the powder can reach up to Mach 3 [15]. A schematic overview of a usual cold spray process can be seen in Figure 2.4.2. The process works by accelerating the material powder using a de Laval nozzle and pressurized gas that's heated. A de Laval (Converging-Diverging) nozzle is a pipe in an hourglass shape that with the help of the pressure differences between both sides accelerates a fluid to supersonic speeds [16]. Another difference is the particle size of the powder, thermal spray particles are normally around 50-100 µm while the particles in cold spray can be as small as 1-50 µm [17].

Currently in the industry cold spray is predominantly used for coating and repair of components. But using cold spray as an additive manufacturing method has been on the rise in the last few years and it's been effective because of the high deposit rate that cold spray offers. Another benefit of using cold spray as an AM method is due to it's relatively low operating temperature, minimizing the risk of varying the material properties due to high heat [18].

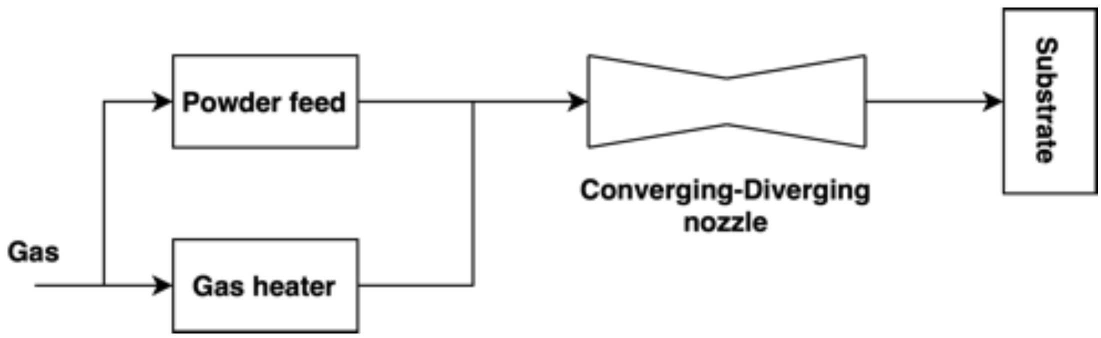


Figure 2.6: Schematic overview of a general cold spray process.

2.5 Cleaning processes

Cleaning is a crucial step in the remanufacturing process, not only because it enables to the operators to properly assess the components for damage and wear, but also since no repair can be done if the component has any contamination.

As mentioned in Section 2.3.3 the most common cleaning methods for Volvo Group's REMAN process is warm water cleaning, ultrasonic and different levels of blasting. The warm water cleaner is used for a majority of the components since multiple parts can be cleaned simultaneously given its big volume. This process is highly effective at removing oil and numerous other common contamination that can be found in the core. One drawback from using warm water cleaning is the effectiveness when it comes to removing more substantial contamination and build-up that exists on certain components that operates under harsher conditions, e.g. inside the cylinder. Therefore, it can be beneficial to consider more abrasive cleaning methods, e.g. ultrasonic cleaning.

The ultrasonic cleaner works by using ultrasound to in order to induce vibrations in the cleaning fluid which in turn generates millions of nano sized bubbles that creates energy by shrinking and expanding. This effect by the bubbles is called cavitation and is what cleans the various components that is lowered down into the cleaner [19]. The rate and intensity of the cavitation is the reason that the ultrasonic cleaner is able to remove greater contaminations and build-up that appear on the components. This process also applies well in cavities and channels.

Blasting is the roughest and most abrasive of all mentioned cleaning methods in this thesis. The method works by shooting small pieces of various materials with the help of high pressure air at the surface of the component that's being cleaned. The materials that are most commonly used in blasting are sand, various plastics, steel grit, baking soda and glass [20], but natural mediums like nut shells also exists. In the automotive industry sandblasting is most commonly used for removing corrosion, paint and carbon [20].

2.6 Previous studies on remanufacturing at Volvo Group

One of the most previous studies in the field of remanufacturing that Volvo Group has carried out is the REMAN of the exhaust gas re-circulation cooler (EGR-cooler). The EGR's purpose is to return a certain amount of the exhaust gases to the combustion chamber through the inlet system in order to reduce NO_x emissions [21]. The EGR-cooler is made out of aluminium and suffers a lot of carbon and soot build up similar to the piston. Throughout the study Volvo's REMAN site in Flen, Sweden, carried out multiple tests where the ultrasonic and warm water cleaner was used. Using the ultrasonic cleaner the majority of soot and carbon build up was successfully removed. Furthermore, it was found that by flushing the EGR-cooler afterwards in the warm water cleaner, remaining debris could be removed. At this step a pressure measurement was also carried out in order to establish the wanted mass flow.

3
Methodology

The methods used in this thesis are presented below. The chapter begins with an method overview followed by a literature study, list of requirements and lastly testing and validation.

3.1 Method overview

In the early stage the thesis mainly focused on a pre-study by collecting information about remanufacturing processes. The reading material has consisted of internal reports and previous studies conducted by Volvo GTT as well as articles and reports within similar fields. Discussions with experts within the company and a visit to Volvo Groups remanufacturing plant in Flen, Sweden, further helped gaining understanding about the topic. In order to find and create a viable process plan for remanufacturing of pistons it's important to discover and understand the already existing resources. Therefore, during the visit to Flen a complete tour of all different stages of the process was done starting from disassembly to a finished REMAN product. From the pre-study a list of requirements was set in order to visualize what types of requirements a remanufactured piston has to meet to be considered "as good as new".

With a list of requirements set, different concepts of potential remanufacturing processes was created. In order to determine the most viable process, discussions was carried out with engineers and experts within the field at Volvo GTT.

Once a concept had been chosen the aim was to create detailed documentation that contained instructions and all relevant data required to remanufacture the pistons. The documentation was then be sent for review to relevant engineers and operators. Furthermore, the documentation was later used for a cleaning test performed in April 2024, see Section 3.4.1.

3.2 Pre-study

As mentioned in Section 3.1, the thesis mainly focused on internal reports and previous studies with the objective to seek out, analyze and compile articles and reports within the same area to be able to discuss and determine a suitable method for a remanufacturing process of the piston.

The purpose of studying the internal reports was to get a good understanding of the previous research and tests that had been carried out by Volvo Group in order to determine if any already existing solutions and/or recommendations that could be beneficial to this thesis. It was also of interest to conclude if any methods or findings has been deemed suitable to similar processes in the past and why.

In order to find previous studies the authors used relevant keywords (listed below) on sites such as Google Scholar, CORE and Web of Science.

- Remanufacturing of pistons
- Repair of pistons
- Repair methods for steel
- Carbon/soot removal
- Additive repair methods

3.3 List of requirements

The pre-study resulted in a list of requirements that a used piston should fulfill in order to be suitable for remanufacturing. The list can be seen in Appendix A and contains general requirements such as no deformation, excessive corrosion and erosion. The requirements for the two types of pistons, Monotherm and Monoweld, doesn't differentiate at this stage, hence only one list of requirements.

3.4 Testing at Volvo Group

During the end of the pre-study phase an opportunity to perform a cleaning test of different pistons was given and involved three different stages: pre-cleaning and disassembly, cleaning and inspection. Before the test, certain instructions needed to be written in order to ease the process for the operators and test engineers at Volvo REMAN in Flen, Sweden. The working methods for the instructions and documentation needed are described in the following sections below.

3.4.1 Piston sample selection

The initial step of the testing procedure was to select different pistons from multiple received cores. To ease the task for the operator a reference document was made, seen in Appendix B, and covers a list of requirements, reference pictures and descriptions on the differences between a Monoweld and Monotherm piston. The sample size was set to 15 units, 5 Monoweld and 10 Monotherm. The amount differs between the two types since the cover plates would be removed for 5 pistons and kept for the remaining samples of the Monotherm in order to see if it had any impacts on the results. Samples was collected from different cores since it was believed that it would represent a greater spectrum of different wear and tear. Some examples of the reference pictures used can be seen in Figure 3.1 below and was taken during the visit to Flen, Sweden, in February 2024.

(a) Top view some visible corrosion on the bowl. *Acceptable wear.*

(b) Side view, some visible carbon build-up to top land. *Acceptable wear.*

(c) Top view, significant corrosion on the bowl. *Not acceptable wear.*

(d) Side view, significant corrosion on the top land. *Not acceptable wear.*

Figure 3.1: Examples of acceptable and not acceptable wear.

Selection of the pistons took place at pre-cleaning and disassembly, where the piston was removed from the cylinder. Piston and snap rings, pins and bushings were also removed at this stage. Each sample was then stamped with an individual number and photographed so potential progress could be documented. Some initial cleaning was also needed since contamination to the ultrasonic cleaner needed to be avoided. The initial cleaning implied using the warm water cleaner.

3.4.2 Ultrasonic cleaning

Since the ultrasonic cleaning of the EGR-cooler, mentioned in Section 2.6, previously had been found successful it was believed that using on the same parameters would be a sufficient starting point, the settings used can be seen in Table 3.1. The pistons did not demand individual cleaning and could therefore be placed in a basket and lowered down in batches of six pistons at a time. The brand of the ultrasonic cleaner is Polysonic of type Sonic-150 and can be seen in Figure 3.2 and 3.3.

Table 3.1: The parameters used for the ultrasonic cleaner.

Frequency [kHz]	Cycle duration [min]	Temperature [°C]	Chemical and concentration
45	40	42.3	Envirostripp stripp HX 50%

Figure 3.2: The ultrasonic cleaner, Polysonic Sonic-150, at the REMAN plant in Flen, Sweden.

Figure 3.3: The inside of the ultrasonic cleaner, Polysonic Sonic-150, at the REMAN plant in Flen, Sweden.

3.4.3 Inspection at Volvo GTT Lundby

After the samples had been cleaned a inspection was performed. To be able to inspect the cooling gallery in the Monoweld pistons the samples first need to be split in half. The top land and ring grooves should then be measured to find possible deviations.

If the deviations are within an acceptable range according to the engineering requirements further processing is still required, such as re-coating. However, if the pistons are below the accepted tolerances, an addition of new material is needed. This can be done using different types of techniques, e.g. thermal or cold spray. The pistons can then be machined down to meet the tolerances.

3.4.4 Additive manufacturing

There are different solutions for adding material to a REMAN piston. Therefore, the most suitable solution needed to consider multiple important factors, e.g. ease of manufacturing, cost and time. The deviations from the acceptable tolerances also played an important part in choosing the most appropriate processing method, e.g. since different AM methods have different bonding properties and are more or less suitable for heavy load operation.

4
Results

In the following chapter the results of this master thesis are presented, this includes the results of the cleaning test performed at the remanufacuting plant in Flen in April 2024 as well as the inspection at Volvo GTT in Lundby.

4.1 Piston test samples and initial cleaning

A total of 15 pistons were selected from multiple received cores during the course of one week in accordance with the instructions described in Section 3.4.1 and shown in Appendix B. All test samples can be seen in Appendix C. Before the test samples were photographed, some initial cleaning was done in order to remove residue by using a cloth. All pistons samples was also stamped with an individual identification number, ranging from 1-15. During discussions with the test engineers in Flen, Sweden, it was also concluded that all test samples first needed to be cleaned in the warm water cleaner in order to avoid contaminating the ultrasonic cleaner. Settings used during the pre-cleaning for the warm water cleaner can be seen in Table 4.1.

Table 4.1: Settings used during the pre-cleaning of the test samples in the warm water cleaner.

Cycle duration [s]	Temperature [°C]	Chemical and Concentration
240	70.3	Castrol Techniclean MP Flex 5%

4.2 Cleaning of test samples

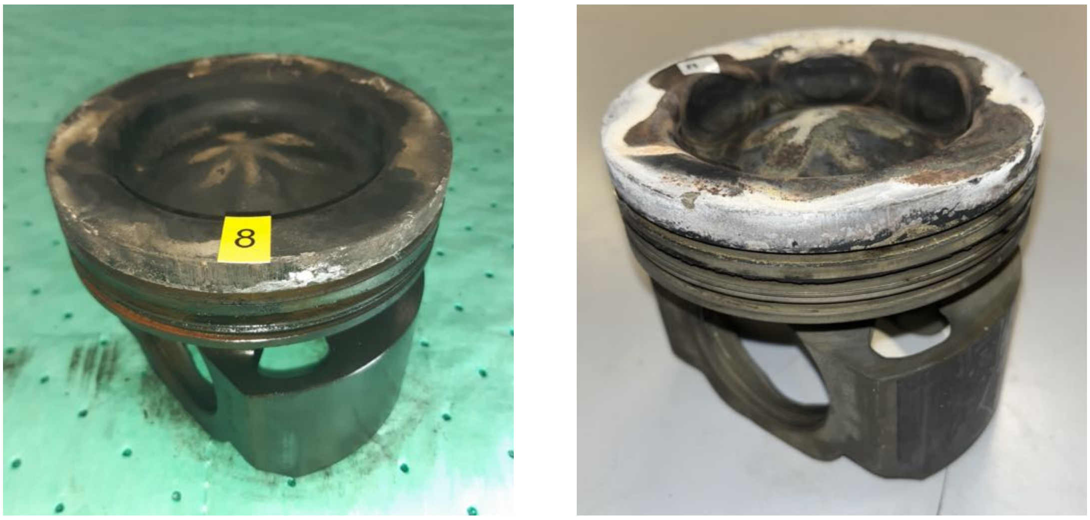
Once the test samples had gone through pre-cleaning the method used for the ultrasonic cleaning was followed as described in Section 3.4.2 with the settings shown in Table 3.1. After completing the ultrasonic cleaning it was concluded that all samples needed to go through another cycle in the warm water cleaner to remove excess chemicals and loose debris. The pistons were then shipped to Volvo GTT in Gothenburg for further inspection.

4.3 Inspection of test samples

The samples were inspected during the middle of May 2024. Before starting the inspection the results were documented and can be seen in Appendix D. To ease the inspection of the oil cooling gallery for the Monoweld pistons, all 5 test samples, ID: 11-15 in Appendices C and D, were delivered to Volvo Groups materials lab in Lundby for cutting. This was needed in order to have complete access since a full overview of the channel cannot be seen due to the oil cooling gallery being completely closed off. The cutting was performed in the area of the 3rd land, and the results can be seen in Appendix E.

4.3.1 Inspection of the overall piston

During inspection of the overall pistons was be seen that some contamination had been removed but a substantial amount of corrosion and coating still existed. During the ultrasonic cleaning the coating had started a chemical reaction with the Castrol Techniclean MP Flex (seen as the white and yellow residue in Figure 4.1b). When inspecting the bowl and top land it could be seen that the cleaning methods used did not have the full effect as expected since little to no carbon build up had been removed.



(a) Piston 8 before cleaning. **(b)** Piston 8 after cleaning.

Figure 4.1: Comparison of piston 8 before and after cleaning.

4.3.2 Inspection of the oil cooling gallery

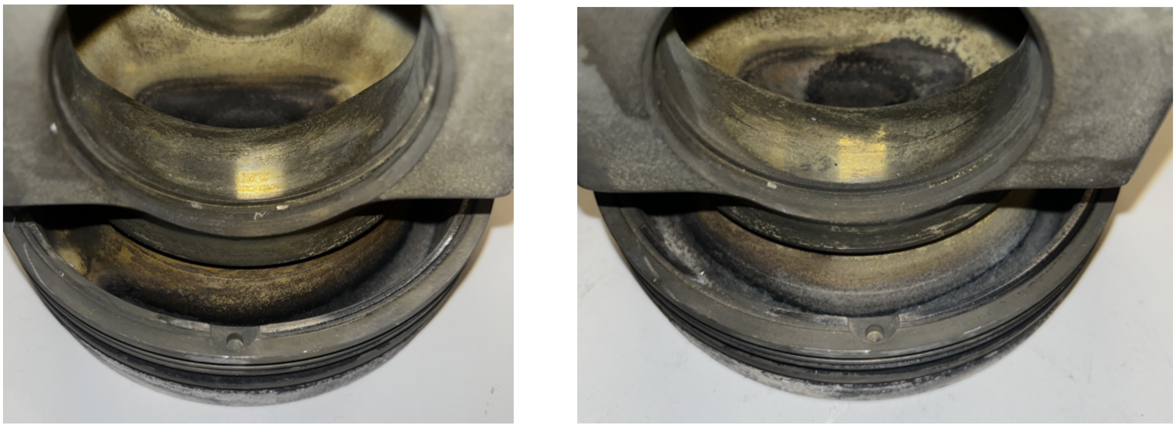
After the cleaning of the Monotherm pistons was completed, five with the cover plates attached and five without, the cover plates were removed and the inspection of the cooling gallery began. Pictures of all cleaned Monotherm piston's oil cooling gallery can be found in Appendix E.

During the inspection of the pistons it could clearly be seen that the effectiveness of the ultrasonic cleaner in terms of removing carbon build up varied. An example of this can be observed in Figure 4.2, for piston 5 the build up in the cooling gallery was considerably less than on piston 4. These pistons were part of the sample group (pistons 1-5) that were cleaned without the cover plates.

(a) Oil cooling gallery of piston 5. **(b)** Oil cooling gallery of piston 4.

Figure 4.2: The cleaning results of the oil cooling gallery for pistons 7 and 9 cleaned without cover plates.

Observing the Monotherm pistons that were cleaned with the cover plates on (pistons 6-10 in Appendix E) it was clear to see that the removal of the carbon build up was roughly within the same range of success as the ones cleaned without. Two examples of this can be seen in Figure 4.3. This meant that the ultrasonic cleaner was not as effective at removing the build up as expected.



(a) Oil cooling gallery of piston 7. **(b)** Oil cooling gallery of piston 9.

Figure 4.3: The cleaning results of the oil cooling gallery for pistons 7 and 9 cleaned with cover plates.

4.3.3 Inspection of the upper compression groove

When inspecting the upper compression groove of the cleaned sample pistons, a similar result as the previous section could be observed. In Figure 4.4 a few pistons are presented.

(a) Ring grooves of piston 6. **(b)** Ring grooves of piston 10.

Figure 4.4: The cleaning results of the upper compression groove for pistons 6 and 10.

Due to the cleaning test being unsuccessful at removing carbon build up, the previously described working method, as mentioned in Section 3.4.3, was not performed since the result of the cleaning test being unsatisfactory.

4.4 Additive manufacturing methods

All AM methods presented in Section 3.4.4 are theoretically possible for remanufacturing of used pistons. However, HVOF and HVAF as presented in Section 2.4.1 is more widely used within in the industry today when comparing it to cold spray. Since cold spray relies on supersonic speed it can start to create cavities upon impact with the substrate, *in this case: the upper compression groove*, due to the high velocity. Further research is needed within this topic to present any viable results and is discussed further in Chapters 5-6.

5
Discussion

In this chapter the challenges of this master thesis are discussed. The discussion mainly focuses on the results as well the chosen approach to the objectives.

5.1 Challenges with piston selection and initial cleaning

Since the piston selection occurs early in the REMAN process there is some challenges when determining what is considered salvageable and if the piston are within the pre-specified boundaries. This challange applies for both the Monotherm and Monoweld piston.

By looking at piston 1 and 10 in Figures 5.1a and 5.2a it can be seen that both pistons have similar build up before cleaning, where piston 1 suffer some additional corrosion but are otherwise very similar. By comparing the results after the cleaning test in Figures 5.1b and 5.2b the outcome deviates greatly for the two pistons, where the cleaning has been quite successfully for piston 10. This is however not the case for piston 1 where a substantial amount of build up and coating still exists. Therefore, it can cause some challenges when performing the selection during disassembly since the quality may appear similar by eye but the outcome after cleaning is completely different.

In order to make a successful selection, it's implied that the operators will need a great amount of training and/or previous experience since the state of the pistons is only determined through a visual inspection. It can also result in some strains on the process itself since this inspection will, in a best case scenario, be executed for 1500 engines a month. It is therefore believed that implementing this type of inspection will be time consuming not only in terms of education and training but also during operation.

(a) Piston 1 before cleaning.

(b) Piston 1 after cleaning.

Figure 5.1: Cleaning results of piston 1.

(a) Piston 10 before cleaning.

(b) Piston 10 after cleaning.

Figure 5.2: Cleaning results of piston 10.

5.2 Challenges with the AM process

The biggest challenges that presents itself when adding material with AM to a already existing component is the bonding between the added material and the part. In order to know with certainty that HVOF and HVAF is suitable for REMAN of heavy duty pistons a detailed micro structure material analysis is needed to see if the bonding properties is sufficient enough, especially since the pistons needs operate under very high temperatures and pressure.

5.3 Challenges with cleaning of the pistons

As mentioned in Section 4.3.2 the effectiveness of the ultrasonic cleaner for removing carbon build up was quite low. One reason for this could be that the concentration of the chemical used in the ultrasonic cleaner is to low in order to effectively remove the carbon build up. Another possibility is that the carbon has a stronger bond to the steel of the pistons compared to the aluminium that makes up the EGR-coolers. This is not as big of an issue for the upper compression groove since it can be machined away before starting to add material, but that also adds another process needed to remanufacture the pistons. Therefore, it means that REMAN of the Monoweld piston is not looking promising, further cleaning tests are needed in order to draw any further conclusions, but the possibility of a higher impact on cost and the environment could be of concern and are discussed in Chapter 6.

6 Conclusion

This chapter presents the conclusions drawn from the results of this thesis and provides suggestions of how continued research could be carried out.

This thesis have mainly focused on finding an appropriate method to enable remanufacturing of used forged steel pistons for heavy duty applications, where the suggested solutions and processes were limited to already existing machinery in Volvo Group's REMAN site in Flen, Sweden. During the pre-study it was found that no similar research had been carried out when it comes to the actual cleaning process except for the EGR cooler mentioned in Section 2.6. It was therefore believed that physical testing would provide the most value to the project. From the results of the cleaning test it was concluded that the biggest challenge was to establish proper cleanliness of the closed cooling gallery in the Monoweld piston. From the results the following conclusions could be drawn.

Cleaning of the upper compression groove was found to be sufficient enough for further remanufacturing, since additional machining can be done in order to properly prepare the groove. Furthermore, inspection, additive manufacturing and processing needs to be carried out as well as a re-coating. For machining and re-coating the pistons should be returned back to the original equipment manufacturer. If this process were to be implemented, it would imply that the process from disassembly to finished remanufactured piston would include eight new process steps in comparison to what is carried out today at the factory. This is in theory feasible with the equipment available, but additional training of personnel would be required for the early inspection phase when selecting the pistons. It is also important to consider the additional costs of operators and machining time as well as transportation. As previously mentioned in Section 2.1 the purchase price for a completely new piston from Mahle currently ranges between 50-55 euro. Considering the implementation costs as well as the operational time of the warm water and ultrasonic cleaner it is reasonable to question if remanufacturing the pistons is of any economic advantage.

It is also important to consider the level of environmental sustainability with implementing the remanufacturing process. As previously mentioned in Section 1 steel is currently the most recycled material in the entire world. Since the piston material currently is recycled, it never breaks the cycle of circularity as described in Chapter 1. Therefore, it would be of interest to perform a life cycle assessment (LCA) where the CO_2 emissions of the current recycling process versus the remanufacturing process are compared.

The conclusion from the outcome of the cleaning test for the oil cooling gallery was found not applicable to the Monoweld piston, where further testing is needed in order to find a suitable cleaning method. This could for example include change of chemical solution or concentration used in the ultrasonic cleaner. However, this would mean opting towards a stronger chemical or concentration, whether how this in turn would effect the environment is another aspect to consider. Regarding the cleaning of the cooling gallery in the Monotherm piston the test was found to be sufficient enough where further machining can be a suitable option to remove remaining build-up. This can be done together with the machining of the grooves. The conclusion is therefore that cleaning of a used Monotherm piston in theory is possible when only considering the upper compression groove and cooling gallery, but continued research on cleaning of the piston bowl still needs to be considered.

6.1 Future work

For further research within remanufacturing of used forged steel pistons there are several different areas that would be of interest to investigate further. The future research can be divided into several topics and are described under their corresponding subsections below.

6.1.1 Life cycle assessment

In order to fully determine the environmental sustainability of remanufacturing used pistons a useful tool would be to perform a life cycle assessment (LCA). By performing an LCA, CO_2 emission can be quantified from start, up until end of life and a comparison can be made of the environmental impact, from possible remanufacturing versus buying a completely new part. The drawbacks of performing a life cycle assessment is that it's time consuming and often takes multiple years to develop, but from a sustainable business perspective it's a very competitive tool on the market.

6.1.2 Production process and cost analysis

Since no analysis has been carried out during this thesis on optimizing the remanufacturing process in terms of efficiency and cost there would be interesting to evaluate whether the process can be optimized in terms of number of machines and personnel involved in order to find the optimum remanufacturing method from a production perspective.

Once an ideal process plan has been mapped out, further research can be made on operational costs of the production of remanufactured pistons. The stakeholder can then easily form a definite decision whether it would be possible to implement the remanufacturing process on a larger scale from a sustainable process and cost point of view.

6.1.3 Processing method and AM analysis

This thesis has mainly focused on a literature study when discussing suitable additive manufacturing methods, where further research and testing is needed to properly determine the suitability of different AM methods. A micro structure analysis would be needed to determine the correct bonding properties of the different AM methods since the piston is a moving part who suffers both high operating temperatures and mechanical stress.

Bibliography

[1] European Commission. *2050 long-term strategy*. Accessed: May. 26, 2024. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

[2] Ellen MacArthur Foundation. *What is a circular economy*. Accessed: Feb. 01, 2024. URL: https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview.

[3] Stena Recycling. *The value of recycling materials*. Accessed: May. 12, 2024. URL: https://www.stenarecycling.com/news-insights/insights-inspiration/guides-articles/the-value-of-recycling-metals/.

[4] World Steel Association. *Steel is at the core of a green economy*. Accessed: May. 12, 2024. URL: https://worldsteel.org/about-steel/key-messages/steel-core-green-economy/.

[5] John B. Heywood. *Internal Combustion Engine Fundamentals*. 2nd Ed. McGraw-Hill Education, 2018, p. 11.

[6] MAHLE Aftermarket Inc. *Genuine heavy duty replacement parts*. Accessed: Feb. 16 2024. URL: https://www.mahle-aftermarket.com/media/local-media-north-america/pdfs-&-thumbnails/catalogs-and-literature/engine-parts-hd/hd-1-618-genuine-clevite-heavy-duty-parts.pdf.

[7] P.K. Mallick. *Materials, Design and Manufacturing for Lightweight Vehicles*. 2nd Ed. Woodhead Publishing, 2021. Chap. 8.8.1. DOI: https://doi.org/10.1016/C2018-0-04153-5.

[8] MAHLE GmbH. *Piston and engine testing*. 2016. Chap. 1.3.3.8. URL: https://link.springer.com/book/10.1007/978-3-658-09941-1.

[9] Advocating recycling in Europe. *Metal Recycling Factsheet*. Accessed: May. 5, 2024. URL: https://circulareconomy.europa.eu/platform/sites/default/files/euric_metal_recycling_factsheet.pdf.

[10] V. T. Le, H. Paris, and G. Mandil. "*Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies*". In: *International Journal on Interactive Design and Manufacturing* 12.2 (Apr. 2017). ISSN: 1955-2505. DOI: 10.1007/s12008-017-0395-y. URL: http://dx.doi.org/10.1007/s12008-017-0395-y.

[11] M. I. Boulos P. L. Fauchais J. V.R. Heberlein. *Thermal Spray Fundamentals*. Springer New York, NY, 2014. DOI: https://doi-org.proxy.lib.chalmers.se/10.1007/978-0-387-68991-3.

[12] Metallisation Limited! *Introduction to Thermal Spray and Engineering Applications*. Accessed: Feb. 29, 2024. URL: https://www.metallisation.com/applications/thermal-spray-engineering-applications/.

[13] Höganäs. *Deposition Techniques, Extend component life with HVOF and HVAF coating*. Accessed: April 29, 2024. URL: https://www.hoganas.com/en/powder-technologies/surface-coating/hvof/.

[14] L.L. Silveira a et al. "*Study of the corrosion and cavitation resistance of HVOF and HVAF FeCrMnSiNi and FeCrMnSiB coatings*". In: *Surface and Coatings Technology* (2019), pp. 910–922. DOI: https://doi.org/10.1016/j.surfcoat.2019.06.076.

[15] M. Ashokkumar et al. "*An overview of cold spray coating in additive manufacturing, component repairing and other engineering applications*". In: *Journal of the Mechanical Behavior of Materials* 31.1 (2022), pp. 514–534. URL: https://doi.org/10.1515/jmbm-2022-0056.

[16] ANSYS inc. *Converging–Diverging Nozzle*. 2024. Chap. 4. URL: https://courses.ansys.com/index.php/courses/internal-compressible-flows/lessons/converging-diverging-nozzle-lesson-4/.

[17] HTS Coatings. *Cold Spray Technology and How It Compares to Thermal Spray*. Accessed: March 5, 2024. URL: https://htscoatings.com/blogs/our-craft-our-culture/cold-spray-vs-thermal-spray.

[18] H. Assadi et al. *Cold spraying – A materials perspective*. Elsevier Ltd., 2016. DOI: https://doi.org/10.1016/j.actamat.2016.06.034.

[19] Donald M. Mattox. *Handbook of Physical Vapor Deposition (PVD) Processing*. 2nd Ed. Elsevier Inc., 2010, pp. 498–501. DOI: https://doi.org/10.1016/C2009-0-18800-1.

[20] Total Materia. *Abrasive Blast Cleaning: Part One*. Accessed: March 20, 2024. URL: https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=KTS&NM=388.

[21] W. A. Majewski and H. Jääskeläinen. *Diesel Emissions and Their Control*. 2nd Ed. SAE International, 2023. Chap. 16, pp. 575–576. ISBN: 978-1-5231-5802-7.

A

List of requirements

Requirements:

- No deformations
- No excessive amount of corrosion
- No excessive amount of erosion
- Part number still visible
- No cracks
- Small to no scratches allowed on the piston skirt

B

Instructions for piston sample selection

Document created by: Alexandra Lund and Dennis Söderlund
Date: 20-03-2024

Instructions for Piston sample selection

The purpose of this document is to clearly present which types of pistons are wanted in order to test different cleaning methods. The pistons can be collected from different types of heavy duty engines as long as they meet the criteria's shown in this document. Ideally the sample pistons should not be collected from the same core in order to get a broader representation of the variance in quality. The piston rings should also be removed before cleaning.

Table 1. An overview of the desired piston samples.

Type	**Material**	**Quantity**	**Quality**
Monotherm	Steel	5 with cover plate 5 without cover plate	No cracks or excessive amount of corrosion. No scaling or erosion on top surface (See ref. pictures below)
Monoweld	Steel	5	No cracks or excessive amount of corrosion. No scaling or erosion on top surface (See ref. pictures below)

Once the pistons have been selected, they should be stamped with an individual number and photographed.

1. Reference pictures

1.1 Monotherm

The Monotherm piston can be identified by the removable cover plate for the cooling gallery (see figure 1).

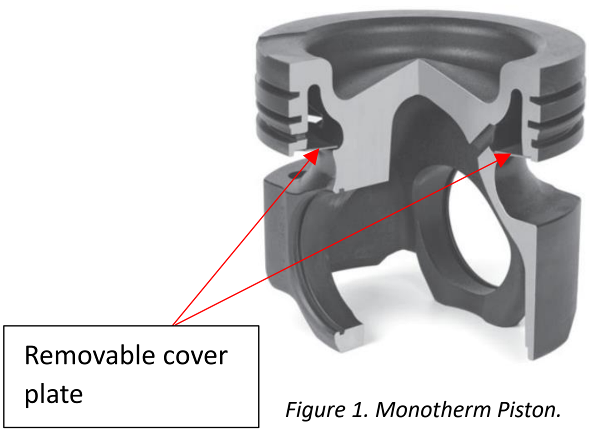


Figure 1. Monotherm Piston.

1.2 Monoweld

The Monoweld piston can be identified by the length of the skirt (longer than the Monotherm) and a completely closed off cooling gallery, except for the inlet and outlet holes that can be seen from the bottom.

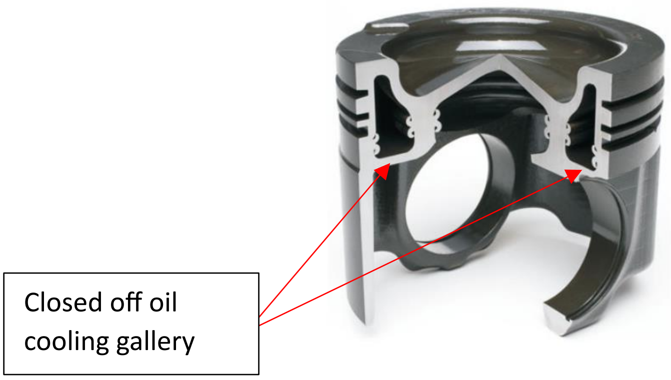


Figure 2. Monoweld Piston.

1.3 Quality

To be able to find the proper settings for the ultrasonic cleaning process, pistons with different levels of carbon build-up and wear is needed. In section 1.3.1 a series of reference pictures for ***usable*** pistons can be seen. In section 1.3.2 a few examples are shown that are deemed ***not suitable*** for cleaning and should therefore be scrapped.

1.3.1 OK Quality



1.3.2 Not OK Quality

Figure 4. Excessive corrosion on Top Land.

Figure 3. Extreme Deformation and Cracks.

Figure 5. Excessive corrosion on Crown.

1.4 Cleaning

Once the pistons have been stamped and photographed the goal is to clean them in the ultrasonic cleaner. The settings and parameters should be same as for the EGR-cooler since similar build-up can be found on the pistons. In case the pistons need any pre-cleaning to avoid high contamination in the ultrasonic cleaner that is ok as long as communicated.

C
Piston test samples

Monotherm Piston samples

Test sample 1 – ID: 1

Figure C1.1. Overview of test sample 1.

Figure C1.2. Bottom view of test sample 1.

Figure C1.3. Side view of test sample 1.

Test sample 2 – ID: 2

Figure C2.1. Overview of test sample 2.

Figure C2.2. Bottom view of test sample 2.

Figure C2.3. Side view of test sample 2.

Test sample 3 – ID: 3

Figure C3.1. Overview of test sample 3.

Figure C3.2. Bottom view of test sample 3.

Figure C3.3. Side view of test sample 3.

Test sample 4 – ID: 4

Figure C4.1. Overview of test sample 4.

Figure C4.2. Bottom view of test sample 4.

Figure C4.3. Side view of test sample 4.

Test sample 5 – ID: 5

Figure C5.1. Overview of test sample 5.

Figure C5.2. Bottom view of test sample 5.

Figure C5.3. Side view of test sample 5.

Test sample 6 – ID: 6

Figure C6.1. Overview of test sample 6.

Figure C6.2. Bottom view of test sample 6.

Figure C6.3. Side view of test sample 6.

Test sample 7 – ID: 7

Figure C7.1. Overview of test sample 7.

Figure C7.2. Bottom view of test sample 7.

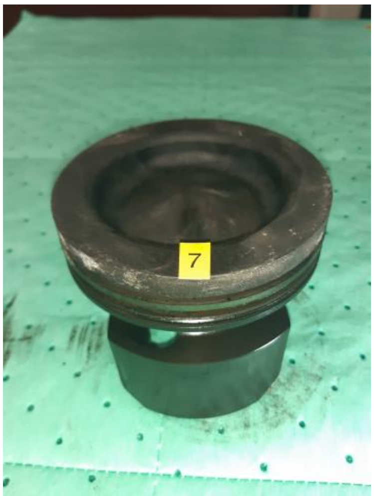


Figure C7.3. Side view of test sample 7.

Test sample 8 – ID: 8

Figure C8.1. Overview of test sample 8.

Figure C8.2. Bottom view of test sample 8.

Figure C8.3. Side view of test sample 8.

Test sample 9 – ID: 9

Figure C9.1. Overview of test sample 9.

Figure C9.2. Bottom view of test sample 9.

Figure C9.3. Side view of test sample 9.

Test sample 10 – ID: 10

Figure C10.1. Overview of test sample 10.

Figure C10.2. Bottom view of test sample 10.

Figure C10.3. Side view of test sample 10.

Monoweld Piston samples

Test sample 11 – ID: 11

Figure C11.1. Overview of test sample 11.

Figure C11.2. Bottom view of test sample 11.

Figure C11.3. Side view of test sample 11.

Test sample 12 – ID: 12

Figure C12.1. Overview of test sample 12.

Figure C12.2. Bottom view of test sample 12.

Figure C12.3. Side view of test sample 12.

Test sample 13 – ID: 13

Figure C13.1. Overview of test sample 13.

Figure C13.2. Bottom view of test sample 13.

Figure C13.3. Side view of test sample 13.

Test sample 14 – ID: 14

Figure C14.1. Overview of test sample 14.

Figure C14.2. Bottom view of test sample 14.

Figure C14.3. Side view of test sample 14.

Test sample 15 – ID: 15

Figure C15.1. Overview of test sample 15.

Figure C15.2. Bottom view of test sample 15.

Figure C15.3. Side view of test sample 15.

D

Results of piston cleaning test

Ultrasonic cleaning of Monotherm test samples: Results

Result of test sample 1 - ID 1

Figure D1.1. Overview of test sample 1 after cleaning.

Figure D1.2. Bottom view of test sample 1 after cleaning.

Figure D1.3. Side view of test sample 1 after cleaning.

Result of test sample 2 - ID 2

Figure D2.1. Overview of test sample 2 after cleaning.

Figure D2.2. Bottom view of test sample 2 after cleaning.

Figure D2.3. Side view of test sample 2 after cleaning.

Result of test sample 3 - ID 3

Figure D3.1. Overview of test sample 3 after cleaning.

Figure D3.2. Bottom view of test sample 3 after cleaning.

Figure D3.3. Side view of test sample 3 after cleaning.

Result of test sample 4 - ID 4

Figure D4.1. Overview of test sample 4 after cleaning.

Figure D4.2. Bottom view of test sample 4 after cleaning.

Figure D4.3. Side view of test sample 4 after cleaning.

Result of test sample 5 - ID 5

Figure D5.1. Overview of test sample 5 after cleaning.

Figure D5.2. Bottom view of test sample 5 after cleaning.

Figure D5.3. Side view of test sample 5 after cleaning.

Result of test sample 6 - ID 6

Figure D6.1. Overview of test sample 6 after cleaning.

Figure D6.2. Bottom view of test sample 6 after cleaning.

Figure D6.3. Side view of test sample 6 after cleaning.

Result of test sample 7 - ID 7

Figure D7.1. Overview of test sample 7 after cleaning.

Figure D7.2. Bottom view of test sample 7 after cleaning.

Figure D7.3. Side view of test sample 7 after cleaning.

Result of test sample 8 - ID 8

Figure D8.1. Overview of test sample 8 after cleaning.

Figure D8.2. Bottom view of test sample 8 after cleaning.

Figure D8.3. Side view of test sample 8 after cleaning.

Result of test sample 9 - ID 9

Figure D9.1. Overview of test sample 9 after cleaning.

Figure D9.2. Bottom view of test sample 9 after cleaning.

Figure D9.3. Side view of test sample 9 after cleaning.

Result of test sample 10 - ID 10

Figure D10.1. Overview of test sample 10 after cleaning.

Figure D10.2. Bottom view of test sample 10 after cleaning.

Figure D10.3. Side view of test sample 10 after cleaning.

Ultrasonic cleaning of Monoweld test samples: Results

Result of test sample 11 - ID 11

Figure D11.1. Overview of test sample 11 after cleaning.

Figure D11.2. Bottom view of test sample 11 after cleaning.

Figure D11.3. Side view of test sample 11 after cleaning.

Result of test sample 12 - ID 12

Figure D12.1. Overview of test sample 12 after cleaning.

Figure D12.2. Bottom view of test sample 12 after cleaning.

Figure D12.3. Side view of test sample 12 after cleaning.

Result of test sample 13 - ID 13

Figure D13.1. Overview of test sample 13 after cleaning.

Figure D13.2. Bottom view of test sample 13 after cleaning.

Figure D13.3. Side view of test sample 13 after cleaning.

Result of test sample 14 - ID 14

Figure D14.1. Overview of test sample 14 after cleaning.

Figure D14.2. Bottom view of test sample 14 after cleaning.

Figure D14.3. Side view of test sample 14 after cleaning.

Result of test sample 15 - ID 15

Figure D15.1. Overview of test sample 15 after cleaning.

Figure D15.2. Bottom view of test sample 15 after cleaning.

Figure D15.3. Side view of test sample 15 after cleaning.

E

Results of piston cleaning test for the oil cooling gallery and upper compression groove

Monotherm test samples: Results of the ultrasonic cleaning of the oil cooling gallery and upper compression groove

Cleaning result of oil cooling gallery and upper compression groove of test sample 1 - ID 1

Figure E1.1. Piston 1 cooling gallery after cleaning.

Figure E1.2. Piston 1 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 2 - ID 2

Figure E2.1. Piston 2 cooling gallery after cleaning.

Figure E2.2. Piston 2 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 3 - ID 3

Figure E3.1. Piston 3 cooling gallery after cleaning.

Figure E3.2. Piston 3 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 4 - ID 4

Figure E4.1. Piston 4 cooling gallery after cleaning.

Figure E4.2. Piston 4 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 5 - ID 5

Figure E5.1. Piston 5 cooling gallery after cleaning.

Figure E5.2. Piston 5 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 6 - ID 6

Figure E6.1. Piston 6 cooling gallery after cleaning.

Figure E6.2. Piston 6 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 7 - ID 7

Figure E7.1. Piston 7 cooling gallery after cleaning.

Figure E7.2. Piston 7 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 8 - ID 8

Figure E8.1. Piston 8 cooling gallery after cleaning.

Figure E8.2. Piston 8 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 9 - ID 9

Figure E9.1. Piston 9 cooling gallery after cleaning.

Figure E9.2. Piston 9 upper compression groove after cleaning.

Cleaning result of oil cooling gallery and upper compression groove of test sample 10 - ID 10

Figure E10.1. Piston 10 cooling gallery after cleaning.

Figure E10.2. Piston 10 upper compression groove after cleaning.

Monoweld test samples: Results of the ultrasonic cleaning of the oil cooling gallery

Cleaning result of oil cooling gallery of test sample 11 - ID 11

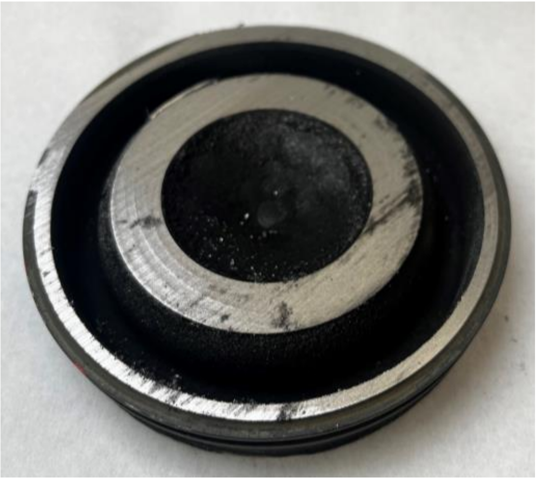


Figure E11.1. Cross sectiononal view of piston 11 top part of cooling gallery after cleaning.

Figure E11.2. Cross sectional view of piston 11 bottom part of cooling gallery after cleaning.

Cleaning result of oil cooling gallery of test sample 12 - ID 12

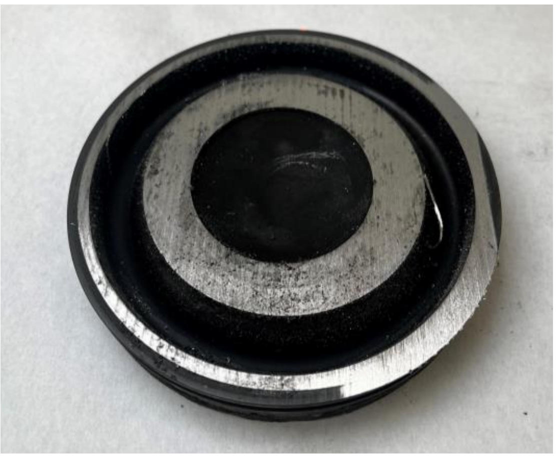


Figure E12.1. Cross sectiononal view of piston 12 top part of cooling gallery after cleaning.

Figure E12.2. Cross sectiononal view of piston 12 top part of cooling gallery after cleaning.

Cleaning result of oil cooling gallery of test sample 13 - ID 13

Figure E13.1. Cross sectiononal view of piston 13 top part of cooling gallery after cleaning.

Figure E13.2. Cross sectional view of piston 13 bottom part of cooling gallery after cleaning.

Cleaning result of oil cooling gallery of test sample 14 - ID 14

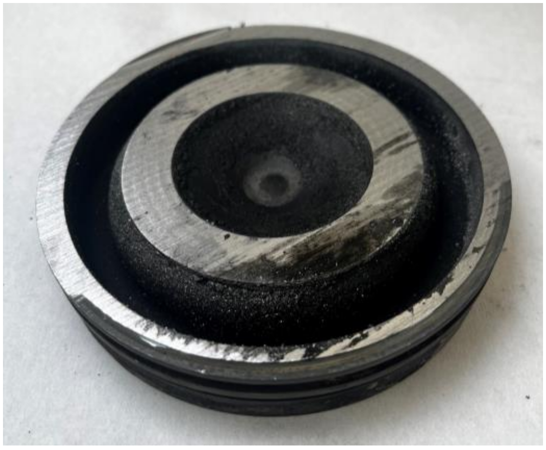


Figure E14.1. Cross sectiononal view of piston 14 top part of cooling gallery after cleaning.

Figure E14.2. Cross sectiononal view of piston 14 top part of cooling gallery after cleaning.

Cleaning result of oil cooling gallery of test sample 15 - ID 15

Figure E15.1. Cross sectiononal view of piston 15 top part of cooling gallery after cleaning.

Figure E15.2. Cross sectional view of piston 15 bottom part of cooling gallery after cleaning.

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

AVANCEZ
1829
CHALMERS
UNIVERSITY OF TECHNOLOGY