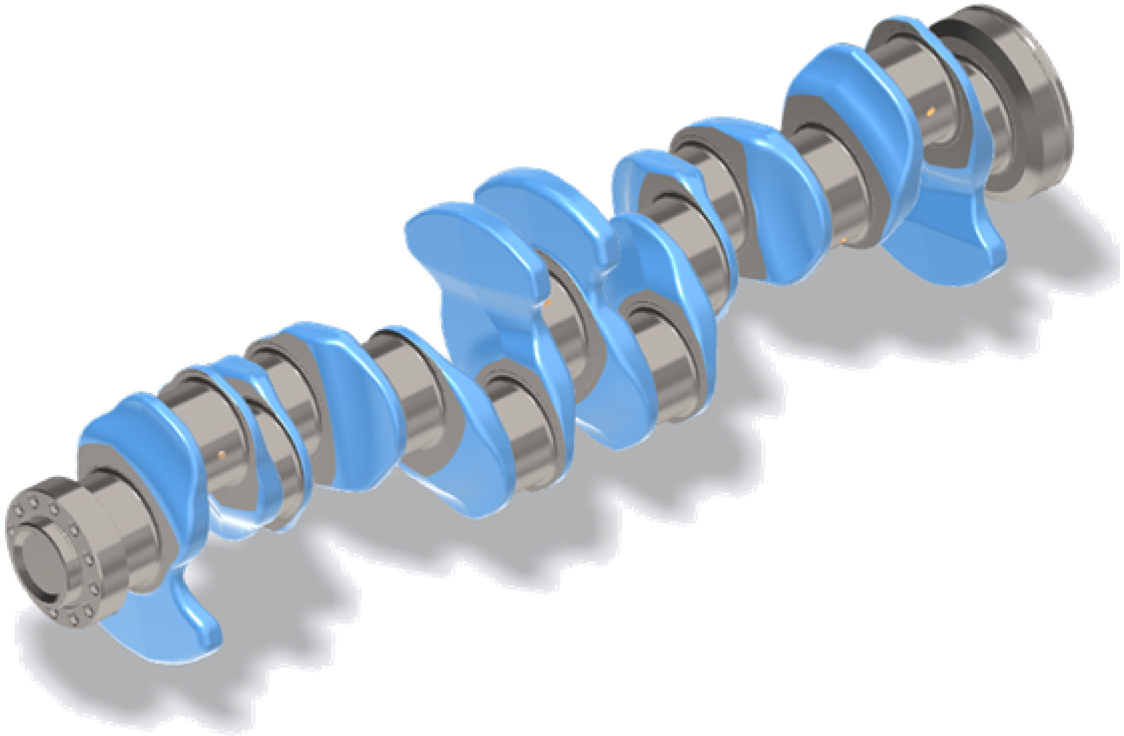

Cold Spraying as a Repair Method for Crankshaft Journals

An Explorative Study Regarding the Technical Feasibility

Master's thesis in Product Development

Matilda Blomgren & Stefán Gunnarsson

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor: Venkatesh Sritharan, Volvo Group Trucks Technology
Supervisor: Malin Höckefors, Volvo Group Trucks Technology
Supervisor and Examiner: Christer Persson, Chalmers University of Technology

Master's Thesis 2023
Department of Industrial and Materials Science
Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A side view of a 3D modeled crankshaft.

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Abstract

In this study, the feasibility of repairing crankshaft journals with cold spraying was investigated. It was researched through a systematic literature study, and contact with cold spraying companies, with the main focus on the parameters affecting the coating properties; surface hardness and adhesive strength, machinability of the cold sprayed coating, and limitations to the shape and size of repair. The most critical factor affecting the deposit hardness and adhesive strength is the impact velocity. The size and shape of the repair are limited by both the cold spraying process capacity and the crankshaft design. The design elements limiting shape and size are the critical zones; radiuses, oil holes, and the lower part of the pin journals. Machining the cold sprayed coating is possible, however, it can be problematic due to the critical zones and simultaneous machining of two materials. The cold spraying companies, which differ by the pressure system they specialize in, have recommended materials for the repair, only the recommendation from the high pressure cold spraying company can fully meet the design requirements. For low-pressure cold spraying, three feedstock materials have been recommended, Ni/Zn, Al/Zn, and Cu/Zn composites. For high-pressure cold spraying, two feedstock materials have been recommended, a tungsten carbide with nickel and cobalt, and a tungsten carbide with stainless steel. The latter can be further developed to meet the crankshaft requirements. The recommended materials must comply with Volvo's list of substances. The recommended feedstock materials include substances on the lists. The materials shall therefore be assessed if allowed to be used, if not it must be considered if other feedstock materials are available, or if the material open for development can be optimized with the lists in mind. A detailed recommended plan of testing is presented with the purpose of defining the unknown parameters of the coatings; compatibility and strength, and to verify that the coating meets all journal requirements.

Keywords: Cold spray, Crankshaft, Journal, Low-pressure cold spray, High-pressure cold spray

Acknowledgements

We would like to thank Linda Rydén for giving us the chance to work on this project and Malin Höckefors for assisting us with the project. We gratefully acknowledge the support of Venkatesh Sritharan, our main supervisor at Volvo Trucks, for being an endless well of information and for always meeting us with kind and constructive help. We would also like to express our deepest gratitude to the people at VRC Metal Systems and Titomic for assisting us during this process. Last but not least we'd like to thank Christer Person, our supervisor at Chalmers, for guiding us through this process.

Matilda Blomgren, Stefán Gunnarsson, Gothenburg, June 2023

List of Acronyms

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

ASI	Adiabatic Shear Instability
DE	Deposition Efficiency
FR	Flattening Ratio
GTS	Gun Traverse Speed
HDE	Heavy-Duty Engine
HDEP	Heavy-Duty Engine Platform
HPCS	High-pressure Cold Spray
LPCS	Low-pressure Cold Spray
PF	Plane of Fracture
SoD	Stand-off Distance
TAT	Tensile Adhesion Test

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1

Introduction

The awareness and importance of sustainability are increasing globally. The agenda of 2030 [1] for sustainable development is approaching and the effects of extracting and emitting fossil energy resources are getting more and more evident. With this in mind companies and organizations are approaching ways to implement sustainability and circularity in their business chains.

A company adapting to this change is Volvo Group. They have vehicles on the market driven by various energy sources and are developing technology towards making their heavy-duty engine platforms (HDEP) more sustainable and circular to lower the carbon footprint of the supply chain. One way of implementing circularity to an already existing component, according to the circular business model, is to manage the disposal and to investigate if the scrapped parts can be refurbished and reused, to prolong their lifetime [2]. Volvo Group has a remanufacturing department (Reman) within the organization repairing components to produce remanufactured engines for distribution. Remanufactured engines have the same requirements as new engines and therefore the refurbished parts need to be as new when re-assembled in the remanufactured engines, the complete remanufacturing process can be seen in Appendix A. Which components can be repaired and re-assembled depends on the damage and the capacity of the allowed repair method. Today few and limited repair methods are allowed on the crankshaft and in this study, it will be investigated if an alternative repair method, cold spraying, is suitable for the crankshaft journals to reduce the number of crankshafts being scrapped. The crankshaft is a material-dense and robust component and its main function is to convert the linear motion made by the combustion in the piston chamber into rotary motion which then transmits through the flywheel. The connecting components are the connecting rods to the piston and the bearings and at each ends damper and flywheel, and the crankshaft is located in the center of the engine block.

Over a thousand damaged engines are delivered to the remanufacturing department every year, some of which include a crankshaft that fulfills the technical requirements and can be reused without refurbishing. The crankshafts that do not fulfill the requirements, and cannot be repaired with the existing repair methods, are scrapped. The most common reason for why a crankshaft can't be reused is due to scratches on the journals. Occasionally particles infiltrate the thin oil film in the gap between the crankshaft journal and the bearing. These particles are residue particles from manufacturing or a result of dirty oil. These minor particles cause scratches on the journal and the bearing and in extreme cases can cause a gap in the thin oil film and result in seizure of the engine as the lack of oil creates friction and tear between the journal and bearing surfaces and results in a heat build-up. In most cases, the range of the scratches' dimensions are so small that they don't affect the engine performance. But since a reused crankshaft is required to be as new, no scratches or other deviations from the original design are allowed. The only option for removing these superficial scratches today is to grind the component to a smaller diameter. If the scratches are deeper than 1 mm or if the crankshaft is in the lower range of the diameter tolerance, it can't be ground and has to be scrapped. Another damage applicable for the cold spray repair is dented journals. These dents originate when handled incorrectly in manufacturing or when disassembled from the engine, which occurs rarely. It is assumed that the requirement for repairing dents and scratches are the same.

It is therefore of interest to Volvo Group to find an alternative repair method for these scratches, and other surface damages, to avoid the permanent scrapping of repairable and reusable components. An alternative repair method investigated by Volvo is cold spraying. Concluded by a sample test initiated by Reman, in 2021, the method shows potential. Still, it needs to be further investigated before a decision on whether an implementation at the remanufacturing site is beneficial or not.

1.1 Problem Definition

The scope of this study is to investigate the feasibility and capability of cold spraying as a repair method for Volvo's crankshaft journals. The goal is to conclude the affecting parameters for the cold spraying processes and the recommendation of implementation for the journals. If repair is possible a material list of suitable materials for the feedstock will be presented along with a test plan which verifies the feasibility of the repair method.

This work targets the following aspects of the cold spray process and its suitability specifically for Volvos heavy-duty engine (HDE) crankshaft journals: material bonding, surface hardness, machinability, and shape and size.

This study is limited to internal information at Volvo regarding the HDE crankshaft design and company standards, external research among prior published work, and external expert knowledge from cold spray companies. Investigation of the implementation requirements and needs at Reman are out of the scope, due to the unavailability of the department.

It is out of the scope to conclude results made by tests on the component, in addition to the economical and environmental aspects of implementing cold spraying as a repair method. The study is delimited to only investigate the feasibility of cold spraying as a repair method for the crankshafts produced by Volvo with their specific material compositions and properties. The repair method must also comply with the company standards for substances and processes. It is assumed that heat-treating the cold sprayed coating after the deposition will change the micro-structure and properties of the journals, therefore any heat after-treatment is not included in the study.

Due to confidentiality, sensitive information is excluded from this paper.

1.1.1 Research Questions

The aim of the project is to decide if cold spraying is a suitable repair method for the crankshaft journals in regard to the technical requirements of the component and remanufacturing. To determine this according to research methodology, specific research questions are defined and presented below.

Research questions:

1. What parameters affect the bonding of the feedstock and substrate?
2. What parameters affect the surface hardness of the feedstock material?
3. Can a repaired crankshaft journal with cold spraying meet the crankshaft requirements?
4. Which feedstock material is suitable for the repair of the crankshaft journals and does it comply with Volvo's lists of substances?
5. Is machining of a cold sprayed coating possible, and are the crankshaft manufacturing processes applicable?
6. Which type of repairs are feasible from a cold spray deposition standpoint and what elements of the journals limit the shape and size of the repair?

2

Methodology

In this chapter, the way in which the study was conducted is presented, along with the methods and tools used. The study was an explorative research study that used both primary and secondary sources. Explorative research is research investigating unstudied subjects to help define and frame the constraints. The primary sources were accessed with a qualitative approach to gather in-depth crankshaft-applied considerations regarding the cold spray implementation. The secondary sources were approached with a quantitative approach through a systematic literature study to gather information systematically regarding the coating properties. The DMIAC method, from lean six sigma, was applied to the work process for increased structure. DMAIC is a methodology used for improvement, some changes to the process and method were made. DMAIC is an acronym that stands for: define, measure, analyze, improve, and control [3].

2.1 Define

The define phase was approached by defining the scope of the study, and its delimitations. It included how the study would be conducted, and what methods would be used. This included analyzing the prior research done by Volvo and at which phase of the process Volvo need further development, the crankshaft requirements, what information was available on cold spraying and how it could be found, and how to test the finished product, and verifying the result.

2.2 Measure

The measure phase of the study focused on what information was known, what information was available and what was unknown. This included internal research on information regarding the crankshaft design, parameters, and performance in addition to gathering information on cold spraying through secondary sources. In specific the parameters of cold spraying affect the cold sprayed coating properties. The gathering of information was done by conducting a literature study.

2.2.1 Internal Research

Internal research was conducted to gather knowledge regarding the specific crankshafts at Volvo Group. The research included crankshafts that are produced today and crankshafts that are not in production but are out in the field. This research included technical reports, engineering reports, and design drawings including specific parameters of each crankshaft.

To incorporate a systematic way of reading through published articles, a systematic literature study was conducted to gather theoretical information on cold spraying, general information about cold spraying, the parameters of the process that affect the result specifically, and prior research on using cold spraying on engine components to get an understanding of the feasibility and usage of the method today. This literature study was limited to the English language.

Systematized Review

A systematized review was conducted by searching at *Web of Science* for keywords regarding different aspects of the field of study. This gave 881 results. The articles were exported as a list and taken through a screening process. This screening process was conducted to limit the number of articles to a fraction of the original search and leave only articles relative to the study. There was no time-frame set on the literature, as the technology was quite new and therefore all information was relevant.

Article Screening

The screening process consisted of two different screening gates. The first raised the question of whether the article was relative to the study depending on the title of the article, while the other questioned if the article was relative depending on the abstract of the article. For these criteria, the articles were judged relevant, not relevant, or maybe. The articles not relevant by the title, and then abstract, were excluded while the relevant and maybe relevant articles moved on in the process. In Table 2.1, the keywords used are presented along with the total number of articles that came up, and were relative in the title and abstract screening. Columns including two numbers separated by a hyphen present both the number of articles relevant and maybe relevant, in that order.

Table 2.1: Screened articles by keywords

Keywords	**Total amount**	**Title screening** Yes - Maybe	**Abstract screening** Yes - Maybe
"Cold Spray*" + C38	0		
"Cold Spray*" + C45	0		
"Cold Spray*" + Crankshaft	0		
"Cold Spray*" + Review + Steel	36	19 - 9	13 -1
"Cold Spray*" + Bond* + Steel	183	18 - 58	53 - 5
"Cold Spray*" + HPCS + LPCS	8	8 - 0	3 - 0
"Cold Spray*" + "Hardness"	596	43 - 158	52 - 1
"Cold Spray*" + "Surface Hardness"	9	5 - 4	4 - 4
"Cold Spray*" + "Grinding"	17	1 - 13	0 - 0
"Cold Spray*" + "Machinability"	9	1 - 7	3 - 0
"Cold Spray*" + "Journal"	23	1 - 16	1 - 0

Full Text Review

After screening the articles for their relevance in terms of article title and their abstract, a small percentage of the original sampling of articles was left. These articles were fully read, if relative, and used in the study they were referenced. A direct flow of the process can be seen on Figure 2.1

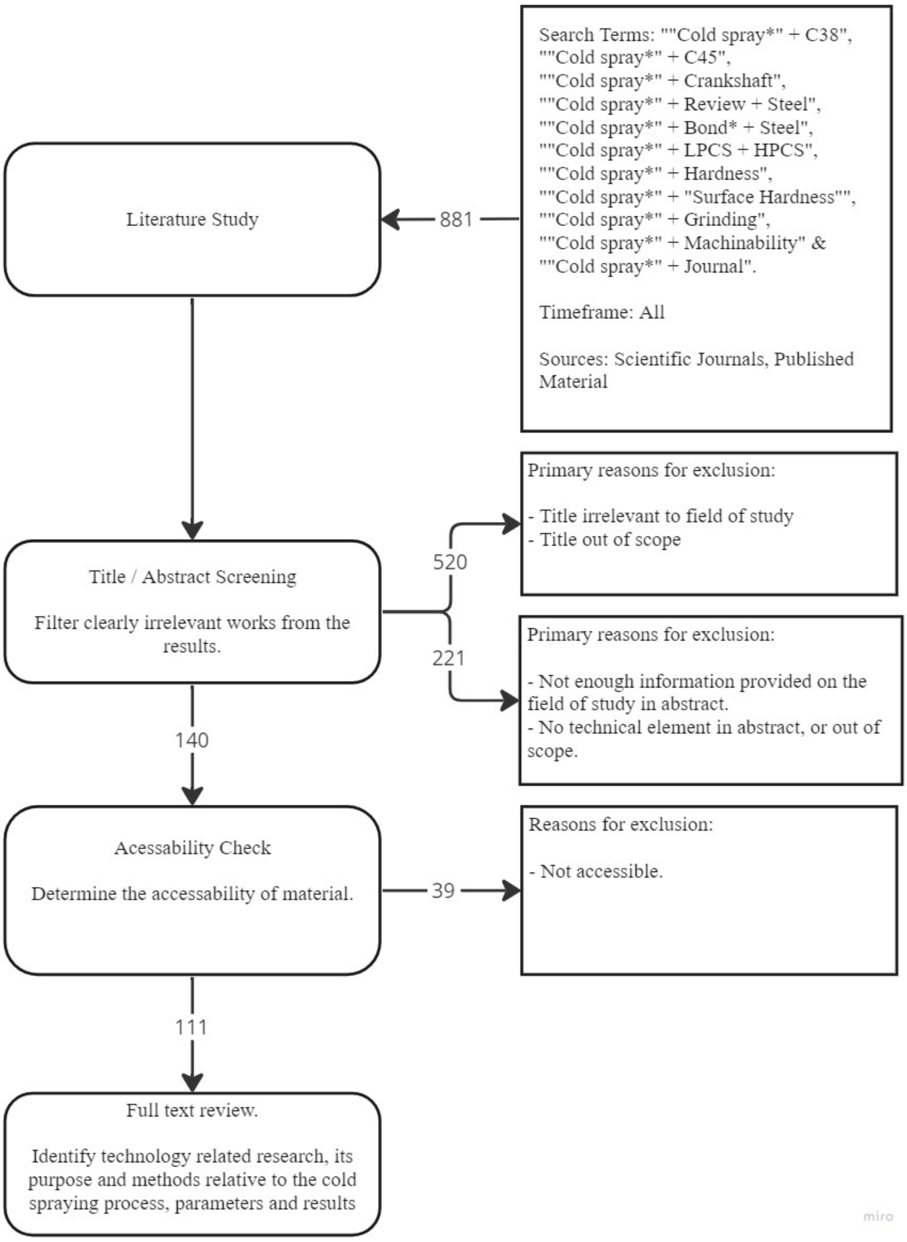


Figure 2.1: Systematic Literature Review Process

2.3 Analyze

The analysis phase of the study was used to analyze the information gathered, find knowledge gaps and iterate the research to a point where all attainable knowledge of the field of study was had. This included specific parameters on the components that need to be met, the parameters of the cold spraying process that affect the coating properties, and what solutions are available on the market. To fill these knowledge gaps expert knowledge was needed. The cold spraying market was analyzed and companies working with cold spraying were contacted.

2.3.1 Expert Knowledge

The field of this study, cold spraying, is case specific since the properties of the finished coating are based on the properties of the substrate material, the properties of the feedstock material, the requirements of the component, and what environment the materials need to endure. Little to no accessible research could be found on cold sprayed coatings on crankshafts or other engine components or materials which need to meet similar requirements as the crankshaft, and therefore, primary research sources and expert knowledge were needed. Volvo had prior collaboration with one company on this matter, however, to ensure the validity of the feasibility of the method other companies with different application experiences of the cold spraying method were approached.

Semi-structured Interviews

The conducted interviews were set up in an informal way. Questions were sent out to the experts before interviews. The interviewees answered both verbally and in written text. Information from meetings, interviews, or through email had to be agreed upon to be disclosed.

2.4 Improve

The improvement part according to the DMIAC methodology was adapted to optimize. It includes the optimization or rather the material selection for the repairs available. In specific, defining what materials are available today, what characterizes them, their properties, and how a cold sprayed coating using these materials would perform on a crankshaft journal.

2.5 Control

Control was applied to look into the way in which the results can be verified. As research can only theoretically prove the feasibility of the repair method, tests will have to be conducted to fully ensure the success of the repair.

Implementing Test Plans

A thorough test plan was structured taking all design requirements into consideration. As the repaired crankshafts are included in remanufactured engines, they need to meet the same requirements as a newly manufactured crankshaft. Therefore it's of great importance that every requirement is fully met. Multiple tests, each made for various requirements, were planned, which included the setup, the parameters and the process of the test, what properties meant to be measured, and the desired result.

2.6 Hardness Conversion

As there are many ways to measure hardness, and different units are used for each way of measuring, the conversion of units was needed to be clear and use the same unit throughout the thesis. This conversion was made using a conversion chart from Buehler.com [4] a company that makes hardness measuring machines. This chart was chosen due to its great detail of the used units of hardness measurement. The conversion chart can be found in Appendix B. Converting the units of the measured hardness is complex, as the test procedures are different, meaning that different results will be measured using different hardness tests. Therefore it is important to state that the conversion is an approximation and done with the purpose of comparison, and not a precise conversion.

3

The Crankshaft and Technical Requirements

"The crankshaft is essentially the backbone of the internal combustion engine" [5]

There are three different variants of the Volvo Trucks heavy-duty crankshaft for the three different sizes of HDE that Volvo Group produces; 11 l, 13 l, and 16 l. The size of the journals varies as well since the journals' size and shape are determined by bearing loads. The sizes of the crankshafts vary between 1066mm - 1256mm and the weight is from 102kg - 160kg. The crankshafts are forged from carbon steel. They are made of five different material compositions of the carbon steel C38 and C45. The difference between C38 and C45 is the percentage of carbon in the steel, as their name implies their approximate carbon amount (C38 $\approx$ 0.38% carbon). There are four variants of C38 for the crankshaft and one C45. The variant depends on the size of the engine, at which site it's manufactured, and the market segment the component is manufactured for. The requirements for the different variants of C38/45 state the chemical composition, mechanical properties, grain size, and hardenability along with other relevant requirements, such as if there are any explicit standards deviated or applied.

The crankshaft is located in the lower part of the engine, connected to the pistons, the flywheel and the damper, seen in Figure 3.1. It consists of crank webs, main-bearing journals, pin-bearing journals, counterweights, and a flywheel a damper flange, seen in Figure 3.2. Volvo's crankshaft journals have an oil passageway in the center to make sure that the component is lubricated while in use. There are two types of journals; pin and main journals. The journals connected to the pistons with connecting rods are the pin journals, which are pressure driven by the combustion itself. The main journal center determines the axis of rotation of the crankshaft and is fixed by bearing caps within the engine block.

As mentioned, the purpose of a crankshaft is to convert the linear motion of the pistons into rotational motion in the crankshaft and transfer energy from the combustion chamber to the driveline through the flywheel. The flywheel smooths out the engine's power pulses and stores energy to provide rotation to the axles. This applies various high forces to the crankshaft, therefore crankshafts need high fatigue strength and wear resistance [5]. This requires a high surface hardness and a fine surface roughness, especially on particular parts of the crankshaft such as the journals.

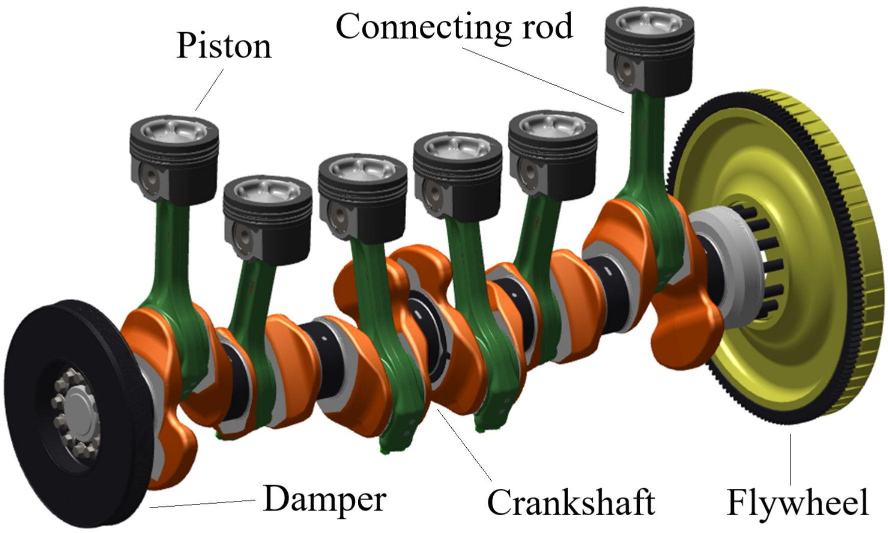


Figure 3.1: Crankshaft with connecting components

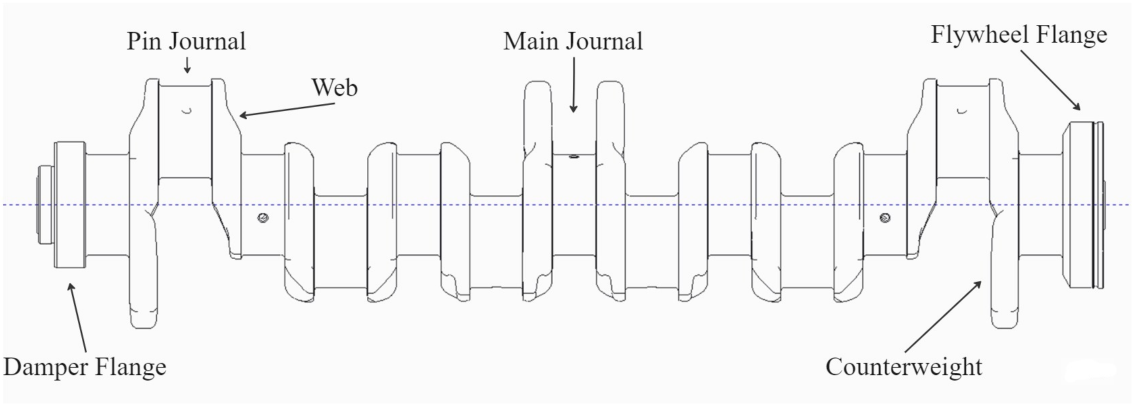


Figure 3.2: The different parts of the crankshaft and its terminology

3.1 Manufacturing Process

The general manufacturing process of the crankshaft starts with milling the rough shape of the whole crankshaft, this includes all flanges, journals, and counterweights. Next, the oil holes in the journals are drilled and the whole component is deburred. Deburring is the process of removing small imperfections known as burrs which commonly occur on machined metal products. After the deburring, the crankshaft is induction hardened, then tempered. The induction hardening process is made on the journals to achieve high surface hardness. To ensure that no cracks have occurred during this process, a magnetic particle inspection is conducted on these surfaces.

After the crack inspection, all holes are drilled and threaded. These holes are the fasteners on each side of the crankshaft that hold the crankshaft in place. After that the grinding of surfaces that need a smooth surface finish takes place, this is done on the crankshaft journals as well as the top surface on the counterweights to achieve the correct design size. These surfaces are then polished/super finished and before the manufacturing is complete the whole component is cleaned.

This manufacturing process is long and includes various machining and detailing. This not only makes the component expensive due to the material cost but the manufacturing cost as well. Repairing and remanufacturing instead of manufacturing new crankshafts is therefore beneficial.

3.2 Technical Requirements

The crankshaft requirements regarding the journals are the crankshaft drawing, crankshaft induction hardening, and the C38/45 material requirements. Each requirement document has its required standards for the processes of determining the requirements. All assessed requirements are presented in table 3.1 along with their respective content.

Table 3.1: Technical requirements for the crankshaft

Document	Content
Steel C38/45	Chemical composition Mechanical properties Grain size Hardenability
Crankshaft Drawing	Dimensions and tolerance Cleanliness Bending fatigue strength
Geometrical Tolerances	Surface Roughness Roundness Straightness Parallelism
Crankshaft Induction Hardening	Surface Hardness Case Depth Material Structure in critical zones Material Structure in other zones

3.3 Wear Type for Journal

The most common damage, for the journals are superficial scratches. These scratches vary in width and placement on the journal in the rotational direction but most often cover 360° around the journal or a minimum of around 120°. The scratches occur when particles infiltrate the thin oil film in the gap between the crankshaft journal and the bearing. These particles come from different sources. They are residue from the sand casting for the engine block and cylinder head, grease build-up from dirty oil or they can come from small metal tears around the oil pin as a result of the chamfer not being machined properly.

The type of wear the journals are damaged by, due to the particle infiltration, is abrasive wear. Abrasive wear is surface disintegration caused by an external body or material particle. It can be divided into two categories based on its loading; high- and low-stress abrasion or two or three body abrasion [6], shown in Figure 3.3. When abrasive particles are compressed between two machining parts and compressed means high-stress abrasion and are defined as three-body abrasion. Low stress is defined as two-body abrasion and occurs when a sharp or harder particle disintegrates a surface.

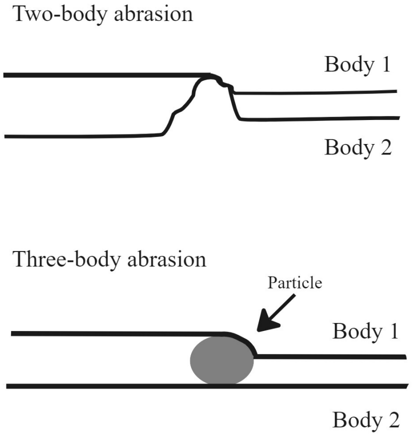
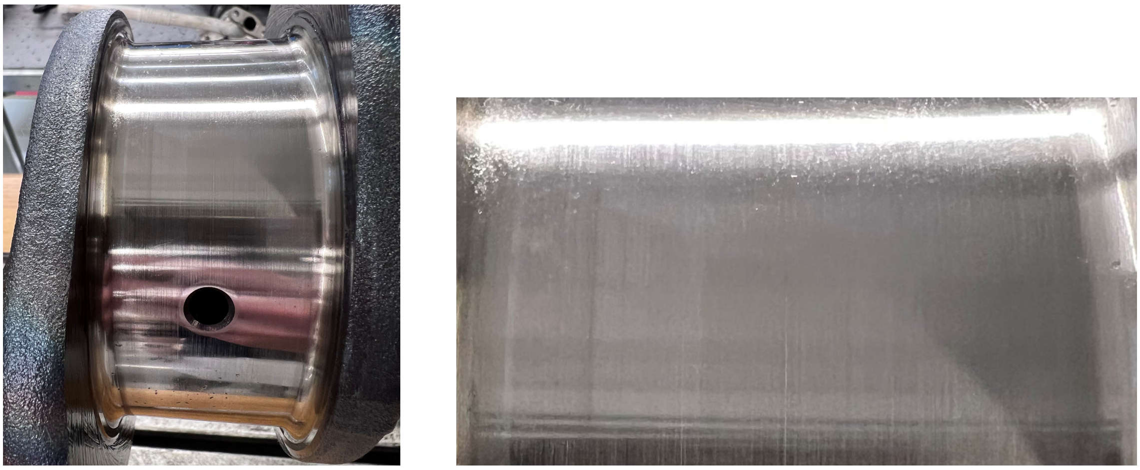


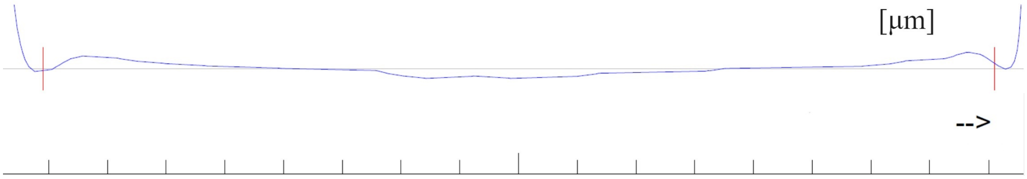
Figure 3.3: Two and tree-body abrasion illustration

The abrasive wear type on the crankshaft journals is three-body abrasion, due to the particles being compressed between the bearings and the journals present in the oil film. The wear behavior is influenced by the material composition, sliding speed, hardness, Young's modulus, the normal load, and the contact temperature [7].

A journal surface that is according to the drawing requirements on the surface is presented in Figure 3.4, and a deviating surface with scratches in Figure 3.5. Comparing the straightness curves the reference surface has a smoother surface without a large deviation from the straightness requirement. Most scratches can be seen even if they are superficial since the rotating motion and oil film creates visible tracks done by the damaging particles. The straightness curve on the surface in Figure 3.5c shows how the straightness fluctuates and the dimensions for the two deepest curves in microns. The red vertical marking on the left and right sides is the approved straightness deviation.

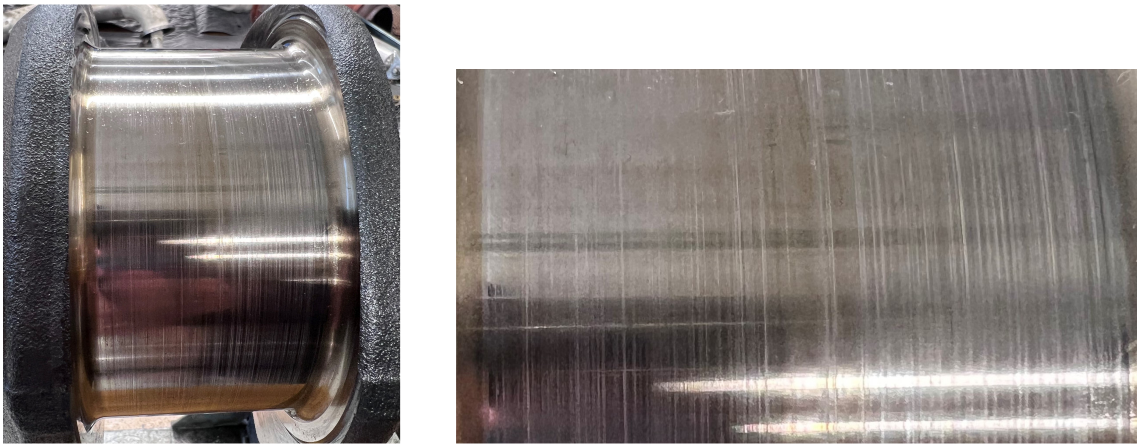


(a) Reference journal surface **(b)** Reference journal surface, close up

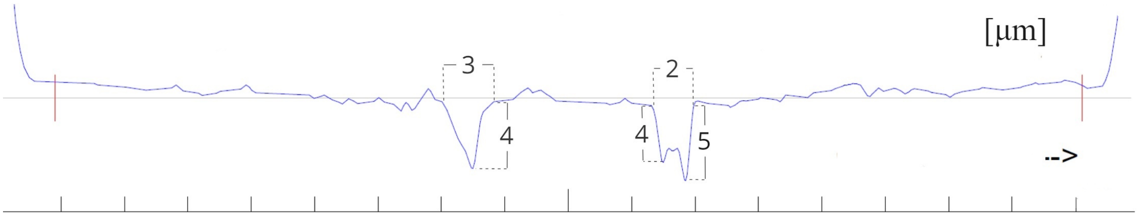


(c) Straightness curve for the reference journal

Figure 3.4: Reference surfaces on the journals without scratches and its straightness curve



(a) Deviating journal surface with scratches **(b)** Deviating journal surface with scratches, close up



(c) Straightness curve for the deviating journal and dimensions for the two deepest scratches

Figure 3.5: Deviating journal surface with scratches and its straightness curve

3.4 Allowed Crankshaft Repairs and Limitations

Two repair methods for the crankshaft today are allowed by Volvo today. These are spray welding and brush plating, and allow repair of the crankshaft diameter dimensions and surface for the position of the damper, the vibration damper, and the front flange end marked in Figure 3.6. For the journals, the only permitted machining is grinding to a maximum of 1.0 mm under the standard dimension in the steps of 0.25 mm, 0.5 mm, and 1.0 mm and then polished. Meaning that if there are scratches or dents deeper than 1.0mm the crankshaft needs to be scrapped. This method cannot be executed for journals on the lower tolerance limit for the diameter as there will be no margin for the machining deviations. As thermal spray welding is a thermal process it cannot be used for the journals as it will harden the deposited area of the substrate and locally change the micro-structure and its mechanical properties. With brush plating, the hardness requirement cannot be reached and the only allowed substance is two variants of nickel which is a substance on Volvo's substances list presented in section 5.3.1.

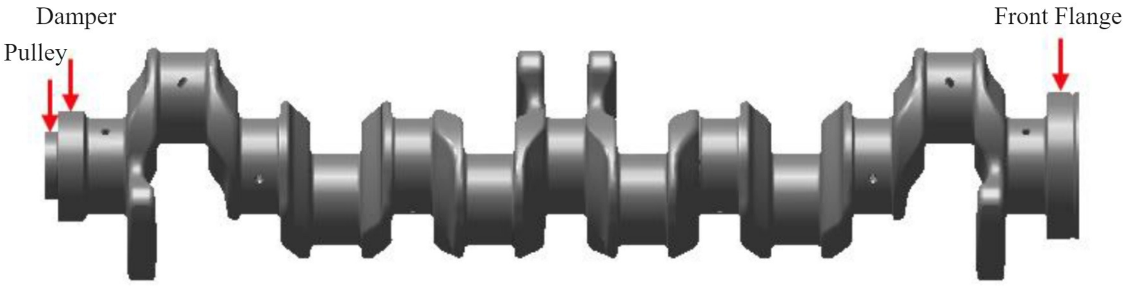


Figure 3.6: Allowed crankshaft surface repairs with spray welding and brush plating

3.5 Cold Spray Repair Constraints

The crankshaft requirements directly affecting the area of the repair for the cold spray are the tensile stress requirement, induction hardening case depth and the geometrical tolerances which are surface hardness, surface roughness, roundness, and straightness. Their values are presented in Table 3.2 along with how they influence the cold spray repair. The specification parameters for the crankshaft which affect the cold spray are presented in Table 3.3. The requirements and specifications need to be assessed either through feedstock material properties, setup parameters, or through testing. The tensile stress requirement and its characteristic the stress behavior of the cold sprayed coating needs to be defined, and how to translate the requirement applied to the coated material properties.

Table 3.2: Constraining technical requirements for the journals and respective cold spray driver

Surface Requirement	Value	Unit	Cold Spray Driver
Tensile stress	700	MPa	Feedstock material selection
Surface hardness	50 - 58	HRC	Feedstock material selection
Induction hardening case depth	[redacted]	mm	Repair depth
Surface roughness journal radius	[redacted]	Ra	Machining
Surface roughness journal	[redacted]	Ra	Machining
	[redacted]	Rz	Machining
	[redacted]	Rk	Machining
	[redacted]	Rpk	Machining
	[redacted]	U Rvk	Machining
	[redacted]	L Rvk	Machining
	[redacted]	L Mr2	Machining
Roundness	[redacted]	mm	Machining
	[redacted]	mm/°	Machining
	[redacted]	mm/°	Machining
Straightness	[redacted]	mm	Machining
Main journals	[redacted]	mm	Machining
Pin journals	[redacted]	mm	Machining
	[redacted]*	mm/mm	Machining

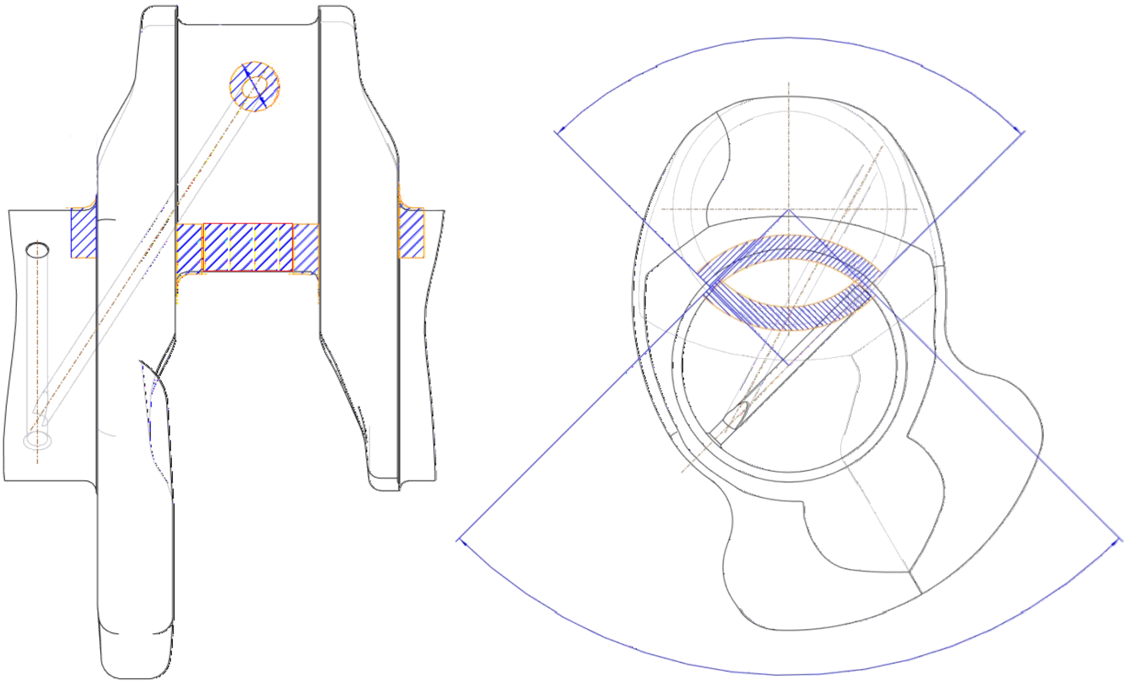
* evaluation length

Table 3.3: Technical specifications for the journals and respective cold spray drivers

Design specification	Metric	Cold Spray Driver
Journal bearing	Bearing material composition	Feedstock bearing compatibility
Rotation speed	0 - 2400 rpm	Adhesive strength
Hydrodynamic lubrication	Type of oil	Feedstock compatibility
Stress characteristics	Tensile, compression, torsion	Feedstock material strength
Critical journal surface zones	Radius, oil hole, in journals: Lower part	Area of repair
Journal working temp.	110 - 180 °C	Feedstock temp. resistance
Induction hardening temp.	[redacted] °C	Feedstock impact temp.

3.5.1 Critical Journal Zones

There are critical zones of the journals due to bending fatigue characterization and torsion. When the crankshaft is loaded it experiences both bending and torsional forces. The journals, therefore, have critical zones where they experience higher compressive and tensile stresses. The cold spray deposition onto these zones needs to be further investigated through testing. The critical zones from the bending fatigue behavior are the radiuses in the top part of the main journals and the bottom part of the pin journals. The lower part of the pin journals experience tensile stresses from the strokes by the combustion. The critical areas from bending are highlighted in blue in Figure 3.7. From the torsional stresses, all the radiuses (both between the web and for the oil holes) experience higher stresses.



(a) Front view **(b)** Side view

Figure 3.7: Critical zones by bending forces

In combination with the torsional, compressive and tensile stresses the critical areas of the journals for all journals are highlighted in blue in Figure 3.8 and are the radius between the journal and the webs and oil hole radiuses, along with the lower part of the pin journals.

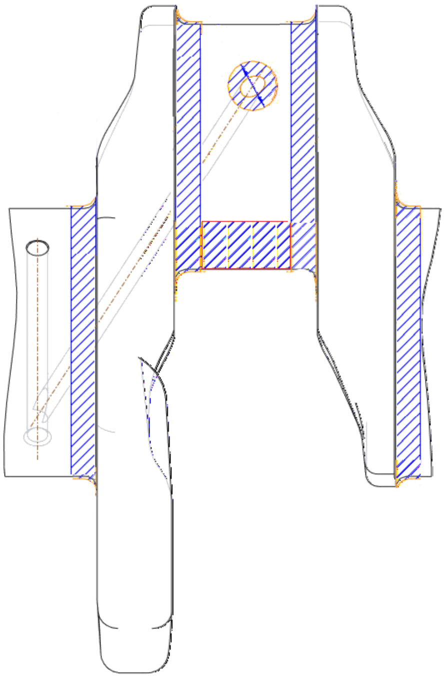


Figure 3.8: Critical zones by bending and torsional forces

3.5.2 Case Depth Requirement

As the crankshaft needs to withstand the cyclic loads and the transmission within the lubricated environment requiring a high surface hardness is required. To reach the required surface hardness, an induction hardening process is used on the crankshaft journals in the manufacturing process. The hardening of the journals also increases the crankshaft strength. This process more than doubles the hardness of the surface, making the surface wear-resistant. The case depth for all journals is [redacted] mm and the drawing view with markings is presented in Figure 3.9. Any damage deeper will penetrate an unhardened zone and create irregularities that deviate from the original micro-structural design and the strength of the crankshaft will decrease. Any damage deeper than [redacted] mm can therefore not be repaired and it needs to be tested how deep the repair can be without interfering with the durability.

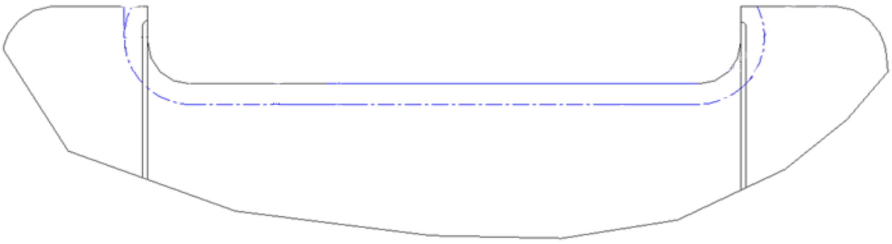


Figure 3.9: Case depth requirement marking

4

Cold Spraying Theory

In this chapter theoretical and technical information regarding cold spraying is presented. The information was gathered with a systematic literature review and presents the answers to research questions 1, 2 and 3, regarding parameter relations to bonding, surface hardness and journal requirements.

The cold spray technology is an additive manufacturing method and can be used as a coating technology that allows repairs and structural protection for metals, polymers, ceramics, and composite materials [8]. The deposition technique is a solid state process, where a pulverized feedstock bonds to the substrate material due to the plastic deformation of the pulverized particles, deformed by the high-velocity impact [9]. The cold spray method was developed in the 1980s and commercialized in the 1990s [10], and the interest in the method has been growing since then, seen in Figure 4.1 were the number of publications and citations for cold spray have been increasing since the beginning of the 21st century. The fields of application for cold spraying are biomedical, energy, electronics, and more, most relevant for this study automotive, and aerospace.

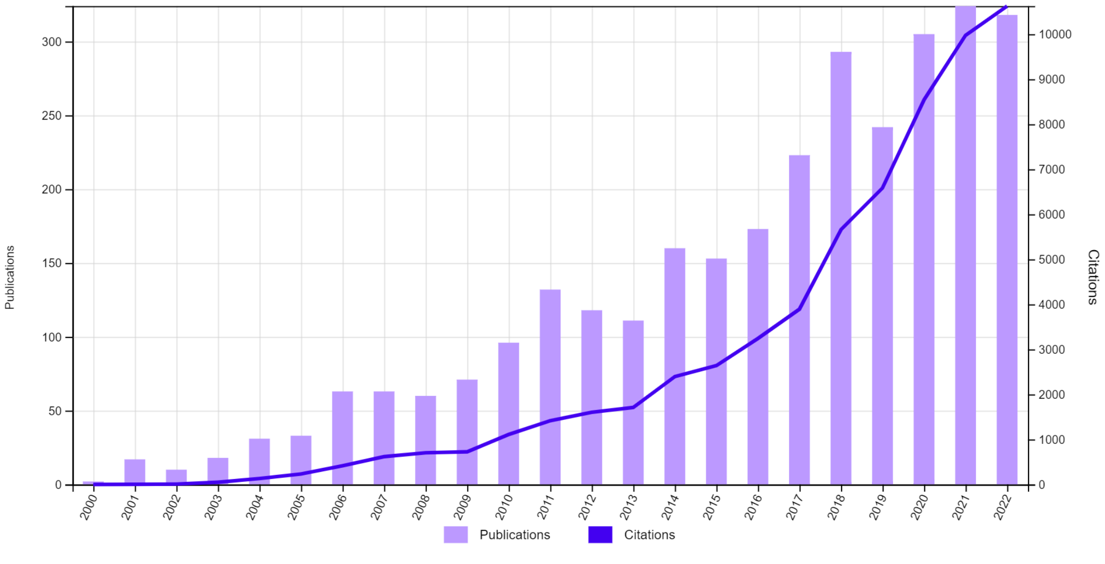


Figure 4.1: Publications and citations on "Cold Spray*" for the time period 2000-2022 [11]

Cold spray is categorized into two different pressure systems; low pressure cold spraying (LPCS) and high pressure cold spraying (HPCS), the schematics of the systems can be seen in Figure 4.2 and 4.3. Their main difference is the gas working temperature and pressure and the specific differences are mentioned in section 4.3.1.

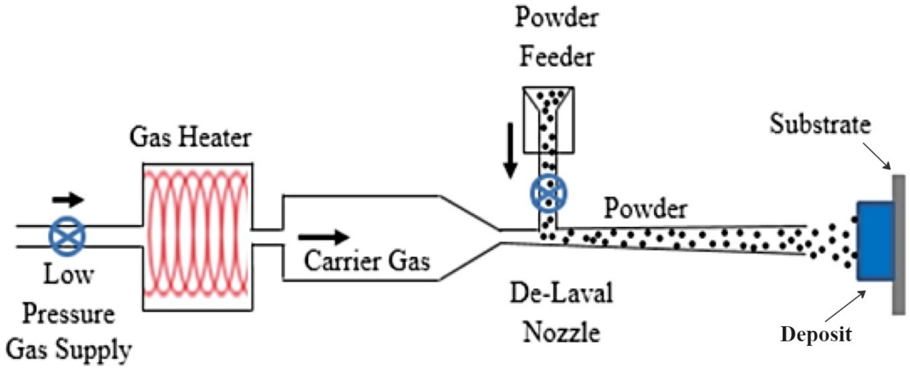


Figure 4.2: Schematic diagram of the LPCS system [12]

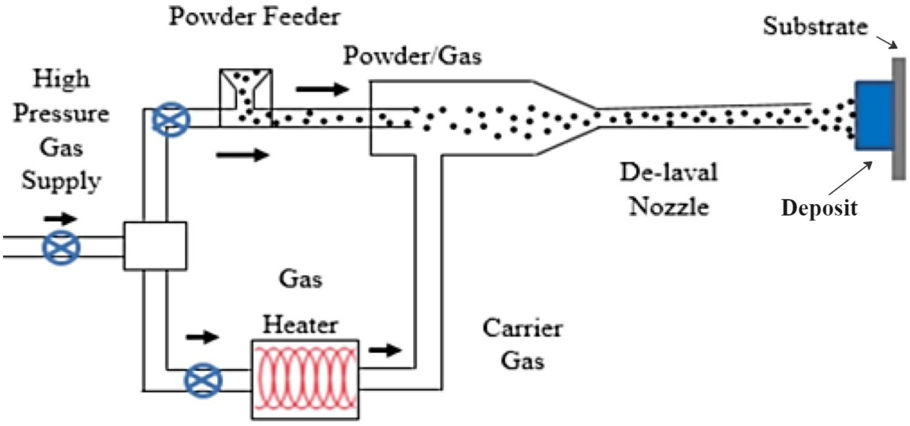


Figure 4.3: Schematic diagram of the HPCS system [12]

The pulverized coating particles are accelerated with high pressure compressed gas, usually helium, nitrogen, or air, at supersonic speed in the range of ≈ 300 - 1200 m/s. [13][8] The coating layer bond on the substrate through the conversion of the kinetic energy to plastic deformation and internal heat release, leading to metallurgical and mechanical bonding. The deposition process is a solid state process due to the operating temperature being below the feedstock's melting temperature. This differentiates cold spraying from conventional thermal coating processes, where the particles are melted. The physical shape of the nozzle varies but the most common one is the Laval nozzle [8]. The hourglass shape compresses the gas which enables the acceleration of the particles to supersonic speed.

The benefits of cold spray compared to thermal spraying comes from the difference in the working temperature. Thermal spraying has a working temperature range of 1000 - 5000 °C while cold spray is at 350 - 1000 °C, hence the method has a lower thermal impact. Therefore cold spray does not experience the same oxidation levels, residual thermal stress, evaporation, shrinkage porosity, and evaporation to the same extent as thermal processes. Even if it has the lowest gas temperature compared to conventional thermal processes, it has the highest particle velocity, the different ranges are presented in Figure 4.4. The cold spray method can be used to create thin, thick, or even bulk-form free-form coatings with a handheld or automated gun. Since the bonding relies on the plastic deformation of the feedstock it needs to be a relatively ductile material, such as aluminium, copper, ductile steels, nickel-based alloys, or ceramics in a ductile metal matrix. [13]

The technology has been developed rapidly over the last decade but still limitations prohibit the current systems. Sun et al. [10] stated three main limitations aspects to be further developed; the portability of the spray gun along with the spray temperature and pressure accuracy., nozzle clogging and wear, and inner-hole spraying systems.

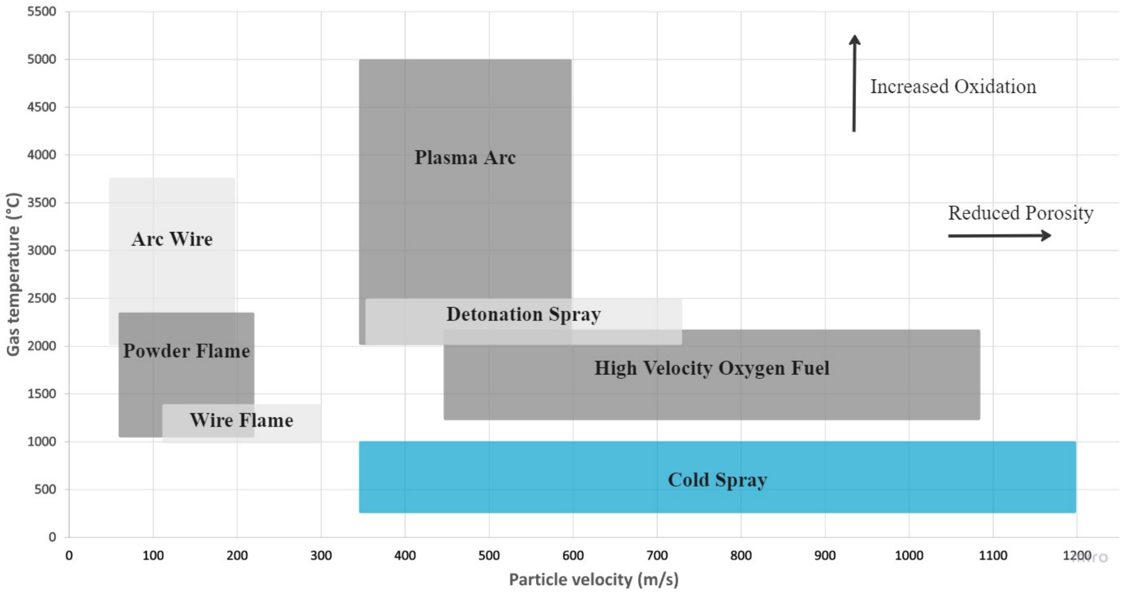


Figure 4.4: Comparison of the particle velocity and gas temperature for the cold spray process and other thermal surface coating processes [13] [14]

As the purpose of this study is to research the feasibility of using cold spray as a repair method for crankshaft journals, the deposited coating properties have to meet the requirements of the crankshaft journals. These requirements include high surface hardness for wear resistance and high adhesive strength for durability. For this reason, these two properties, along with the influencing parameters, are the primary focus of this chapter.

4.1 Material Bonding

As mentioned cold spray is a high-velocity coating technique, due to this the microscopic structures upon impact are challenging to analyze. The bonding process depends on setup parameters determining the impact and the material properties of both the feedstock and substrate and their respective relation, making the bonding process intricate. The interface bonds metallurgically and mechanically due to the conversion of the kinetic energy into heat and deformation [8]. Metallurgical bonding results from chemical bonding between the substrate and feedstock resulting in a homogeneous surface mix while mechanical interlocking or bonding is when the coating deforms and fills the microscopical substrate voids and adheres. The in-flight particle kinetic energy result in plastic deformation and heat leading to strain, adiabatic shear instability (ASI), and jetting which is formed at the interface of the particle boundary [15]. ASI happens when the atomic structures of the feedstock and substrate are compressed into direct contact as a result of the breakage of the oxide films due to the high interfacial temperature and pressure. It is stated that the metallurgical and mechanical bonding occurs when the particles get jet formations at impact which facilitates ASI, though it has been debated whether ASI is a precondition for the bonding leading to the metal-jet formation on the interface or not [16] [9].

With optimal bonding, the adhesion strength becomes the highest, and the parameters for the feedstock to bond to the substrate depending on the physical setup, spray conditions, nozzle geometry, spray parameters, feedstock, and substrate properties. [8].

4.2 Surface Hardness

When it comes to wear resistance, surface hardness can be a critical factor, depending on the type of wear, since surface hardness directly affects the tribological (wear, friction and lubrication) performance of materials [17]. As the wear type of the crankshaft journals is abrasion, surface hardness is a critical factor. Materials deposited through cold spraying are in general harder compared to the raw materials, due to the finer micro-structure obtained with the cold spraying process and a work hardening effect [18], also known as strain hardening. This strain hardening process happens when particles impact the surface at high velocity, and plastic deformation occurs, this process is further explained in section 4.4.1. Impact velocity has proven to be the most critical factor affecting the hardness of the cold sprayed coating [19][20], since it has a direct relation to the capability of the particles to deform. This means that every parameter of the cold spray process that influences impact velocity indirectly influences the hardness as well.

4.3 Setup Properties

This section presents the setup properties of cold spraying that affect the desired coating properties; deposit hardness and adhesive strength.

4.3.1 Low- vs. High Pressure Cold Spray

As mentioned, the cold spray method is categorized into two different processes; low pressure cold spraying (LPCS) and high pressure cold spraying (HPCS). The LPCS process uses lower pressure, gas temperature, and feedstock particle speed while HPCS functions at higher parameter values, visible in Table 4.1. The injection position of the powder within the nozzle differs for the two processes. For LPCS the powder is injected in the expanding part of the Laval nozzle while for HPCS it's injected in the convergent part to achieve higher speed, seen in Figure 4.2 and 4.3. Due to the difference in speed and pressure, the properties of the feedstock material properties vary for the two processes. Due to the higher speed of HPCS, the material characteristic of the powder is better suited for materials with higher melting points and strength than for LPCS. But a negative effect of the stronger particles is the wear and clogging build up on the nozzle.

It has been reported by Koivuluoto et al. [19], that when using HPCS the cold sprayed material undergoes more strain-hardening, due to the higher particle velocity, and therefore achieves higher hardness values than if using LPCS.

Table 4.1: LPCS and HPCS operating parameters [10][21][14][22]

Parameters	**LPCS**	**HPCS**
Propellant gas	N_2, Air	N_2, He
Gas Temperature (°C)	20 - 650	300 - 1000
Gas Pressure (MPa)	0.6 - 1	1 - 5.5
Gas flow rate (m^3/h)	15 - 30	50 - 150
Particle speed (m/s)	≤ 600	800 - 1400
Injection location	Downstream	Upstream
Powder characteristics	High melting point, Lighter	Low melting point, Stronger

The wear properties of the cold sprayed coating on the journals is a critical aspect when determining if the coating endures the same lifetime as the C38 and C45. A comparative study on the wear rate of aluminium coatings by LPCS and HPCS done by Manap et al.[12] concluded that the LPCS surface had the highest microhardness as well as the highest wear resistance. They indicated that the LPCS coating had the lowest porosity between the two and it influenced both the mechanical and wear properties, meaning that the porosity is a contributing factor to the wear rate. A study made by Cetin, Tazegul, and Sabri Kayali [23] investigated the effects of parameters affecting the hardness with Cu/Cu in relation to porosity, concluding that the sample with the lowest porosity has the highest hardness.

4.3.2 Deposition Efficiency

The deposition efficiency (DE) is the ratio between the deposited powder and the total utilized powder weight, the feedstock fraction successfully sprayed on the substrate. The DE is dependent on the parameters: spray angle, substrate surface, feedstock morphology, and interface temperature [24]. Each specific setup between feedstock and substrate has a different optimum for the DE.

4.3.3 Gas Parameters

Presented in this section are the parameters of the cold spraying process influenced by the carrier gas and its properties.

Gas Type

Helium, nitrogen, and compressed air are commonly used as the working gases for cold spray. Nitrogen is less expensive and more accessible than helium and is therefore preferred over helium. However, helium shows higher deposition efficiency for hard sprayed materials such as steel, titanium, and more metal substrates and has the lowest molecular weight which promotes capabilities of higher velocity hence commonly used in high pressure systems [8]. Air, on the other hand, is commonly used with low pressure as it enhances oxidation and is used with materials not as affected by it such as Al, Zn, and Sn [24].

Gas Temperature

The gas temperature has been proven to, indirectly, affect the adhesion strength [8]. An increased temperature increases the particle velocity according to the equation (4.1).

$$v = \sqrt{\gamma R T} \tag{4.1}$$

where, T = gas temperature at nozzle (K), R = constant gas constant, and γ = heat capacity ratio = $\frac{C_p}{C_v}$ - C_p = gas constant at constant pressure, C_v = gas constant at constant velocity.

With higher temperatures, it has been proven that adhesion strength increases. In 2011, a study by Meng et al. [18] investigated the influence of gas temperature for steel on steel and it resulted in an increase by roughly 50% of adhesive strength with a temperature difference from 450 °C to 550 °C and the hardness increased by 6%.

Gas Pressure

Higher pressure increases the particle velocity, leading to higher kinetic energy exchange, and enhancing the bonding properties [25]. With higher pressure, it is more common to use feedstocks with a higher density in material implementation for the HPCS and LPCS. Higher pressure results in higher hardness for the coating. Koivuluoto et al. [19] investigated the hardness difference between copper for a low- and high pressure setup and the high pressure resulted in a 14% harder coating.

4.3.4 Setup Parameters

Presented in this section are the setup parameters of the cold spraying process and the effect they have on the coating properties.

Stand-Off Distance

The stand-off distance (SoD) is the distance from the nozzle to the substrate surface. The particle velocity depends on the SoD and therefore affects the impact and therefore the interfacial properties. According to Singh et al., [8] the two conditions for the optimization of the SoD are the distance where the bow shock for the feedstock particles has disappeared and that the gas velocity is higher than the impact velocity. The effects of the SoD were studied by Cetin, Tazegul, and Sabri Kayali [23] on a copper substrate and concluded that the coating hardness differed from the tested distances and an SoD of 20 mm had the highest hardness.

Gun Traverse Speed

The gun traverse speed (GTS) is the rate at the speed at which the feedstock leaves the nozzle during the deposition. The GTS affects the bond strength, coating porosity, and coating hardness [26] as it affects the velocity upon impact.

Spray Angle

The spray angle is the angle between the nozzle and the substrate upon deposition and affects the adhesive strength. The most common angle is 90° but on tests made with aluminium alloys for both substrate and feedstock, the strongest adhesion strength was reported with 60° [8], indicating that a perpendicular angle is not always the optimal depending on the desired properties.

Nozzle geometry

The nozzle used for cold spray is the Laval nozzle. Its characteristic is the hourglass-shaped internal geometry making the deposition experience the converging-diverging outlet seen in Figure 4.5. For the LPCS and HPCS, the inlet gas is either placed at the converging or diverging side, but the nozzle geometry is the same. The barrel length is the length from the nozzle throat to the nozzle outlet. When configuring the Laval nozzle, the expansion ratio defines the result, which is the ratio between the outlet and throat. The spray parameters, such as temperature, gas, and velocity are affected by the nozzle design. An increase of specific parameter values such as the barrel length, nozzle diameter, and even shape of the nozzle have been observed to increase the particle velocity [8].

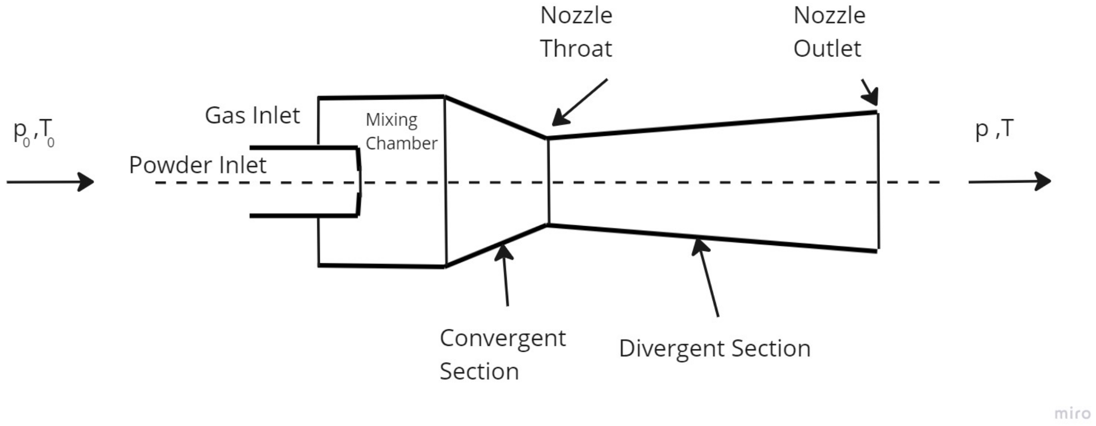


Figure 4.5: Cross-section of the Laval nozzle schematics [8]

4.4 Material properties

The material properties of both the substrate and feedstock, and the relation between them influence the coating properties. This section presents the influencing material properties for both the feedstock and substrate when cold spraying.

4.4.1 Feedstock Properties

The material selection of the feedstock for cold spray defines the properties of the coating as it does not affect only the deposition but the final coating properties. Presented below are the influencing parameters of the feedstock on the cold spray deposition.

Impact Velocity

A key parameter for the proper coating build-up is particle impact velocity. It affects the adhesive strength and the coating properties [24][19]. Optimal bonding is enhanced when the particle impacts the substrate at a velocity equal to or higher than the lower boundary of the critical velocity, V_{cr}, and below the higher boundary, the erosion velocity V_{er}. When the particle impact velocity is higher than the erosion velocity the particles begin to erode with a shot-peeing effect. The general effect of the two velocities is illustrated in Figure 4.6.

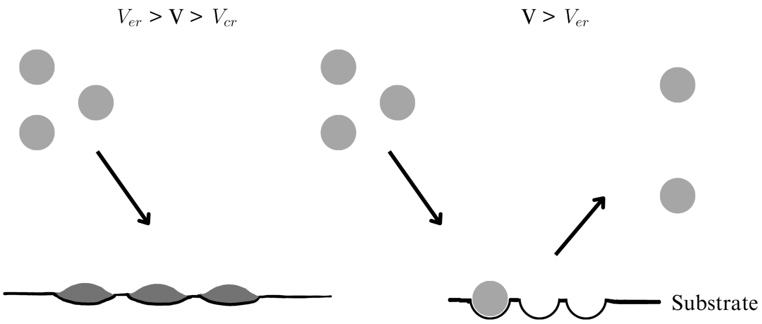


Figure 4.6: Schematic illustration of the coating effects for the critical velocity and erosion velocity

An expression based on numerical simulation in equation 4.2 with Cu on Cu states that the critical velocity can be estimated by the particle temperature [9]. For this equation, it is notable that the material parameters need to have similarities to the experimental setup with copper to be viable.

$$v_{cr} = 667 - 0.014\rho + 0.08T_m + 10^{-7}\sigma_{uts} - 0.4T_{P_i} \tag{4.2}$$

v_{cr} = critical velocity, ρ = density of feedstock material, σ_{uts} = ultimate tensile strength of feedstock material, T_{P_i} = particle temperature at impact (K), T_m = feedstock material melting temperature (K).

Another equation that expresses the critical velocity is equation 4.3. It is based on spray experiments based on powder with Copper and Steel 316L, derived with numerical and experimental methods [27].

$$v_{cr} = \sqrt{\frac{A\sigma}{\rho} + Bc_p\,(T_m - T)\Big)} \tag{4.3}$$

where, σ = temperature dependent flow stress, ρ = density, c_p = the heat capacity, T_m = melting temperature, T = mean temperature of particle upon impact, and A and B are fitting constants.

Both the equations derived by experiments and simulation used the impact temperature as a parameter along with respective feedstock material and mechanical properties parameters.

The impact velocity affects the surface hardness of particles sprayed. Champagne et al.[20] proved, with a calculated model, that with higher impact velocity, the material would reach a higher hardness. The model was based on an aluminium composite. The same study proved that cold sprayed nickel has a hardness that is 60% higher than that of fully work hardened nickel, cold sprayed stainless steel 33%, and aluminium 48%. Faccoli et al. conducted a study [28] focusing on martensitic steel and came to the conclusion that hardness is mainly affected by the high impact velocity of the solid particles accompanied by the deformation process that occurs upon impact.

Particle Size

The particle size of the feedstock affects the critical velocity boundaries and the particle velocity. According to Assadi et al.[9] there is no optimal particle size for CS in general and must be optimized for each specific material combination and spraying condition. The particle size influences the acceleration of the particles and the heat capacity and depends on the spraying conditions. Poirier et al. [29] investigated the adhesive strength of particle size variation for copper deposited on steel substrate. They found that with lower particle sizes, the adhesive strength increased. As particle size directly affects the particle velocity, and therefore the impact velocity, it has an effect on the hardness of the cold sprayed coating.

Morphology

The morphology of the feedstock particle influences the impact properties and the interface. The most common morphology are either irregular or spherical particle shapes for the cold spray deposition [8]. The spherical shape leads to higher adhesion strength due to the jet formation and has a deeper infiltration in the substrate surface [9]. Irregular morphologies build an inconsistent interface and deform more as a consequence of not penetrating the surface as much.

When cold sprayed particles impact the surface at high speeds, the particles go through a strain-hardening process. This strain hardening process changes the shape of the particles to a flatter shape as can be seen in Figure 4.7. During this process the material properties change, making the material harder[20]. When particle deformation is measured, it's presented as flattening ratio (FR), which is the ratio between the initial diameter, d_0, and the final width, w_1, and height, h_1 of the particle.

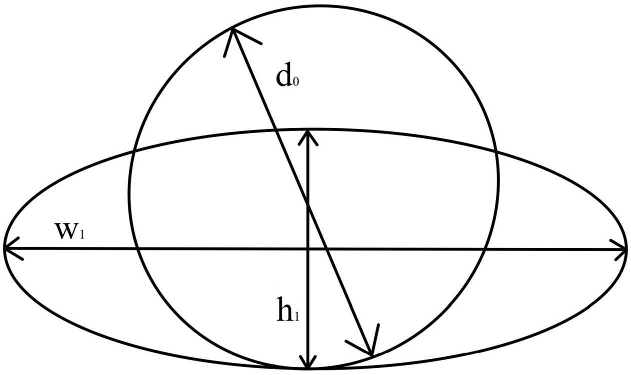


Figure 4.7: Particle deformation and flattening ratio parameters

4.4.2 Substrate properties

The substrate's material properties influence the bonding mechanisms due to it influencing the feedstock deformation upon impact. Below mentioned are the surface parameters primarily influencing the first layer of the deposition.

Surface Roughness

The surface roughness influences the first contact layer of the substrate and feedstock. Previous studies show that surface roughness affects the adhesion strength but with conflicting results, this is stated by Singh et al.[8], who concludes that further investigation is needed on what effect the substrate surfaces have on the adhesive strength. For each specific feedstock substrate combination the surface preparation method needs to be optimized. Examples of investigated surface roughness preparation methods are grit-blasting, grinding, semi-polishing, and polishing [8] [30] [31]. A study done by Hussain et al. [32] with a deposited copper coating on an aluminium alloy substrate showed that the surface preparation also influenced the coating hardness. They investigated polished (Ra = 0.05), ground (Ra = 0.4), and grit-blasted (Ra = 3.9) surfaces. The grit-blasted surface showed the highest hardness with an increase of 79 % compared to the ground surface and a 56 % increase compared to the polished surface. The hardest surface (grit-blasted) had the lowest measured adhesive strength of the three different prepared surfaces.

Oxide Layer

To secure the metallurgical bonding the substrate's oxide layer needs to be penetrated upon deposition. A thicker oxide layer for the metal requires a higher critical velocity as an increase in the oxide film thickness decreases the deposition efficiency [33] [34].

Feedstock substrate hardness relation

The properties of the coated surface depend on the feedstock material, how it bonds, the adhesion strength, hardness, surface finish, and more. The bonding mechanisms are affected by the relationship between particle-substrate hardness. The deformation of the softer particles has lower compressive strength than the hard resulting in better bonding. In general, there are four different cases for the particle-substrate hardness relation. These are: soft/soft, soft/hard, hard/hard, and hard/soft, and are illustrated in figure 4.8. The hard/soft combination results in particles that have not been deformed much, but have deeply penetrated the substrate interface. Compared to the other combinations, the soft/soft case results in both the particles and substrate deforming the most but with the least erosion effect. This combination has the highest adhesion strength of the four cases [8], the temperature was studied among the cases at the interface region and the soft/soft showed a wider high-temperature region than the rest. This is due to the material property of the high ductility, low strain hardening, and high thermal-softening effect [35]. The hard/hard combination leads to small plastic deformation and causes erosion. Lastly, when the feedstock particles are soft and the substrate hard, results in the feedstock having high deformation upon deposition but not penetrating the substrate as deep [35]. Assadi et al. [9] state that the hardness and density should have similar properties for the feedstock and substrate to result in better bonding.

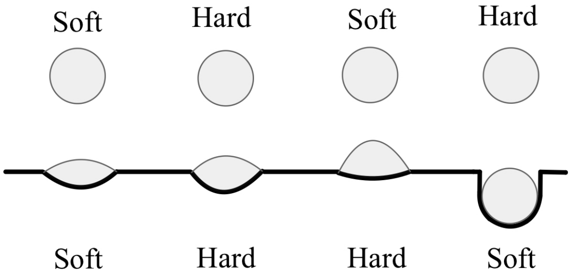


Figure 4.8: Illustration of the combinations of the particle-substrate relationship and its interlocking [24]

Temperature

To pre-heat the substrate has been shown to have an effect on the adhesive strength as it promotes deformation [8]. Goldbaum et al. [36] investigated the adhesion strength for Ti particles on a Ti substrate pre-preheated to 400 °C. The adhesion strength increased significantly. Watanabe et al. [37] came to the same conclusion with their investigation on pre-heating on Cu, Fe, and A5083 (aluminium alloy). The effect on the coating hardness was unnoted.

4.5 Experimental Data on Steel Substrates

As mentioned in Section 4.3.1, there are two different types of cold spraying, LPCS and HPCS, which result in different cold sprayed coatings. LPCS is more commonly used for softer materials, that do not need as much pressure or velocity to deform on the sprayed substrate surface. While HPCS is more commonly used for harder materials, that reach higher hardness and adhesive strength. An important coating characteristics for the purpose of the journal repair are hardness and adhesive strength and as the study focuses on applying a cold sprayed coating on steel crankshaft journals, a review was conducted to establish what values of adhesive strength and hardness have been reached in research using steel as a substrate. Table 4.2 and Table 4.3 present experimental work, where steel was used as a substrate with the respective adhesive strength, hardness values, feedstock materials, and pressure system. Based on the gas pressure the high or low pressure system is noted. The full detailed tables including the setup parameters can be found in Appendix D.

The adhesive strength varied between 5,9 MPa to 85 MPa and the hardness between 24,8 - 61 ± 2,18 HRC. The substrates for these results were either made of carbon steel, same as the crankshaft, or mild steel (low-carbon steel). The feedstock achieving the highest hardness came from the same study and either contained tungsten carbide (WC) or nickel (Ni).

Table 4.2: Expermental cold spray adhesive strength from literature with a steel substrate

Source, Year	Adhesive strength [MPa]	Substrate	Feedstock	HPCS/LPCS
[38], 2009	85	Mild Steel	CP-TI	HPCS
[18], 2011	73 ± 3	IF Steel	SS304	HPCS
[29], 2019	72	Steel	Cu	HPCS
[39], 2007	34 ± 4	Mild Steel	Al2319	HPCS
[39], 2007	25 ± 3	Mild Steel	Ni	HPCS
[40], 2008	16.1	CS* Q235A	Ti	HPCS
[25], 2020	15 ± 0.75	SS316L	Cu	-
[39], 2007	15 ± 4	Mild Steel	Ti	HPCS
[39], 2007	10 ± 2	Mild Steel	Ti-6Al-4V	HPCS
[41], 2010	6 - 7*	SUS304	Cu	HPCS
[42], 2021	5.9 ± 0.4	Mild Steel	K32	LPCS

* Average

Table 4.3: Experimental cold spray hardness from literature with a steel substrate

Source, Year	**Hardness [HRC]**	**Substrate**	**Feedstock**	**HPCS/LPCS**
[43], 2022	61 ± 2.18	Carbon Steel	WC-Co	HPCS
[43], 2022	58.22 ± 1.93	Carbon Steel	WC-Ni	HPCS
[43], 2022	55.22 ± 2.39	Carbon Steel	$CR_3C_{2-}NiCr$	HPCS
[43], 2022	55.16 ± 1.83	Carbon Steel	WC-Co-Cr	HPCS
[43], 2022	54.72 ± 0.71	Carbon Steel	WC-CR_3C_2-Ni	HPCS
[44], 2021	53	1045 Carbon Steel	NiCr	HPCS
[45], 2020	52.3	SS316L	Inconel 625	LPCS
[46], 2022	52.3	SS304L	SS304L	HPCS
[45], 2020	46.1	SS316L	CrC-NiCr	LPCS
[47], 2022	43.2	Carbon Steel	$Al_{0.5}CoCrFeNi_2Ti_{0.5}$*	HPCS
[45], 2020	40.8	SS316L	SS316L	LPCS
[48], 2017	32.2	Steel 1020	Ti+Ti6Al4V	HPCS
[18], 2011	25.6	IF Steel	SS304	-
[38], 2009	24.8	Mild Steel	CP-Ti	HPCS

Not only do most of the studies use HPCS, but the highest values of both the adhesive strength and the hardness are reached when using HPCS. There are a lot of different reasons for this, including; higher particle velocity, higher pressure, and the selection of gas, which ultimately affects the properties of the cold sprayed coating as has been mentioned previously in this chapter.

4.6 Machinability

It's important that a cold sprayed coating deposited on a crankshaft journal is machinable, as the surface has to be ground, lapped & polished to meet the surface roughness requirement. In general, machinability is affected by various factors, the ones related to the machined material are micro-structure, grain size, hardness, chemical composition, along with yield- and tensile strength [49].

According to Zheng & Liu [50], the best machinability is achieved when the ductility, work hardening, and abrasiveness are not too high. They further state that hard particles, such as carbides and nitrides, are not optimal for machining as they cause increased tool wear. It's important to note that even if a material is machinable, the wear of the tool can be greatly affected by the material composition, most notably oxidation can lead to increased tool wear, but this can be solved by using the correct machining tools for each case of material [51]. Therefore, when assessing the machinability of materials, all aspects of the machining system have to be considered, as the material of the tool and cutting speed is said to be the most important parameters, but also having an optimal relationship between the machined material and the process parameters [50].

4.7 The Correlation of Cold Spray Parameters

The parameters influencing the desired coating properties; adhesion strength and surface hardness, have been presented in section 4.3.1 - 4.4.2, in specific research question 1, 2, and 3 what parameters affect the bonding between the substrate and the cold sprayed coating, what parameters affect the surface hardness of a cold sprayed coating, and experimental data achieving the surface hardness requirement of the crankshaft journal. The parameters affecting these two properties, adhesive strength and surface hardness are presented in Figure 4.9.

In conclusion, prior to spraying, the setup properties and deposition efficiency need to be evaluated to establish the optimal parameters for the desired properties. The most critical parameter for bonding and hardness is the impact velocity as it determines the conversion of energy to the particle deformation. The required hardness of 50 - 58 HRC for the journals has been reached with carbon steel as a substrate (HPCS), which is a similar material as the. crankshaft C38 and C45, indicating possible of meeting the hardness requirement.

Silvello et al. [52] investigated the correlation between some of the discussed parameters as input and output with multi-objective simulation. The result is presented in table 4.4 (with particle velocity and deposit hardness highlighted) and shows the proportionality of the parameters, 1 means directly proportional and -1 is inversely proportional. The bigger deviation from 0 the bigger influence. The result concludes that particle velocity has the most influence on all parameters since all but particle hardness is valued. The setup parameter influencing the deposit hardness the most is the particle velocity as it presents the highest absolute value among the parameters for the setup. The positive number indicates that an increase in velocity will proportionally increase the deposit's hardness. Since the coating properties are not only material dependent but are also influenced by the system, hence equipment, expert knowledge of both LPCS and HPCS systems is needed to conclude if a cold sprayed repaired crankshaft journal can meet the manufacturing requirements.

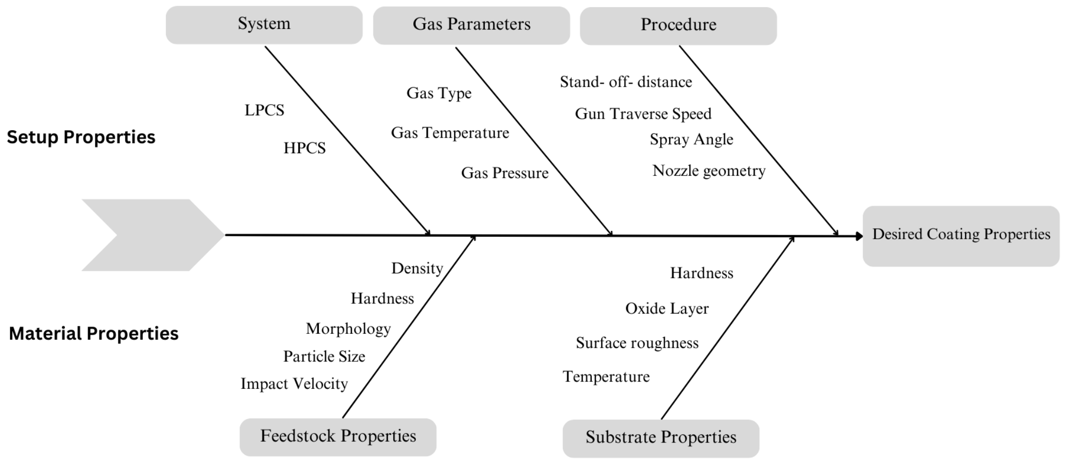


Figure 4.9: Parameters of the cold spray process that affect the desired coating properties

Table 4.4: The correlation coefficients between some of the cold spray parameters [52]

	Correlation Coefficients										
Input/Output	**Density**	**Particle diameter**	**Particle hardness**	**Gas pressure**	**Gas temperature**	**Gas density**	**Particle velocity**	**Deposit hardness**	**Porosity**	**DE**	**FR**
Density	1	0	0,745	0	0	0	-0,316	0,578	-0,056	0,579	-0,249
Particle diameter	0	1	0	0	0	0	-0,431	-0,187	-0,213	0,104	0,097
Particle hardness	0,745	0	1	0	0	0	0	0,935	0,109	0	-0,324
Gas pressure	0	0	0	1	0	0,893	0,594	0,417	-0,682	0,768	0,804
Gas temperature	0	0	0	0	1	-0,702	0,498	0,297	-0,471	0,592	0,897
Gas density	0	0	0	0,893	-0,702	1	-0,341	-0,458	-0,395	-0,738	-0,582
Particle velocity	-0,316	-0,431	0	0,594	0,498	-0,341	1	0,682	-0,734	0,803	0,817
Deposit hardness	0,578	-0,187	0,935	0,417	0,297	-0,458	0,682	1	0	0	-0,352
Porosity	-0,056	-0,213	0,109	-0,682	-0,471	-0,395	-0,734	0	1	0	-0,819
DE	0,579	0,104	0	0,768	0,592	-0,738	0,803	0	0	1	0
FR	-0,249	0,097	-0,324	0,804	0,897	-0,582	0,817	-0,352	-0,819	0	1

DE - Deposition efficiency
FR - Flattening ratio

5

Expert Knowledge

The cold sprayed coating properties depend on the setup parameters of the process and material properties material. For further understanding and deeper knowledge, experts were contacted to get information regarding the feasibility of repairing crankshaft journals with cold spraying. This chapter presents the answers to research questions 3, 4, and 5, regarding the machinability of a cold sprayed coating, material selection and the limitation of size and shape of repairs. The information was gathered through external research via experts, specifically cold spraying companies.

The expert selection was based on contact accessibility and company experience. Several companies in the industry of cold spray were approached, some of which could not provide knowledge due to the lack of experience, lack of equipment, or the company being market specific for another industry than automotive. These companies are presented in Appendix C.

In-depth knowledge regarding cold spray and the feasibility of using it for crankshaft journal repairs was provided by two companies; Titomic and VRC Metal Systems, the location of which can be seen in Fig 5.1.

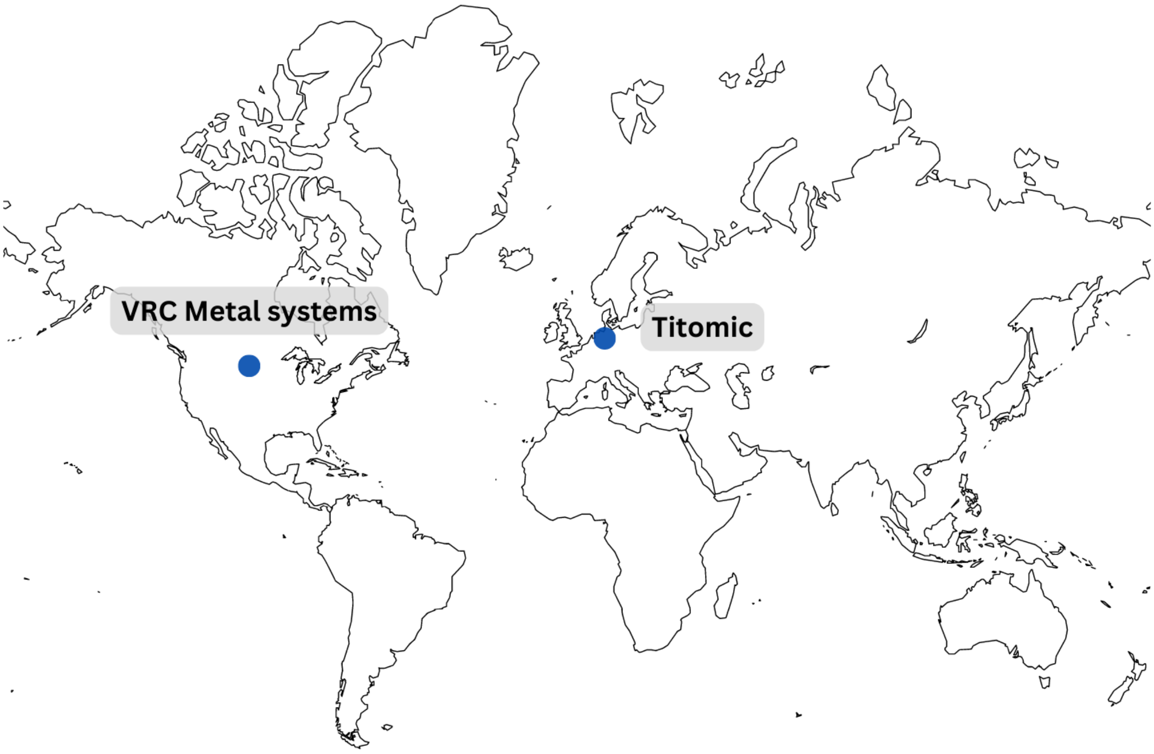


Figure 5.1: Location of Titomic and VRC Metal Systems

To get an understanding of the experience of these companies related to repairs on engine components, the capacity of their cold sprayed coatings and the feasibility of the repair, pre-defined topics were assessed during semi-structured meetings. These topics are presented in Table 5.1, were related to their general experience with cold spraying and in regards to cold spraying engine components, specifically crankshafts. Topics were also related to the characteristics of their coatings; surface hardness, adhesive strength, and machinability as well as properties that need to be considered such as the material properties of the substrate (crankshaft), the crankshaft requirements and the feasibility of using cold spraying for journal repair. The crankshaft environment and functions, requirements and design parameters were assessed to make sure that the information provided would be applicable to the crankshaft journal, in regards to setup parameters and feedstock material.

Table 5.1: Research topics

T. NR.	Topics
1	Prior experience with cold spraying, in specific what components.
2	Prior experience with repairing damaged components, and what type of damage.
3	Coating properties such as hardness, adhesive strength & machinability.
4	Effect that substrate material has on the cold sprayed coating.
5	What kind of pre-treatment is needed.
6	Limitations to their cold spray process.
7	Recommended feedstock materials.

5.1 Titomic

Titomic is a company located in the Netherlands that specializes in low- and high pressure cold spraying. Titomic and its associated companies have worked with cold spray for close to 20 years and have prior experience with repairing engine components. Titomic has prior experience working with Volvo, as the initial study with cold spraying was conducted in 2021, which focused on the adhesive strength. Titomics' experience with cold spraying spans over various technological industries, using cold spray for repair. Titomic has repaired engine components before, including camshafts and crankshafts, details of which are confidential. As Titomic focuses on LPCS the hardness requirement of the crankshaft journal is unreachable, however, a solution using LPCS could possibly work due to the wear behavior of the material. The average adhesive strength of Titomic's cold sprayed coatings is 40 MPa. Titomic's feedback is summarized in Table 5.2.

Table 5.2: Topic feedback, Titomic

T. NR.	Summarized Answer
1	Various components, including camshafts, train engine components and crankshafts.
2	Repaired various components and damages, including wear resistance and corrosion repair.
3	Max hardness 35 HRC, average adhesive strength 40 MPa, machinable but wears out the tools.
4	Hardness of the substrate affects adhesive strength, not the surface hardness.
5	Possible without pre-treatment, pre-treatment can enhance particle bonding.
6	Focus on LPCS, hardness requirement can't be reached
7	K714, K-80-13, and K-01-11 (Ni/Zn, Al/Zn and Cu/Zn composites)

Titomic recommends spot repairs for dents and scratches, and state that by using spot repair the applied forces will distribute more on the unrepaired surface of the crankshaft journal, but believe this aspect would be problematic on full journal repairs, as the coating would have to endure all forces applied on the journal. For these repairs, Titomic has recommended three different materials, presented in Section 5.1.1. They state that it is possible to machine the materials, but due to the Al_2O_3 in the material compositions, the tools for machining wear out quickly.

Titomic states that there is no surface preparation needed to successfully apply the materials to the surface of the journal and that a visual inspection or a surface roughness test will ensure that the coating has filled the superficial scratches, however to prevent particle release it's possible to deepen scratches and prepare the surface. The materials recommended by Titomic have a recommended coating thickness of 0.05 - 50 mm.

5.1.1 Recommended Feedstock Materials

The materials Titomic recommended are presented in Table 5.3, along with their material composition, hardness value, adhesive strength, and temperature resistance. The particle size of the materials ranges from 2 - 30 μm.

Table 5.3: The recommended feedstock materials and their properties

Material	**Composition**	**Hardness**	**Adhesive Strength**	**Temp. Resistance**
K-714	Ni 50%, Zn 15% Al_2O_3 35%	90 - 110 HB	38 - 46 MPa	1200 °C
K-80-13	Al 55%, Zn 15%, Al_2O_3 30%	50 - 60 HB	55 - 60 MPa	500 °C
K-01-11	Cu 30% Zn 40% Al_2O_3 30%	85 - 95 HB	25 - 33 MPa	800 °C

K-714 is recommended for full journal repair and spot repair, while K-80-13 and K-01-11 are recommended as alternative materials for spot repair. Titomic states that the coating material will perform the same way as the base material of the coating would in an oil film. Titomic states that the impact temperature of the particles is at a micro-scale. Tensile testing on the low pressure coating materials has not been performed by Titomic yet, however, Titomic state that by using heat treatment it is possible to get better tensile properties, this comes out of experience from tests using high pressure sprayed materials.

The setup parameters of the cold spray process are the same for the three materials, presented in Appendix E.

5.2 VRC Metal Systems

VRC Metal Systems is a company located in the U.S., founded in 2013 to commercialize research with the US Army Research Laboratory and SDSM&T, and leading the US market in cold spray technology. They provide HPCS for both manufacturing and corrosion and wear repair and have experience in engine components remanufacturing.

VRC Metal Systems offer a wide variety of services ranging from selling cold spray equipment and their installation to cold spraying components at their own facilities. VRC is experienced with using cold spraying for repair and repairing all sorts of components, including work on pipe joints, shafts, corrosion-resistant layers and complex components for the US Navy and Airforce. VRC uses HPCS and is therefore capable of meeting the hardness requirement. The adhesive of their coatings often exceeds the limit of the testing procedure, due to glue failure, which fails at around 69 MPa. VRC's topic feedback is summarized in Table 5.4.

Table 5.4: Topic feedback, VRC Metal Systems

Q. NR.	Question Group
1	Various components including circular surfaces and Airforce components.
2	Various components (not engine) and damages, corrosion repairs, restoration, etc.
3	Can reach 60 HRC, adhesive strength over 69 MPa, easily machinable.
4	Feedstock and substrate should have similar hardness and metallurgical compatibility.
5	Grinding recommended.
6	None.
7	Tungsten Carbide (WC), Cobalt & Nickel composite, and (WC) with Stainless-Steel.

VRC recommends both spot and full journal repairs. For both repairs, The recommended materials are tungsten carbide composites. According to VRC, both of these material compositions are machinable through grinding, lapping or similar processes, and can reach a fine surface roughness. There is no pre-treatment necessary for superficial scratches, however, if the scratches are 1 mm deep, it is recommended to blend the surface down to the depth of the scratch and widening it by 3 - 4mm. The recommended procedure includes grinding, to widen the scratches, to allow for better bonding capabilities, and ensure fully coating the surface. The process of blending can be seen in Fig 5.2.

(a) Damaged crankshaft journal **(b)** Scratch is widened by grinding

(c) Sprayed pocket **(d)** CS coating is ground and polished

Figure 5.2: The process of blending prior to the cold spraying deposit

When choosing the feedstock material, VRC states that it is important to choose a material with a similar hardness as the substrate and that there is a need for metallurgical compatibility between the feedstock and substrate. VRC further state that this is easy to achieve when steel is used as a substrate, which is the case.

5.2.1 Recommended Feedstock Materials

VRC offers a variety of materials that achieve over 50 HRC in surface hardness. They are generally a composite of a hard material to achieve the required hardness, and a softer material, which work hardens substantially. Their hardest materials are mostly a composite of tungsten carbide in metal. The materials recommended by VRC are presented in Table 5.5, along with their hardness and adhesive strength. The main method of testing adhesive strength is a tensile adhesive test which uses glue. The most common failure during this test for these materials is glue failure rather than cohesive and adhesive coating failure. The glue used fails at 69 MPa, and therefore the adhesive strength of the coating exceeds that value.

Table 5.5: The recommended feedstock materials and their properties

Material composition	**Hardness**	**Adhesive Strength**	**Temp. Resistance**
WC, Ni, Co, Cr, Fe, Nb+Ta, Mo, & Ti	55 - 64 HRC	69 MPa (**) <	1000 °C
WC+SS	40 - 52 HRC (*)	69 MPa (**) <	(*)

(*) Development possible.
(**) Glue failure.
SS = Stainless steel

The materials recommended by VRC are both blends of tungsten carbide and metal. Tungsten carbide with stainless steel composite has been used before by VRC, and they state that the composite could be developed to reach a higher hardness value, than the existing powdered composite available today. WC+SS is a material still under development, therefore the composition is not determined, and can specifically be developed for the journal requirements of the crankshaft. VRC uses the 300 series of stainless steel. VRC stated that the particle impact temperature of their process is approximately 100 °C. The process gas temperature set-points are high, up to 700 °C, but the process gas temperature decreases in the expanding section of the nozzle. The exposure times are short, and the journals are substantial heat sinks, so the journal surface is unlikely to get anywhere near hot enough to disrupt any heat treatment that has been done. Tensile testing has not been performed on the coating materials. The setup parameters of the cold spray process are presented in Appendix E.

5.3 Expert Research Result

In conclusion, considering the journal requirements, both companies have provided information regarding the technical feasibility of using cold spraying as a repair method for crankshaft journals. Titomic can not reach the surface hardness requirement, as their maximum hardness is measured at 36 HRC, while VRC can reach a hardness of 50 - 60 HRC, which is higher than the requirement of the journals. As mentioned, Titomic's material recommendations include aluminium oxide (Al_2O_3), which enhances the wear resistance of the material, and could therefore be a solution without reaching the surface hardness requirement, which is set for wear resistance.

To answer research question 3, regarding meeting manufacturing requirements, 4, regarding the material selection, 5, regarding the machinability, and 6, regarding the shape and size, the companies have recommended feedstock materials, size and shape of repair and stated that it is possible to machine the cold sprayed coating, presented in Table 5.6. As the induction hardening process brings the temperature of the hardened zone over [redacted] °C it's of high importance that the cold spraying process does not apply heat at such a high level. VRC stated that the particle impact temperature of their process is approximately 100 °C, which does not conflict with the maximum work temperature allowed for the surface. Titomic could not provide a value for the temperature.

Table 5.6: Cold spray expert answers to research questions 4 - 6

RQ	**Titomic**	**VRC**
3	Cannot reach hardness requirement	Can reach hardness requirement
4	K-714, K-80-13 & K-01-11	WC+Ni&Co, WC+SS
5	Machinable, tools wear out	Easily machinable
6	Spot repair	Spot and full journal repair

5.3.1 Screening of Substances

At Volvo Group standards need to be met when it comes to what material is included in component and processes. These standards are STD 100-0002, 0003 and 0005, or as they are called; black list, grey list, and red list.

- The STD 100-0002 [53] **black list** contains chemical substances which **must** not be present in the processes or chemical products within the Volvo Group.
- The STD 100-003 [54] **grey list** contains chemical substances which **should** not be present in the processes or chemical products within the Volvo Group and
- The STD 100-005 [55] **red list** contains chemical substances which shall be **declared** and substances that **must** not be present in Volvo Group products placed on the market.

These lists have to be considered as they are a limiting factor on what materials are available for use.

Critical materials on Volvo's red list of substances are there for one or more of the three following reasons:

- being at risk of supply disruptions or limitations due to, e.g. resource depletion
- having a large impact on the company or region
- being at risk for ESG (environmental, social, and governance) violations at various stages of the supply chain

Materials on Volvo's red list of substances that must be declared, must be declared with the source of the minerals in accordance with the OECD (Organisation for Economic Co-operation and Development) Due Diligence Guidelines, which according to OECD "helps companies respect human rights and avoid contributing to conflict through their mineral purchasing decisions and practices" [56].

Both companies have recommended materials on the substance lists. The substances are on the red list and grey list. The recommended materials are presented in Table 5.7, with the lists of substances they conflict with. The substances present on Volvo's list of substances, included in the recommended materials are presented in Table 5.8, including the conflicting lists as well. K-80-13 is the only material not containing substances on any lists.

Both of the feedstock materials from VRC are on the grey list, due to their content of cobalt and nickel. The stainless steel 300 series always contains nickel and chromium.

Table 5.7: Recommended material screening with Volvo's substance lists

Material Name	Black list	Grey list	Red list (Critical)	Red list (Declarable)
K-714		X		
K-80-13				
K-01-11		X		
WC+Ni&Co		X	X	X
WC+SS		X		X

Table 5.8: The recommended feedstock material and substance screening with Volvo's substance lists

		Black list	**Grey list**	**Red list**		
Material	**Substance/Material**			Critical	Declarable	**Risk**
K-80-13	Aluminium (Al)*					-
WC+Ni&Co WC+SS	Chromium (Cr)**					-
WC+Ni&Co	Cobalt (Co)		X	X		C,R
K-01-11	Copper (Cu)			X		-
WC+Ni&Co WC+SS	Iron (Fe)*					-
WC+Ni&Co WC+SS K-714	Nickel (Ni)		X	X		A,C,E
WC+Ni&Co	Niob (Nb)					-
WC+Ni&Co	Molybdenum (Mo)			X		-
WC+Ni&Co	Tantalum (Ta)				X	-
WC+Ni&Co WC+SS	Tungsten (W)				X	-
WC+Ni&Co	Titanium (Ti)			X		-
WC+SS	(Stainless) Steel*		X			-
K-714 K-80-13 K-01-11	Zink (Zn)					-

Risk:
A = Allergen, C = Carcinogenic,
E = Dangerous for the environment,
R = Harmful to reproduction.

* - Aluminium, iron, and, steel are presented in the red list of substances as materials that can drive sustainability, due to the reusability of the material with the note "These materials have been added due to their carbon footprint (CO2 equivalents), which can be reduced by the content of recycled material and/or by using fossil-free technologies for manufacturing". This implies that these materials should be considered with the possibility of using recycled content.

** - Hexavalent chromium (chromium (VI)) is on the black list of materials, due to its harmful nature, but chromium in its original form is not.

Stainless steel is included in the material that can be developed by VRC. This material offers the opportunity to selectively avoid conflicting with Volvo's list of substances, meet the requirements and be optimized during the testing process, presented in Section 7.2. Volvo's lists of substances must be considered when choosing the stainless steel blend as stainless steel can include various materials, including materials on the lists.

6

Critical Zones and Cases of Machining & Deposition

This chapter presents the critical zones of the crankshaft journal, and the cold spraying cases available for the critical zones in addition to the benefits and drawbacks of pre-machining the journal surface or not, with the purpose of answering research question 6, regarding the elements limiting the shape and size of repair. Whether the substrate is pre-treated (machined) before the cold spray deposit or not implicates the coating conditions. Both pre-machining and not comes with its benefits and drawback, which must be defined.

6.1 Unmachined

When spraying directly on a damaged crankshaft journal the size of the superficial scratches can be a problem. Table 6.1 presents the processes of cold spraying an untreated crankshaft journal, along with the benefits, drawbacks and what must be defined. This process is presented in Fig 6.1a.

Table 6.1: Benefits and drawbacks of cold spray deposition directly on journals

Process	Benefit	Drawback	Define
Deposition on substrate	-	Size of scratches	Ensure scratch filled
Machining	-	Coating dimensions Two materials	Minimum coating dimensions Simultaneous machining operable

When spraying directly on a damaged crankshaft journal the size of the superficial scratches can potentially be a problem and it must be ensured that the scratches are filled completely. Due to the small size of the scratches, the dimensions of the cold sprayed coating are affected. The limits of the coating dimensions must be defined, specifically if coating superficial scratches and machining the surface to geometrical requirement standards is possible, and how the coating performs with these dimensions. When machining the surface to geometrical requirement standards, the surface of the journal will include two materials; the original crankshaft and the cold sprayed coating. This could prove to be a problem as when machining two different materials simultaneously, they will react differently to the machining tool and the end result might vary.

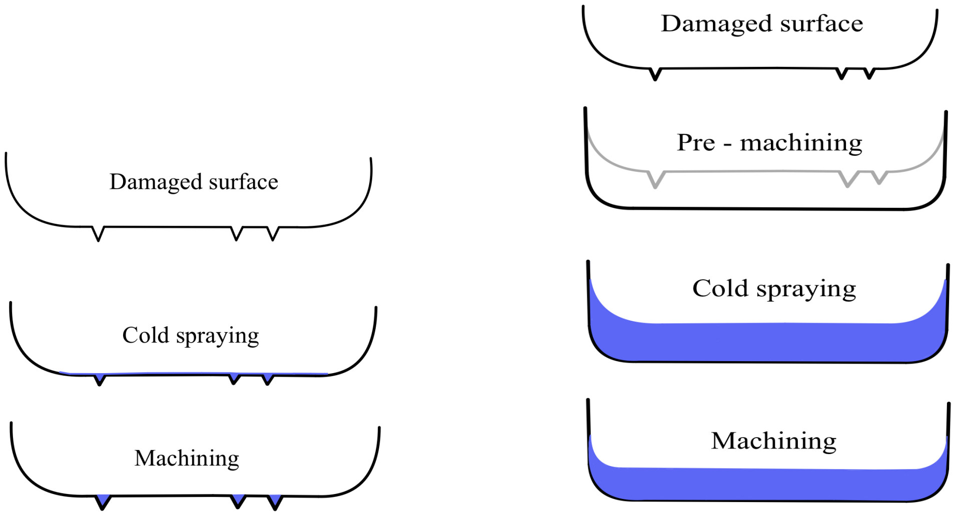
6.2 Pre-machined

When pre-machining the surface of the crankshaft journal, to prepare for cold spraying, full control of the cold-sprayed coating dimensions is gained. Table 6.2 presents the processes of cold spraying a pre-treated crankshaft journal, along with the benefits, drawbacks and what must be defined. This process can be seen in Fig 6.1b.

Table 6.2: Benefits and drawbacks of cold spray on pre-treated journals

Process	**Benefit**	**Drawback**	**Define**
Pre-treatment	Control coating dimensions	Removal of CZ Removal of IH zone	Max. removal of CZ Max. removal of IH zone
Deposition on substrate	Uniform substrate surface Optimal coating properties	-	-
Machining	One material	-	-

Pre-treating the crankshaft journal by polishing, grinding, or grit-blasting, enables full control of the dimensions of the cold-sprayed coating. It also raises the question if the critical-, and induction-hardened zones can be removed, and if so how much. Machining the surface of the journals will allow for optimized coating properties, as mentioned in section 4.4.2, and will enhance the bonding capabilities as any disadvantage from not having a straight substrate, caused by the scratches, will be removed. When machining the cold sprayed coating, only one material is machined, enabling full optimization of the machining tools allowing optimal machinability and a higher possibility of reaching the geometrical requirements.



(a) Process without pre-machining **(b)** Process with pre-machining

Figure 6.1: Processes of cold spray a journal with and without pre-treatment

6.3 Critical zones

The critical zones for the journals are the areas experiencing the peak stresses during the engine working phase. These areas contribute to the deposition design space whether sprayed onto or not. This section presents the effects of cold spraying the critical zones, and the effect the critical zones have on the design space.

6.3.1 Radius

The journal radius experiences higher stresses due to torsion of the crankshaft and bending fatigue behavior. When depositing material with cold spray on the radius, the durabiility perfomance needs to be evaluated through testing. The deposition implications are mentioned in Table 6.3, and cases are illustrated in Figure 6.2. When depositing onto the radius the removal depth needs to be defined and the radius needs to be recreated by machining. This enables the coating to be uniform for the journal. The drawback of not spraying the radius is always creating a circumferential edge between the radius boundary and the coating. This means that the machinability of the surface will decrease as the two material surfaces are machined simultaneously. The allowed depth of radius removal and coating thickness needs to be defined.

Table 6.3: The two cases for cold spray deposition of the radiuses

Case	**Deposition**	**Critical pre-grind & refinement area**	**Benefit/ Drawback**	**Define**
R1	Yes	Radius	Enable uniform coating area/ coating stress durability	Max. depth of removal
R2	No	Circumferential material boundary	/Decreased machinability	Distance to radius

(a) Case R1 **(b)** Case R2

Figure 6.2: Illustration of the cases for deposition on the radius

6.3.2 Oil Hole

All six pin journals and three of the seven main journals have oil holes. The benefits and drawbacks of spraying the oil holes and not are presented in Table 6.4, and the deposit cases are illustrated in Figure 6.3. When cold spraying onto the oil hole the radius needs to be recreated. For both cases regarding the oil hole, the machinability is decreased. The result of leaving the hole uncoated is a circumferential material boundary in close proximity to the hole radius.

Table 6.4: The two cases for the cold spray deposition of the oil holes

Case	**Deposition**	**Critical pre-grind & refinement area**	**Benefit/ Drawback**	**Define**
O1	Yes	Oil hole	Enable uniform coating area/ Decrease machinability, Chamfer recreation, coating stress durability	Max. depth of removal
O2	No	Circumferential material boundary	No chamfer recreation/ Decreased machinability	Distance to hole

(a) Case O1

(b) Case O2

Figure 6.3: Illustration of the cases for deposition on the oil holes

Machining of the crankshaft journals is done in a rotational motion. If the oil hole can not be sprayed it is assumed that the 360° area over the journal is left uncoated. A case where only the oil hole is left uncoated is not feasible.

6.3.3 Lower Part of the Pin Journals

Due to bending fatigue behavior, the lower part of the pin journal experiences higher stress and is classified as a critical zone. The benefits and drawbacks of spraying and not spraying the lower part of the pin journals are presented in Table 6.5, and the deposit cases are illustrated in Figure 6.4. If sprayed the depth and width needs to be defined for the coating to withstand the stresses. The LP1 case enables the coating to be uniform as it won't result in an axial material boundary like LP2. With an axial material boundary, the rotation of the crankshaft will be perpendicular to the boundary and cause increased wear, and tear of the coating.

Table 6.5: The two cases for cold spray deposition of the lower part of the pin journals

Case	**Deposition**	**Critical pre-grind & refinement area**	**Benefit/ Drawback**	**Define**
LP1	Yes	-	Enable uniform coat/ coating stress durability	Max. dimensions of removal Max. coating stress
LP2	No	Axial material boundary	/Decreased machinability Increased wear	Distance to lower part

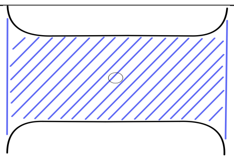
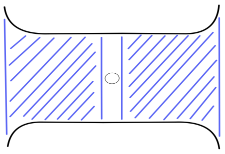
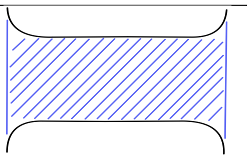
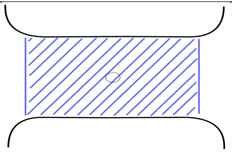
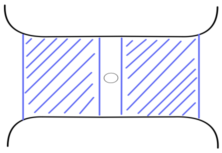
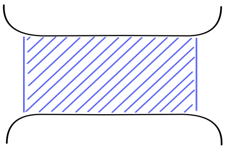
(a) Case LP1 **(b)** Case LP2

Figure 6.4: Illustration of the cases for deposition on the pin journals

6.4 Main Journal

The combination matrix for depositing cold spray onto all the critical zones on the main journals is presented in Figure 6.6. The last column, OX, represents the case for the main journals without oil holes. For all combinations, the maximum depth of the coating needs to be defined through testing. For the combinations including R2 and O2, the maximum allowed width along with the distance to the critical zones needs to be defined.

Table 6.6: Main Journal

	O1	O2	OX
R1			
R2			

6.5 Pin Journals

The combination for depositing cold spray onto all the critical zones on the pin journals is presented in Figure 6.7 (LP1) and 6.8 (LP2). The only combination not leaving a material boundary between the coating and substrate is R1O1 for LP1. All of the LP2 cases will leave an axial material boundary and significantly decrease as the machinability as all machining is done with rotational motions.

Table 6.7: Pin Journal Case 1 (LP1)

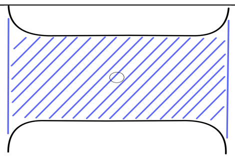
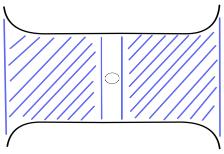
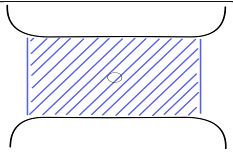
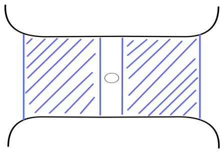
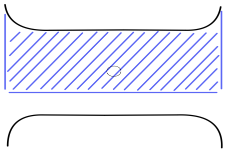
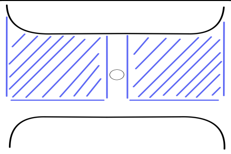
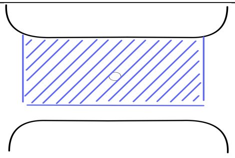
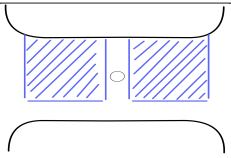
	O1	O2
R1		
R2		

Table 6.8: Pin Journal Case 2 (LP2)

	O1	O2
R1		
R2		

The cases of repair have been presented along with the benefits and drawbacks of each case. To summarize there are two cases for each critical zone, spraying them and not spraying them. The limitation of using cold spraying as a repair method comes from how the coating performs in the critical zones. To fully conclude which cases, if any, are feasible, and answer research question 6, regarding the elements limiting the shape and size of repair, testing is needed.

7

Verification of the Feasibility

This chapter presents a recommended test plan to verify and quantify the performance of a potential cold spray repair. It also presents how to measure adhesive strength along with the Volvo standards for testing. In the recommended test plan the following are measured: adhesive strength, deposit hardness, geometrical journal requirements, geometrical bearing requirements, wear rate, tool dressing cycles, oil consumption, bending and torsional strength, and the crankshaft lifetime in a field engine. The purpose of each test along with what the measurement test quantifies is defined in Appendix F. All measured properties except adhesive strength and wear rate are done by tests according to Volvo standards.

7.1 Adhesive Strength Test

Due to the high cyclic motion and the different load cases on the crankshaft the bonding strength required for the coating interface for the journals needs to be defined and optimized. Since the CS process hasn't been implemented at Volvo, the measuring of adhesive strength needs to be defined and standardized. There are different ways to measure the adhesive strength. The adhesive strength can be measured with a tensile adhesion test (TAT) or tensile adhesion-free (TAT adhesive-free) test [15]. There are several variants of adhesive-free tests depending on the loading. The different tests are schematically illustrated in Figure 7.1. The most commonly used method is TAT (ASTM C633-13).

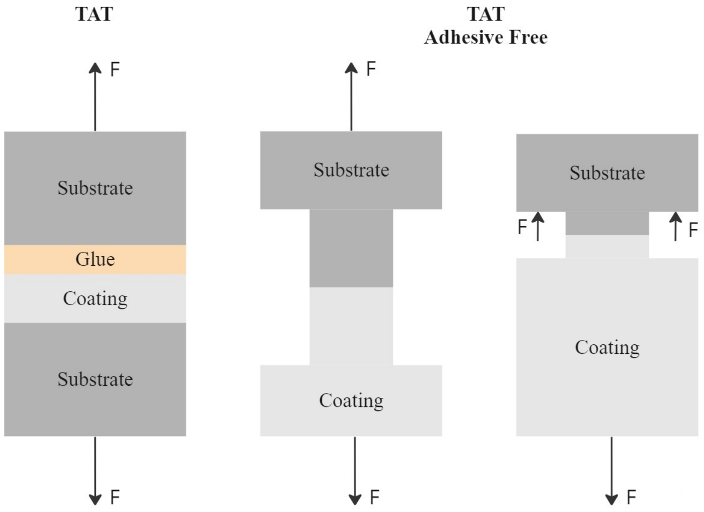


Figure 7.1: Schemes for adhesive testing, with and without adhesive (two variants)

The tensile adhesion test with and without a bonding agent measures the required tensile load to cause interface bonding failure (uniaxial stresses) between the coating and substrate and is defined as:

$$\text{Adhesion Strength [MPa]} = \frac{\text{Tensile Load}_{\text{failure}}}{\text{Sectional Area}}. \tag{7.1}$$

TAT

Conclusive results from TAT are adhesive failure, cohesive failure, and glue failure, seen in Figure 7.2. Inconclusive results from TAT are a mixed failure of all or some of the conclusive [57]. Adhesive failure is when the plane of fracture (PF) is entirely between the coating and substrate. Cohesive strength is when the PF is entirely within the coating. Lastly, glue failure is when the PF is within the glue layer. Glue failure is a result of a weaker glue than both the adhesive and cohesive strength.

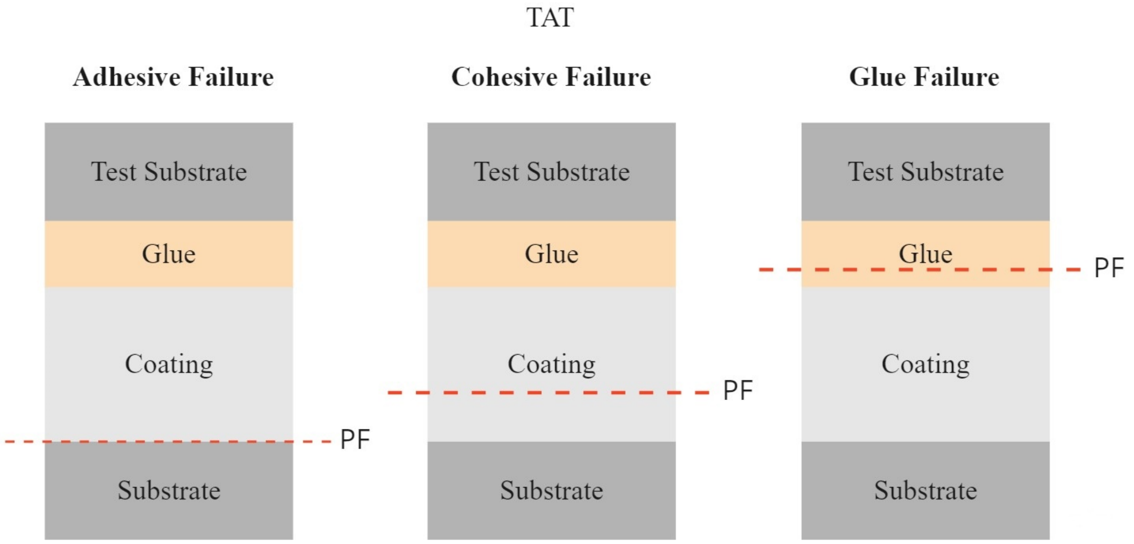


Figure 7.2: The conclusive TAT results with the respective plane of failure (PF)

TAT adhesive free

This test allows testing of the tensile properties of two bonded materials without the need for a bonding agent. The test specimen is deposited directly onto the substrate and then machined into an I-shape with the interface of the substrate and coating in the center of the specimen gauge. The TAT adhesive-free test has different standards depending on the position of the loads, one example is ASTM E8 (middle illustration Figure 7.1. The conclusive results from using a TAT adhesive free method is both adhesive and cohesive failure seen in figure 7.3. Inconclusive results are if the PF is in the substrate or a mix of both adhesive cohesive failure.

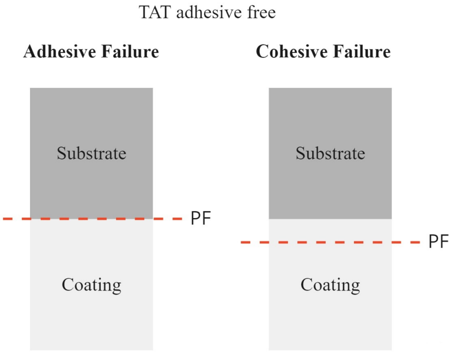


Figure 7.3: The conclusive TAT adhesive free results with the respective plane of failure (PF)

7.1.1 Wear Rate

Wear rate is currently not defined for the crankshaft journals as it is measured by the change of diameter. Implementing a wear rate test for the journals would allow a reference to be set for the C45/C38 which can be comparable to a wear rate test for the potential coat. Wear rate is measured by material degradation. To measure the degradation of a material by particle sliding the specific wear rate and wear rate are defined in equation 7.2 and 7.3. The specific wear rate W is calculated with the wear volume v, divided by the normal force F_n and the sliding distance d. The wear rate V is the product of the specific wear and wear constant K.

$$W = \frac{v}{F_n d} \tag{7.2}$$

$$V = KW \tag{7.3}$$

Testing of the sliding wear can be done by a pin-on-disc test where the test specimen is placed on a rotating disc with different applied loads as seen in figure 7.4 with the setup parameters: velocity (m/s), environment, temperature (°C), humidity (%), speed of motor (rpm), sliding distance (m), track diameter (m), duration (s).

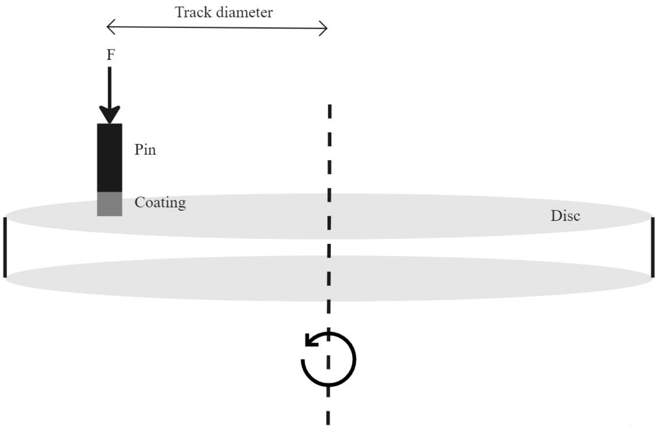


Figure 7.4: Schematic diagram of pin-on-disc tribotest

7.2 Recommended Plan of Testing

Presented in this section is the recommended test plan to verify the feasibility of using cold spray as a repair method for crankshaft journals. The plan includes which tests shall be conducted, the procedure, purpose, measurement, quantification, and verification of each requirement that must be met for the cold spray repair to be feasible. The recommended test plan, seen in Fig 7.5, includes six tests: a pre-treatment and hardness/adhesive test, a machinability test, a bending fatigue test, a torsional fatigue test, an engine durability test, and a field test, each verifying different elements of the cold-sprayed coating. Included in the recommended test plan is an optional wear rate test.

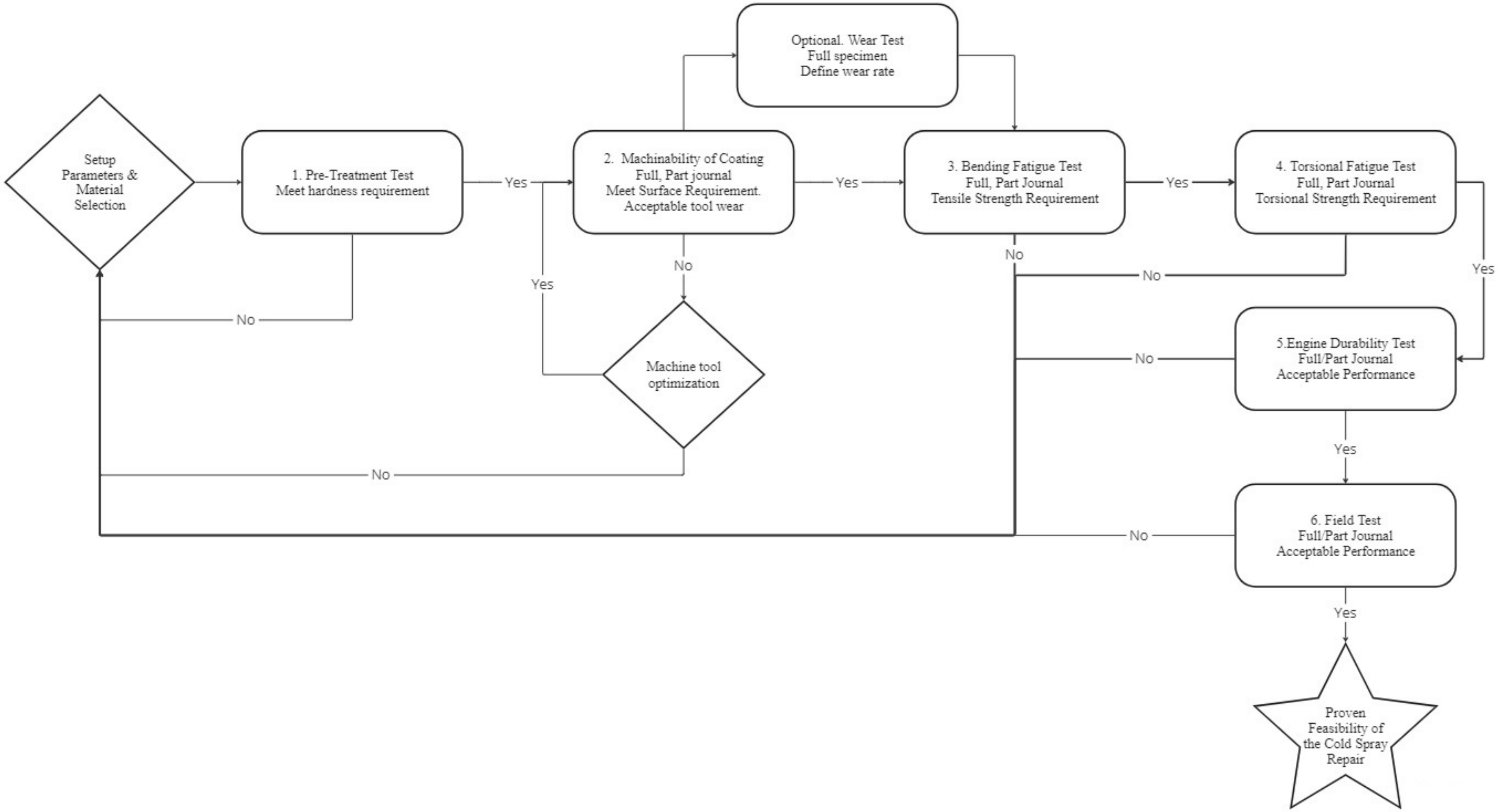


Figure 7.5: Decision flowchart for the recommended plan of testing

7.2.1 Test 1: Pre-treatment & Hardness/Adhesive Test

A pre-treatment and micro-structure test needs to be conducted to verify which pre-treatment of the crankshaft journals will result in the best coating characteristics; adhesive strength and surface hardness, as the surface roughness of the substrate has shown to influence these characteristics mentioned in section 4.4.2. If the surface hardness is within the crankshaft requirement range the pre-treatment that results in the highest adhesive strength is optimal.

This test shall be conducted on 3 pieces of samples, with the same properties as a manufactured journal surface, that is, the same surface hardness and material properties (C38/C45). The three samples shall be pre-treated in three different ways; polished (as the journal surface), ground, and grit-blasted. The adhesive strength and the deposit hardness shall be measured by an adhesive test and hardness test.

The procedure shall be as follows.
1. Surface preparation of samples.
2. Cold spray supplier sprays the prepared samples.
3. Bonding strength and deposit hardness measured.

If the surface hardness requirement is not met, an assessment of the coating material must be made, and the material must be optimized to meet the required surface hardness.

Titomic, the company specializing in LPCS, recommended materials that can not reach the surface hardness requirement, but instead provide increased wear resistance. If further development of the project is done in collaboration with Titomic, the wear resistance of the materials has to be tested separately and then tested with the recommended test plan to verify the feasibility of the materials

7.2.2 Test 2: Machinability Test

A machinability test needs to be conducted to verify that the crankshaft surface and applied cold sprayed coating, both full journal and part journal, can reach the geometry requirements of the crankshaft; surface straightness, surface roundness, and surface roughness. In this test, the wear of the tool used is measured and assessed as well. As both full journal repairs and part journal repairs are under investigation, two tests shall be conducted, for each case respectively.

The machinability test shall be conducted on a crankshaft journal sample. The crankshaft journal shall be prepared with the optimal preparation, found from the pre-treatment and micro-structure test, and ground & polished according to the crankshaft requirement standards. The geometry and tool degradation shall be measured.

The procedure of the test is as follows:
1. Journal sample is pre-treated with optimal surface preparation from test 1.
2. cold spray Supplier sprays the prepared samples.
3. Machine accordingly to geometrical requirements.
4. Measure geometry and tool degradation.

For the different cases, the different measurements, and results need to be considered.

Full Journal

When testing the full journal coating, the measurements of the geometry test need to meet the above-mentioned requirements. In addition to that, the tool used shall be optimized for the best result and tool wear, using a tool degradation test.

Part Journal

For the part journal repair, both the cold sprayed coating and the unrepaired journal surface will be machined simultaneously. The machining will have different effects on the different materials, resulting in different final results. It is important that both surfaces of the crankshaft journal, both sprayed and not sprayed, meet the geometrical requirements. If the unified surface does not meet the requirements, the material needs to be assessed and optimized. As the tool has to be optimized for machining both materials simultaneously, the tool wear needs to be measured through a degradation test and optimized to reach an acceptable wear rate.

7.2.3 Test 3 & 4: Bending & Torsional Fatigue Test

The fatigue tests are conducted by clamping a section of a crankshaft to a bending or a rotational arm. Force is then applied to the crankshaft part then inspected. The torsional fatigue test is assumed to use the same process as the bending fatigue test, with a rotating arm instead of a bending arm.

The procedure of both the bending and torsional fatigue test is as follows:
1. Journal sample is pre-treated with optimal surface preparation from test 1.
2. cold spray Supplier sprays the prepared samples.
3. Machine accordingly to geometrical requirements.
4. Measure bending and torsional fatigue.

7.2.4 Test 5: Engine Durability Test

An engine durability test needs to be conducted to determine the dimension limits of the cold sprayed coating, along with defining the adhesive strength requirement, material strength, coating wear, and bearing- and oil compatibility. This will verify the functionality of a cold-sprayed coating applied to the crankshaft journals. In this test, the geometry, adhesive rupture/cohesive rupture, coating wear, bearing wear, and oil consumption is measured.

The engine durability test shall be conducted on several crankshafts, with different parameters of the cold sprayed coating; depth and width, both full journal and part journal repair, for each case mentioned in section 6.3. The crankshaft journals shall be prepared with the optimal result from the pre-treatment and micro-structure test, cold sprayed by the supplier, ground & polished according to the crankshaft requirement standards and placed in a test engine. The engine shall be run for [redacted] hours, with intervals, taken apart after each interval and inspected/measured, with the purpose of verifying that the coating, bearing or performance has been affected.

The procedure of testing varies for the full journal and part journal repair, and for the various cases of repair different measurements and results need to be considered.

Full Journal

For the full journal repair, there is one case, spraying the full journal with all critical zones. Each case shall be tested, measured, and verified, with varying depths of the cold-sprayed coating. The test shall include a deposition depth deeper than the case depth and below and the limitations of the depth of the cold sprayed coating shall be determined, by an iterative test procedure. The proposed depths of the coating are decreased in steps of 1 mm, starting from a depth of 4 mm from the surface of the journal. The purpose of the varied depth of cold spraying when testing, is to define the dimensional limits of the cold spray repair in regards to shape and size and define the result when repairing above, on the boundary, and under the induction hardened zone.

The procedure of the test is as follows:
1. Pre-treatment with optimal surface preparation from test 1
2. Sprayed by cold spray supplier according to the specified depth
3. Machine accordingly to geometrical requirements
4. Engine tested for [redacted] hours, with intervals. After each interval the engine is taken apart and the crankshaft and bearing are inspected/measured.

The cold-sprayed coating must meet the geometrical requirements; surface hardness, surface roughness, and surface straightness.

Part Journal

For the part journal repair, there are 9 cases; full journal without radius, with and without oil holes, and with and without lower part of pin journals. Each case shall be tested measured and defined. The limitations of the width and depth of the cold sprayed coating shall be determined separately, by an iterative test procedure, where the depth of the coating is increased in steps of 1 mm, starting from a depth of 4 mm from the surface and the width in steps of 1/4 of total journal surface, starting from 1/4 mm. The purpose of testing with varied widths and depths is to define the dimensional limits of the cold spray repair in regards to shape and size and verify the result of spraying above, on the boundary, and beneath the induction hardened zone.

When testing for depth, the procedure of the test is as follows:

1. Pre-treatment with optimal surface preparation from test 1
2. Sprayed by cold spray supplier according to the specified depth
3. Machine accordingly to geometrical requirements
4. Engine tested for [redacted] hours, with intervals. After each interval the engine is taken apart and the crankshaft and bearing are inspected/measured.

When testing for width, the procedure of the test is as follows:

1. Pre-treatment with optimal surface preparation from test 1
2. Sprayed by cold spray supplier according to the specified width
3. Machine accordingly to geometrical requirements
4. Engine tested for [redacted] hours, with intervals. After each interval the engine is taken apart and the crankshaft and bearing is inspected/measured.

Regarding both full- and part journal repair

If an adhesive- or cohesive rupture occurs, it is verified by a visual inspection. In this case, the adhesive strength or the cohesive strength of the coating is not sufficient. The cold-sprayed coating must meet the geometrical requirements; surface hardness, surface roughness, and surface straightness, after engine testing. At last, the coating must not affect the bearings or the oil consumption. In the case of rupture, not meeting geometrical requirements or affecting the bearing or oil consumption, the material must be assessed and optimized.

If the crankshaft journal and cold sprayed coating meet all requirements; geometrical, wear, adhesive, cohesive, and compatibility, the feasibility of using the cold spray as a repair method for crankshaft journals has been proven.

7.2.5 Test 6: Engine Field test

The engine field test is conducted by putting the cold spray repaired crankshaft in an engine of a customers Volvo truck. The engine field test is over a few thousand kilometers. If no problems occur, the feasibility of the cold spray repair has been proven.

8

Discussion

To reduce the number of HDEP crankshafts being scrapped within the Volvo Group it has been investigated if cold spray could be used as a repair method for the journals to increase sustainability and circularity. It has been done by assessing the cold spray parameters influencing the journal requirements, specifically bonding and hardness. The method of choice was a systematic literature study to study published work and a qualitative question-based data collection getting component-applied insights from cold spray experts, representative from low- and high pressure companies. The study was explorative and did not conclude results made by tests. It is debated in this chapter how the limitations, delimitations, and choice of method influence the result and what needs to be further considered.

As the study was an initial R&D project, any economic aspects were not included. The main focus of the study was researching if the technical requirements could be met, and the parameters influencing the desired coating properties. The cold spray cost per repair has to be revised and compared to the cost of manufacturing the equivalent amount to define economic profitability. The purpose of the study origin from increasing the sustainability of the supply chain. In order to quantify the environmental impact of using cold spray the impact and energy consumption has to be established for the repair and compared to the equivalent of the manufacturing. This can be done with a comparative life cycle analysis.

The cold sprayed coating properties strongly depend on the setup parameters of the process. When conducting the systematic literature study the main focus of the study was the requirements of the crankshaft journals and the research questions (surface hardness, adhesion strength, machinability, and limitations of shape and size). The cited sources all did research with different end goals in mind, resulting in using different setup parameters and pressure systems, and can therefore not be proportionally compared. An alternative approach would have been to work more with cold spraying companies and question which parameters of the process can be optimized to meet the crankshaft requirements, and what limitations their cold spraying process has. This could have proved beneficial, especially since no prior accessible/official research has been conducted with cold spraying, where the goal is to meet requirements similar to the crankshaft requirements, and the parameters of the cold spraying process depend on the desired results.

It has been investigated if the cold spray deposit can meet the hardness requirement. The surface hardness requirement of the crankshaft journals is set due to the increased wear resistance and durability. The wear behavior of a material does not only depend on the surface hardness but is also load case-specific and which substances are within the material composition play a significant role. During the study, the question was raised if wear behavior would have been a better-suiting focus point, and if it would have resulted in different results, instead of focusing on surface hardness which is only one aspect of wear resistance. For example, it is evident that the materials recommended by Titomic can not reach the surface hardness requirement, but all materials include aluminium oxide, which has an enhancing effect on the wear properties. Titomic states that K-714 can reach up to 110 HB, this can be misleading as the same material could reach 350 - 800 Vickers depending on the location of the testing and the presence of aluminium oxide in the material. Though it can also have an abrasive effect on the bearings as the aluminium oxide is very hard compared to the rest of the material. This is not the case for the recommended materials from VRC as the materials have a higher and a more uniform hardness. As mentioned in Section 2.6, hardness cannot be proportionally converted and depends on the scale depending on the performed measurement. Therefore the requirement should be investigated from a wear performance standpoint rather than neglecting the feedstock choice due to its measured hardness not meeting the requirement.

Both materials recommended by VRC include nickel, due to the use of the 300 series for stainless steel. Stainless steel is categorized into five series. The 300 series (austenitic), used by VRC, is the largest, and includes nickel. The 400 series (martensitic with ferritic consolidate), contains very little, or no nickel. For further development it's important to consider the possibility of using the 400 series, which VRC state is worth investigating so that the material is nickel free. As nickel is included in the material composition for the crankshaft, a feedstock material including nickel could still be viable to use, since it is challenging to avoid due to the characteristics it brings to the material composition. As mentioned in 5.3.1, hexavalent chromium (chromium (VI)) is on the black list of substances, but not chromium in its original form. Hexavalent chromium is formed when metallic chromium is broken down, through a process applying heat at high levels, such as welding and thermal spraying. When using cold spray there is not enough energy in the process to change the state of the material, and therefore a feedstock material including chromium is safe to use.

The parameters affecting the desired coating properties, surface hardness and adhesive strength, have been presented, and it's evident that impact velocity is the most critical parameter of the setup. This further concludes that HPCS shows more promise, than LPCS, in regards to feasibility due to the higher pressure resulting in higher particle velocity and therefore impact velocity. As mentioned, the question remains if the surface hardness requirement is essential or not. As the surface hardness requirement is set for increased wear resistance, using a softer material with equal wear resistance might be a solution. If that is the case, LPCS might work as well. The optimal impact velocity depends on the critical velocity for the feedstock material, thus the choice of material and setup parameters are interconnected.

The cold sprayed coating will have to meet the surface roughness requirement of the crankshaft, and will therefore be ground, polished, and lapped. When machining a part journal repair, two different materials are machined at the same time. The materials will react differently, making it hard to get a uniform surface. This is not the case with a full journal repair, as only the cold sprayed coating is machined. If full journal repair proves to be feasible, it will be the optimal repair for all crankshaft journals, as the procedure of defining scratches, repair area and pre-machining will stay the same and the repair process will be a standard procedure applicable for all journals. Due to the unavailability of the remanufacturing site, no considerations for the project were adapted to the remanufacturing process. For future development of this project, the machining capability along with on-site limitations have to be defined.

Another aspect to consider is the coating compatibility with the bearings. It needs to be further investigated, not only by testing but concluded by the material compatibility, done by the material technology department at Volvo. As the feedstocks contain different substances their impact on the bearing needs to be assessed as if it can prone to an unwanted chemical reaction.

It's of high importance that the impact temperature of the particles during the cold spraying process is not higher than the induction hardening temperature so that the deposition process does not affect the material properties of the journal surface, VRC state that the impact temperature is approximately 100 °C, however, Titomic could not provide a value, but it can be assumed that it is lower than 100 °C due to Titomic using LPCS while VRC uses HPCS, with higher setup parameters that directly affect the impact temperature.

The tensile properties of the cold sprayed coating are vital. As the tensile requirement of the crankshaft journal can not be directly translated to a tensile requirement for the coating, and no tensile strength information is available from the cold spray companies, the only way to verify the tensile strength is by testing.

The complexity of the crankshaft, and its journals, is immense, and meeting all the requirements of the crankshaft is a challenge. If cold spraying does not prove to be a feasible repair method for crankshaft journals, the possibility of using cold spraying as a repair method for other components or other parts of the crankshaft can potentially be feasible as the material properties of the cold sprayed coating are versatile and can be optimized both with the choice of material and setup parameters.

9

Conclusion

In conclusion, the research questions have been answered with information gathered through a systematic literature review, and expert knowledge. In addition to theoretical feasibility, a recommended plan of testing has been presented, with the aim of verifying and proving the technical feasibility of using cold spraying as a repair method for crankshaft journals.

The parameters affecting bonding strength, and surface hardness have been presented, concluding that impact velocity, and therefore the parameters that directly affect impact velocity, has the most influence.

Recommended materials have been presented along with the setup parameters of the cold spraying process. Three materials were recommended by Titomic (LPCS), and two by VRC Metal Systems (HPCS). The different pressure systems determine the process and influence the desired material properties. Experts state that with the correct feedstock material, cold spraying setup and pre-treatment, manufacturing requirements are technically reachable using cold spray as a repair method for crankshaft journals. However, the surface hardness requirement can only be met by VRC. They further state that CS coatings are machinable, and can be ground, lapped, and polished to reach the geometrical requirements of the crankshaft journals, meaning that the manufacturing processes for the crankshaft are applicable.

The two recommended materials by VRC are present on Volvos substance lists, with WC+SS as the only viable option as WC+Ni & Co is on the black list and therefore strictly prohibited. This material is under development and the exact substances can both be modified depending on the desired properties.

Regarding the shape and size of repair, experts have recommended pre-treatment of the journal scratches on two occasions: when the depth of the scratch is smaller than 0.050 mm (Titomic) and when the depth of the scratch is 1 mm or larger (VRC). A recommended plan of testing has been presented, including the testing of the limitations of the coating dimensions as well as the critical zones of the crankshaft journal; radiuses, oil holes, and the lower part of the pin journals.

To take this project forward, and conduct the recommended test plan, a decision has to be made regarding the material selection. To make that decision, the economic and environmental aspects of the repair must be questioned. If the feedstock materials can reach the crankshaft requirements when used as a cold-sprayed coating needs to be further tested.

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A

Volvo Remanufacturing Process

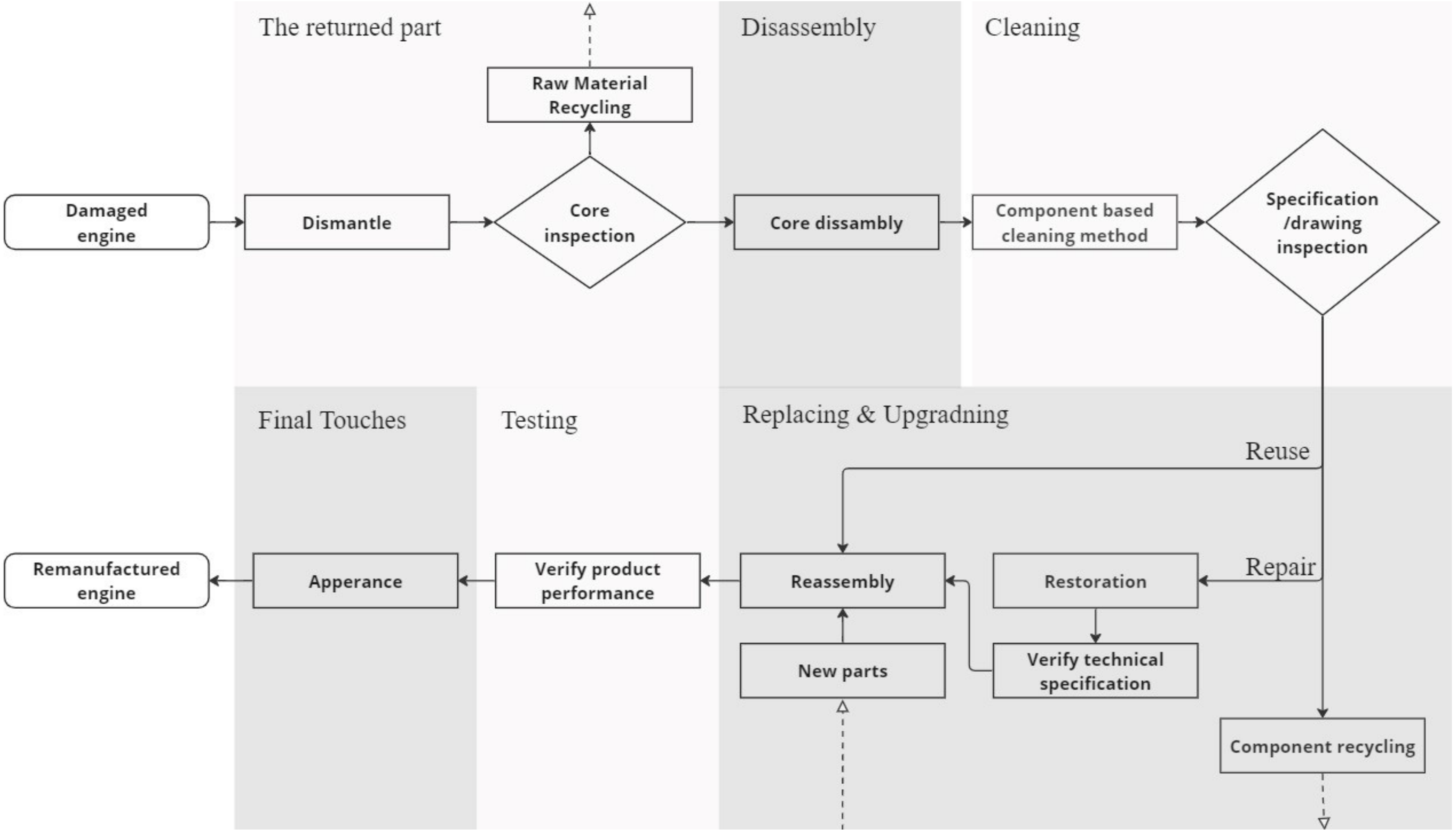


Figure A.1: Remanufacturing process from damaged to remanufactured engine [58]

B

Conversion Chart

Table B.1: Hardness conversion chart [4]

Vickers	Brinell	HRC
940	-	68
920	-	67.5
900	-	67
880	-	66.4
860	-	65.9
840	-	65.3
820	-	64.7
800	-	64
780	-	63.3
760	-	62.5
740	-	61.9
720	-	61
700	-	60.1
690	-	59.7
680	-	59.2
670	-	58.8
660	-	58.3
650	618	57.8
640	608	57.3
630	599	56.8
620	589	56.3
610	580	55.7
600	570	55.2
590	561	4.7
580	551	54.1
570	542	53.6
560	532	53
550	523	52.3
540	513	51.7
530	504	51.1
520	494	50.5
510	485	49.8
500	475	49.1

Vickers	Briness	HRC
490	466	48.4
480	456	47.7
470	447	46.9
460	437	46.1
450	428	45.3
440	418	44.5
430	409	43.6
420	399	42.7
410	390	41.8
400	380	40.8
390	371	39.8
380	361	38.8
370	352	37.7
360	342	36.6
350	333	35.5
340	323	34.4
330	314	33.3
320	304	32.2
310	295	31.2
300	85	29.8
295	280	29.2
290	276	28.5
285	271	27.8
280	266	27.1
275	261	26.4
270	257	25.6
265	252	24.8
260	247	24
255	242	23.1
250	238	22.2
245	233	21.3
240	228	20.3

Vickers	Briness	HRC
235	223	-
230	219	-
225	214	-
220	209	-
215	204	-
210	199	-
205	195	-
200	190	-
195	185	-
190	181	-
185	176	-
180	171	-
175	166	-
170	162	-
165	156	-
160	147	-
155	147	-
150	143	-
145	138	-
140	133	-
135	128	-
130	124	-
125	119	-
120	114	-
115	409	-
110	105	-
105	99.8	-
100	95	-
95	90.2	-
90	85.5	-
85	80.7	-
80	76	-

C

Contacted Cold Spray Experts

Table C.1: Contacted Cold Spray Companies

Company Name	**Contacted**	**Helpful**	**Comment**
VRC Metal Systems	Yes	Yes	HPCS
Titomic	Yes	Yes	LPCS
Höganäs	Yes	No	Powder manufacturer
Hannegard ASB Industries	Yes	No	Recommended thermal spray
Safina	Yes	No	Powder manufacturer (Cu based)
OrelTech	Yes	No	Market specific for printer electronics
Cold Metal Spray (UK)	Yes	No	No reply

D

Experimental Adhesive Strength and Hardness

Table D.1: Experimental CS adhesive strength from literature with a steel substrate and setup parameters

Source, Year	**Adhesive Strength [MPa]**	**Substrate**	**Feedstock**	**GTS** $[mm/s]$	**CT** $[mm]$	**CG**	**GP** $[MPa]$
[38], 2009	85	Mild Steel	CP-TI	80	-	N_2	1,5
[18], 2011	73 ± 3	IF steel	SS304	-	1,2	N2	3
[29], 2019	72	Steel	Cu	3,7	3-4*	He	5
[39], 2007	34 ± 4	Mild Steel	Al2319	-	10	Air	2,8
[39], 2007	25 ± 3	Mild Steel	Ni	-	10	Air	3
[40], 2008	16,1	CS* Q235A	Ti	80	1	N_2	2
[25], 2020	15 ± 0.75	SS316L Steel	Cu	-	-	-	-
[39], 2007	15 ± 4	Mild Steel	Ti	-	10	Air	2,8
[39], 2007	10 ± 2	Mild Steel	Ti-6Al-4V	-	10	Air	2,8
[41], 2010	6-7*	SUS304	Cu	20	7	N_2	1-3*
[42], 2021	5,9 ± 0,4	Mild Steel	K32 (Al2O3+Ni)	5	6,8-8,5	Air	0,9

Table D.2: Experimental CS hardness from literature with a steel substrate and setup parameters

Year	**Hardness [HRC]**	**Substrate**	**Feedstock**	**GTS** $[mm/s]$	**CT** $[mm]$	**CG**	**GP [MPa]**
2022[43]	$61 \pm 2,18$	Steel	WC-Co	80	0,8	N_2	3.5
2022[43]	$58,22 \pm 1,93$	Steel	$WC - Ni$	80	0,54	N_2	3.5
2022[43]	$55,22 \pm 2,39$	Steel	$CR_3C_{2-}NiCr$	80	0,6	N_2	3.5
2022[43]	$55,16 \pm 1,83$	Steel	WC-Co-Cr	80	0,52	N_2	3.5
2022[43]	$54.72 \pm 0,71$	Steel	WC-CR_3C_2-Ni	80	0,55	N_2	3.5
2021[44]	53	1045 Steel	NiCr	1	0,3	N_2	4
2020[45]	52.3	Steel SS316	Inconel 0,625	-	8	He	0.3
2022[46]	52.3	Steel SS304L	Steel SS304L	-	2	N_2	5.5
2020[45]	46.1	Steel SS316	CrC-NiCr	-	8	N_2	0.4
2022[47]	43.2	Carbon Steel	$Al_{0.5}CoCrFeNi_2Ti_{0.5}$*	-	-	N_2	5
2020[45]	40.8	Steel SS316	Steel SS316	-	10	He	0.3
2017[48]	32.2	Steel 1020	Ti plus Ti6Al4V	300	2	N_2	4
2011[18]	25.6	IF Steel	SS304	-	1,2	N_2	3
2009 [38]	24.8	Mild Steel	CP-TI	80	-	N_2	1.5

GTS - gun torch speed
CT - coating thickness
CG - carrier gas
GP - gas pressure

*feedstock annealed at 1000 °C

E

VRC and Titomic Setup Parameters

Table E.1: Titomic setup parameters

Parameter	**Value**
Gas Temperature	400 °C
Pressure	0.5 - 0.6 MPa
SoD	5 - 15 mm
Spray Angle	70 - 90 °
Gas	Compressed Air or N_2
Traverse Speed	50 - 100 mm/s

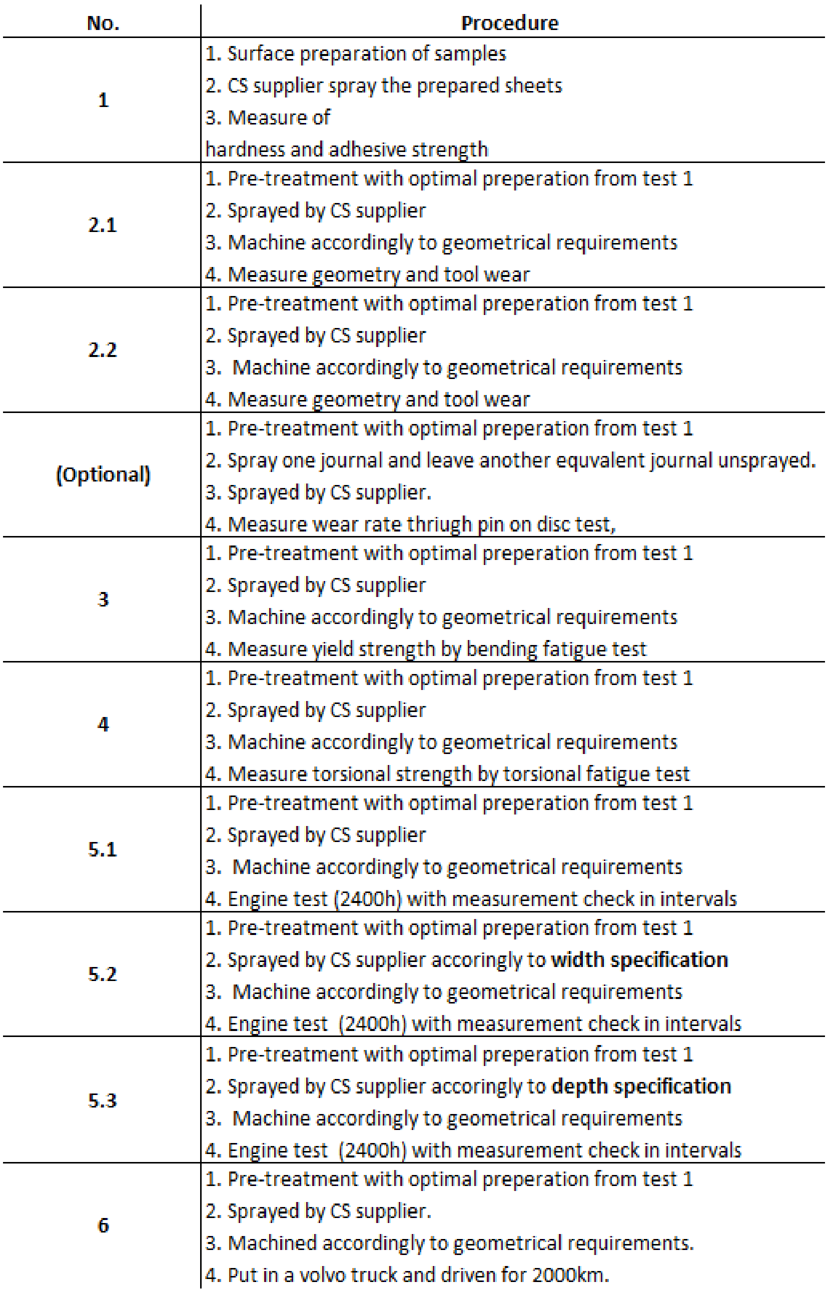
Table E.2: VRC setup parameters

Parameters	**Value**
Gas Temperature	650 - 700 °C
Pressure	5.5 - 6.6 MPa
SoD	10 - 30 mm
Spray Angle	90°
Gas	Compressed Air or N_2
Traverse Speed	100 - 500 mm/s

F

Recommended Test Plan

Table F.1: The procedure for the recommended tests



No.	Procedure
1	1. Surface preparation of samples 2. CS supplier spray the prepared sheets 3. Measure of hardness and adhesive strength
2.1	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier 3. Machine accordingly to geometrical requirements 4. Measure geometry and tool wear
2.2	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier 3. Machine accordingly to geometrical requirements 4. Measure geometry and tool wear
(Optional)	1. Pre-treatment with optimal preperation from test 1 2. Spray one journal and leave another equvalent journal unsprayed. 3. Sprayed by CS supplier. 4. Measure wear rate thriugh pin on disc test,
3	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier 3. Machine accordingly to geometrical requirements 4. Measure yield strength by bending fatigue test
4	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier 3. Machine accordingly to geometrical requirements 4. Measure torsional strength by torsional fatigue test
5.1	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier 3. Machine accordingly to geometrical requirements 4. Engine test (2400h) with measurement check in intervals
5.2	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier accoringly to **width specification** 3. Machine accordingly to geometrical requirements 4. Engine test (2400h) with measurement check in intervals
5.3	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier accoringly to **depth specification** 3. Machine accordingly to geometrical requirements 4. Engine test (2400h) with measurement check in intervals
6	1. Pre-treatment with optimal preperation from test 1 2. Sprayed by CS supplier. 3. Machined accordingly to geometrical requirements. 4. Put in a volvo truck and driven for 2000km.

Table F.2: Detailed description of the recommended tests

No.	Test	Test Speciemens	Specimen Material	Specimen Shape	Surface Preparation	Location	Coat dimension	Purpose	Measure	Quantify
1	Pre-treatment & Hardness/Adhesive strength test	3 pcs Sample with journal properties Crankshafts	C38/C45	Supplier Preference	1. Polished (as journal) 2. Ground 3. Grit-blasted	CS Supplier	Same as sample	Determine pre-treatment with highest adhesion strength within the hardness requirement	Adhesive strength Deposit Hardness	Conclusive adhesive rupture Deposit hardness
2.1	Machinability Test	Crankshaft Journal Main/pin optional	C38/C45	Full dimension	Optimal preparation from Test 1	Reman (Volvo)	Full Journal	Determine the machinability of coating. Determine the tool wear.	Geometrical requirements Tool dressing cycles	Machinability of coating. Tool wear
2.2	Machinability Test	Crankshaft Journal Main/pin optional	C38/C45	Full dimension	Optimal preparation from Test 1	Reman (Volvo)	Part Journal	Determine the simultaneous machinability of coating and substrate. Determine the tool wear.	Geometrical requirements Tool dressing cycles	Simultaneous machinability of coating and substrate. Tool wear
(Optional)	Wear Rate	Crankshaft journal Coat sample	C38/C45 and feedstock	Disc	Optimal preparation from Test 1	Reman (Volvo)	Full specimen	Determine reference wear rate on journal and compare to wear rate of	Wear rate	Wear
3	Bending fatigue test	Crankshaft	C38/C45	Full Dimension	Optimal preparation from Test 1	Reman (Volvo)	Full Journal With/Without Oil hole + Radius	Determine the yield strength	Coat bending strength	Crankshaft durability
4	Torsional fatigue	Crankshaft	C38/C45	Full dimension	Optimal preparation from Test 1	Reman (Volvo)	Full Journal With Oil hole + Radius	Determine the torsional strength	Coat torsional strength	Crankshaft durability
5.1	Engine Durability Test	Crankshaft	C38/C45	Full dimension	Optimal preparation from Test 1	Test Cell (Volvo)	Full Journal With/Without Oil hole + Radius	Determine dimension limits of full journal repair - depth Determine adhesive strength requirement Determine coating wear Determine bearing compatability	Geometrical requirements Bearing geometrical requirement Oil consumption test (min/max clear)	Adhesive rupture/Cohesive rupture Journal wear Bearing wear Oil compatability
5.2	Engine Durability Test	Crankshaft	C38/C45	Full dimension	Optimal preparation from Test 1	Test Cell (Volvo)	Part Journal Vary width	Define depth dimension limits of part reapir material strength. Determine adhesive strength requirement Determine coating wear Determine bearing compatability	Geometrical requirements Bearing geometrical requirement Oil consumption (min/max clear)	Adhesive rupture/Cohesive rupture Journal wear Bearing wear Oil compatability
5.3	Engine Durability Test	Crankshaft	C38/C45	Full dimension	Optimal preparation from Test 1	Test Cell (Volvo)	Part Journal Vary depth	Define width dimension limits of part repair based on: Minimum case depth Determine adhesive strength requirement Determine coating wear Determine bearing compatability Determine oil compatability	Geometrical requirements Bearing geometrical requirement Oil consumption (min/max clear)	Adhesive rupture/Cohesive rupture Journal wear Bearing wear Oil compatability
6	Field Test	Crankshaft	C38/C46	Full dimension	Optimal preparation from Test 1	Field (Volvo)	Full Journal Part Journal	Determine the lifetime of coating	Lifetime distance (km)	Life time

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