

Impact on Cold Spray Repairs

Damage mechanisms of cold spray repairs subjected to low velocity impact

Master Thesis Materials Science and Engineering
Margot van Hecking Colenbrander

Impact on Cold Spray Repairs

Damage mechanisms of cold spray repairs
subjected to low velocity impact

by

Margot van Hecking Colenbrander

Student number: 4679806

Supervisors: John-Alan Pascoe & Vera Popovich
Company supervisor: Marcel van Wonderen
Project Duration: November 2024 - May 2025
Faculty: Mechanical Engineering
Master: Materials Science and Engineering

Preface

This master's thesis report is the final product of my thesis project spanning over the last nine months. Nine months ago, I had never heard of cold spray—it was a completely new concept to me. However, as I dived deeper into the topic, I discovered that it wasn't actually a 'new' technology in the aerospace industry, as I had initially thought. Cold spray has given me great joy and amusement by learning to fully understand the process and develop a very interesting project together with my supervisors. I had the great opportunity to explore the aviation industry at a global Dutch company, KLM. This allowed me to learn more about the engineering and maintenance of aircrafts, logistics around the Schiphol Airport, the integration of new aircraft types and specifically the process of repairing engines. A special thank you to my KLM supervisor Marcel van Wonderen, who showed me every corner of Schiphol-Oost. Due to the great interest of the aerospace industry in cold spray and the enthusiastic/open minded approach of my professor John-Alan, I was able to visit several partners. The collaboration with Airbus gave me the opportunity to visit Airbus at their facility in Toulouse, one of the highlights of my project, an incredible experience! Dr. Vera Popovich, thank you for the opportunity to collaborate with the faculty of Aerospace Engineering during my master thesis, this gave me the opportunity to explore the aviation industry more! Your critical feedback helped me to zoom out and look at my project from a different angle, giving me new perspectives. Special gratitude to my daily supervisor, Dr. ir. John-Alan Pascoe for introducing this topic to me, your continuous excitement, energy, curiosity and valuable feedback every two weeks has helped me greatly! It is very cool to work with someone with such passion for his field.

Furthermore, I want to thank Mary Patrick for the valuable input, spraying session at SAMXL, conversations, suggestions and helping me navigate through this project, no matter what, you were there with a smile on your face! Thank you to the CSAR program for inviting me for your meetings, which gave me valuable insights in the applicability of cold spray into the aviation sector. Additionally, thank you to Alexander Uithol, Dave Ruijtenbeek and Ed Rooesen from the DASML hall at Aerospace Engineering, for helping me with the impact test and coupon preparation, creating a reliable set up and fixing the problems of the tower. You guys are the heart of the testing facility which we as students rely on! From KLM E&M I want to thank, Ralph Lelieveld, Hakim Idrissi, Christiaan de Ruijter, Kim Waringa for your continuous support and excitement at the KLM Laboratory. It was a true pleasure working with you! Tim Bos, thank you for joining me on several cold spray trips, your critical thinking, interesting conversations and suggestions along the way!

A special thank you to my family and friends who have supported me every second along the way of this master thesis but also along some difficult times of the M.Sc. program itself!

Finally, thank you to the Netherlands Research Council (NWO) Open Technology Program for receiving support through the 'CSAR' (grant no: 20434) project, Airbus and Titomic Europe. Without your support this master thesis would not have been possible!

*Margot van Hecking Colenbrander
Delft, May 2025*

Abstract

This report investigates the damage behavior of cold spray repairs subjected to low velocity impact (LVI) loading, with a focus on their potential application for aircraft cowling inlet lip repairs. Cold spray technology is increasingly considered as a promising alternative to traditional thermal spray and Laser-clad technologies due to its ability to significantly reduce repair costs, decrease residual tensile stresses in parts and decrease turn-around time during maintenance and overhaul. Unlike conventional thermal spraying methods, cold spray operates at temperatures below the melting point of the feedstock powder, allowing particles to remain in the solid state throughout the deposition process. As a result, it avoids the formation of heat-affected zones, preserves material properties, and induces favorable compressive residual stresses. These advantages make cold spray particularly suited for both structural and non-structural aerospace repairs. However, insufficient research exists to verify the quality of cold spray repairs on aircraft components to obtain the technology certified.

The primary objective of this research was to identify and characterize the dominant damage mechanisms that occur in cold spray coatings and repairs under LVI conditions. Six types of cold sprayed aluminum alloy coupons were evaluated, including both flat coatings and double curved blend-out repairs and cold spray depositions of AA1XXX and AA2024. The depositions were applied using either a robotic system or a manual gun. All specimens were subjected to controlled impact loading via drop weight and/or quasi static indentation tests. The results were analyzed using high-speed camera imaging, optical microscopy, and scanning electron microscopy of both surface and cross-sectional features.

Key output parameters such as dent depth, dent width, absorbed energy, and crack formation were analyzed and compared across different coupon types and impact energies. Results show that:

- Deposition geometry plays a critical role in how the material deforms under impact.
- The ductility of the deposition and substrate materials (e.g., AA1XXX vs. AA2024) influences both energy absorption and crack resistance for varying impact location.
- Coarse-grit surface preparation enhances bonding and increases resistance to delamination compared to finer surface treatments.
- Barely visible impact damage does not apply to cold spray depositions as a dent is always visible. However, the substrate (non-impact side) showed different crack thresholds and damage mechanisms compared to the cold spray deposition. The substrate cracked more severely compared to the cold spray deposition.
- Manual gun-sprayed depositions exhibit non-uniform properties, leading to variable crack thresholds across the repair area.

To compare performance independently of thickness, the impact data was normalized by the deposition thickness. This revealed that thin coatings (like AA1XXX on top of AA2024) show lower energy absorption per millimeter compared to blend-out repairs.

In conclusion, the study highlights the critical influence of deposition material, geometry, thickness, and surface treatment on the performance of cold spray repairs under impact. It demonstrates key differences between robotic and manual spray systems, particularly in terms of uniformity and damage thresholds. The results show that cold spray depositions are able to withstand low velocity impact and can thus be used to repair dents in cowling inlet lips. The insights contribute to the ongoing research to integrate manual cold spray gun systems into aerospace repairs.

Contents

Preface	i
Abstract	ii
Nomenclature	x
1 Introduction	1
1.1 Engine Cowling inlet lip	2
1.2 Aim of Thesis Project	3
1.3 Structure of Thesis	3
2 State of the Art	4
2.1 Cold Spray	4
2.1.1 Deposition process	5
2.1.2 Bonding mechanism	7
2.1.3 Microstructure and Mechanical behavior of cold spray depositions	8
2.2 Impact Testing	11
2.2.1 Dynamics of impact	12
2.2.2 Quasi static indentation test for low velocity impact	14
2.2.3 Numerical analysis	14
2.3 Conclusion Literature and Research Objectives	15
2.3.1 Research gaps	16
2.3.2 Research objectives	16
2.3.3 Thesis approach	16
3 Materials	18
3.1 Materials	18
3.1.1 Coupon types	18
3.1.2 Impact location	19
3.1.3 Original plan	20
3.2 Material properties	21
3.2.1 Feedstock material	21
3.2.2 Substrate material	21
3.3 Coupon preparation	22
3.3.1 CSHP - Coating	22
3.3.2 MPAir - Coating	22
3.3.3 RepAir - Repair	22
3.3.4 Gun - Repair	23
3.3.5 Cowling - Repair	23
3.3.6 Milling	24
3.3.7 Roughness	24
3.4 Cold Spray Systems	24
4 Method	26
4.1 Impact testing	26
4.1.1 Impact tower	26
4.1.2 Hand-held tower	27
4.1.3 Quasi static indentation	28
4.2 Additional equipment	29
4.2.1 High speed Camera	29
4.2.2 Indenter	29

4.2.3	Clamping system	30
4.3	Data procession	30
4.3.1	Trial and error	30
4.3.2	QSI data analysis	31
4.3.3	Energy absorption - Impact tower	31
4.3.4	Characterization	33
4.4	Flowability	35
5	Results	36
5.1	Deposition bonding	36
5.1.1	AA2024 deposition	36
5.1.2	AA1XXX deposition	37
5.2	Surface analysis	38
5.3	Thresholds	40
5.3.1	Cracks	40
5.3.2	Delamination	51
5.3.3	Barely visible impact damage	55
5.4	Impact behavior: Data-driven perspective	58
5.4.1	Dent width and depth	58
5.4.2	Absorbed energy	60
5.5	Normalization	63
5.5.1	CSHP	63
5.5.2	Coupons 2-5	65
5.6	Flowability	67
5.6.1	Rheometer	67
5.6.2	LDA	67
5.7	Model dent depth	67
5.8	Quasi static indentation test	69
6	Discussion	71
6.1	Deposition	71
6.1.1	Deposition quality cold spray AA2024	71
6.2	Crack threshold	71
6.2.1	CSHP coupons	71
6.2.2	Gun Side indent threshold	71
6.2.3	RepAir Mid indent and Cowling Threshold	72
6.2.4	Substrate vs deposition cracks	73
6.2.5	Type of cracks	73
6.2.6	Delamination	74
6.2.7	Barely visible impact damage	74
6.2.8	Allowable damage limits	75
6.3	Energy Absorption	75
6.3.1	Depth and width	75
6.3.2	MPAir	75
6.3.3	Cowling	76
6.3.4	30J Impact	76
6.4	Dent Behavior	77
6.4.1	Shear plug	77
6.4.2	Second dent	77
6.4.3	Elongation and accumulation	78
6.4.4	Separation Al_2O_3	79
6.5	Flowability	80
6.6	Dent depth model	81
6.7	QSI vs LVI	81
6.8	Experimental Issues	81
6.8.1	Impact tower	82
6.8.2	Coupon preparation	82

7 Conclusion	84
7.1 Research Questions	84
7.2 Additional Findings	85
7.3 Final Remark	86
8 Recommendations	88
References	89
A Appendix	93
A.1 Additional found literature	93
A.1.1 Dendritic microstructure	93
A.1.2 Heat treatment	93
A.2 Compliance test QSI	94
A.3 Flowability	94
A.4 Database results	95
A.4.1 Dent depth model values	96
A.5 Python codes	96
A.5.1 Graphs Absorbed Energy	96
A.5.2 Graphs Threshold	97
A.5.3 Normalized values	97
A.5.4 QSI results	98
A.5.5 Dent depth model - Optimization	100
A.5.6 Johnson-Cook model	101

List of Figures

1.1	Cowling of KLM engine	2
1.2	Cold spraying a cowling	3
2.1	Cold spray deposition process [6]	5
2.2	Particle and gas behavior in the nozzle [4].	6
2.3	AA2024 cold spray particles - 1300x.	7
2.4	Bonding Mechanism. (a) impacting particle, (b) oxide layer breakage due to severe deformation, (c) extrusion of oxide layer, (d) jetting formation [12].	8
2.5	Cold spray deposition grain morphology, a) before impact, b) during impact, c) after multiple impacts [14]	8
2.6	Bonding mechanism of a particle. (a) Stress distribution upon particle impact (b) Strain distribution upon particle impact [15].	9
2.7	Residual stresses upon (a) Single particle deposition, (b) Single deposition layer, (c) Two deposition layers, (d) Three deposition layers, (e) Four deposition layers [15].	9
2.8	2D simulation of Al particles from start to end of impact on AA2024-T3 substrate (a) No surface treatment, (b) fine grit-blasted, (c) medium grit-blasted, (d) coarse grit-blasted [19].	10
2.9	Transparticle and interparticle cracks in different loading directions [23].	11
2.10	Bonding Mechanism. (a) Smooth fracture, (b) Little rough fracture, (c) Rough fracture. Modified from [24].	11
2.11	Low velocity impact (LVI) regions during aircraft operation with aircraft speed [26]. . . .	12
2.12	Free Body Diagram and dynamic free diagram of the impact test.	13
3.1	The six types of coupons.	18
3.2	3D view of coupon types 1-5.	19
3.3	Impact locations RepAir and Gun coupon.	20
3.4	The seven types of specimens	20
3.5	Preparation of coupons MPAir, RepAir and Gun.	23
3.6	Preparation Cowling.	23
4.1	Impact test tower	27
4.2	Set up for impact testing with impact tower	27
4.3	Hand held tower	28
4.4	Quasi Static Indentation test	29
4.5	Indenter types: a) Hand held, b) Indenter 2, c) Indenter 3	30
4.6	Clamping system	30
4.7	Location 1 indenter - high speed camera.	32
4.8	Location 2 indenter - high speed camera.	32
4.9	Radial and Tangential cracks	35
5.1	Bonding quality, a) CSHP - 168x, b) CSMP - 168x	37
5.2	Bonding quality, a) CSHP - 336x, b) CSMP - 336x	37
5.3	Bonding quality, a) MPAir - 168x, b) RepAir - 168x, c) Gun - 168x	37
5.4	Bonding quality, d)MPAair - 336x, e) RepAir - 336x , f) Gun - 336x	38
5.5	Surface morphology of disrupted particle-particle interface of MPAir coupon (157J), a) 700x, b) 800x	38
5.6	Surface morphology CSHP, a) natural - 200x, b) milled, 200x	39
5.7	Surface morphology AA1XXX, a) natural - 120x, b) milled - 200x	39
5.8	Surface morphology: a) CSMP - 120x, b) substrate AA2024 - 200x	39

5.9	Cross section RepAir bond - 700x	40
5.10	LVI impact dents per impact joule - 30x	41
5.11	QSI impact dents per impact joule - 30x	41
5.12	Cracks in LVI coupons - 200x	42
5.13	Surface of coupons 33x SEM a) MPAir, b) RepAir Mid, c) RepAir Side, d) Gun Mid, e) Gun Side, f) Cowling	43
5.14	MPAir coupons after impact - 30x	44
5.15	MPAir coupons after impact SEM - 200x	44
5.16	Regions in dent - 20x	45
5.17	RepAir Mid coupons after impact - 30x	45
5.18	RepAir Mid coupons after impact - 200x	46
5.19	RepAir Side coupons after impact - 30x	46
5.20	RepAir Side coupons after impact - 200x	47
5.21	Gun Mid coupons after impact - 30x	47
5.22	Gun Mid coupons after impact - 200x	48
5.23	Gun Side coupons after impact - 30x	48
5.24	Gun Side coupons after impact - 200x	49
5.25	Cowling coupons after impact - 30x	49
5.26	Cowling coupons after impact - 200x	50
5.27	Crack Threshold	50
5.28	Crack in deposition a) Transparticle crack CSHP - LVI 4J coupon - 200x, b) Transparticle crack in MPAir 140J - 950x	51
5.29	Delamination deposition in CSHP 4J (LVI) - 100x	51
5.30	Delamination in MPAir coupons - 30x	52
5.31	Delamination in MPAir coupons a) 140J impact, b) 125J impact - 168x	52
5.32	RepAir Mid and Side cross section - 30x	52
5.33	Delamination in Gun Mid coupon - 30x	53
5.34	Delamination in Gun Mid coupon - 168x	53
5.35	Delamination in Gun Side coupon - 30x	53
5.36	Delamination in Gun Side coupon - 168x	54
5.37	Delamination Threshold	54
5.38	Delamination within deposition - 30x	55
5.39	Four-split crack in the back of substrate MPAir 140J	56
5.40	Visible crack and back crack threshold	57
5.41	Shear plug failure angle - 30x	57
5.42	CSHP coupons: Impact energy vs a) Dent depth, b) Dent width	59
5.43	Coupons 2-5: Impact energy vs a) Dent depth, b) Dent width	60
5.44	CSHP coupons: Impact energy vs a) absorbed energy, b) percentage absorbed energy	61
5.45	2-5 coupons: Impact energy vs a) absorbed energy, b) percentage absorbed energy	62
5.46	Impact energy vs velocity before impact per coupon	63
5.47	Normalized (over thickness) graphs CSHP a) Dent depth, b) Dent width, c) Absorbed Energy, d) Percentage Absorbed Energy.	64
5.48	Normalized (over thickness) graphs coupons 2-5 a) Dent depth, b) Dent width, c) Absorbed Energy, d) Percentage Absorbed Energy.	66
5.49	Depth prediction vs measured depth CSHP	68
5.50	Depth prediction vs measured depth a) MPAir, b) RepAir mid indent	68
5.51	Depth prediction vs measured depth c) RepAir side indent, b) Gun mid indent	68
5.52	Depth prediction vs measured depth a) Gun side indent, b) Cowling	68
5.53	Coupon 1 Force Deflection curve	69
5.54	Coupon 1 Force Deflection curve - peak value	70
6.1	Deposition geometry after milling a) Gun sprayed (AX), b) Robotic sprayed (Titomic)	72
6.2	Different locations of cracks a) RepAir Mid coupon - 100x, b) RepAir Side coupon - 100x	73
6.3	Two dents after impact - 30x	78
6.4	Elongation and Accumulation - 30x	79

6.5	Accumulation in MPAAir coupons, a) original deposition thickness -30x , b) thickness after impact -30x	79
6.6	Segregation lines of Al_2O_3 and AA1XXX particles 30x	80
7.1	Robotic vs Manual gun cold spray	87
A.1	Compressibility results	94
A.2	Flowability results	94

List of Tables

3.1	Material properties [40, 41, 43, 19]	22
3.2	Surface roughness values R_a and R_z	24
3.3	Parameters per cold spray system	25
4.1	Coupon impact specifics	31
4.2	Coupon thickness	33
5.1	Particle size	38
5.2	Back cracking coupons	58
5.3	Rheometer Analysis	67
5.4	LDA Analysis	67
5.5	Particle size	67
5.6	Fitting parameter k	69
7.1	Crack threshold	84
7.2	Delamination threshold	85
7.3	Damage threshold	85
A.1	Compliance values for QSI test	94
A.2	Compressibility measurement	94
A.3	Flowability measurement	95
A.4	LDA measurement	95
A.5	Database testing	95
A.6	Dent depth values predicted and measured	96

Nomenclature

Abbreviations

Abbreviation	Definition
AA	Aluminium alloy
Al_2O_3	Aluminium oxide
AM	Additive manufacturing
ASB	Adiabatic shear band
ASI	Adiabatic shear instability
BFE	Basic flowability energy
BSE	Back scatter electron
BVID	Barely visible impact damage
CSHP	Cold spray high pressure
CSMP	Cold spray medium pressure
FRI	Flow rate index
FOD	Foreign object damage
HAZ	Heat affected zone
LDA	Laser diffraction analysis
LVI	Low velocity impact
M	Mach number
NDT	Non destructive technology
OEM	Original equipment manufacturer
OM	Optical microscopy
QSI	Quasi static indentation
SED	Secondary electron
SEM	Scanning electron microscopy
Ti	Titanium

Symbols

Symbol	Definition	Unit
C	Compliance	[mm/N]
δ	Deflection of coupon	[mm]
$\dot{\epsilon}^*$	plastic effective strain rate normalized to reference strain rate	[1/s]
E	Energy	[J]
E_k	Kinetic energy	[J]
$E_{k_{in}}$	Kinetic energy of indenter before impact	[J]
$E_{k_{out}}$	Kinetic energy of indenter after impact	[J]
$E_{k_{absorbed}}$	Kinetic energy absorbed	[J]
$E_{k_{abs}}$	Kinetic energy absorbed	[J]
F	Force applied	[N]
g	gravitational acceleration	[m/s ²]
h	height	[m]
k	stiffness	[N/mm]
m	mass	[kg]

Symbol	Definition	Unit
π	Pi	
r	radius	[mm]
R_a, R_z	Surface Roughness	[μm]
s_1, s_2	Distance at two position	[m]
σ_y	Yield strength	[MPa]
t_1, t_2	Time at two points	[s]
t	Thickness	[mm]
T_{melt}	Melting temperature	[$^{\circ}C$]
T_{room}	Room temperature	[$^{\circ}C$]
v	Velocity	[m/s]
v_{in}	Velocity of indenter before impact	[m/s]
v_{out}	Velocity of indenter after impact	[m/s]
w	dent depth	[mm]

1

Introduction

In the aerospace sector, the substantial costs associated with replacing damaged components have caused continuous research into advanced repair methodologies. One increasingly attractive solution is additive manufacturing (AM), which facilitates reconstruction of material layers following the removal of damaged sections, effectively restoring components to their original geometry and the ability to create new parts from scratch. Cold spray technology is an additive manufacturing technology which has received more and more attention the last few years, due to its promising use as a repair method. Cold spray utilizes high-velocity powder particle acceleration to deposit materials onto a substrate at supersonic speeds. The supersonic deposition results in bonding between the powder particles and the substrate, allowing for successive layering to rebuild damaged areas. Unlike conventional thermal spray processes, cold spray operates below the melting temperature of the feedstock material. As the particles remain in the solid state during deposition, little to no heat-affected zones are formed and residual tensile stresses are reduced. This helps to preserve the material's original mechanical properties and minimizes oxidation, thermal distortion, and residual tensile stress.

Another advantage of cold spray over traditional thermal spraying is that cold spray enables the formation of dense depositions of several millimeters thick. The resulting material properties of the deposition are largely influenced by the spraying parameters, such as gas temperature and pressure, stand-off distance, and surface preparation. Factors like surface roughness and the presence of a passive oxide layer play a critical role in determining the adhesion strength of the deposition [1].

To certify a new repair technology like cold spray, a lot of research is required to ensure the quality of the repair. Due to the little existing research on the mechanical properties of cold spray depositions, the technology has not been fully certified. Small repairs on main landing gear brackets have been approved and performed as repairs but this does not give the approval for repairs on other components. The lack of knowledge on the properties of cold spray repairs is a bottleneck towards proving the quality of cold spray repairs and obtain certification from Original Equipment Manufacturers (OEMs) for large-scale repairs. Extensive research is required to understand cold spray behavior including:

- Mechanical properties: The impacting particles generate a high degree of plastic deformation, which influences the microstructure and mechanical properties of the material.
- Adhesion and bonding: Understanding the dominant bonding mechanism between the substrate and particles and particle-particle bonding.
- Loading: Predicting the behavior of cold spray repairs for different types of loading which an aircraft is subjected to.
- Process control: The cold spray is highly sensitive to changes in process parameters and requires extensive research for every material [2].

New interest from the aerospace sector is shown in cold spray by industry leaders such as, General Electric, Airbus and Pratt & Whitney, with the goal to get the repairs certified. Airlines conducting their own maintenance, such as KLM, stand to gain substantial advantages from adopting and allowing cold

spray repairs. By repairing components such as engine cowling inlet lips, rather than replacing them, airlines can considerably reduce costs, extend component life, and promote more sustainable use of materials. For example, a new cowling inlet lip for a GenX engine costs €500.000. Versatility and the ability to address a wide range of damage—from minor pitting to significant wear—are essential in the highly regulated aerospace industry, where even small material loss can disapprove components for service. Cold spray technology offers the essential capabilities and therefore presents a promising solution for repairing damage, such as that found on cowling inlet lips. Furthermore, the operational convenience of portable cold spray equipment significantly enhances its practical value. These devices allow for rapid, on-site repairs, substantially reducing aircraft downtime from typically two days required for component replacement to approximately two hours. Instead of disassembling and transporting damaged parts to hangars, mobile cold spray machines enable efficient, localized repairs within hours, optimizing resource utilization and operational efficiency [3].

1.1. Engine Cowling inlet lip

Through a step-by-step approach, this research aims to investigate the repair of the cowling inlet lips, illustrated in Figure 1.1, using cold spray technology and assess its effectiveness as a viable repair technology. Damage to engine cowlings, such as that caused by impacts from foreign objects like small stones or gravel, serves as a practical case study for evaluating the potential of cold spray as an effective repair solution. Impacts typically cause localized plastic deformation, creating dents in aluminium cowling inlet lips. Such surface irregularities can disrupt airflow over the cowling inlet lip, potentially damaging the engine and its performance and causing further operational problems. Since cowling inlet lips are not primary structural components, their repair requirements are less complex, making cold spray a particularly suitable solution in these early stages of the development of the process. The traditional cowling inlet lip repair method involves removing and replacing damaged sections with precision cut pieces of new or spare cowlings inlet lips, a time-consuming and costly process that requires extensive equipment and aircraft downtime. In contrast, portable cold spray equipment allows for precise, efficient, and localized repairs which can be produced while the aircraft is at the gate. By eliminating the need to remove and transport cowling inlet lips, cold spray significantly reduces downtime, costs, and logistical complexity associated with traditional repair methods.



Figure 1.1: Cowling of KLM engine

1.2. Aim of Thesis Project

To advance the approval process for cold spray repairs in the aviation industry, it is essential to conduct research on the behavior of cold spray repairs under operational conditions. When repairing dents caused by impact, it must be considered that the repaired area may be subjected to another impact and is damaged. Currently, no knowledge exists regarding the behavior of cold spray repairs under impact loading, forming the basis for this research. Key questions arise: What happens to a cold spray repair when it is impacted again? Does it compromise the integrity of the cowling inlet lip? Or, more critically, could the repair detach entirely and pose a risk to the engine? The damage mechanisms occurring play a critical factor in assessing the behavior of the cold spray and thus the reliability of the repair method. Additionally, there is a lack of knowledge regarding the quality differences between repairs applied by robotic systems and those applied manually. Therefore, this research also includes a comparison of the damage mechanisms observed in cold spray repairs produced by robotic spraying versus manual spraying.

This master thesis project is the final part of the Master program *Materials Science and Engineering* from the *TU Delft*. The main focus of this thesis was to understand the dominant damage mechanisms in cold spray repairs which are subjected to low velocity impact. The research of this master thesis was done in collaboration with the Faculty of Aerospace Engineering, TU Delft, KLM Engineering and Maintenance, Airbus and Titomic Europe.

1.3. Structure of Thesis

This thesis is organized into seven chapters following the standard academic reporting structure. Chapter 2 provides an extensive review of existing literature and the current state-of-the-art on damage mechanisms in cold spray repairs due to impact. The chapter identifies critical research gaps, laying the foundation for the research objectives of this thesis. Chapters 3 and 4 explain the experimental approach, including the materials selected, the test setups used, and the analytical methods used for data evaluation. Chapter 5 presents the experimental results obtained, which are critically analyzed and discussed in Chapter 6. Finally, Chapter 7 summarizes and concludes the research findings, explicitly addressing the initial research objectives based on the insights gained from the results and discussion. Following the conclusions, recommendations for research directions related to damage mechanisms in cold spray repairs are proposed in Chapter 8.

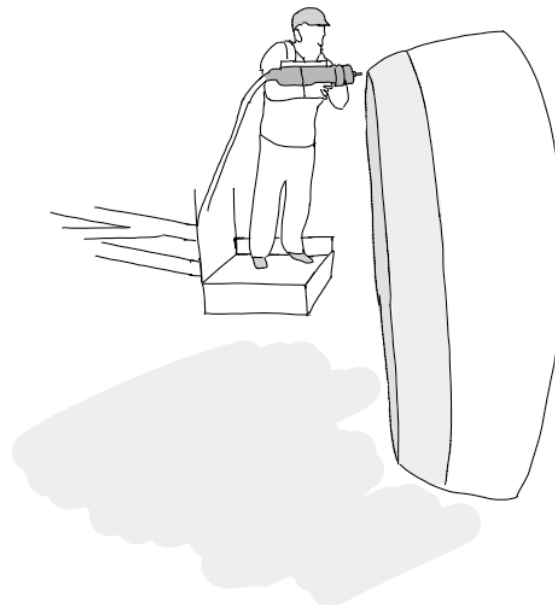


Figure 1.2: Cold spraying a cowling

2

State of the Art

This section outlines the current state-of-the-art of the academic work done on cold spray, this in order to prepare for the experimental work done during this thesis. The section starts with the fundamental principles of cold spray and its advantages over traditional thermal spraying. Secondly, the bonding mechanism of the powder particles with the substrate is discussed, along with the microstructure and mechanical behavior of cold spray upon loading. Impact testing will be discussed after, followed by two methods which try to predict cold spray behavior. Lastly, the main conclusions from the found literature are presented, leading to the research gaps and research objects for thesis. A short outline of the thesis approach is also given.

2.1. Cold Spray

Cold spray deposition is an additive manufacturing technology that is categorized as a thermal spraying process, in which a gas jet accelerates the powder particles to a supersonic speed. At high enough velocities, the powder particles plastically deform and bond with the substrate as they impact the substrate. Reaching the critical velocity is of importance, as particles at lower velocities will bounce off from the substrate and no bonding will take place. With excessively high velocities, the particles erode the substrate rather than bond to it [4].

Compared to other thermal spraying processes, cold spray differs because it is driven by kinetic energy. Traditional thermal spraying processes, like plasma spray and high velocity oxy-fuel (HVOF) are electric and chemical driven, respectively (thermal energy). During the kinetic process of cold spray, the powder particles are kept in the solid state, since the melting temperature will not be reached, preventing microstructural changes due to melting. The bonding of the particles and the substrate (and between particles) is achieved by severe plastic deformation of the powder particles. Cold spray can deposit different materials such as metals, ceramics or polymers, but is limited to depositing ductile materials because the powder particles need to be able to deform plastically to bond with the substrate. Aluminum alloys such as, AA2024, AA6061, and AA7075 are among the most extensively researched materials for cold spray applications, particularly in the aerospace sector. These alloys are commonly used in structural and non-structural aircraft components due to their favorable combination of mechanical properties and corrosion resistance. AA2024, AA6061, and AA7075 are suitable for load-bearing structures and AA6061 and AA7075 have moderate resistance against corrosion. In addition to metallic alloys, cold spray has also been applied to materials reinforced with carbides or oxides, extending its utility to more wear- and heat-resistant coatings. Ceramic materials such as CoCrAlY, often used as thermal barrier coatings in engines, and more brittle compounds like titanium dioxide (TiO_2) have also been successfully investigated for cold spray deposition [1].

Cold spray has advantages over traditional thermal spraying processes such as:

- The temperature remains below melting temperature of the powder particles. Thus the material entering the cold spray machine (almost) equals the material that comes out of the machine, keeping the material in solid state.

- The microstructure of the powder particles is enhanced due to the severe plastic deformation upon impact of the powder particles on the substrate. The plastic deformation induces work hardening and dynamic and static recrystallization, causing grain refinement and enhancing mechanical properties.
- No (or very little) heat affected zones (HAZ)s are created in the deposition.
- At the same time, compressive residual stresses are induced due to the severe plastic deformation, improving the mechanical properties.
- Minimal to no oxidation occurs on the sprayed particles as the temperature is kept relatively low compared to traditional thermal spraying.
- Thicker depositions with higher bond strength can be produced due to lower tensile residual stresses induced by the process.
- Lower porosity, cold spray can reduce the porosity to below 1%. Traditional thermal spraying has a porosity around 5% [1].

From an operational point of view, cold spray has some more advantages over thermal spraying:

- No combustion fuels are needed.
- The spray pattern of the nozzle is small, requiring less to none masking of the sprayed part.
- The cold spray can also be used as an additive manufacturing method in which free-standing forms are built up or repaired from scratch.
- Cold spray machines exist in portable configurations, allowing the operator to take the repair method to the aircraft, reducing the time an aircraft is out of operation [1, 4].

2.1.1. Deposition process

In the deposition process of cold spray, powder particles ranging from 5 to 100 μm are accelerated to supersonic velocities ($> 1500\text{m/s}$) through compressed air, helium or nitrogen. The compressed gas is injected into two separate tanks, the gas heat tank, the gas running through is called the process gas and the powder feedstock tank in which the gas is called the carrier gas, see Figure 2.1. Both gas streams, the process and carrier gas come together in the nozzle. The powder particles are heated by the process gas, inducing thermal softening, but stay below melting temperature. The nozzle has a converging section, in which sonic velocity is reached due to the reduction in cross-section area and a diverging section, in which supersonic speed is reached due to the cross-section expansion, pressure change and heated gas stream. The supersonic speed is required to get to the critical velocity v_c ; the particle velocity needed to ensure bonding. If the velocity stays below the v_c no adhesion will take place, the particles bounce off the substrate. Velocities surpassing v_c will also not result in bonding, the particles will erode the substrate if $v \gg v_c$. The powder particles reach the supersonic velocity of 1500 m/s at the end of the nozzle and the particles are bombarded onto a substrate, around 10 - 50 mm away from the nozzle tip [5]. However the exact velocity at the tip of the nozzle depends on several process parameters and the pressure system.

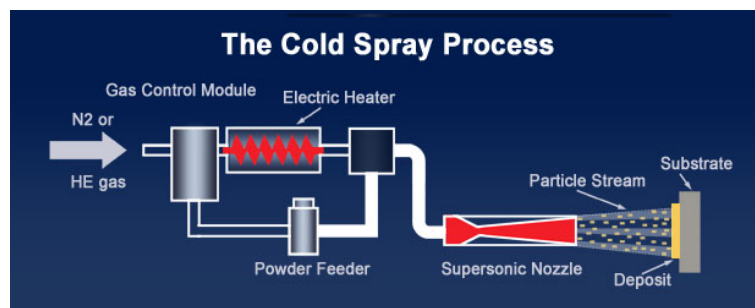


Figure 2.1: Cold spray deposition process [6]

Nozzle

The nozzle is the most critical component in the cold spray system. The nozzle provides the required kinetic and thermal energy necessary for the powder particles to bond with the substrate. The critical velocity, v_c must be reached within the nozzle to achieve bonding. The nozzle is divided into three regions in which the gas is accelerated from subsonic to supersonic velocity, classified by the Mach number [7]:

- Converging section: the gas is accelerated from subsonic to near sonic ($M < 1$).
- The throat: the smallest cross-sectional area in which the flow gets to sonic conditions ($M = 1$).
- Second diverging region: gas flow reaches supersonic speed ($M > 1$).

Following the principle of thermodynamics and fluid dynamics:

$$PV = nRT \quad (2.1)$$

The reduction in cross-sectional area and the drop in pressure in the converging section cause an increase in velocity as the mass flow remains constant. In the diverging section, the air can expand again due to the increase in cross-sectional area. The pressure and density drop, further accelerating the powder stream to supersonic velocity [4]. Figure 2.2 shows the effect of changing nozzle geometry on the velocity and temperature of the gas and particle stream.

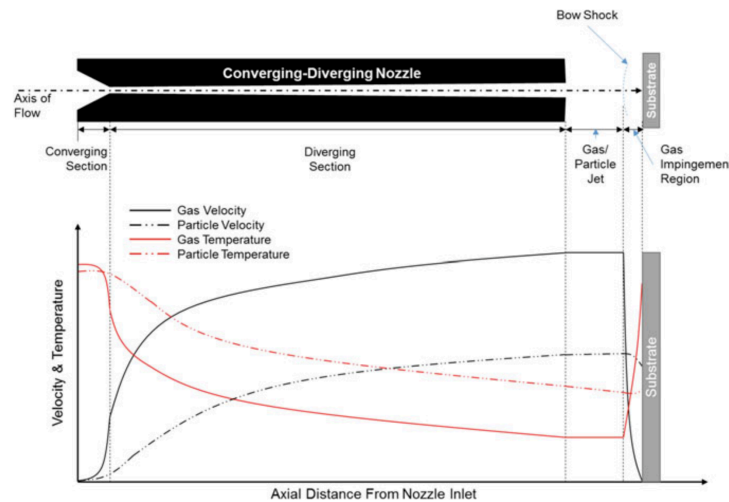


Figure 2.2: Particle and gas behavior in the nozzle [4].

The spray angle, the standoff distance and nozzle traverse speed affect the porosity and deposition efficiency of the process. Too high values will result in non-uniform deposition and thus porosity, as lower values decrease the mechanical properties of the deposition. The most used spray angle found in literature is 90 degrees, which minimizes porosity and transfers the highest amount of momentum and thermal energy [8].

Powder properties

The size, geometry and mechanical properties of the feedstock powder plays an important role on the deposition quality and the tuning of the process parameters. In general, larger particles reduce the critical velocity, but excessively large particles may not reach the critical velocity because they can not be accelerated enough. However, as stated by Champagne, particles that are too small *'do not have enough momentum to penetrate through the gas stagnation zone that is created between the nozzle and substrate due to the impingement of the supersonic jet ahead of the substrate'* [1]. Small particles do accelerate easier and undergo more plastic deformation, enhancing bonding with the substrate. Smaller particles also reduce the distance between the particles themselves, decreasing the porosity. The optimal particle size is between 20 and 60 μm [9]. A non-uniform particle size distribution could

result in thickness differences of the deposition, causing differences in the mechanical properties of the deposition. The non-uniform distribution also influences the flowability of the powder, causing problems within the nozzle. The particle shape has an influence on the drag forces acting on the particle. Less spherical particles achieve higher velocities compared to perfectly spherical particles. However, non-spherical particles tend to stick together, resulting in agglomerates which are more difficult to deposit. Non-spherical particles also have a higher surface area, increasing the oxide content [1]. Several AA2024 powder particles are visualized the Figure 2.3 below, taken by the author during this research.

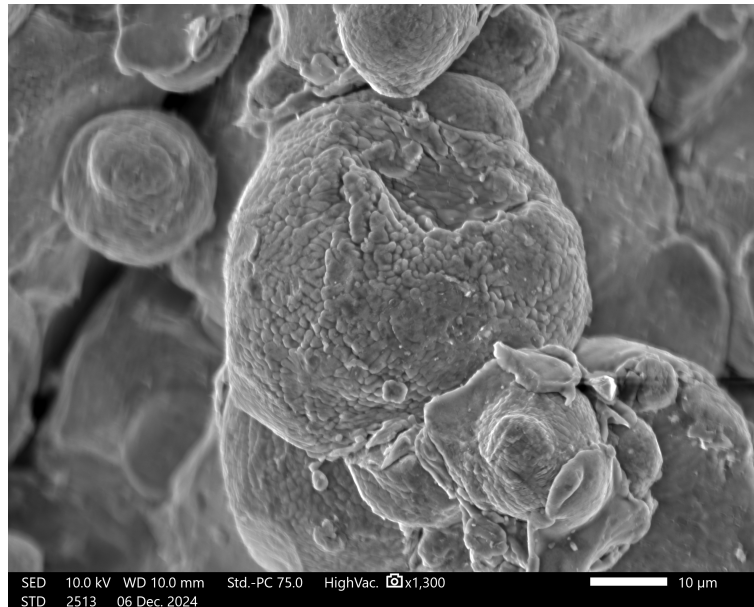


Figure 2.3: AA2024 cold spray particles - 1300x.

2.1.2. Bonding mechanism

The bonding mechanism of cold spray makes the technology unique compared to other thermal spraying techniques. By understanding the bonding mechanism of the deposition with the substrate, the behavior of the cold spray can be further understood and optimized. However, it is still unclear which bonding mechanism is dominant in cold spray. Three main phenomena seen in the bonding are metallurgic bonding, mechanical interlocking, and adiabatic shear instability. For bonding to occur between metals, the oxide layer on the substrate must be broken. Oxide layers grow on the metal substrate and powder particles as soon as the metal is exposed to air. To remove the severity of the oxide layer, the substrate should be roughened right before deposition. However, milliseconds after the surface is grit-blasted, a thin oxide layer is formed. This thin oxide layer must be broken before bonding can occur. The supersonic impact of the particles on the substrate ruptures the thin oxide layer, allowing for clear contact between the surfaces, which is the basis for metallurgic bonding, this can be seen in Figure 2.4. As particles impact the substrate, they plastically deform, inducing shear stresses and localized heating, setting the right conditions for metallurgic bonding. Mechanical interlocking can be enhanced by pre-roughening the substrate surface, creating peaks and valleys which help the powder particles to interlock and bond [4].

The adiabatic shear instability (ASI) theory explains the occurrence of the localized heating for the bonding. As the powder particles plastically deform upon impact, the temperature rises locally, disrupting the oxide layer and enabling a clear contact between the particles and deposition (jetting). The heat generated also softens the material, promoting the movement of dislocations and releasing stresses. As the strain rate exceeds $10^4 s^{-1}$, the thermal softening increases and adiabatic shear instability is reached. After another layer of particles are impacted, the heat increases further and the viscous flow eliminates the stresses, creating perfect conditions for high-quality bonding [10]. Moreover, the rapid cooling at the interface leads to a finer microstructure in collaboration with recrystallization of the interface. The orientation difference of the ultra-fine grains causes bridging connections between local contact points. The connections result in interlocking recrystallized grains, which promotes the bonding

of the particles [11].

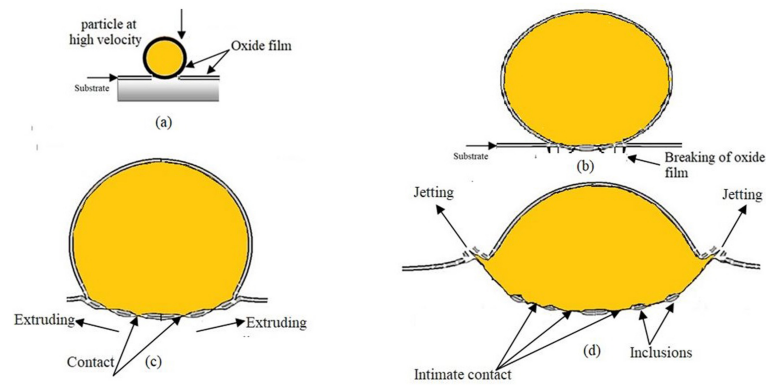


Figure 2.4: Bonding Mechanism. (a) impacting particle, (b) oxide layer breakage due to severe deformation, (c) extrusion of oxide layer, (d) jetting formation [12].

2.1.3. Microstructure and Mechanical behavior of cold spray depositions

Cold spray depositions produce a tight multi-layer structure of flat particles with a characteristic microstructure, see Figure 2.5. The grains are elongated due to the adiabatic shear instability and exhibit a random crystallographic structure, inherent to a large amount of plastic deformation and dislocation movement. The elevated temperatures of the adiabatic shear instability drive recrystallization, rearranging the large number of dislocations into a tight network. This lowers the energy stored in the grains and further refines the grains. The grain refinement due to plastic deformation and recrystallization is a key factor in enhancing the mechanical properties of the cold spray deposition [13].

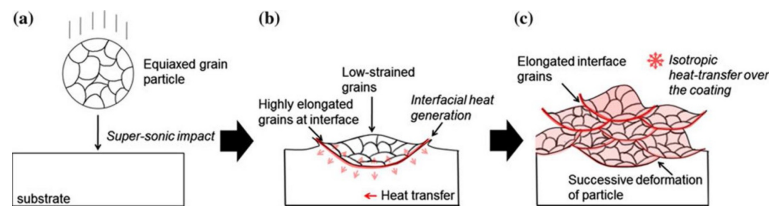


Figure 2.5: Cold spray deposition grain morphology, a) before impact, b) during impact, c) after multiple impacts [14]

Residual stresses

Residual stresses are formed in cold spray deposition due to the large amount of plastic deformation, affecting the quality of cold spray deposition. The residual stresses are dependent on the strain due to the impact and thermal or hardness mismatch between the substrate and deposition. Upon impact of one particle, tensile stresses are formed around the interface between the substrate and particle, as compressive stresses are present in the upper part of the particle. The plastic deformation of the particle is the highest around the interface, as the bonding mechanism takes place over there. The Lagrangian-Euler method can be used to model cold spray deposition and analyse the stresses arising after deposition. As can be seen in Figure 2.6, σ_x is primarily compressive and changes into tensile throughout the depth of the depositions. The tensile stresses are highly concentrated in the middle section of the deposition near the interface and around the upper edges of the interface. Plastic deformation takes place most severely around the edges, resulting in high effective strain. The compressive strains are thus most present in the interface region as tensile strains are present near the top of the particle.

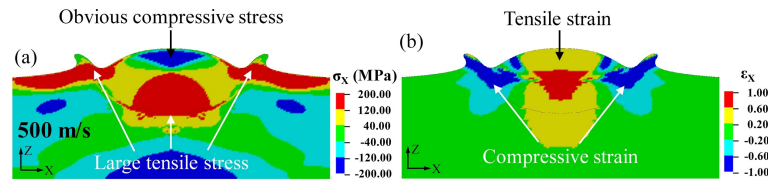


Figure 2.6: Bonding mechanism of a particle. (a) Stress distribution upon particle impact (b) Strain distribution upon particle impact [15].

As a new layer of particles impact the previous deposited particles, the stress distribution changes slightly. The layers which are deposited first will have the most plastic deformation as multiple layers of particles impact upon them. The change in residual stresses due to a new layer of particle deposition is seen in Figure 2.7. The tensile stresses (red) increase around the interface as a new layer is deposited, however the overall residual stresses decrease as more plastic deformation occurs by adding a new layer. The plastic deformation causes surface expansion, transforming tensile stresses into compressive stresses (blue), enhancing the micro hardness of the overall deposition [13, 15].

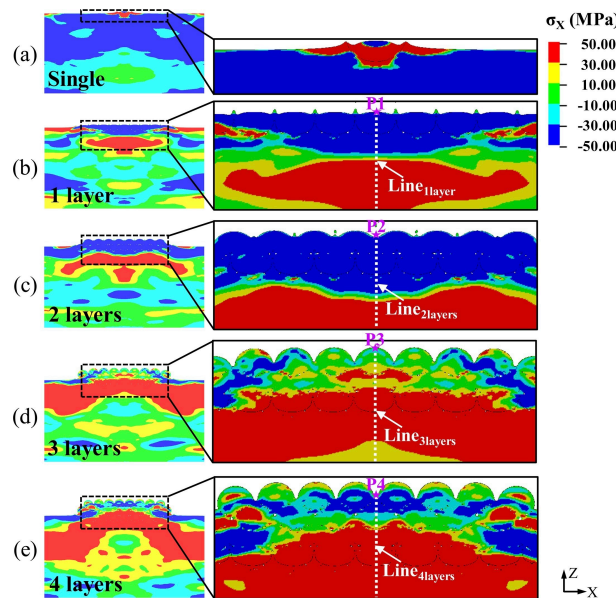


Figure 2.7: Residual stresses upon (a) Single particle deposition, (b) Single deposition layer, (c) Two deposition layers, (d) Three deposition layers, (e) Four deposition layers [15].

Mechanical properties

The adhesion strength for cold spray deposition is increased with increasing deposition thickness. However, there is a limit to this, as thickness' exceed 4.3mm, for Ti-64 for example, the adhesion strength decreases. This is caused by stress reliefs around the substrate-deposition interface, which loosens the mechanical bonding of the particles with the substrate [16].

The morphology of the deposition-substrate interface significantly influences particle bonding during cold spray deposition. Specifically, increased substrate roughness enhances the available contact area, facilitating particle interlocking and promoting stronger bonds. Ziemian et al. [17] demonstrated that fatigue strength is highly dependent on substrate surface preparation methods and cold spray parameters. Their findings revealed that substrate treatments such as grit-blasting or shot peening could enhance the fatigue life of aluminum specimens up to 50%. Sharma et al. [18] investigated the effects of different surface preparation techniques, comparing glass bead blasting with silicon carbide (SiC) and alumina grit-blasting. Their study concluded that glass bead blasting provided the best coating characteristics, achieving the highest performance in bend and pull tests as well as improved tensile strength [18]. Blochet et al. [19] examined how interface morphology influences the bond strength in aircraft

repairs. Their research indicated that grit-blasting, which creates surface craters, enhances particle anchoring and results in increased particle deformation upon impact. Additionally, they observed that the severity of the grit-blasting significantly affects bonding quality; fine grit-blasting creates smaller surface features, which are easily removed by larger impacting particles, reducing effective contact area and thus weakening deposition adhesion [19]. The different pre-treatments and corresponding amount plastic deformation found in the research is shown in Figure 2.8.

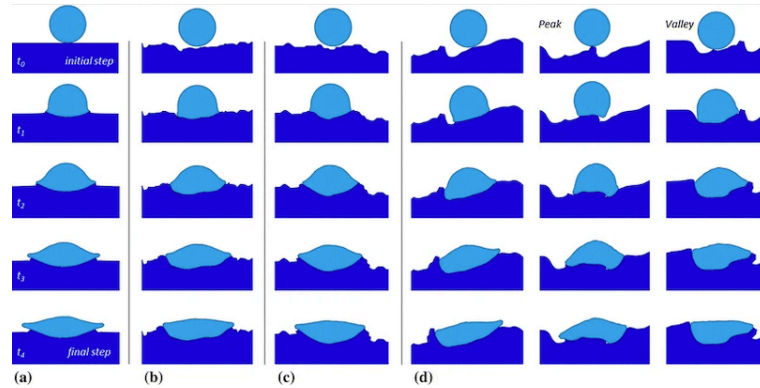


Figure 2.8: 2D simulation of Al particles from start to end of impact on AA2024-T3 substrate (a) No surface treatment, (b) fine grit-blasted, (c) medium grit-blasted, (d) coarse grit-blasted [19].

Damage formation

Damage mechanisms in cold spray depositions have been investigated under mechanical loading. In particular, research has focused on understanding the differences between ductile and brittle feedstock powders as deposition material. Ductile materials mainly fail due to shear stress components, having a network of cracks. Brittle materials show delamination as primary failure mode. Morrison et al. [20] investigated the fatigue performance of a repair made with AA6061 cold spray. A typical (metal) fatigue crack growth behavior was observed with striations. The crack initiated at a notch, propagated through the cold spray deposition and split at the end of the deposition, separating the deposition from the substrate, causing delamination [20]. The fatigue performance of the deposition is strongly influenced by the defects in the deposition layers. Defects act as stress concentration areas in which crack initiation and propagation is more likely to happen. The effect of the ductility on the crack growth was investigated by Kovarik et al. [21]. Brittle materials were found to fail by forming one large crack, while ductile materials exhibit a network of cracks in the highly deformed zones due to loading stresses [21].

Delamination upon bending researched by Bond et al. [22] found that delamination between the substrate and deposition occurred before the main crack, reached the interface. Using digital image correlation, it could be seen that the main crack and delamination grew simultaneously and that at some point the main crack started to propagate in the 45° direction towards the interface. The crack fracture was mainly transparticle, with little interparticle cracking.

Conflicting findings have been found regarding the fracture behavior of cold spray, as both isotropic and anisotropic behavior is reported. Anisotropic behavior is seen due to the flattened particles creating an inhomogeneous microstructure and thus differing mechanical properties in different loading directions. Varying cracks paths are seen for in-plane and out-of-plane loading using scanning electron microscopy (SEM). In-plane loading shows cleavage-like fracture, indicating interparticle fracture as dominant failure mode, while perpendicular loading shows transparticle cracks, visualized in Figure 2.9.

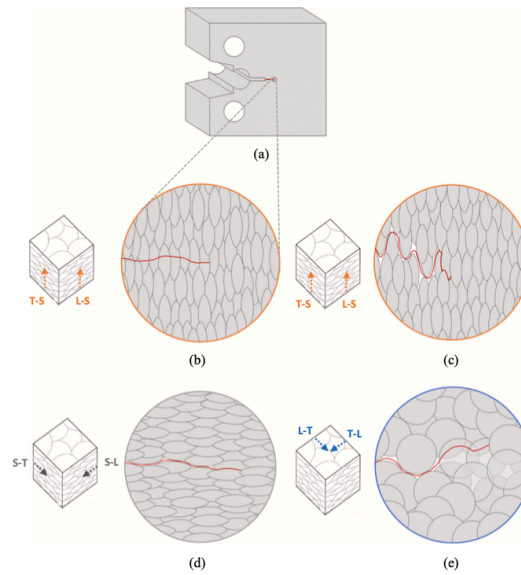


Figure 2.9: Transparticle and interparticle cracks in different loading directions [23].

Transparticle cracks have a higher energy threshold and thus fracture toughness, as more energy is needed to fracture a particle compared to fracturing an interparticle bond. Interparticle cracking requires less fracture energy, but follows a longer crack path, occurring mainly in shear mode failure. The longer crack path increases the fracture toughness of the interparticle fracture, resulting in a nearly equivalent value as for the transparticle fracture toughness. The key factors which determine the type of crack at particle level are the fracture mode, fracture energy and the crack length. The interaction between these three determines which fracture mode is energetically more favorable [23]. Interparticle fracture (brittle) is characterized by a smooth fracture surface with nano-size dimples on the fracture surface, corresponding to some degree of ductility. As transparticle fracture (ductile) has a rougher surface. Figure 2.10 shows the transformation of the smooth interparticle fracture surface to the rough transparticle fracture surface [22, 24].

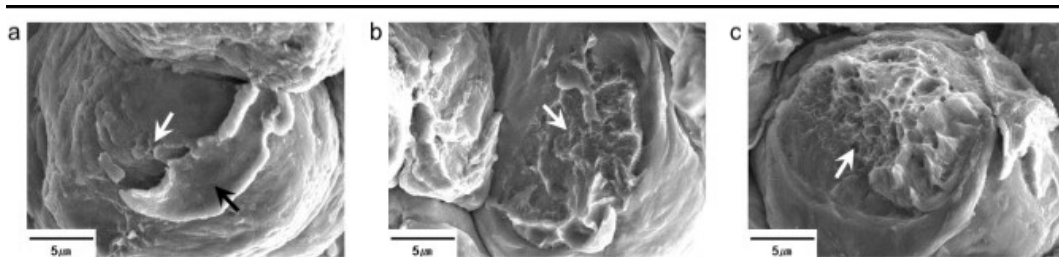


Figure 2.10: Bonding Mechanism. (a) Smooth fracture, (b) Little rough fracture, (c) Rough fracture. Modified from [24].

2.2. Impact Testing

This thesis focuses on the impact of foreign objects on cold spray depositions. Impact can be categorized by the severity of the impact, following the research of Jawaid et al. [25], these categories are divided by impact velocity [26]:

- Low velocity impact (LVI): $< 30\text{ m/s} \Rightarrow$ Stones or bird collision
- High velocity impact (HVI): $30\text{ m/s} - 200\text{ m/s} \Rightarrow$ Car accident at highway
- Ballistic velocity impact: $200\text{ m/s} - 15000\text{ m/s} \Rightarrow$ Bullet hit
- Hypervelocity impact: $> 15000\text{ m/s} \Rightarrow$ Orbit movement (outer space)

The impact velocity which is researched in this thesis is low velocity impact, $< 30\text{m/s}$. Damage caused by LVI can be difficult to detect by visual inspection, in composites, this type of damage is also known as barely visible impact damage (BVID). Barely Visible damage occurs when significant internal damage occurs with little to no visible signs of the damage on the surface [2]. In composite this could lead to dangerous situations in which fiber or matrix cracking occurs without visible notice. For metals there is always a sign of damage on the surface which indicates the internal damage. However, for cold spray depositions it is not investigated if BVID applies or not. The situations in which aircraft are subjected to low velocity impact are during take-off and landing and taxiing, as small stones or gravel on the runway hit the aircraft, see Figure 2.11. Tools dropped during maintenance or collisions with other vehicles can also result in LVI. During taxiing, small stones can be chipped up by wheels and results in an impact velocity between $1.5 - 4.5\text{m/s}$ on the cowling, during take-off the impact velocity of stones increases, $8 - 24\text{m/s}$. Collisions with seagull during the listed operations are in the range of $14 - 22\text{m/s}$ [26].

As no research has been done on impact testing on cold spray repairs, this chapter will give the basic principles of impact testing on metals and the behavior of metals upon impact loading.

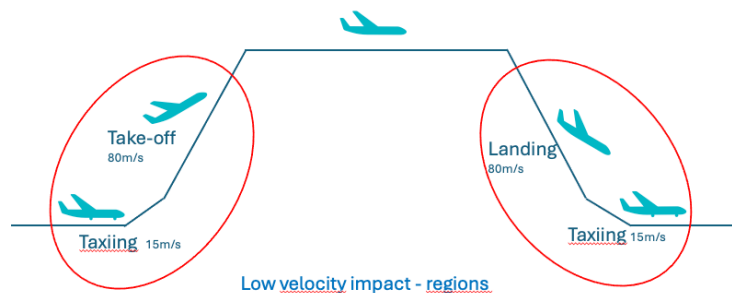


Figure 2.11: Low velocity impact (LVI) regions during aircraft operation with aircraft speed [26].

2.2.1. Dynamics of impact

Impact at low velocities could result in an elastic, plastic or fluid-like response of the material, or a combination of these. Studies done on LVI and the dynamics focus on the fracture and fragmentation of the impacted object. The most severe damage due to LVI consists of holes and cracks, which reduce the material's strength. The conservation of energy principle states that the energy absorbed by the impacted object is equivalent to the impact energy. As for low velocity impact, the first law of vibrations can be used, the contact duration of the impacting object on the impacted object is longer than the time which is required for the impact wave to reach the edges and travel back to the point of impact, similar to a quasi static situation. Using the energy balance model, in which the total energy of the system is conserved, high vibrations modes, friction and other losses of energy are neglected. The response of the impacted object is closely related to multiple factors such as, the dimensions of the object, the impactor weight, radius and velocity [27, 28, 29].

Stress waves

As a foreign object, such as a stone, hits an aircraft cowling for example, localized compressive stresses arise around the point of impact. For a very short moment, the cowling responds elastically, quickly after the stresses exceed the yield strength of the material due to the high impact energy. The material plastically deforms and a dent forms. The region below the dent undergoes local deformation causing localized thinning or stretching of the material, and could possibly initiate cracks due to the tensile stresses. The energy of impact generates stress waves (shock or elastic waves) propagation outwards from the point of impact. These stress waves move rapidly through the material, potentially causing additional damage away from the point of impact itself.

The kinetic energy of the stone is mainly absorbed by three mechanisms:

- Plastic deformation
- Generation of heat

- Formation and propagation of cracks or delamination [30].

Impact testing

The impact test setup should be designed in such a way that the test can be performed on repeat multiple times under the same circumstances. Many factors have an effect on the impact behavior of the impacted material, thus it is required to use the exact same set up every impact test.

For the analysis, the impact testing is simplified to a plate fixed on both sides, which can be simplified to a beam with two fixed ends, see Figure 2.12. The impactor creates a concentrated load in the middle of the beam, compressive stresses are generated on the impacted side, while tensile stresses occur on the non-impacted side. An equilibrium is achieved by the forces present in the system: impact force, reaction force, and inertial force. The impact itself is so fast that the viscous damping force is very small and can be neglected. Since the fast impact event causes localized dynamic deformation and stress waves, in which adhesion mechanics and high-strain-rate effects play a role, the system can not be analysed and simplified to a static beam deflection model.

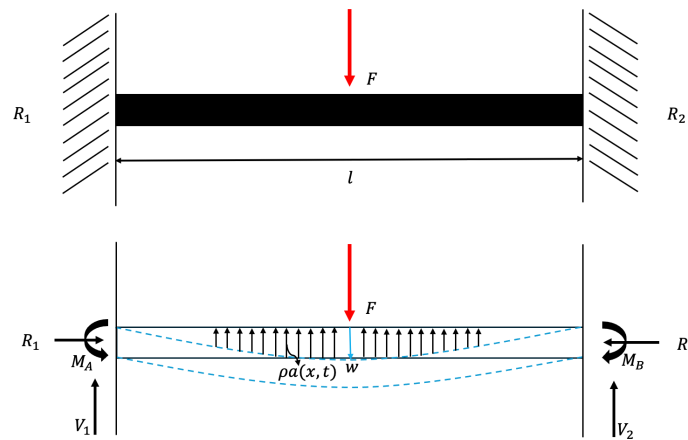


Figure 2.12: Free Body Diagram and dynamic free diagram of the impact test.

F is the force (impact) on the beam, l the length of the beam, V the shear force, and M the moment. W is the deflection of the beam due to the bending that occurs and R the reaction force from the clamp. $\rho a(x, t)$ is the distributed inertial force, the density of the beam times the acceleration of the beam.

In the dynamic loading system, the impact force is not completely resisted by the reaction R only, the inertial force also plays a role. If the impact is very fast, the maximum impact force could be completely resisted by the inertial resistance of the beam. The dynamic bending moment and the shear force in the beam depend on this inertial resistance and the maximum impact load. The forces in the system can not be calculated as in a static equilibrium, if the assumption is made that the impact force is completely resisted by the inertial forces, equilibrium equations can be estimated. However, here is no study yet that predicts that the impact force is completely resisted by the inertial forces regarding cold spray depositions.

Following Newton's Second Law, the inertial forces act in the opposite direction as the accelerating force (impactor) on the body (coupon) and is equal to the accelerating force multiplied by the mass of the body. In other words, a resistive force acts against the impact. During the impact, stress waves propagate through the coupon traveling away from the point of impact in radial direction. These compressive and tensile waves travel at the speed of sound through the material. At the clamped sides, these waves are reflected and cause an interference pattern increasing the local stress. The clamped sides resist movement and thus create a bending moment in the coupon, while the inertia forces try to resist this bending deformation. At the same time shear waves, traveling at a lower speed, cause shear failure near the impact zone.

The inertial forces of the plate can exceed the yield strength of the material due to the high acceleration of the impactor. This influences the deformation of the coupon as a localized dynamic effect. Inertial forces also increase the strain rate and therefore increase the resistance of a material to deformation, leading to a more brittle material.

How the compressive, tensile, shear and bending waves are considered depends on the duration of the impact by the indenter. During low velocity impact, the time of impact is long compared to the transition time for all the stress waves, it could even be analysed as a quasi static case. The duration of impact is mainly controlled by the projectile-to-panel mass ratio.

To properly model the forces in the system the following need to be considered:

- Strain rate effects.
- Wave propagation and reflection at the substrate-deposition interface.
- Dynamic force equilibrium [24, 30, 31].

2.2.2. Quasi static indentation test for low velocity impact

A quasi static indentation (QSI) test can be used to simulate low velocity impact (LVI) because the strain rate, inertial effect and failure mechanisms under low velocity impact closely resemble those at quasi static conditions. Several studies, including those by Li and Huang [32, 33] have conducted comparative analyses of the two tests. However differences are expected for the results of QSI, and LVI, since there are limits for the comparison, which are discussed below. Most of the research is done for composites, using the ASTM D6264-98 for QSI and the D7136-05 standard for LVI [32]. Allen et al. [34] concluded that QSI is a usable method for the analysis of low velocity impact damage and that the load-displacement curve of a sandwich beam under LVI and QSI are similar [33].

Since the QSI test impacts very slowly, the velocity component does not play a role, resulting in a different strain rate. The differences between QSI and LVI lie mostly in the strain rate, failure mechanisms and loading conditions:

- **Loading type:** The loading for QSI is slow, gradually increased and controlled, the velocity component is taken out of account. LVI has a sudden dynamic load application, a rapid process.
- **Strain Rate:** The strain rate for LVI is higher, LVI has a moderate strain rate $10^2 - 10^4 s^{-1}$. QSI has a low strain rate between 10^{-4} and $10^{-1} s^{-1}$.
- **Failure mechanisms:** Both show plastic deformation after the yield strength is reached, QSI shows local yielding while LVI has wave propagation and could fracture sooner.
- **Material response:** During QSI dislocations have time to stabilize after motion, which results in a more ductile response. For LVI the dislocations are restricted by the higher strain rate, resulting in less ductile behavior and stiffer material.
- **The surface indentation area** is larger under QSI compared to LVI.
- Due to the **stiffer material**, more energy can be applied with LVI to have the same amount of deflection as QSI [35].

The strain rate difference has an effect on material properties, a higher strain rate will result in higher yield strengths. The higher strain rates prevent the dislocations in the crystal lattice from moving and reorganization and work hardening appears. Higher stresses are required to initiate plastic deformation.

The Young's modulus is expected to stay constant under differing strain rates. Only at extremely high strain rates, such as shock loading, the Young's modulus slightly increases. The stiffness, depends on the strain rates and geometry of the specimen. Under higher strain rates the stiffness increases as a result of the higher yield strength. Also, the dynamic effect in LVI, causing wave propagation, creates a resistance to deformation, resulting in higher stiffness [35].

2.2.3. Numerical analysis

The Johnson-Cook model has been used in several researches to model the plasticity behavior of cold spray [19, 36]. The Johnson-Cook model takes into account strain hardening, strain rate hardening,

and thermal softening. Material-related constants, and material properties such as Young's modulus and melting temperature are used in the formula to express the yield strength, Formula 2.2. The Johnson-Cook model and the Mie-Grüneisen equation of state, which describes the elastic behavior are combined by Blochet et al. Together, these models describe the elastic and plastic behavior of cold spray and show promising results; However, they assume isotropic mechanical and thermal properties, while the literature is still in doubt about the type of behavior. Varying values are also found for the mechanical properties of cold sprayed materials, which leaves room for optimization of the simulation and modeling of the cold spray behavior.

$$\sigma = (A + B\epsilon^n)(1 + C \ln \dot{\epsilon}^*) \left(1 - \left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}\right)^m\right) \quad (2.2)$$

For more information about the formula and parameters refer to [19].

To be able to predict the mechanical behavior of cold spray under varies types of loading, a simulation of the deposition process itself is also valuable. The challenge of modeling cold spray is describing the complex high strain rate deformation of subsequent impacting particles. Secondly, the interaction between incoming particles and already deposited particles during the spraying process has not been researched enough to simulate the exact behavior of the cold spray. However, multiple studies have shown promising results [24, 19, 36] simulating the cold spray behavior with finite-element methodology, using non-linear transient finite element. Results of the numerical models are close to the experimental results. The thermomechanical response of the impacting particles can be analysed by implementing a full coupled thermal-stress component. An explicit time integration algorithm is also needed for the relatively short dynamic response and large deformations of the particles. The Lagrangian-Euler Method has also been used by Wang et al. [15] to model the complex interactions during impact and deformation of the particles, due to its ability to handle large deformation situations. The Eulerian method describes the material flow, while the Lagrangian method tracks the individual particle movements and deformations. Combining the two, the dynamic interactions can be captured and the material behavior, especially at the particle interface, can be predicted. However there are limitations for this method, such as capturing the highly localized thermal effects and the ability to simulate numerous particles simultaneously.

2.3. Conclusion Literature and Research Objectives

This literature review, presents the relevant state-of-the-art findings on the damage mechanisms of cold spray repairs due to impact. This was completed in order to have a fundamental framework for the experiment of this thesis project. The main conclusions from the literature review are presented, followed by the research gaps and research objectives. Lastly, the research approach is explained.

Conclusions

- The dominant bonding mechanism of the cold spray particles is not clear, however, three mechanisms play an important role: metallurgic bonding, mechanical interlocking, adiabatic shear instability.
- The residual tensile stresses after deposition are mostly present around the interface with the substrate.
- The fracture behaviour of a cold spray deposition under fatigue loading is dependent on the ductility of the deposition material and the numbers of defects in the deposition layers.
- The degree of anisotropy in cold spray is currently unknown, with mixed results demonstrating either isotropy or anisotropy.
- Interparticular cracking has a lower energy threshold and shows smooth fracture surfaces with dimples, but occurs during brittle fracture. Transparticular cracking requires more energy and shows rough fracture surfaces.
- Low velocity impact causes compressive stresses around the point of impact and tensile stresses at the non-impacted side.

- The fast impact causes stress waves and localized dynamic deformations resulting in high strain rates.
- The clamped system creates a bending moment, while the shear waves cause shear failure near the impact zone.
- Quasi static indentation testing can be used as low velocity impact test due to similar strain rates, inertial effects and failure mechanisms.
- Modeling the damage mechanism in cold spray during impact is difficult due to high strain rates, inelastic behavior and the interaction between the solid state particles.

2.3.1. Research gaps

Based on the investigated literature, clear research gaps exist in the damage behavior of cold spray repairs subjected to low velocity impact.

- Impact testing on cold spray repairs.
- A better understanding of the failure mode(s) in cold spray deposits.
- The adhesion strength of the cold spray deposition.
- A comprehensive analysis of stress distribution in cold spray deposits.
- The relationship between the mechanical properties of cold spray deposits and those of bulk material.
- The impact energy level at which barely visible impact damage (BVID) occurs, if it occurs.

2.3.2. Research objectives

Based on the research gaps, the main research question for this thesis is:

What are the dominant failure mode(s) in a cold spray repair subjected to low velocity impact?

The following sub-questions were posed to explore this further:

- Q1. *At which impact energy level does a cold spray deposition begin to crack?*
- Q2. *Does Barely Visible Impact Damage occur in the repair? If so, at what impact energy level does it start?*
- Q3. *Do interparticle and transparticle cracks appear? Does one type occur before the other, or do they occur simultaneously?*
- Q4. *Does delamination between the substrate and deposition occur? If so, at what impact energy level does it occur?*

2.3.3. Thesis approach

To answer the research objectives, the research is done in three stages. First, the cold spray coupons had to be produced, with great attention for closely repeating the same pre- and post- treatment for each type of coupon. Secondly, the coupons were impact tested, starting with trial runs to find a bigger range in which the thresholds are present. Afterwards the impact range was slowly decreased to find more exact thresholds. The analysis of the coupons was done in two ways, visually with the optical microscope and the SEM and data analysis was done using the data from the high-speed camera and geometry of the dents.

Damage definitions and thresholds

In order to examine damage in this research, the definitions of damage from General Electric are used, following the Commercial Engine Standard Practices Manual - SPM for thermal spray coatings [37, 38]:

- Crack: Cracks are only ratable when greater than 0.127mm (0.005 inch) in total length. Examination shall be performed at 200x.

- Delamination: A separation or horizontal defect that follows, or is associated with contour or the linear build-up that must be greater than 254 micrometers (0.010inch) to be ratable. Examination shall be performed at 200x.
- Separation: A defect that follows, or is associated with, the contour of the interface. It must be greater than 127 micrometers (0.005 inch) to be ratable.

The minimum crack length to be considered a crack is thus 0.127mm. The minimum delamination length to be considered delamination is 254 micrometers (0.010inch).

If damage is detected during visual inspection, the severity of the damage decides if the cowling inlet lip should be repaired immediately or if the component is still serviceable. The OEMs provide maintenance manuals for the "allowable damage limits" with which a component is allowed to operate. A cowling inlet is allowed to operate with cracks and delamination present in the aluminium metal structures (including repairs already present), until the allowable damage limits. The following guidelines are set up for the different types of damage for an A330 cowling inlet lip. If the crack or delamination lengths exceeds the limits, the OEM should be contacted for further instruction and the component is not serviceable

- The allowable crack length for operation is 76.2mm (3.00 inches). The crack should be examined every "A" check and an external patch (aluminium sealing tape) should be installed. During the "C" check the damage should be repaired.
- The maximum allowable dent size is 127mm (5 inches) in diameter, with a maximum dent depth of 10% of the diameter.
- Regarding delamination, the separation between substrate and deposition is not allowed to surpass 25,4mm (1 inch) and can not be within 254mm (10inches) from other defects. Five delamination are the maximum allowable amount of delaminations in an area. Again, the delamination should be examined every "A" check and repaired at the "C" check.

A check: Regular inspection every 400-600 flight hours.

C check: Comprehensive inspection every 18-24 months [39].

3

Materials

This chapter explains the different types of coupons which have been impact tested. Differences between the coupon materials, manufacturing process and pre-post treatments are discussed as well along with the three different cold spray systems which were used.

3.1. Materials

3.1.1. Coupon types

To understand the damage behavior of cold spray depositions, five different types of coupons (plus one reference coupon) were used in this research. The specifications are outlined in Figures 3.1 and 3.2. In each step, one or two parameters were changed, so their effect on the damage behavior could be analyzed. Over five steps a cold spray coating changes to a double-curved cowling with a circular repair configuration. The six different coupon types are explained in more detail below. In the remainder of this report, the terms coating, repair, and deposition refer to the specific definitions established for this research:

- Coating: Rectangular, flat deposition
- Repair: Non-rectangular deposition
- Deposition: Both coating and repair

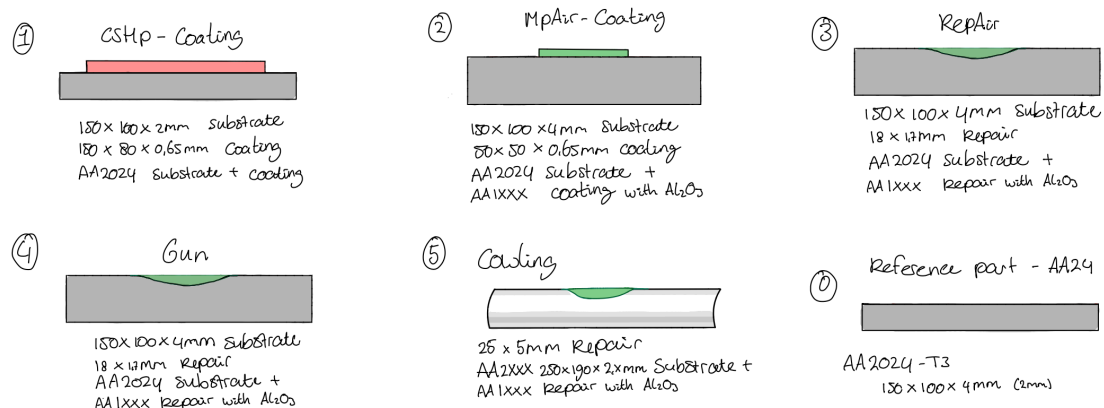


Figure 3.1: The six types of coupons.

• 1. CSHp - Coating

Substrate: Aluminium alloy 2024-T3 plate of 150x100x2mm

Coating: Aluminium alloy 2024 powder of 150x80x0.65mm

Machine: High pressure cold spray

- **2. MPAir - Coating**

Substrate: Aluminium alloy 2024-T3 plate of 150x100x4mm

Coating: Aluminium alloy 1XXX powder with aluminium oxide of 50x50x0.65mm

Machine: Medium pressure cold spray

- **3. RepAir - repair**

Substrate: Aluminium alloy 2024-T3 plate of 150x100x4mm

Repair: Aluminium alloy 1XXX powder with aluminium oxide deposition of 18mm in diameter (width) and maximum repair depth of 1.7mm

Machine: Medium pressure cold spray

- **4. Gun - repair**

Substrate: Aluminium alloy 2024-T3 plate of 150x100x4mm

Repair: Aluminium alloy 1XXX powder with aluminium oxide deposition of 18mm in diameter (width) and maximum repair depth of 1.7mm

Machine: Hand Gun cold spray - medium pressure system

- **5. Cowling - repair**

Substrate: Aluminium alloy 2XXX cowling of 250x190x2.X mm

Repair: Aluminium alloy 1XXX powder with aluminium oxide deposition of 5mm in diameter (width) and maximum repair depth of 5mm

Machine: Hand Gun cold spray - medium pressure system

- **0. AA - Reference Part**

Substrate: Aluminium alloy 2024-T3 plate of 150x100x4mm

The parameters changing per coupon are:

- 1-2: Pressure system high to medium pressure and deposition material changed from AA2024 to AA1XXX.
- 2-3: Geometry of deposition from a coating to a repair.
- 3-4: Robotic arm system to hand gun (manual) system.
- 4-5: Flat substrate to double curved substrate and substrate material changes from AA2024 to AA2XXX.

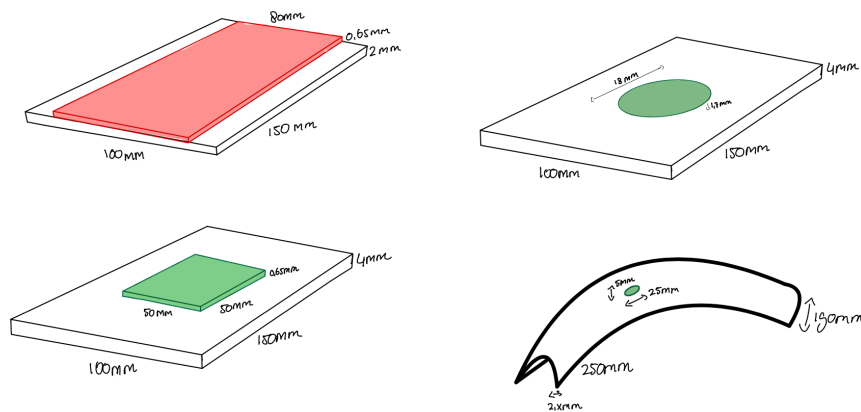


Figure 3.2: 3D view of coupon types 1-5.

3.1.2. Impact location

Coupon types 1, 2, and 5 were impacted in the middle of the deposition. The RepAir and Gun coupons, type 3 and 4 were impacted at two distinct locations: in the center of the deposition, referred to as the Mid indent, and at the edge of the deposition, where both the deposition and the substrate were impacted, referred to as the Side indent. Figure 3.3 illustrates the two different impact locations.

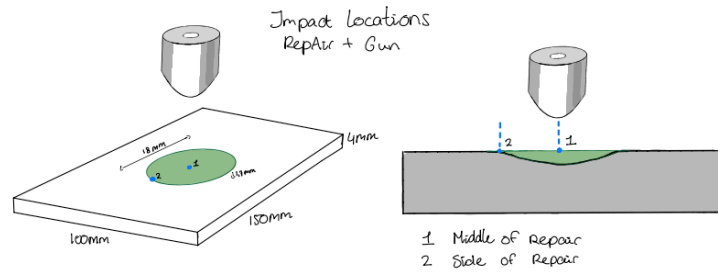


Figure 3.3: Impact locations RepAir and Gun coupon.

3.1.3. Original plan

The original set-up for the experiment was different. The experiment included 6 coupon types and a reference coupon. In this set up, one parameter changed at the time, except for the last step (5-6). By changing just one parameter at the time, the differences in the results could be more easily be related to the parameter change. The original coupon set up is shown below in Figure 3.4.

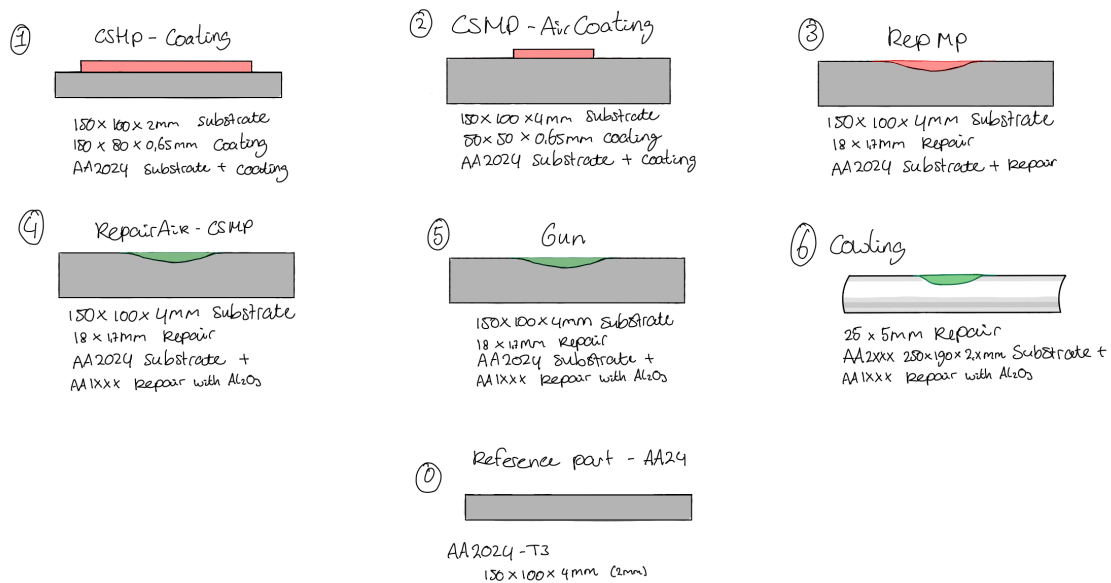


Figure 3.4: The seven types of specimens

The following parameters were to be changed per coupon:

- 1-2: Pressure system changes from high to medium pressure.
- 2-3: Geometry of deposition from a coating to a repair.
- 3-4: Deposition material changes from AA2024 to AA1XXX.
- 4-5: Robotic arm system to hand gun (manual) system.
- 5-6: Flat substrate to double curved substrate and substrate material changes from AA2024 to AA2XXX.

Unfortunately, after several attempts, the second coupon type, CSMP, could not be manufactured. Spraying AA2024 powder with the medium pressure machine resulted in a very low deposition efficiency, 1%. The powder particles did stick to the substrate, but just at a very low amount, the rest of the particles could not bond. For this reason, the choice was made to skip the AA2024 coupons and change the set-up to as explained in Section 3.1.1. This makes the stepwise plan less logical, but due to time and budget limits, this choice had to be made. The cross section and surface of the few coupons that were sprayed with AA2024 are shown in the results and discussion section.

3.2. Material properties

In this research, the material configuration was altered twice: once by changing the deposition material and once by changing the substrate material.

3.2.1. Feedstock material

The deposition material changed from an alloy of aluminium 2024 to pure aluminium, AA1XXX combined with aluminium oxide, Al_2O_3 .

AA2024, part of the 2000 aluminium alloy series, is an aluminium composite with copper as its primary alloying element. It has superior strength, good workability and good fatigue resistance, but poor resistance against corrosion. Using post heat treatments can further improve the strength. Due to their high strength to weight ratio the 2XXX series and especially the AA2024 is commonly used in the aerospace industry, and for gears and bolts [40].

AA1XXX, part of the 1000 aluminium alloy series, consists of 99% pure aluminium which is highly resistant to corrosion. The ductility is high, making it suitable for applications in which extensive forming is required. However, its tensile and fatigue strength is poor, making it unsuitable for structural parts [41].

The aluminium alloy 1XXX is mixed with aluminium oxide, Al_2O_3 , for two main reasons. Al_2O_3 particles are hard and brittle, breaking the thin oxide layer on the substrate when they impact the substrate. The oxide layer needs to be removed to allow bonding between the substrate and deposition. The second reason why aluminium oxide is mixed with the AA1XXX is because of the ductile behavior of the AA1XXX. Spraying pure AA1XXX would result in clogging of the AA1XXX inside the spraying nozzle, the nozzle will eventually 'cold spray' itself on the inside. By mixing AA1XXX with aluminium oxide particles, the aluminium oxide particles will erode the layer build-up of AA1XXX inside the nozzle and prevent too much clogging. In other words, the aluminium oxide cleans the nozzle of the AA1XXX. The addition of the ceramic Al_2O_3 particles increases the deposition efficiency, however there is also a downside to the addition. The brittle particles make the cohesion between the pure ductile aluminium and brittle Al_2O_3 particles not ideal. Differing hardness exists over the deposition as a results from the weak bonding between the two types of particles. As the percentage of Al_2O_3 is increased, the material becomes more brittle. Research has shown that 30 wt% is the limit for optimal deposition efficiency and good bonding between the Al_2O_3 and AA1XXX [42].

The exact composition of the used metal powder is confidential. For simplicity the AA1XXXX and Al_2O_3 mix will from now on be named AA1XXX.

3.2.2. Substrate material

Secondly, the substrate material was changed from AA2024-T3 to AA2XXX. The cowling (5th coupon) that was sprayed is made of AA2XXX.

AA2XXX is also part of the 2000 aluminium alloy series and also has copper as its main alloying element. AA2XXX is an age-hardenable alloy that is suitable for high-strength structural components used in high-temperature applications. The alloy is resistant to stress corrosion cracking, making it suitable for high-stress aerospace structures and high-temperature applications. However, AA2XXX is sensitive to corrosion, due to its slightly higher Cu content, compared to AA2024 [43].

Mechanical properties of the three different materials used are listed below in table 3.1, along with some properties of the cold sprayed AA1XXX material found in the literature.

Table 3.1: Material properties [40, 41, 43, 19]

Parameter	AA2024	AA1XXX	AA2XXX	AA1XXX CS
Density	2,78 g/cm^3	2,705 g/cm^3	2,97 g/cm^3	2.7 g/cm^3
Tensile yield strength	324 MPa	103MPa	250 +/-MPa	
UTS	469 MPa	110MPa	360 +/- MPa	
Youngs modulus	73 GPa	69 GPa	73 GPa	
Poisson's ratio	0,33	0,33	0,33	0,33
CTE at 20-200°C	24,7 $\mu m / m ^\circ C$	24,5 $\mu m / m ^\circ C$	23 +/- $\mu m / m ^\circ C$	
Elongation at break	10-15%	10%	8-12%	
Hardness Vickers	137	< 80	100	

3.3. Coupon preparation

The coupons were produced following a stepwise plan. Since all coupon types differed slightly in parameters, the preparation process was kept as consistent as possible. However, identical preparation could not be ensured, as the coupons were not all manufactured at the same location. The preparation procedure for each coupon is described in the following section.

3.3.1. CSHP - Coating

Coupon type 1 differed primarily from the others, as these coupons already existed prior to the start of the research. Titomic cold sprayed six AA2024-T3 plates using a high-pressure cold spray machine, with each plate containing three depositions of 150x80x0.65 mm AA2024. These six rectangular plates were subsequently cut into three smaller coupons each, measuring 150x100x2.65 mm, resulting in 18 coupons referred to as CSHP. No pre- or post-treatment was applied to these coupons.

3.3.2. MPAir - Coating

For coupon types 2-4, the substrate material had to be prepared before spraying was done. 42 metal coupons were cut from a 2000x1000x4 mm AA2024-T3 plate to 150mmx100x4mm plates. The coupon thickness was doubled (2mm to 4mm) compared to type 1 coupons, the CSHP coupons showed significant bending in the plate due to residual stresses building up after spraying. To reduce the amount of bending, a thicker substrate plate was chosen, this distributes the residual stresses over a bigger surface.

The MPAir coupon set consists of 14 coupons. The coupons were cleaned with acetone, and surface treatment was done by grit blasting aluminium oxide particles, using the cold spray machine itself. A 50x50 mm square in the center of the plate was grit-blasted. This surface treatment was conducted to promote better bonding of the particles to the substrate. Grit-blasting removed the oxide layer—necessary for bonding—and created a textured surface with peaks and valleys that allowed for mechanical interlocking of the sprayed particles. Grit-blasting was performed immediately prior to spraying, to prevent reformation of the oxide layer, which begins forming within seconds upon exposure to air.

After the grit-blast process, the substrates were cold sprayed on top of the grit-blasted surface, with deposition dimensions of 50x50x0.7 mm. The cold spray deposition resulted in an uneven surface since the nozzle moves stepwise over the substrate, with an overlapping step size of 5mm. To obtain a flat surface, the deposition was milled to a clean and even layer, resulting in an average thickness of 0.65 mm. Milling was carried out using a Fehlmann Pickax 56, equipped with a flat mill head at a speed of 1200 mm/min. See Figure 3.5 for the preparation steps of MPAir coupons.

3.3.3. RepAir - Repair

For the repair coupons (RepAir and Gun), a conical chamber—referred to as a blend-out—was milled into the AA2024 substrate. The circular chamber, positioned at the center of the plate, had a width of 18 mm and a maximum depth of 1.7 mm. This geometry was created using a 6 mm diameter mill on the Fehlmann Pickax 56. The mill head moved axially and radially at 12,000 rpm to achieve the desired shape.

Coupon type 3 followed the same cleaning and grit-blasting procedure as the MPAir coupons. The

repair coupons were also milled, using the Fehlmann Pickax 56. After cold spraying, the deposition was milled using the Fehlmann Pickax 56, until the surface matched the original height of the substrate, thereby restoring the original geometry. 16 RepAir coupons were produced. The RepAir coupon preparation is visualized in the Figure 3.5.

3.3.4. Gun - Repair

The chambers in coupon type 4 were fabricated using the same milling process as coupon type 3. After chamber preparation, the coupons were sent to AX for cleaning, surface preparation and spraying.

The surface treatment was done manually, according to AX's standard procedure, right before spraying. The surface was lightly abraded with sandpaper 80 to remove the oxide layer, secondly, sandpaper grade 120 was used to roughen the surface for better bonding. The cleaned surface was degreased using BX until no residue remained on the wipe. The coupons were then cold sprayed using a medium-pressure handheld gun and subsequently milled using the same procedure as coupon type 3. 12 coupons were produced for the Gun type.

The preparation of the coupons RepAir and Gun are visualized in the Figure below, 3.5.

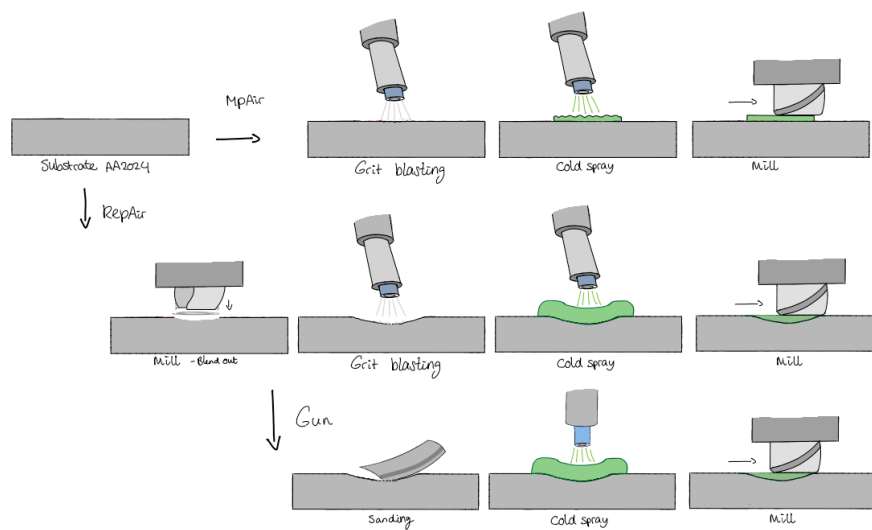


Figure 3.5: Preparation of coupons MPAir, RepAir and Gun.

3.3.5. Cowling - Repair

The cowling coupons were processed at AX's, see Figure 3.6. Four cowling segments were prepared for spraying and testing. A circular dent of 25mm diameter and maximum depth of 5mm was introduced in four cowling pieces of 250x190x2.X mm with a controlled indentation test. The pre surface treatment process is the same as for coupon type 4, by AX. After spraying, the cowlings were milled. This process was performed using the same milling machine as for the other coupons; however, a specialized mold was required due to the double curvature of the cowling surface. Unlike the flat coupons, a spherical mill head was used instead of a flat one, as the latter was unsuitable for the curved geometry. The spherical head could not mill the entire width of the deposition in a single pass, which resulted in visible milling marks on the surface.

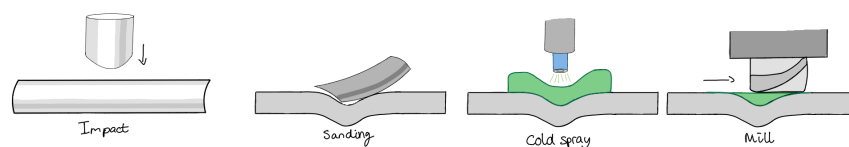


Figure 3.6: Preparation Cowling.

3.3.6. Milling

Coupons type 2–5 were milled following cold spray deposition, a step that directly influenced the properties of the deposition, especially in comparison to type 1 coupons, which remained unmilled. Milling removes the topmost layer of powder particles—often the weakest part of the deposition due to limited plastic deformation [44]. These surface particles receive no further impacts from successive layers and, therefore, exhibit reduced grain refinement and weaker bonding. In contrast, deeper layers within the deposition are subjected to repeated impacts, enhancing their plastic deformation, grain refinement, and mechanical interlocking strength. Beyond simply removing a weak layer, the milling process itself alters the mechanical properties of the deposition. Subtractive machining changes the residual stress distribution and introduces near-surface plastic deformation, which can result in strain hardening. This phenomenon could increase the strength and hardness of the deposition due to the accumulation of dislocations and grain refinement. As grain size is reduced, the number of grain boundaries increases, impeding dislocation movement and resulting in a stronger material—a relationship described by the Hall–Petch equation. This effect is especially pronounced in ductile coatings compared to more brittle materials [45].

Residual stresses introduced by milling also play a critical role in the mechanical behavior of the deposition. These stresses are typically highest near the milled surface and result from plastic deformation and thermal gradients caused by heat generation during machining. As the milling tool shears material at high speeds, localized heating and strain hardening produce changes in volume, leading to the development of residual stress upon load release. The nature of these stresses—whether tensile or compressive—depends on factors such as cutting speed, feed rate, depth of cut, and tool geometry. Compressive residual stresses are generally advantageous, enhancing fatigue and creep life and improving resistance to stress corrosion cracking. In contrast, tensile residual stresses tend to reduce performance in these areas. In shallow milling, compressive stresses dominate, while deeper material removal tends to generate tensile residual stresses. It is important to note that excessive milling can reduce the effectiveness of mechanical interlocking between particles, compromising adhesion strength and lowering the load-bearing capacity of the coating [46].

3.3.7. Roughness

To quantify surface roughness, a roughness test was conducted using the Surtronic Duo, a surface metrology instrument developed by Taylor Hobson AMETEK. Two types of surface treatments were evaluated, each measured four times: one involving aluminum oxide grit-blasting performed by a robotic system at Titomic, and the other involving manual grinding conducted by AX operators. The results, expressed in R_a and R_z values, are presented in Table 3.2.

Table 3.2: Surface roughness values R_a and R_z

Operator	R_a [μm]	R_z [μm]
Titomic	6.5 - 6.63	37.9 - 41.7
AX	2.64 - 3.33	16.1 - 27.3

R_a : represents the average roughness value of the tested area.

R_z : the maximum height difference between a peak and valley in vertical direction of the tested area.

3.4. Cold Spray Systems

Three different cold spray systems were used to prepare the coupons. Coupons type 1 were produced using a high pressure cold spray system at Titomic, the TKF 9000. Coupons 2 and 3 were produced with a medium pressure cold spray system: the D623 Standard medium pressure system at Titomic. The system has a nozzle that moves in the x- and y- direction, and operates with a robotic arm. Coupons 4 and 5 were also produced with the D623 Standard medium pressure system, but a hand-held spray gun was used instead of a robotic arm. The parameters set for the cold spray machine are summarized in the table below 3.3.

Table 3.3: Parameters per cold spray system

Parameter	CSHP AA2024 - Robot	CSMP AA2024- Robot	CSMP AA1XXX - Robot	CSMP AA1XXX - Gun
Temperature	700 °C	700 °C	700 °C	700°C
Pressure	19 bar	19 bar	19 bar	19 bar
Stand-off distance	20mm	20mm	20mm	20-30mm
Nozzle Traverse speed	100mm/s	100mm/s	100mm/s	100mm/s
Spray Angle	90 °	90 °	90 °	90 °
Carrier Gas	Nitrogen	Nitrogen	Nitrogen	Nitrogen

4

Method

In this section the experimental set-up is explained, the different types of impact test which were used are described along with additional equipment required for the impact testing. The impact testing was done on trial and error basis in order to find the different thresholds. The different types of analysis, optical and analytical are outlined and relevant formulas used during the data analysis are given.

4.1. Impact testing

Three different impact tests were used in this research. The impact tower was used to analyse impact energies in the range of 5J and above, a quasi static indentation (QSI) test and a hand-held impact tower were used in the impact energy range of 0-5J.

For the CSHP coupons the QSI and hand-held impact tower were combined in the research. The hand-held impact tower has the disadvantages that it is not instrumented, so no data can be extracted during the impact process. The QSI was used to retrieve more detailed data in the range of 0-5J of impact, next to the hand-held impact tower.

4.1.1. Impact tower

The impact tower works with the potential energy. By changing the height (h) or mass (m) of the impactor, the impact energy changes. In combination with the acceleration due to gravity, $9.81m/s^2$ the impact energy was calculated following Formula 4.1. The distance from the indenter tip to the surface of the coupons was measured and calibrated with the impact software. This was done since the accessible indenters and fixture systems have different heights, resulting in a slightly different value for the height compared to the software. The impact tower is visualized in Figure 4.1.

$$E = m * g * h \quad (4.1)$$

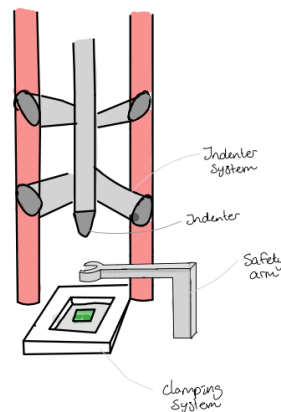


Figure 4.1: Impact test tower

For every test the following procedure is repeated. A coupon was clamped in the fixture and placed underneath the impact indenter. The indenter was clicked into its 'holder' and brought to the required height of release for a certain impact energy. This is automatically done with the impact computer program. The safety was put on, to make sure the indenter is caught after the first impact. After impact, the indenter rebounds from the surface; to prevent a second impact on the coupon, the indenter is caught by the safety arm. At the same time, a high-speed camera recorded the impact, a ruler next to the clamping system was used to measure the traveled distance of the indenter between two moments. The full set up is illustrated below in 4.2.

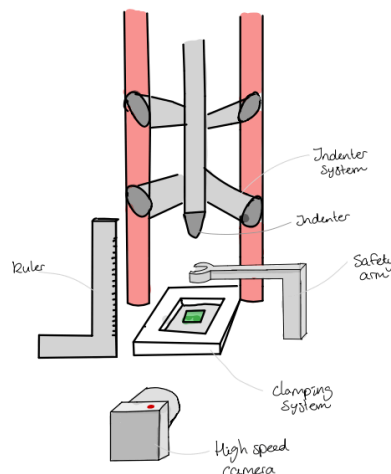


Figure 4.2: Set up for impact testing with impact tower

4.1.2. Hand-held tower

The hand-held tower, Figure 4.3 , works with the same impact energy formula as used for the impact tower, Formula 4.1. The mass of the indenter is 0.688 kg, the height of the indenter is the distance between the upper surface of the specimen and the tip of the indenter, the zero point of the system (scale on the tower) lies 4.4 cm above the actual point of impact, so 4.4 cm is subtracted from the necessary height to set the indenter to the correct height regarding the scale on the tower. The specimen was clamped in, and put right under the impact tower, with the back of the clamping system against the

back of the tower pole. The high-speed camera was placed in front of the impact tower together with the ruler and lamp. The safety of the indenter was released by hand, the indenter fell down in the pipe and impact was made on the specimen. After the impact was made, the indenter bounces back up and was caught by hand to prevent further impact events from occurring after the first impact. The impact of the hand-held tower is much less severe compared to the impact tower, which makes it possible to catch the indenter by hand after it bounces up from the impact.

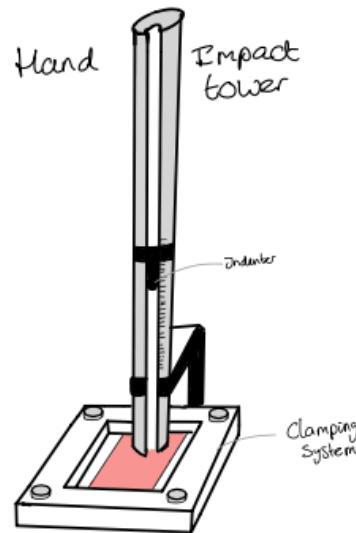


Figure 4.3: Hand held tower

4.1.3. Quasi static indentation

The quasi static indentation test (QSI), Figure 4.4 was used to mimic impact testing from the impact tower, and records the force, deflection, and energy applied to the coupon. The system removes the velocity component as it moves 2mm/minute downward. An indenter of 13mm was attached to the Zwick 10kN machine and the horizontal plate was moved upwards until 50mm away from the indenter. The clamped specimen was placed between the bolts, to make sure it remained in place. The horizontal bar slowly moved upward until the indenter was 100 micrometers away from the specimen. By varying the force applied to the specimen by the indenter, the load applied was changed. The software produces the load in Newton and displacement of the panel as a function of time. Calculating the area underneath the force deflection curve, following the formula for energy (E), 4.3.

$$E = \int_{\delta_0}^{\delta_1} F(\delta) d\delta \quad (4.2)$$

- $F(\delta)$ is the force as a function of deflection (δ).
- $d\delta$ represents the deflection difference between two moments.
- δ_0 and δ_1 are the initial and final displacements, respectively.



Figure 4.4: Quasi Static Indentation test

4.2. Additional equipment

4.2.1. High speed Camera

FASTCAME Mini high-speed camera, was used for the impact tower and hand-held impact tower. The high-speed camera captures images with 6400 frames per second, for three seconds around the moment of impact. The camera was 'pre-loaded' allowing one to record the previous three seconds after clicking the record button, and to capture the exact moment of impact. The velocity before and after impact is calculated by measuring the height difference between two moments before/after the impact. A ruler and a lamp were placed next to the impact tower, aligning the tip of the indenter with the ruler at two different time points, the velocity is calculated with the location and time difference within the impact event.

4.2.2. Indenter

Three types of indenters were used, one indenter especially for the hand-held impact tower since it has its own attachment system. The attachment system for the QSI and impact tower were the same. Two types of indenters are used for the impact tower and QSI test since the crack threshold due to impact differs a lot, a wider range of impact can be investigated with two different indenter radii. The indenters are made of Impax, a pre-hardened steel, manufactured by Uddeholm. It has a high toughness value, which makes it applicable for tools and impact testing. Impax is similar to P20 or 12738 steel [47].

The radius of the indenter has an effect on the damage occurring after impact. A large indenter radius requires more energy to achieve the same force as a smaller one. The impact energy and the stress are spread over a larger area for larger indenters, resulting in more plastic deformation (energy absorption), reducing the crack risk. A smaller indent radius results in higher localized tensile stresses, and a lower impact energy is needed for damage. For ductile materials such as AA1XXX, sharper indenters will allow less time for the material to plastically deform, leading to earlier cracking and brittle cracking. Radial cracks are more likely to occur first due to concentrated tensile stresses [48, 49]. The indenter used for the hand-held tower is almost the same as one of the indenters for the QSI/impact tower, this in order to be able to compare the results. The indenters are shown in Figures 4.5.

- Indenter hand-held tower: 12.7mm radius
- Indenter 1: 13mm radius
- Indenter 2: 6.5mm radius

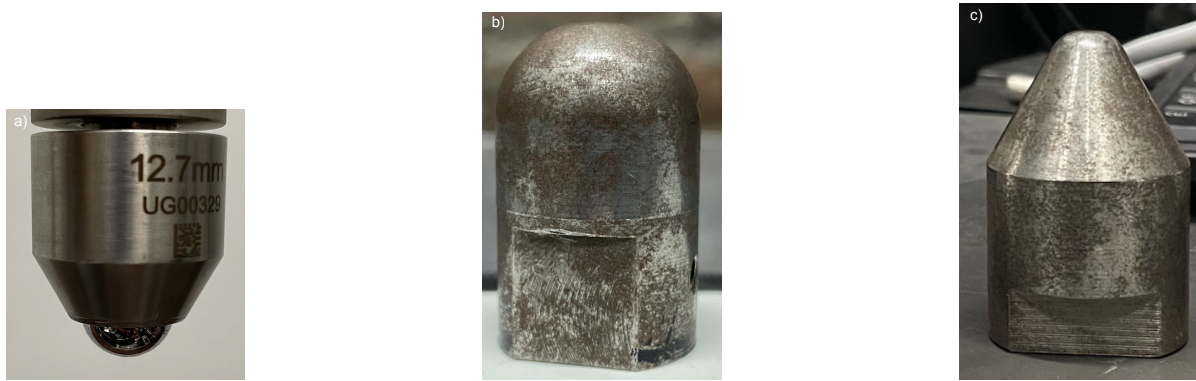


Figure 4.5: Indenter types: a) Hand held, b) Indenter 2, c) Indenter 3

4.2.3. Clamping system

The clamping system that was used is the same for the three types of impact tests, a 115x115 mm square block. The block clamps the specimen with four screws, one at each corner. The clamp has a cutout area of 90x90 mm. The impact was made exactly in the middle of the clamping system, being 45 mm away from the clamping edges. The choice for a rectangular clamping system compared to a circular system was made because of the cold spray coating dimensions. A circular clamping system, distributes the stresses more evenly over the specimen, but the circular clamp would have more overlap on the deposition surface, possibly damaging the cold spray deposition [50]. The rectangular clamp has less overlap on the cold spray coating, resulting in more pressure on the substrate. To protect the cold spraying deposition, two rubber plates are placed on the long ends of the substrate, where the clamping system presses on the deposition; see Figure 4.6. The clamping system was also used for the impact testing of the cowling. The cowling did start as a double curved coupon, however after cutting the coupon, the stresses in the coupon changed and resulted in a nearly flat coupon. The same clamping system as for the other coupons could thus be used for impact testing.



Figure 4.6: Clamping system

4.3. Data procession

4.3.1. Trial and error

The impact tests were done on a trial and error basis. Since there was no knowledge about the impact range at which cracks start to appear in cold spray, multiple tests were performed before the damage threshold was found. The threshold was found by starting at random amount of impact energy with indenter 2. By analysing the coupon for damage, it could be concluded if the next coupon should have a higher or lower impact energy in order to find the threshold. Only tests which were close to the damage threshold are shown and explained in this research. For the CSHP coupons seven trial and error tests had to be done before the threshold was found. For the MPAir deposition it took 10 tests, the RepAir continued with the found crack threshold for MPAir, reducing the trial test to three. For the Gun coupons no trial test had to be done as the testing started with the same impact ranges as RepAir in

which the threshold for crack was found for the Gun coupons. Two Gun coupon tests had to be retaken because the indenter did not hit on the right spot, the impact was made fully on the substrate resulting in disapproved tests. The test specifications per coupon type are listed in the table 4.1 below. For a full overview of the test data see Appendix, A.4, A.5. All the listed impact energies per coupon type were tested only once.

Table 4.1: Coupon impact specifics

Coupon type	Deposition	#of coupons produced	# of coupons analysed	Impact energies [J]	Impact tower	Indenter
CSHP - LVI	Coating	12	6	0.5, 1, 2, 3, 4, 5	Hand held tower	1
CSHP - QSI	Coating	6	5	0.5, 1.1, 2.4, 4, 5	QSI	2
MPAir	Coating	14	4	100, 125, 140, 157	Impact tower	3
RepAir - Mid	Repair	8	6	10, 20, 30, 40, 50, 100	Impact tower	3
RepAir - Side	Repair	8	7	10, 20, 30, 40, 50, 100, 147	Impact tower	3
Gun - Mid	Repair	6	5	10, 20, 40, 50, 100	Impact tower	3
Gun - Side	Repair	6	5	20, 50, 65, 85, 100	Impact tower	3
Cowling	Repair	4	3	20, 50, 100	Impact tower	3

4.3.2. QSI data analysis

For the QSI test the energy load on the coupon is calculated by integrating over the force-deflection curve. This is not exactly equal to the impact energy, used for the impact towers. However, in this research the energy loaded on the coupon at the peak force point will be called impact energy. This is to simplify the system and compare it with the results of the impact towers. To compare the QSI with LVI, the impact energies should be (close to) the same. Since the value of the impact energy of the QSI can only be retrieved after the test is done, some trials were run, in order to find the right amount of force and deflection leading to the required impact energy. The impact energy is found using Formula 4.3.

$$E = \int_{\delta_0}^{\delta_1} F(\delta) d\delta \quad (4.3)$$

To account for the machine's inherent-, compliance, and to isolate the true deformation from the elastic deformation caused by the machine, a compliance test is conducted and used in the calculations. The compliance values were calculated by running a test with the maximum force that was applied during the experiment, 3500N. The indentation was done on a very thick metal plate that does not deflect upon 3500N. The compliance value is calculated as follows from the force versus deflection curve Formulas 4.4 and 4.5:

$$C = 1/k; k = \frac{F_{max} - F_{min}}{\delta_{max} - \delta_{min}} \quad (4.4)$$

For every impact test, the deflection of the compliance test (matching the impact energy) is subtracted from the deflection of the impact test on the CSHP sample. The compliance values are listed in Appendix A.2, Table A.1.

$$\delta = \delta_{CSHP} - (C * F_{max}) \quad (4.5)$$

4.3.3. Energy absorption - Impact tower

The energy absorbed by the coupons is analysed using the kinetic energy of the indenter. During impact testing, part of the energy impacted on the coupon is dissipated through damage, cracking, and plastic deformation, the reminder is absorbed and released by other means like vibrations of the coupon due to the kinetic energy and returned to the impactor. The impact energy calculated using Formula 4.1 is higher than the actual impact energy. During the drop of the indenter, energy was lost to the air resistance and rolling resistance of the impact system. The kinetic energy going inwards the coupon and outwards is calculated with the velocity of the indenter right before and after the impact, using the data from the high-speed camera, as in Formula 4.5. The response of the coupon upon impact is complex, a simplification of the impact has been made to compare the different coupons and their behavior. As the rolling and air resistance of the indenter are small, it was assumed that all the kinetic energy measured right before impact, is the impacting energy, the kinetic energy going in the coupon. The kinetic energy loss of the indenter, the difference between E_{kin} and E_{kout} was assumed to be

fully attributed to plastic deformation and cracking or other damage mechanisms of the coupon. The absorbed energy is stated as the kinetic energy difference between the kinetic energy before impact and kinetic energy of the indenter after impact [51]. The formulas used for the analysis of the kinetic energy are shown below:

$$v = \frac{s_1 - s_2}{t_1 - t_2} \quad (4.6)$$

$$E_k = \frac{1}{2}mv^2 \quad (4.7)$$

$$E_{kabsorbed} = E_{kin} - E_{kout} \quad (4.8)$$

$$E_{kabs} = \frac{1}{2}m(v_{in} - v_{out})^2 \quad (4.9)$$

- v : Velocity of indenter
- v_{in} : Velocity of indenter before impact
- v_{out} : Velocity of indenter after impact
- s_1 : Distance between the indenter and coupon at location 1
- s_2 : Distance between the indenter and coupon at location 2
- t_1 : Time at location 1
- t_2 : Time at location 2
- m : Mass of indenter
- E_k : Kinetic energy
- E_{kin} : Kinetic energy indenter before impact
- E_{kout} : Kinetic energy indenter after impact
- $E_{kabsorbed}$: Amount of kinetic energy absorbed by the coupon

The pictures below, Figures 4.7 and 4.8 show the set-up of the impact tower and the two different locations of the indenter used for analysis.

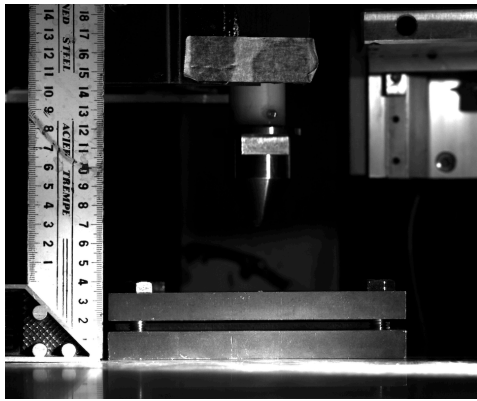


Figure 4.7: Location 1 indenter - high speed camera.

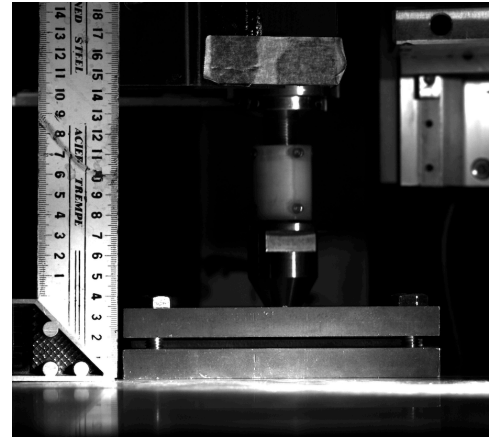


Figure 4.8: Location 2 indenter - high speed camera.

Percentage Absorbed Energy

The percentage absorbed energy from the kinetic energy right before impact is calculated using the following formula:

$$\%E_k = \frac{E_{kabs}}{E_{kin}} * 100\% \quad (4.10)$$

Dent depth model

The mechanical behavior of cold spray deposition have been studied. One model is found to predict the dent depth of a metal plate upon impact. The model uses a fitting parameter, which is used in this research to optimize the model for cold spray. By optimizing the model, the applicability of the model on cold spray can be examined.

Emerson and Souter [52] studied hail impacts on metallic plates, focusing on impact velocity, plate material properties and dent depth caused by hail impacting up to 762 m/s. A model was developed to predict the dent depth by the velocity and mass of the impactor, Formula 4.11 . The following assumptions are made for the model:

- The dent depth w , is small compared to the r , the radius of the plastically deformed region.
- The deformation is purely plastic and irreversible and fully resisted by the membrane forces.
- All the kinetic energy of the impactor is expended in the straining of the plate.

$$w = \frac{v\sqrt{m}}{\sqrt{\sigma_y t}} * k \quad (4.11)$$

v = initial velocity (v_{in}), m = mass, t = thickness of material, k is a constant: $\frac{1}{\sqrt{2\pi}}$ and can be replaced by a fitting parameter. σ_y is the yield strength of the material.

The yield strength required for the dent depth model is calculated with the Johnson-Cook model, 2.2 , using the parameters set for AA1XXX used by Blochet et al. [19]. These are the parameters for pure AA1XXX, so the addition of Al_2O_3 is not taken into account in the mechanical properties.

Normalization

The coupons have different thicknesses; to compare the outcomes of the test in the correct way, a normalized value was calculated for the dent depth, width, absorbed energy, and percentage of absorbed energy. The normalizing value was calculated by dividing the parameters by the coupons thickness, following Formula 4.12.

$$DentDepth_{normalized} = \frac{DentDepth}{thickness} \quad (4.12)$$

The thickness of the different coupons are listed in Table 4.2.

Table 4.2: Coupon thickness

Coupon type	Thickness [mm]
CSHP - 1	2.65
MPAir - 2	4.65
RepAir - 3	4
Gun - 4	4
Cowl	2.X

4.3.4. Characterization

After impact, all coupons were visually inspected. Starting with a 'naked eye' inspection of visible cracks with the naked eye at 0.5 m distance, this was done to determine if BVID could be present. Followed by an inspection at 5 cm of distance with the naked eye for cracks. The depth of the dent is measured and recorded with the TESA.hite 700.

Second, the coupons were inspected with the digital microscope Keyence 1000 - VHX-X1, and an overview picture was made. This in order to find potential cracks under higher magnification (20x-200x) and to make sure the damage due to impact is captured, before the coupons are cut. During the cutting process of the coupons in preparation for the SEM analysis, the coupons could also be damaged, potentially initiating cracks. To be sure the cracks were initiated by the impact test, pictures

before and after cutting are made with the Keyence. The dent width was also measured and noted under a 30x magnification with the Keyence 1000x.

After taking pictures of the indent with the microscope, the coupons were cut with the Struers Secotom-50. The coupons were cut in squares around the dent. The cut-outs range from 10x10 mm to 30x35 mm. The cutout coupons were cleaned with Acetone for 10 minutes and dried. The coupons were analysed from the top view with a Scanning Electron Microscope, SEM from JEOL (JSM-IT700HRLA), using both backscatter and secondary electrons for the analysis. Backscattered Electrons (BSE), are the result of an elastic collision of electrons with atoms in the sample and have high enough energies to penetrate into the sample. They can provide valuable information on the crystallography and topography of the sample. Secondary Electrons (SED) originate from the near-surface of the sample. They are the result of inelastic collisions between primary electrons and the sample. Secondary electrons are valuable for inspecting the topography and surface of the sample [53]. The coupons were also analysed from the side, a cross section was made and inspected with the Keyence and SEM. The SEM was used to find cracks, measure crack length and width, location of the cracks, and to distinguish interparticle from transparticle cracking and transverse and radial cracks.

The coupons were cut close to the dent for the cross sectional view. The coupons are embedded, ground and polished in order to highlight the microstructure; This process was carried out with the Struers Tegramin-30, following the 'Metal' program with 5 different grinding and polishing sheets.

Crack type

Since cold spray deposition remains in solid state structure of the powder particles, interparticle and transparticle cracking may occur. Interparticle cracks propagate along the particle boundaries, whereas transparticle cracks grow through individual particles. The transparticular cracking mainly occurs due to perpendicular loading, correlated to a high fracture toughness in the out-of-plane direction. Interparticle cracking occurs mainly due to in-plane loading and occurs predominantly in the shear mode. This type of crack requires less fracture energy however, it follows a longer crack path as the crack grows around particles, making the crack energy threshold more equivalent [23]. The type of crack can be identified through the fracture surface, as a smooth surface corresponds to an interparticle crack (brittle, black arrow) and a rough fracture surface corresponds to a transparticle crack (ductile) having a cup and cone type of ductile pattern on the particles (white arrows) [24]. The differences can be seen in Figure 2.10.

Cracks could also be designated based on their position relative to the shape of the indent and are influenced by the type of stress. Radial cracks propagate outward from the central point of indent, like the radius. The cracks move perpendicular to the loading surface and propagate away from the stress point along with the stress waves. The impact waves cause radial strains in the material, pushing the material outwards. Materials with low ductility tend to develop radial cracks when subjected to impact, also thin coatings are more prone to radial cracks as the tensile stresses concentrate at a point. Extensive milling could induce radial cracks as the residual stresses change from compressive to tensile.

Tangential cracks run parallel or along the walls of the indent in ring-like or concentric circles. The cracks occur due to stretching of the material around the dent, to accommodate the outward motion. Tangential cracks are common in layered structured materials, as weak bonding strength could cause delamination, tangential cracks also occur in thick coatings which undergo significant stress relief during milling [54, 55]. Tangential cracks are divided in straight-tangential cracks and ring-like tangential cracks for this research. The different type of cracks are visualized in Figure 4.9.

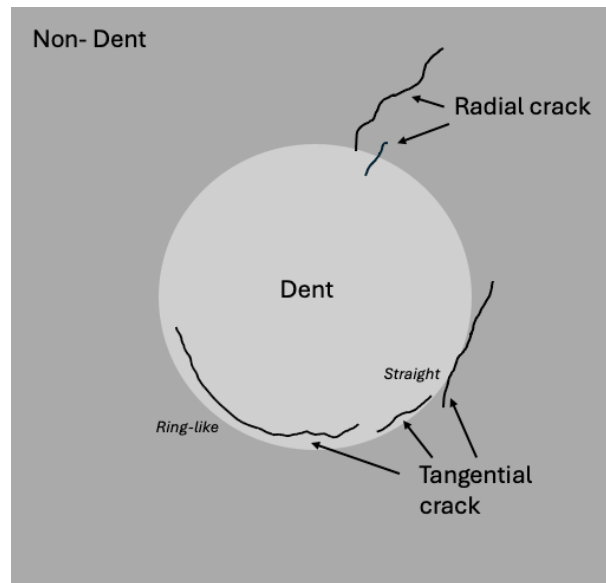


Figure 4.9: Radial and Tangential cracks

4.4. Flowability

A rheometer and a laser diffraction analysis (LDA) were used to measure the flow and deformation behavior of the two different metal powders, AA2024 and AA1XXX. The rheometer test characterizes how a material responds to applied forces and how it flows. The rheological properties help to optimize the spraying conditions. Good flowability and compressibility ensure steady powder feed, proper particle velocities, and uniform powder streams. The most important properties that were measured are the following:

- Compressibility: How density changes upon applied normal stress. The higher percentage relates to more densification under stress, forming denser deposition.
- Basic Flowability Energy (BFE): energy required to create a particular flow. If the flow in the cold spray nozzle is not consistent, the powder will cause blockages/clogging and uneven depositions. Lower BFE values mean an easier powder flow, less energy is needed to let the powder flow, and thus is desirable.
- Flow Rate Index: The sensitivity of the powder to flow rate. Cohesive powders are more sensitive to changes in the flow rate than noncohesive powders, mainly because of the high air content in the cohesive powder. Higher flow rates attract more air, the air acts as a lubricant, reducing the contact between particles, and allowing the powder to be more compressible. This reduces the energy required for the flow, which improves the flowability.

The LDA measures the particle size distribution; in general larger particles reduce the critical velocity required for bonding. However, excessively large particles may not be accelerated enough to achieve the critical velocity. On the other hand, smaller particles plastically deform easier, resulting in higher deposition efficiencies and less porosity. The following three parameters are used for the analysis:

- $D[4,3]$ is the diameter of the volume weight, representing the average size.
- $Dx(50)$ says that 50% of the particles are smaller than this size, the median particle size.
- The span describes the uniformity of the particle size. A value close to 1 means a narrow distribution, the particle sizes do not differ much. A value 2 means a polydisperse distribution.

5

Results

In this section, the results of the experimental work done in this thesis are discussed. First, the bonding of the deposition and substrate are shown and the different surface morphologies are outlined. Second, the different thresholds are presented per coupon, followed by the characteristics of the cracks. The section continues with the data analysis in which the absorbed energy is plotted and compared. The flowability test results and the differences between the LVI and QSI tests are shown at last. Due to the large amount of data and images, supplementary figures and data tables of the results are presented in the appendices.

5.1. Deposition bonding

5.1.1. AA2024 deposition

The bonding interfaces between the substrate and the cold spray depositions of the CSHP and CSMP coupons are shown in Figure 5.1 and 5.2. For the CSHP coupons, both the substrate and deposition were composed of the AA2024 alloy, making it difficult to visually distinguish the interface. A thin interfacial line was observed, with individual powder particles still lightly visible. Black regions appeared within the deposition layer, suggesting the presence of porosity, which likely reduced the mechanical properties of the coating. The average particle size in the CSHP deposition was measured to range between 10 and 50 μm . In the case of the failed CSMP coupons, the deposition and substrate again consisted of the same alloy, resulting in similarly low contrast between the two regions. Compared to the CSHP samples, the particle boundaries in the CSMP coupons were even less distinguishable, and the particle penetration depth could not be reliably determined. The substrate showed visible pink regions, corresponding to copper-rich areas characteristic of the AA2024 alloy. Compared to CSHP, the CSMP coupons exhibited fewer dark regions, indicating a lower porosity level. However, the lack of clear distinction between the deposition and substrate made it difficult to assess the bonding quality or the depth of impact from the sprayed particles. The particle size in the CSMP deposition ranged from 25 to 50 μm . In cross-sectional microscopy images, the copper-rich regions appeared as pink or dark specks. Notably, these were only present in the substrate material and not in the deposited layer, further suggesting differences in particle formation and thermal history between the substrate and the cold sprayed coating.

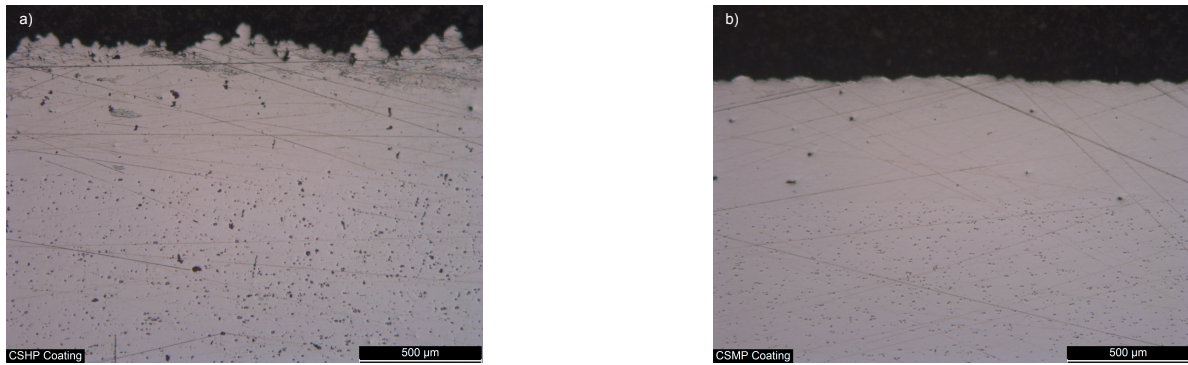


Figure 5.1: Bonding quality, a) CSHP - 168x, b) CSMP - 168x

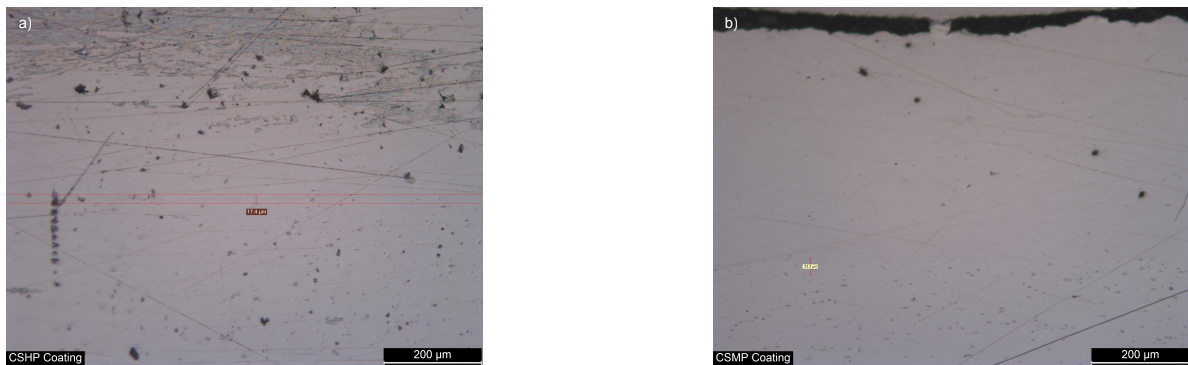


Figure 5.2: Bonding quality, a) CSHP - 336x, b) CSMP - 336x

5.1.2. AA1XXX deposition

For the MPAir coupons, the coating was clearly distinguishable from the substrate. The AA1XXX deposition layer appeared with high contrast, and numerous dark inclusions—identified as aluminum oxide (Al_2O_3) particles—were visible within the deposition, see Figure 5.3. These Al_2O_3 particles contributed to the bonding process by impacting the substrate, breaking the oxide film, and promoting bonding through localized plastic deformation. The particle penetration depth for the MPAir coupons was measured between 50 and 55 μm , highlighted in Figure 5.4. In the RepAir coupons, the penetration depth was even greater, ranging from 63 to 75 μm . The first layers of deposited powder particles were still visible, embedded into the substrate, indicating strong mechanical interlocking. The average particle size for both the MPAir and RepAir coatings ranged from 5 to 20 μm . The Gun coupons also exhibited a clear contrast between the deposition and the substrate. However, the particle penetration depth was shallower, measured between 30 and 35 μm . This shallower penetration may correspond to a weaker mechanical bond between the substrate and the deposition. The average particle size for the Gun coupons was slightly larger, ranging from 10 to 25 μm .

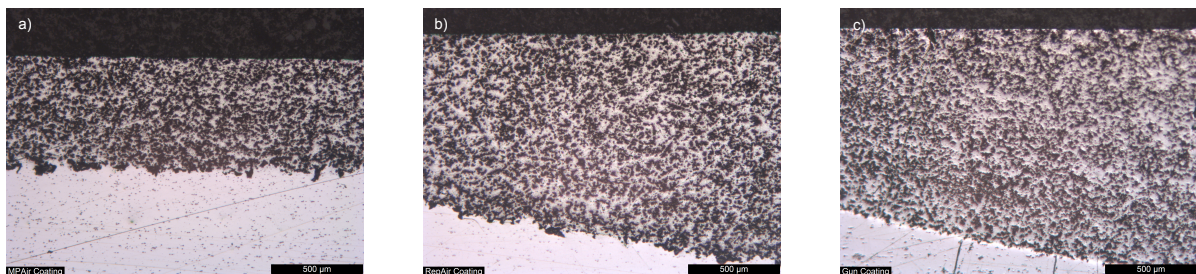


Figure 5.3: Bonding quality, a) MPAir - 168x, b) RepAir - 168x, c) Gun - 168x

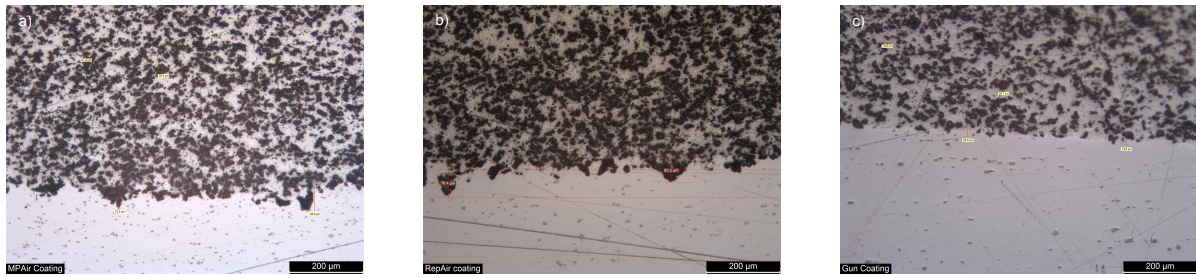


Figure 5.4: Bonding quality, d)MPAir - 336x, e) RepAir - 336x , f) Gun - 336x

Table 5.1: Particle size

Coupon	Datasheet Titomic μm	After spraying μm
CSHP	5-30	10-50
CSMP	5-30	5-50
MPAir and RepAir	5-50	5-25
Gun	5-50	10-25

Following the data retrieved from the powder supplier Titomic, it can be seen that the CSHP and CSMP particle size are larger after spraying. The particles flatten due to plastic deformation during the bonding process [56].

5.2. Surface analysis

The deposition surface was analysed with the SEM to exam the quality of the bonding between the particles. Particles in crack openings were analysed and a characteristic features was observed. A dimple pattern of ductile fracture is also observed at the surface of the particles in the MPAir coupon, see the red arrows in Figure 5.5, suggesting a bounce back of particles, as the particle were not able to bond [24].

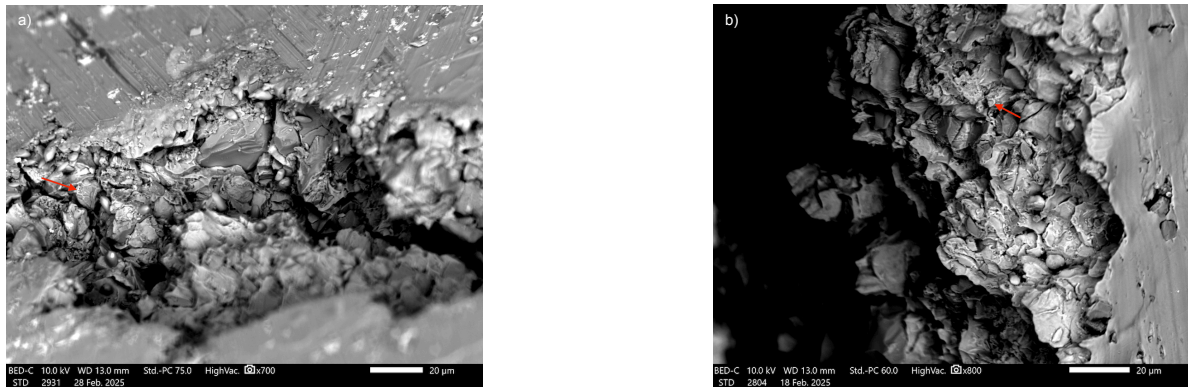


Figure 5.5: Surface morphology of disrupted particle-particle interface of MPAir coupon (157J), a) 700x, b) 800x

Comparative analysis of the coating surfaces revealed notable differences among the CSHP, CSMP, and MPAir coupons. The CSHP coating, Figure 5.6a, exhibited a loosely packed particle structure with minimal interparticle bonding. The particles appeared to sit freely on top of each other, indicating weak cohesion and suggesting poor bonding quality. In contrast, the CSMP coupons, (Figure 5.8a) showed a highly dense and compact surface structure. The deposited particles formed fine, splash-like morphologies with little to no visible spacing between them. While this dense structure suggested improved bonding, it was actually a consequence of very low deposition efficiency (approximately 1%). The critical velocity required for particle bonding was not reached for most particles in the CSMP case. As a result, the majority of the particles did not bond but instead impacted previously bonded particles.

This caused additional plastic deformation of the bonded particles, leading to the dense appearance. For the MPAir and other AA1XXX-based coupons, Figure 5.7, the individual particles remained clearly visible in the non-milled surfaces. In milled samples, directional scratches were visible, corresponding to the milling path. The dark inclusions observed in the surface were attributed to aluminum oxide (Al_2O_3) particles, while the white features corresponded to precipitates in the AA1XXX alloy. In the substrate material, AA2024, copper-rich precipitates were visible as distinct white or dark specks.

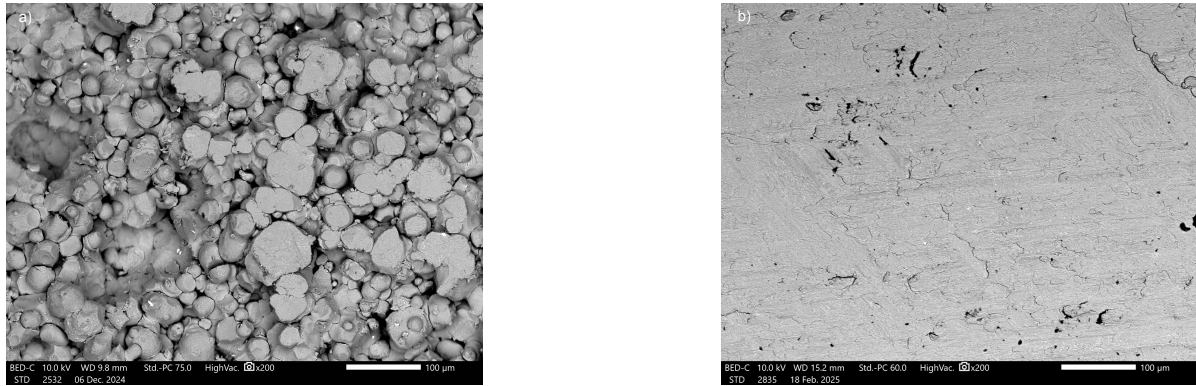


Figure 5.6: Surface morphology CSHP, a) natural - 200x, b) milled, 200x

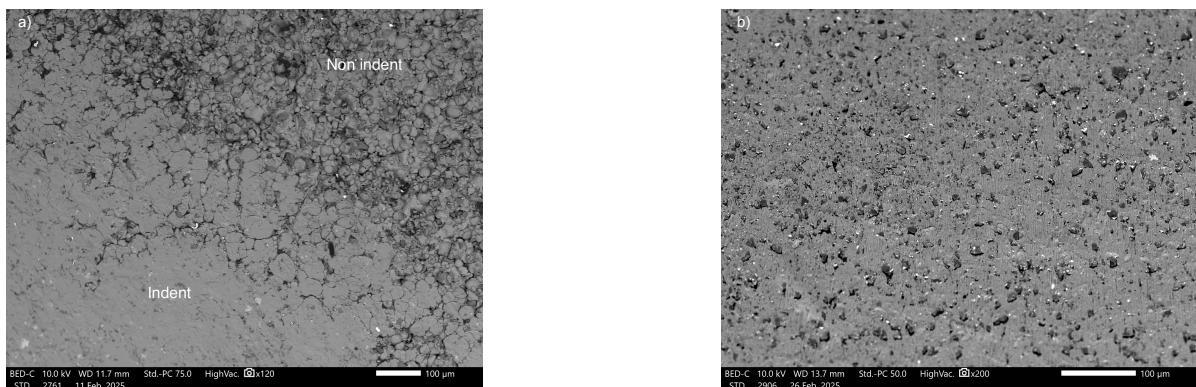


Figure 5.7: Surface morphology AA1XXX, a) natural - 120x, b) milled - 200x

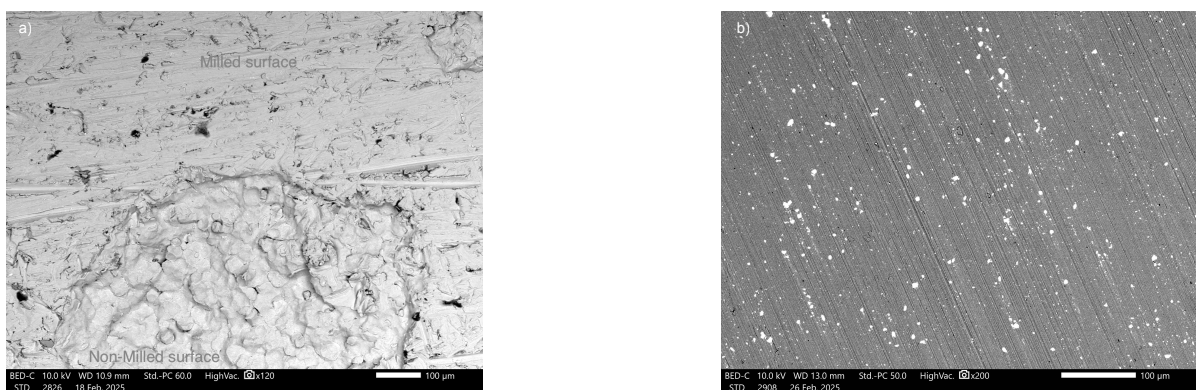


Figure 5.8: Surface morphology: a) CSMP - 120x, b) substrate AA2024 - 200x

Figure 5.9 presents a side-view of a RepAir coupon. In this image, the distinction between the deposition and the substrate was clearly visible. Al_2O_3 particles appeared as dark inclusions (red arrow), and copper precipitates in the substrate were identifiable as the white particles (green arrow). Al_2O_3 particle

accumulation was observed slightly into the substrate (blue arrow). This is attributed to the grit-blast process conducted prior to deposition, during which Al_2O_3 particles impacted the surface to create the necessary roughness. While the goal was to erode the substrate surface to form peaks and valleys, in some cases the Al_2O_3 particles became embedded instead of being expelled. The embedment of the grit (Al_2O_3), used during the surface preparation is commonly observed in soft metal substrates, so this phenomenon is not surprising.

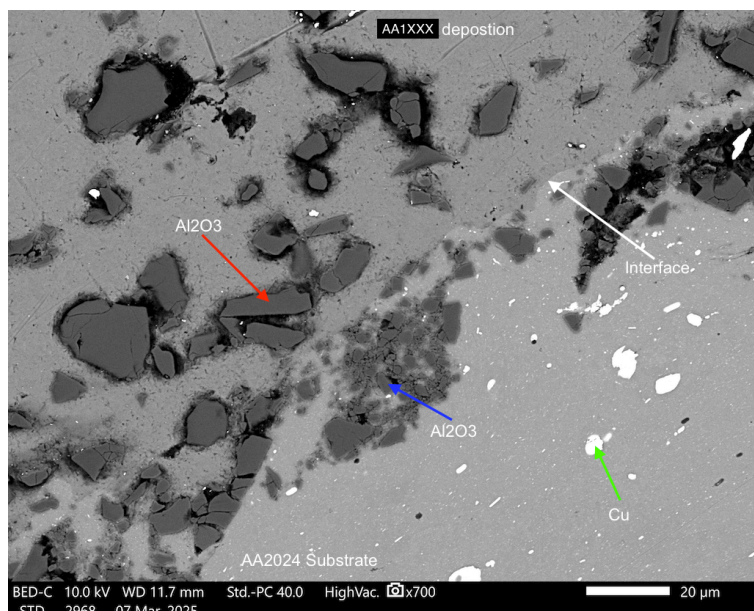


Figure 5.9: Cross section RepAir bond - 700x

5.3. Thresholds

5.3.1. Cracks

CSHP - Coating

Impact testing for the CSHP testing was done with the hand-held tower and the quasi static indentation test in the range from 0-5J of impact, using an indenter radius of 12.7 mm and 13 mm respectively.

The indents are shown in 5.10 and 5.11 for each impact energy, the cracks are pointed out by the red arrows. For the hand-held tower coupons, cracks were visible with the naked eye for 4J and 5J, for the QSI test a crack is visible only for the 4J of impact with the SEM also for 5J of impact. Examination of the coupons with the SEM found cracks for the hand-held impact test for 2J, 3J, 4J and 5J. The cracks in the coupons have a three split configuration as seen in Figure 5.12 The cracks come together in an area that has not been hit by the indenter. As can be seen in the SEM pictures, no milling or post-treatment has been done to the CSHP coupons. This results in a height difference over the deposition. Upon impact, not the whole region underneath the indenter has been hit and 'flattened', the lower layers of the deposition were not hit and kept their characteristic powder particle geometry, highlighted in Figure 5.12. For the 4J of impact, no cracks are visible in Figure 5.10, however the severity of the crack broke the coupon into two pieces along the right side, pointed out with the arrow. The crack lengths present in the hand-held coupon range between 2.8mm and 4mm.

For the QSI test, almost the same impact energies have been tested as for the hand-held tower, 0.5J, 1.1J, 2.3J, 4J and 5J. The QSI test impacted less surface compared to the hand-held impact test. Less particles were flattened as can be seen in Figure 5.11. However the dent width is bigger, leaving a wider but less uniform mark of indent. The average crack size of 4J and 5J are 3 mm and 3.5 mm respectively.

The hand-held impact tower showed a slightly lower crack threshold 1J-2J compared to the QSI, 2.3-4J.

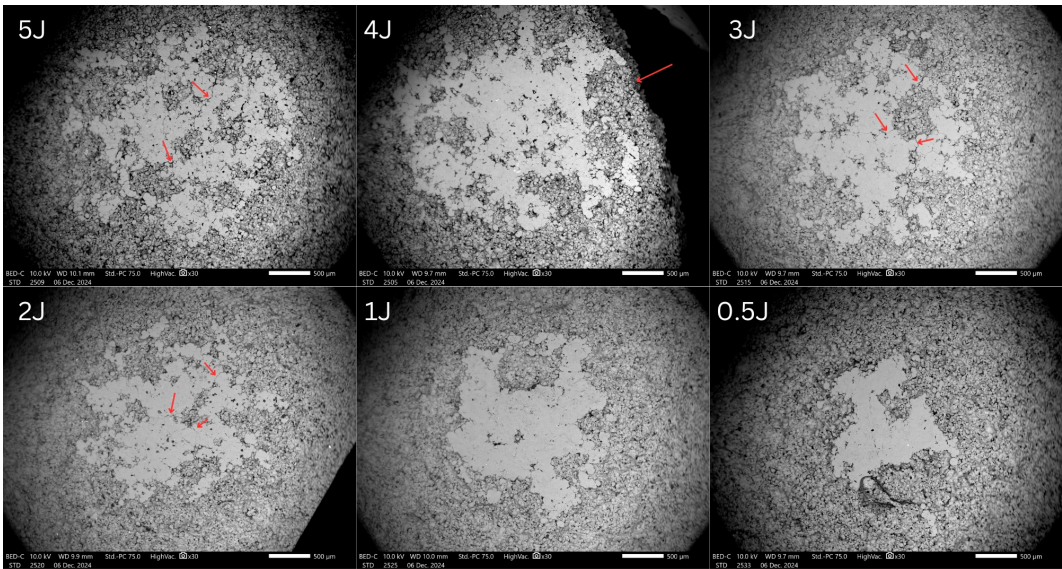


Figure 5.10: LVI impact dents per impact joule - 30x

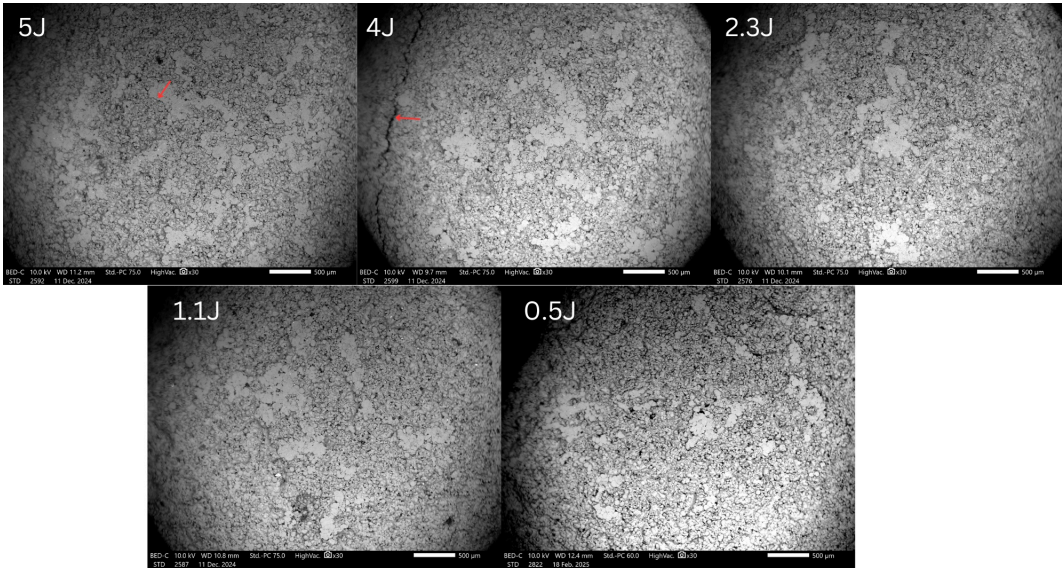


Figure 5.11: QSI impact dents per impact joule - 30x

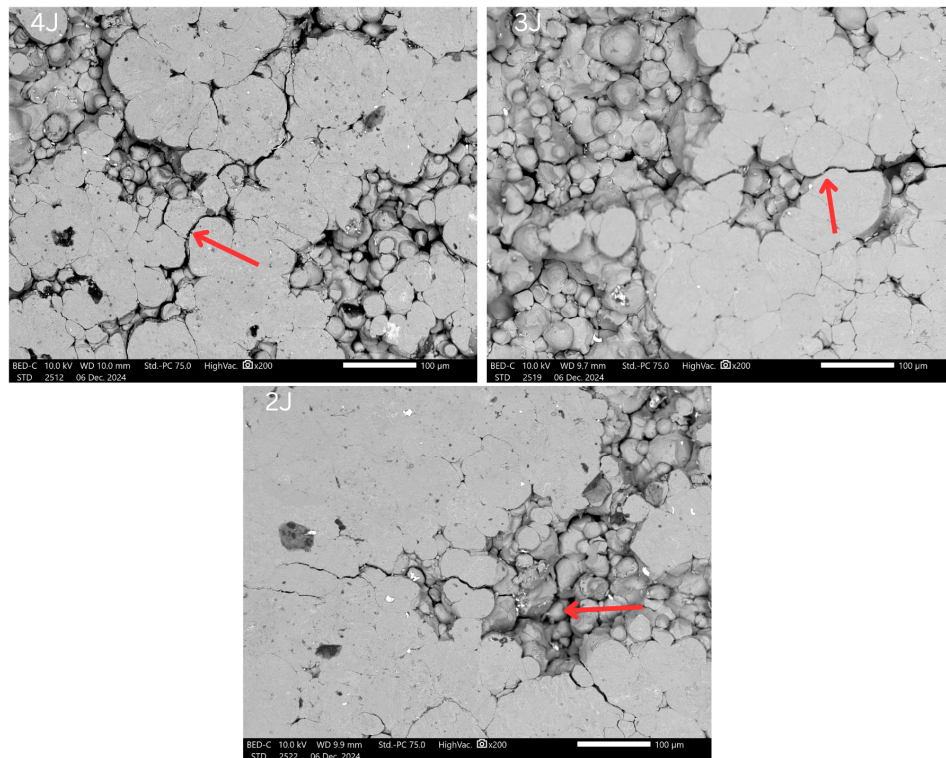


Figure 5.12: Cracks in LVI coupons - 200x

Repair Areas

The MPAir, RepAir Mid, Gun Mid and Cowling coupons have been impacted fully on the cold spray deposition (coating or repair). For the RepAir Side and Gun Side coupons, the impact is partially on the substrate. The different areas for the different coupons are visualized below in Figure 5.13.

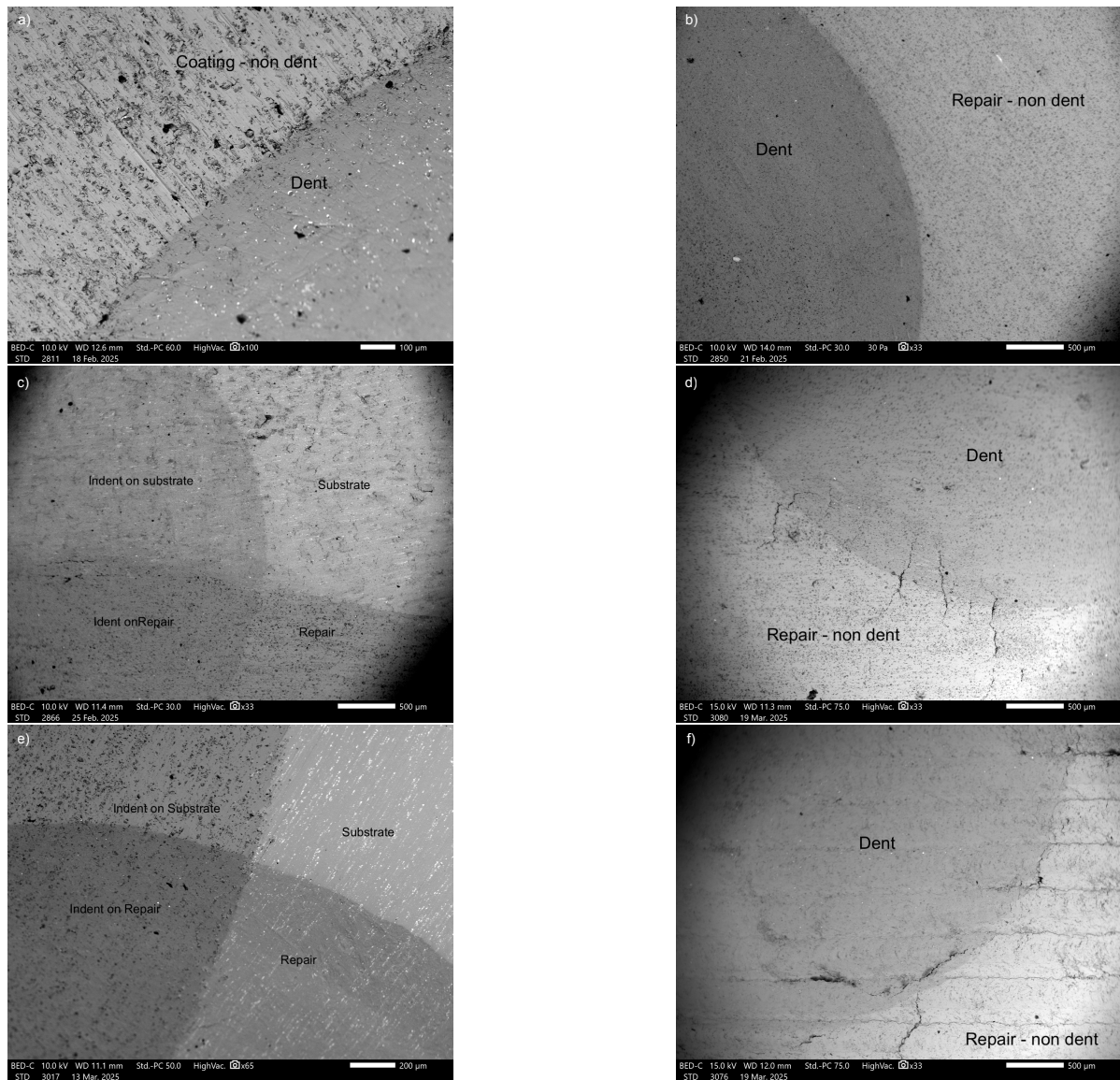


Figure 5.13: Surface of coupons 33x SEM a) MPAir, b) RepAir Mid, c) RepAir Side, d) Gun Mid, e) Gun Side, f) Cowling

MPAair 100-125J - Coating

The impact test of the MPAir coating coupons was performed with a different indenter diameter (6.5mm) compared to the CSHP coupons, since the crack threshold could not be reached with the impact tower and the wider indenter, 13mm. The threshold for cracks in the coating was found between 100J and 125J of impact. A radial crack (around 1880 μm) was visible with the naked eye for 125J of impact, while no cracks could be seen for the 100J impact, neither with the naked eye or SEM. The dents are visualized in the Figure below at a magnification 30, Figure 5.14, the cracks of several coupons are highlighted in Figure 5.15.

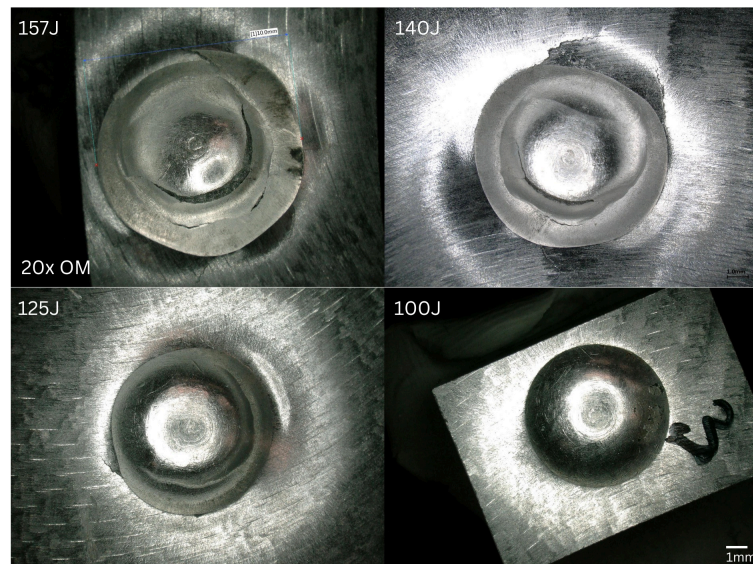


Figure 5.14: MPAir coupons after impact - 30x

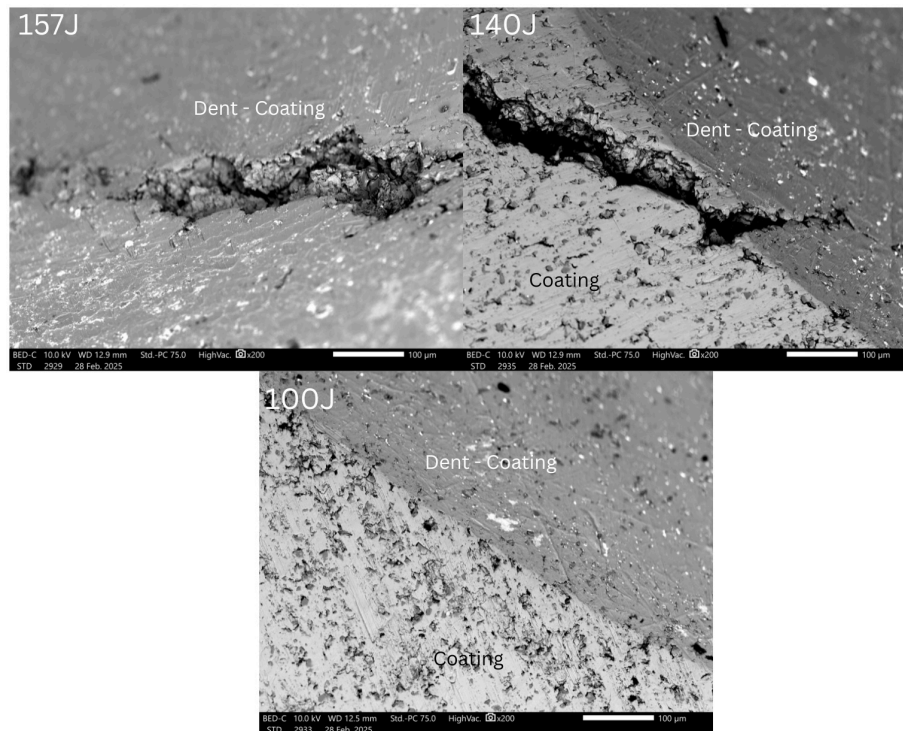


Figure 5.15: MPAir coupons after impact SEM - 200x

The 140J and 157J impact resulted in both radial cracks and ring-like tangential cracks in the sides on the dent. Radial cracks of at least $3000\ \mu\text{m}$ are visible with the eye for both 140J and 157J. The ring-like cracks are seen in both the lowest part of the indent, which is the first part hit by the indenter and still having a horizontal surface, as well as in the 'walls' of the indent, being vertical sides due to the plastic deformation. Some of the cracks in the wall grew all the way up outside the dent itself, transforming into radial cracks. Figure 5.16 shows the regions of the horizontal parts and the walls.

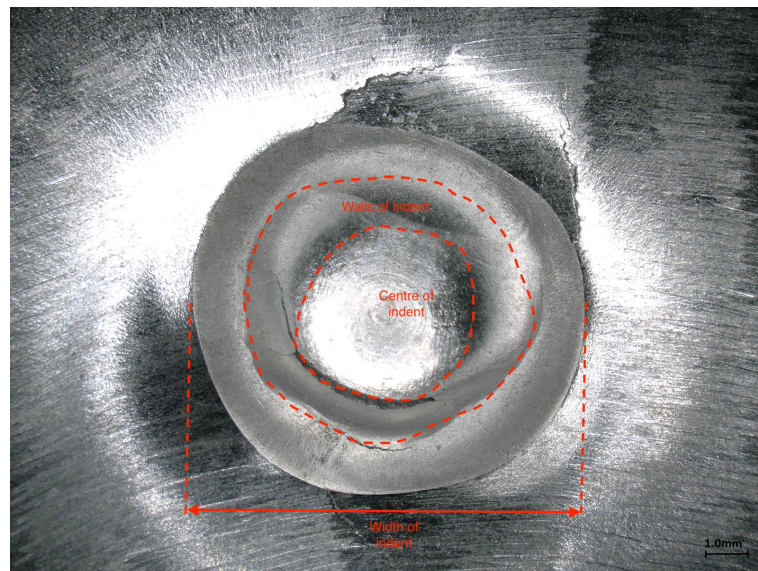


Figure 5.16: Regions in dent - 20x

RepAir middle indent - Repair

For the RepAir middle indentation, the impact range is between 10J and 100J. The threshold for cracks is between 10J-20J. The 100J impact showed an almost full ring-like crack outside the dent, with some radial cracks attached, and a two small ring-like (tangential) cracks in the walls of the indent. All visible with the naked eye, see Figure 5.17. The 50J coupon showed a mixture of tangential and radial cracks, mainly on the edge and outside the dent, visible with the naked eye. The 40J impact coupon showed four radial cracks, leading over the edge of the indent, with an average length of $250\ \mu\text{m}$, only visible with the SEM. The 30J did not show any cracks with the SEM, Figure 5.18. However, the 20J coupon did show cracks with the SEM. A small radial crack of $260\ \mu\text{m}$ is visible on the side of the dent. The 10J did not show any cracks with the SEM.

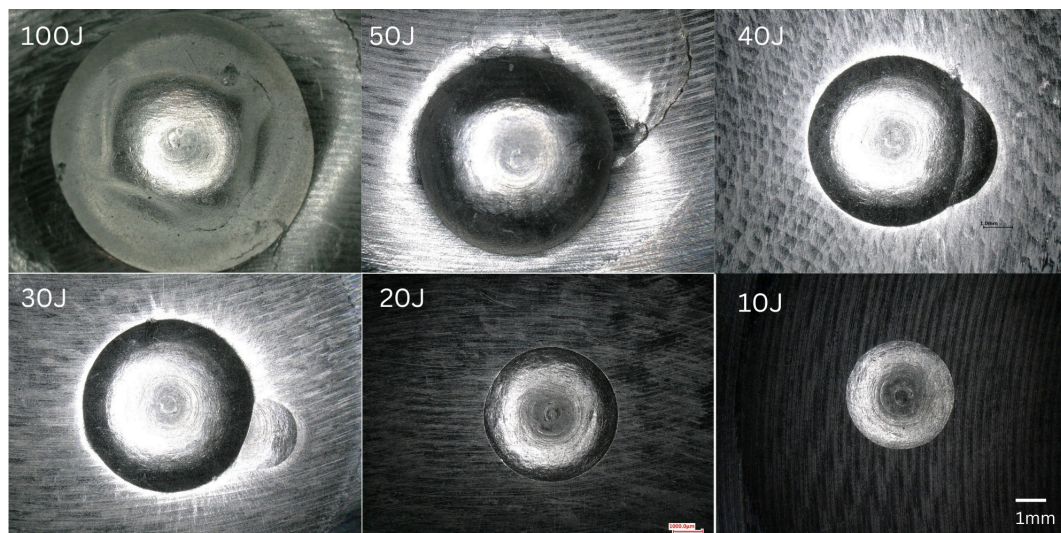


Figure 5.17: RepAir Mid coupons after impact - 30x

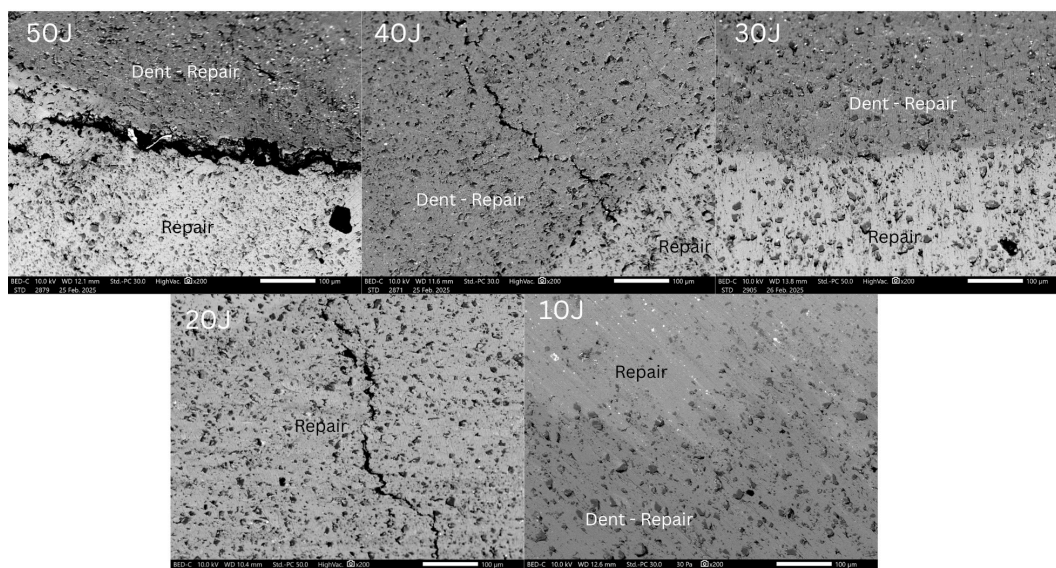


Figure 5.18: RepAir Mid coupons after impact - 200x

RepAir side indent - Repair

The impact range testing for the repaired coupons, coupon type 3, with an impact location at the side of the repair, started at the same range as for the MPAir coupons. The 147J impact penetrated the repair and substrate fully. Decreasing the impact energy from 100J to 10J showed that the threshold for cracks is between 20J and 30J. Only for the 100J impact energy cracks were visible with the naked eye, again ring-like tangential cracks in the dent wall were visible and two radial cracks which are connecting with each other outside the dent, see Figure 5.19. Both ends of the radial crack and the ring crack were located in the repair.

With 50J, 40J and 30J of impact, cracks were visible with the SEM, the cracks appeared on the outer region of the impact with a length between 300-350 μm , in the substrate material, see Figure 5.20. Most cracks were located just outside the dent, in the substrate material, while a few cracks are present in of the dent, in the substrate, Figure 5.20 shows the different regions. Interestingly, no cracks were visible in the dent region of the repair.

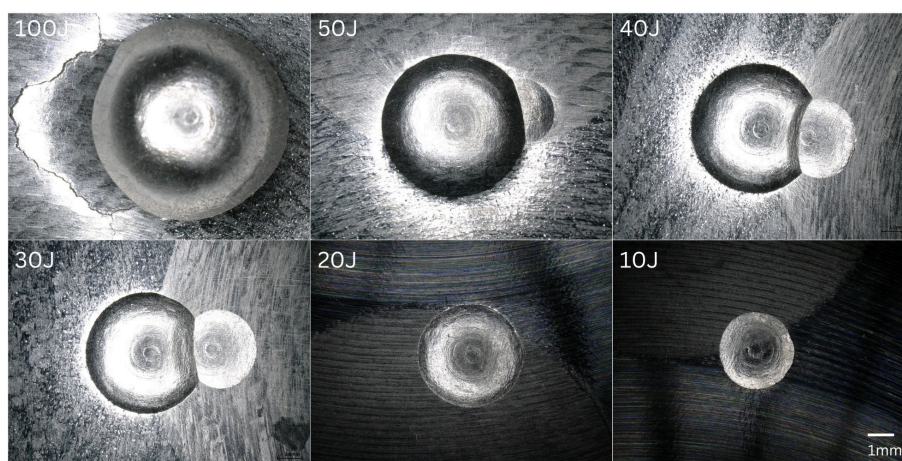


Figure 5.19: RepAir Side coupons after impact - 30x

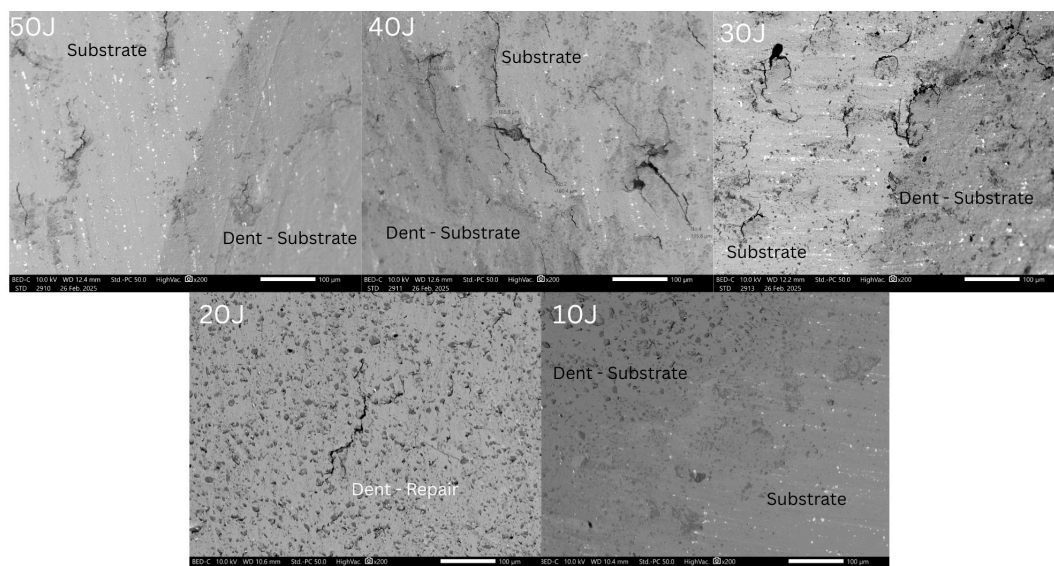


Figure 5.20: RepAir Side coupons after impact - 200x

Gun middle indent - Repair

The impact testing range for coupon type 4, with an indent in the center of the repair was 10J, 20J, 40J, 50J and 100J. Big cracks were visible with the eye for the 50J and 100J (around $3200\ \mu\text{m}$), one small radial crack was visible with the eye for both the 20J and 40J coupons (around $1600\ \mu\text{m}$), Figure 5.21. The 100J impact energy resulted in long radial cracks, one large ring-like crack in the wall and a few small ring-like cracks in the wall. The 50J showed two large radial cracks, connecting with each other and transforming into multiple cracks. The 40J showed multiple radial cracks in the side of the indent of around $1000\ \mu\text{m}$, starting inside the dent, going outwards in the non-impact direction. For the 20J impact, one big crack of $1600\ \mu\text{m}$, and multiple smaller ones around $260\ \mu\text{m}$ were visible. The 10J coupon only showed several small cracks, $< 127\ \mu\text{m}$, this is below the minimal crack length, so could not be called a crack. The threshold for cracks is between 10J and 20J for the Gun middle indent coupon, as can be seen from Figure 5.22.

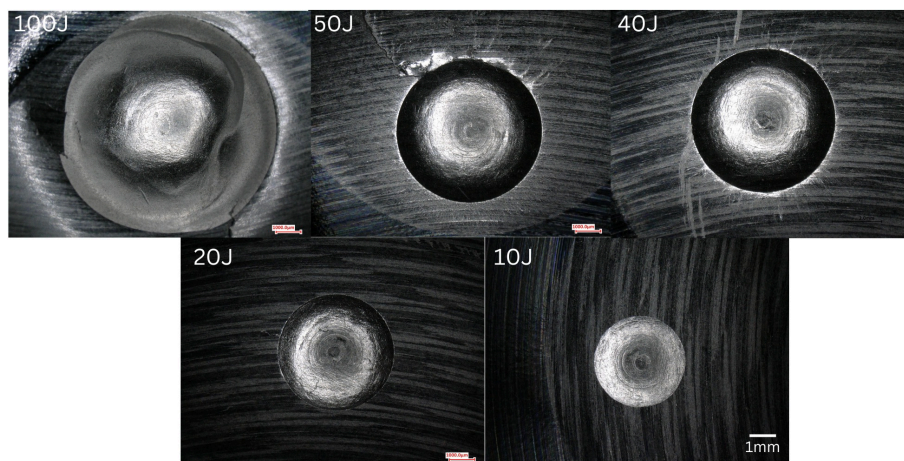


Figure 5.21: Gun Mid coupons after impact - 30x

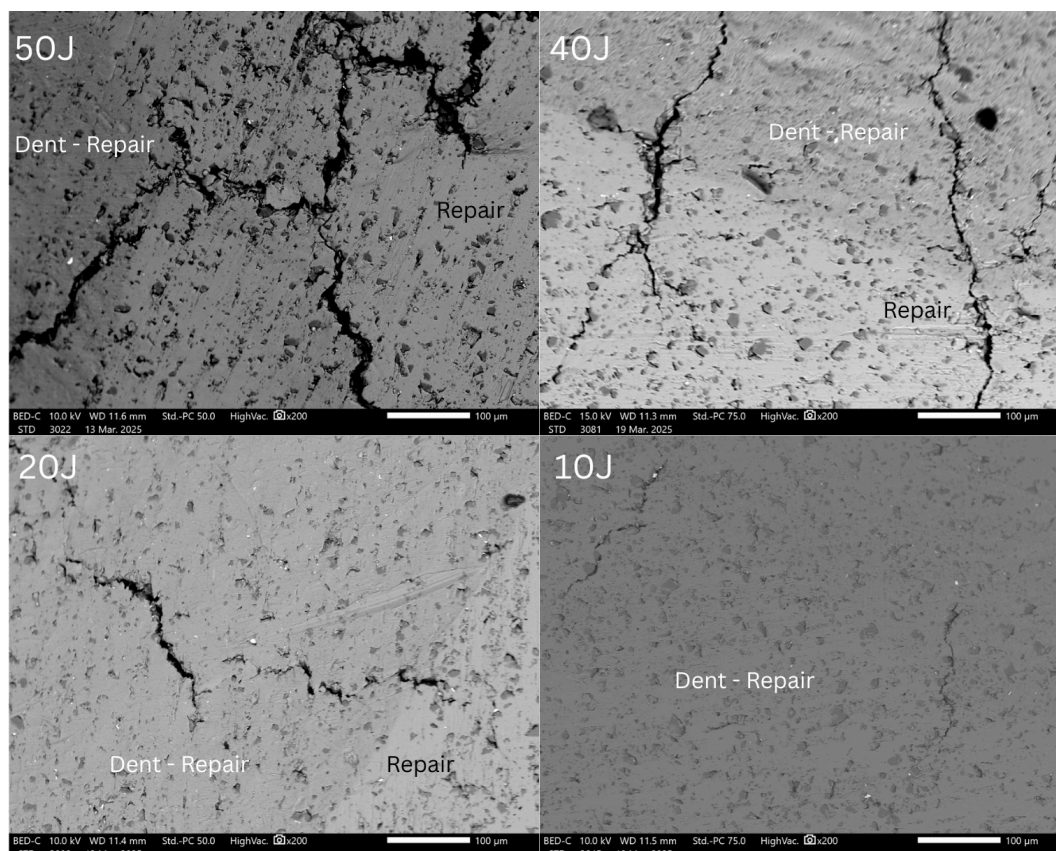


Figure 5.22: Gun Mid coupons after impact - 200x

Gun side indent - Repair

The impact energy levels of 20J, 50J, 65J, 85J and 100J were tested for the Gun middle indent coupons. The 85J and 100J showed big cracks visible with the eye ($3200 \mu m$), located in the repair, see Figure 5.23. The 100J had one severe radial crack and one tangential crack, along with a big ring-like tangential crack in the wall. The 85J coupon had two severe radial cracks, and one ring-like crack in the dent wall. Both the 20J, 50J and 65J impact did not show any cracks with the eye and SEM. The threshold for cracks on the fourth coupon is between 65J and 85J, corresponding with the threshold for visible cracks with the eye. Figure 5.24 shows the different areas without cracks for the other coupons.

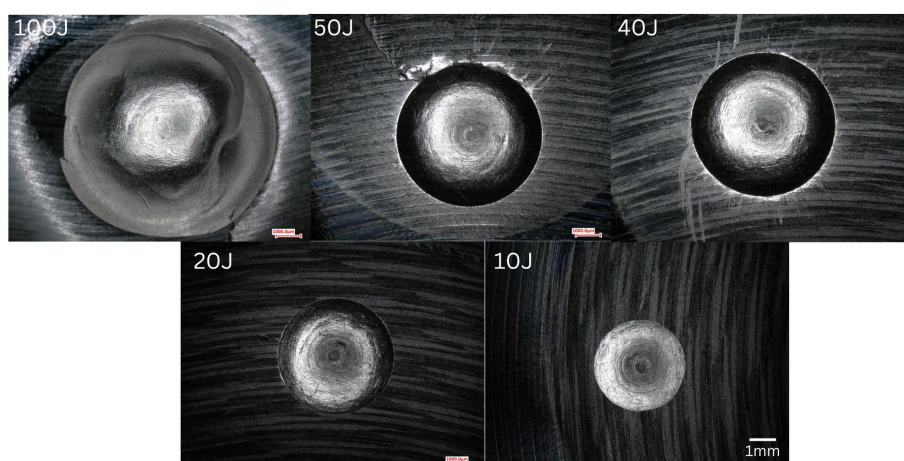


Figure 5.23: Gun Side coupons after impact - 30x

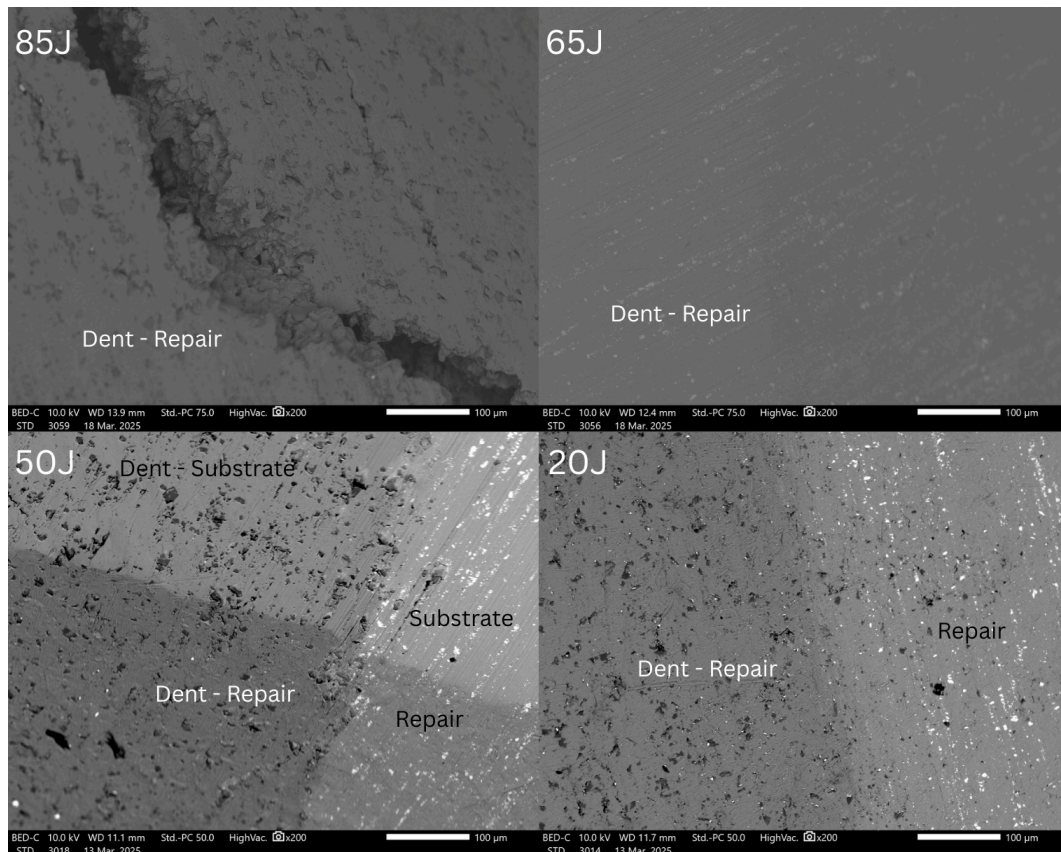


Figure 5.24: Gun Side coupons after impact - 200x

Cowling - Repair

Three pieces of cowling were impacted test with 20J, 50J and 100J. The 100J impact showed severe cracks visible with the eye; A large radial crack at the side of the indent and one large radial crack through the center of the indent (both around $2700\ \mu\text{m}$), Figure 5.25. The 50J showed very small cracks $< 127\ \mu\text{m}$, which is below the minimal crack length. These cracks were visible within the milling lines. For the 20J of impact, multiple cracks were visible ranging up to $1000\ \mu\text{m}$ in length. Both radial and straight tangential cracks are seen around the edges of the indent, Figure 5.26. The crack threshold for the Cowling is difficult to determine since the 50J of impact did not result in cracks. Since multiple cracks are seen for the 20J of impact, the threshold for cracks in the Cowling is set between 0J-20J.

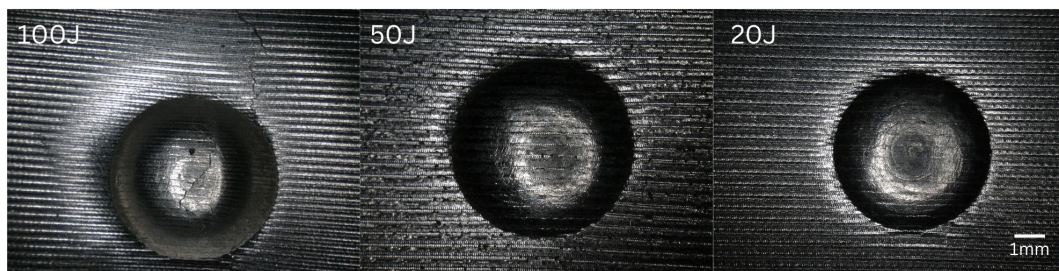


Figure 5.25: Cowling coupons after impact - 30x

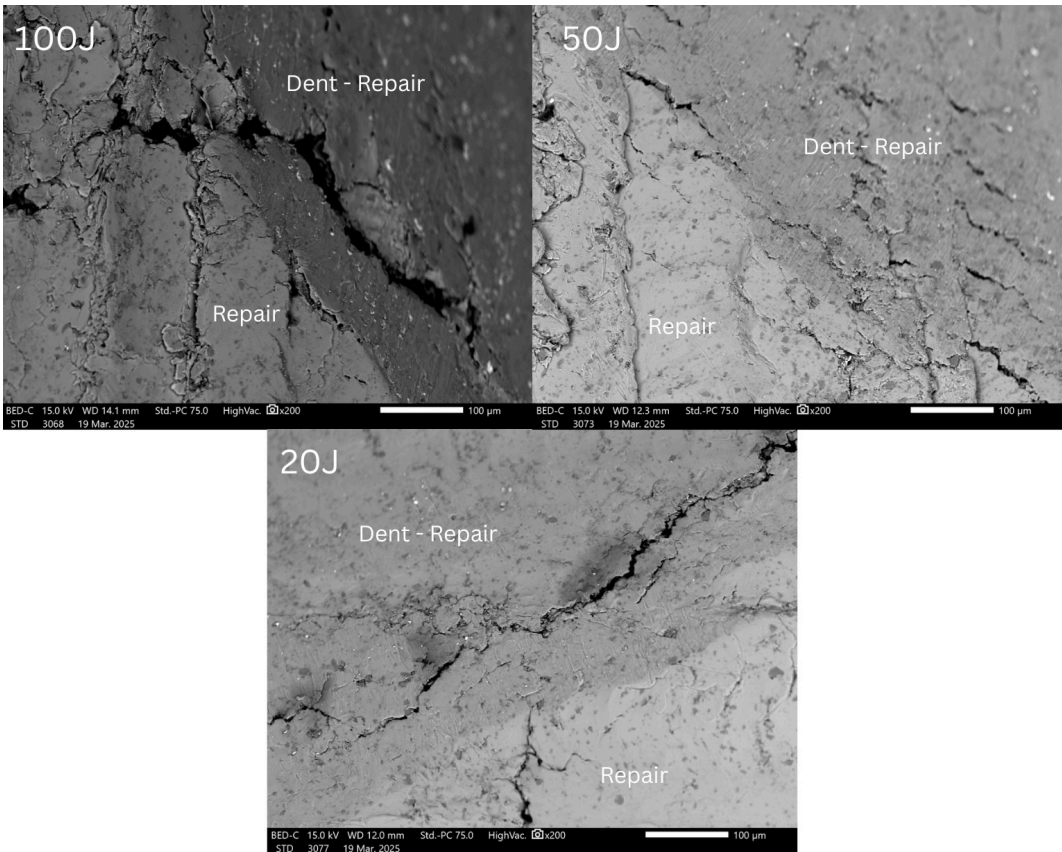


Figure 5.26: Cowling coupons after impact - 200x

Thresholds

The crack thresholds of all coupons are plotted in the graph below Figure 5.40. MPAir showed the highest crack threshold, followed by the Gun Side indent. The RepAir mid, side and Gun mid indent have the same crack threshold, closely followed by the Cowling threshold. The CSHP has a lower crack threshold which could be determined more precisely.

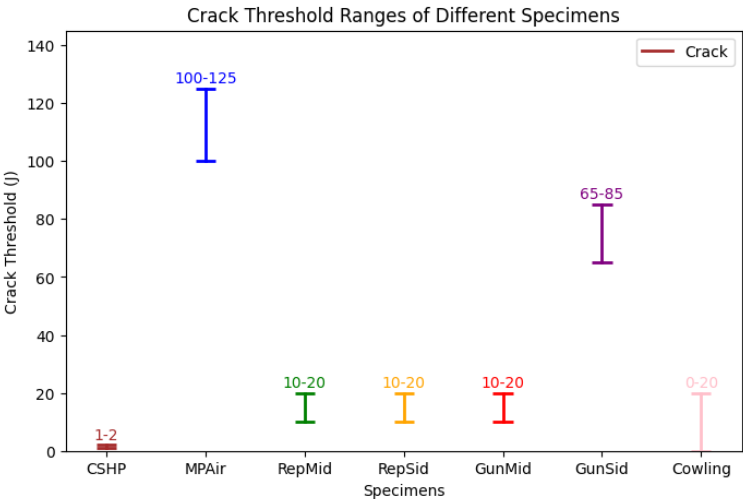


Figure 5.27: Crack Threshold

Type of crack

Within all the cracks, interparticle cracking is observed. However, it could not be examined for all the cracks if transparticle cracking occurred. The SEM analysis is difficult because of the height difference in the coupons. For the CSHP and MPAir coupons, it looks like transparticle cracking is observed, for an impact energy of 4J and 140J, respectively. Figure 5.28 shows the two cracks that are mainly interparticle, but the red arrows point out the two sides of a crack that might look like transparticle. The cup and cone surface is visible on the surface of the particles, indicating transparticle cracking following research of Bae et al. [24].

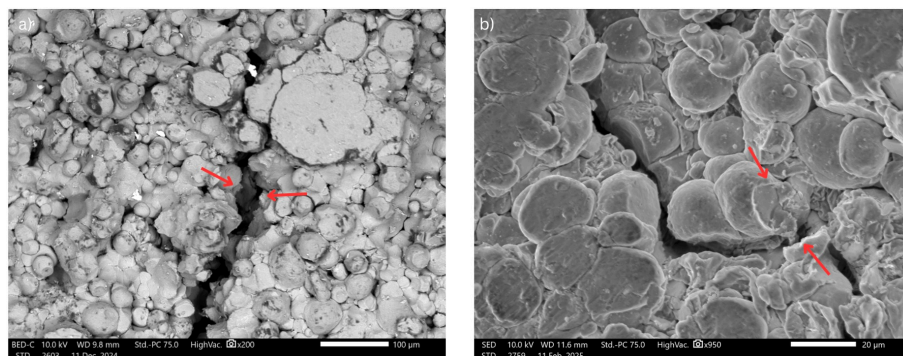


Figure 5.28: Crack in deposition a) Transparticle crack CSHP - LVI 4J coupon - 200x, b) Transparticle crack in MPAir 140J - 950x

5.3.2. Delamination

CSHP

Delamination between the substrate and deposition did occur for the CSHP coupons, however, not for all of them. Some coupons were shown to have some delamination due to impact; other depositions were completely removed during the cutting process. It was noticed that for the CSHP coupons, no pre-treatment/surface roughening was done on the substrate, resulting in a weaker bond between deposition and substrate. Delamination due to impact occurred for 4J and 5J of LVI coupons, while for the QSI test delamination only occurred for 4J of impact. Delamination of the 4J LVI test is shown in Figure 5.29. Thus, the threshold for delamination for the CSHP coupons is between 3J and 4J.

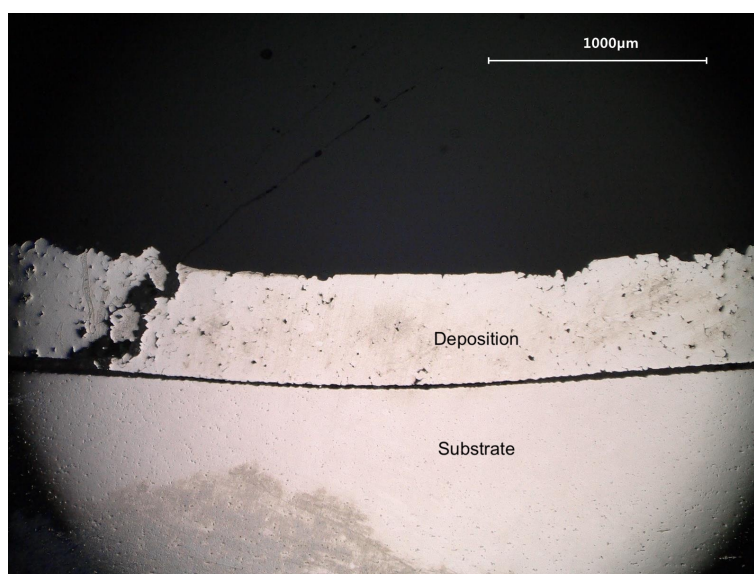


Figure 5.29: Delamination deposition in CSHP 4J (LVI) - 100x

MPAir

Delamination for the MPAir coating coupons is observed after impact, see Figure 5.30. The delamination occurred within the dent itself. A cross-section view was made to visualize this. The pictures in Figure 5.37 show clear delamination for the 125J and 140J of impact, 2.4 mm and 1.2 mm respectively. For 100J of impact no delamination was seen, so the threshold lies between 100J-125J. The delamination does not occur throughout the whole deposition, the delamination occurs mainly in the most deformed parts of the dent.

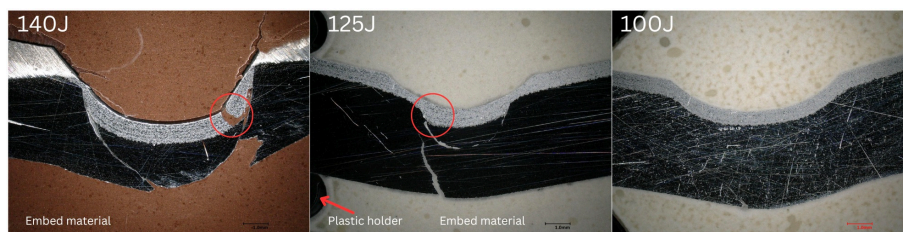


Figure 5.30: Delamination in MPAir coupons - 30x

The two Figures in 5.31 below are zoomed in on the red circles of Figure 5.30 of the a) 140J and b) 125J, highlighting delamination between substrate and deposition.

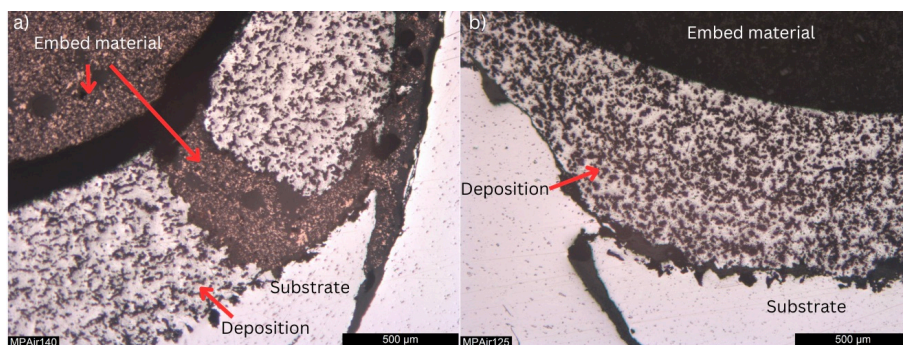


Figure 5.31: Delamination in MPAir coupons a) 140J impact, b) 125J impact - 168x

RepAir

For the RepAir Mid indent no delamination is observed at 100J of impact, this is the highest impact energy applied; however, it can not be excluded that no delamination will happen at higher impact energies, Figure 5.32. The RepAir Side indent showed delamination for 147J of impact, the indenter has penetrated the coupon fully, leaving severe damage as well as delamination. For the 100J of impact, no delamination is observed in the side view. The 147J of impact coupon is not presented since no clear picture could be made of the coupon. The coupon underwent such severe damage that it was impossible to cut and embed the right part in order to visualize the cracks and delamination.

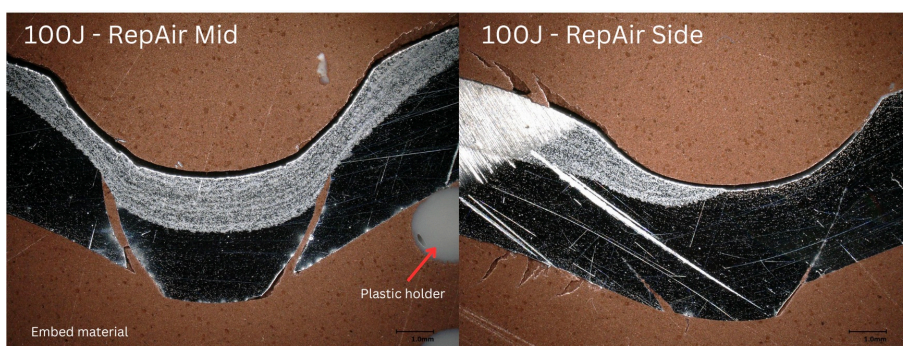


Figure 5.32: RepAir Mid and Side cross section - 30x

Gun

The Gun Mid indent showed delamination for the 100J of impact but not for the 50J of impact. The delamination length is around $3066\ \mu\text{m}$ on both sides of the indent, see Figures 5.33 and 5.34. The Gun Side indent showed delamination for 100J and 85J of impact, with a length of approximately $1817\ \mu\text{m}$ for the 100J. Delamination of the 85J coupon could be observed by analyzing the top surface, which has a length of approximately $3000\ \mu\text{m}$. Figure 5.35 shows the 100J and 65J coupons and Figure 5.36 zooms in on the delamination side of the 100J coupon.

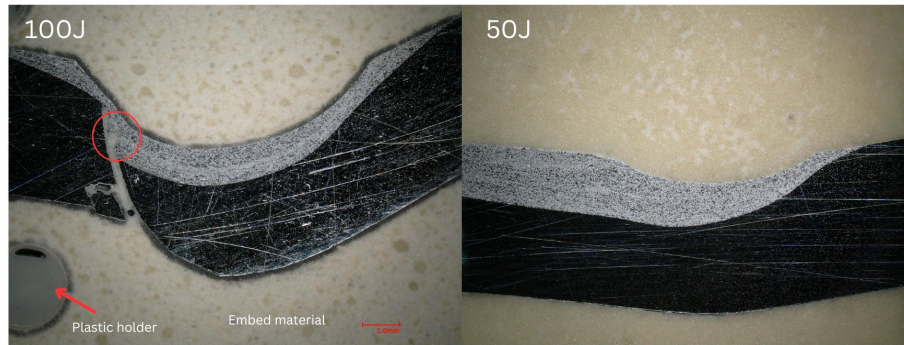


Figure 5.33: Delamination in Gun Mid coupon - 30x

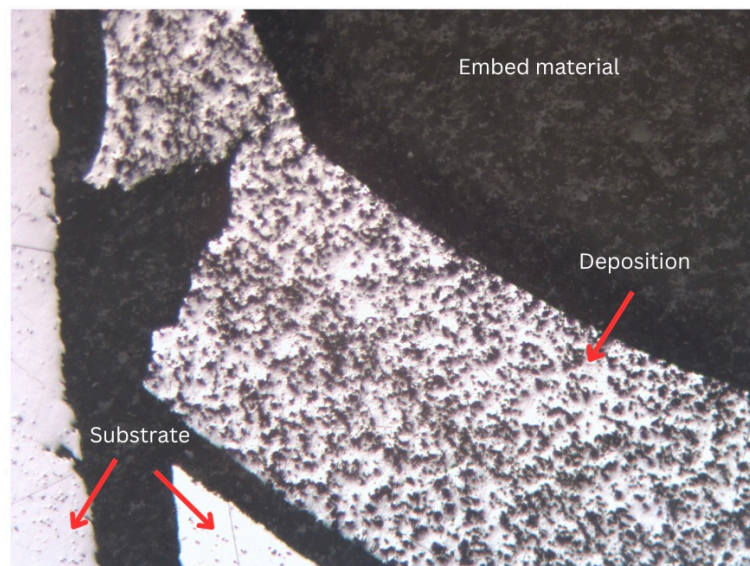


Figure 5.34: Delamination in Gun Mid coupon - 168x

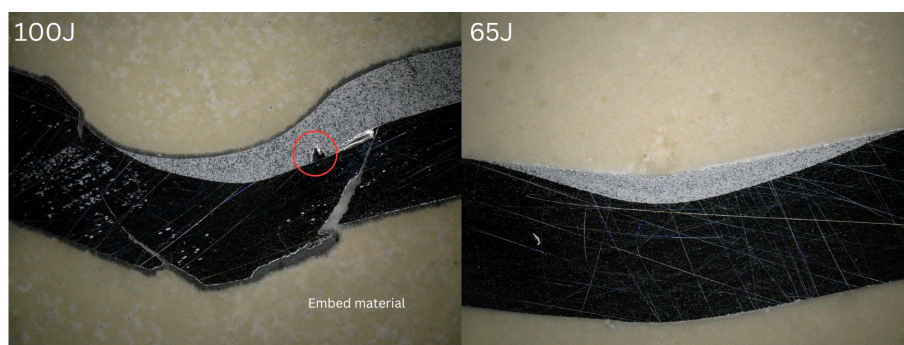


Figure 5.35: Delamination in Gun Side coupon - 30x

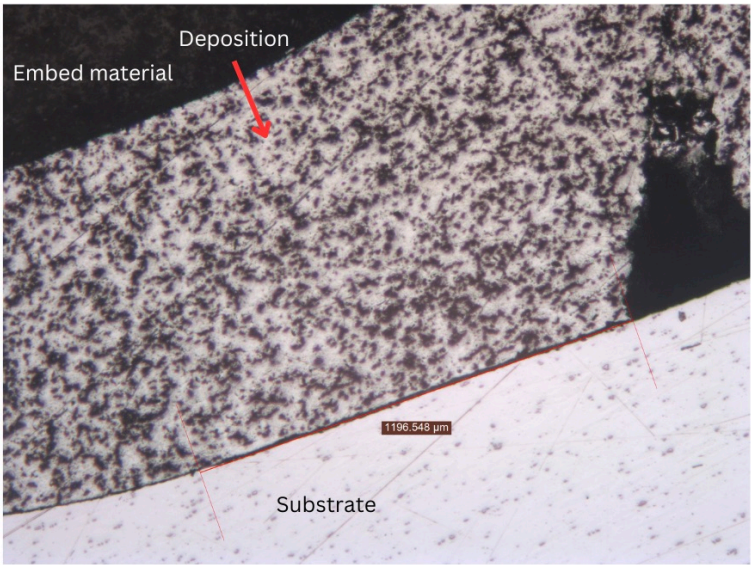


Figure 5.36: Delamination in Gun Side coupon - 168x

Cowling

Due to the complex geometry of the cowling, an analysis of the delamination could not be made. One cowling piece was cut in smaller pieces for microscopy analysis. However, the original cowling had a contour shape (unlike a flat plate), and sectioning relieved some of the residual stresses present within the cowling itself. This release of residual stresses resulted in a drastic change of shape, subsequently damaging the applied cold spray deposition and making the coupon unusable for this research. For this reason the choice was made to not further cut the cowling coupons, in order to not take the risk to damage the coupons which could lead to cracks or delamination. No range is found for the delamination for the coupon types.

Thresholds

The delamination thresholds are summarized in the graph below, Figure 5.37. The RepAir mid and side indent are in line with the MPAir delamination threshold. Both Gun coupons have a lower delamination threshold and the CSHP a significant lower threshold.

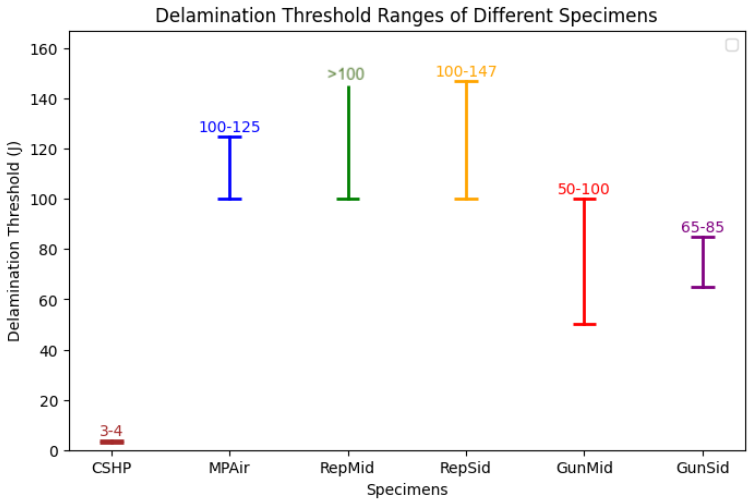


Figure 5.37: Delamination Threshold

Deposition

The delamination described above are all separations of the deposition from the substrate. However, it should be noted that, in one instance, delamination of deposition layers is noted, Figure 5.38. RepAir Mid indent shows delamination for the 50J of impact, the deposition is split in two on the left side of the deposition. The interface of the crack has a high content of aluminium oxide particles, which enhances the brittle behavior.

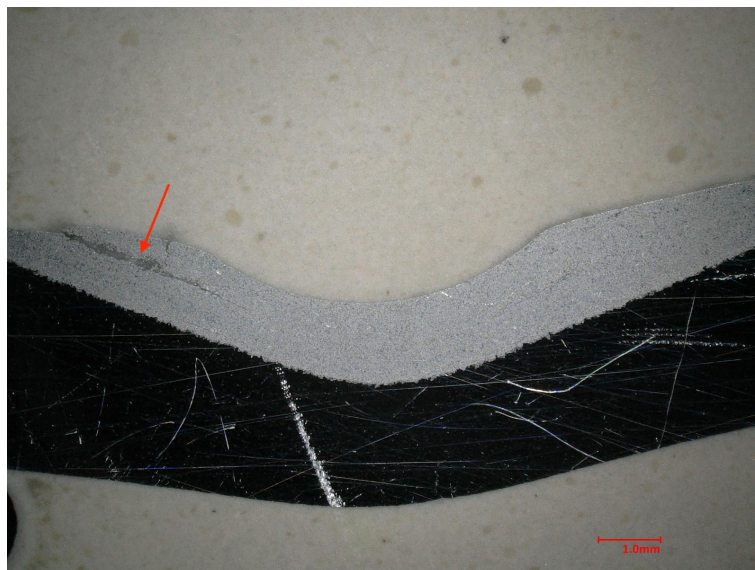


Figure 5.38: Delamination within deposition - 30x

5.3.3. Barely visible impact damage

For cold spray repairs BVID does not apply (for impact testing) since the dent due to impact is always visible. In composite, BVID applies when there is no/barely visible damage on the surface, but there is internally. The plastic deformation observed on the surface reveals underlying internal damage. However, the severity of plastic deformation and presence of visible cracks do not align with the internal damage and the damage to the substrate. For two of the five tested coupon types, cracking of the substrate, 'back cracks' occurs before cracks are visible with the naked eye on the cold spray deposition. The presence and severity of back cracking in the different coupons will be analysed below.

CSHP

For the CSHP coupons no back cracking is seen for either the LVI and QSI coupons.

MPAir

Observing the back side of the coupons, all the coupons (100-157J) show cracks in the substrate, so also for the 100J of impact for which no cracks are seen in the coating, the substrate does show four-split cracks. The 125J, 140J and 157J all show a four-split crack with an increasing degree of material that has been pushed out.



Figure 5.39: Four-split crack in the back of substrate MPAir 140J

RepAir middle indent

The back of the coupons show cracks for the 50J and 100J impact, as for the lower impact energies, only severe plastic deformation is seen. The 100J impact shows a four-split crack with shear plugging. For 50J of impact, a four-split crack is seen.

RepAir side indent

Cracks at the backside of the coupon are only visible for the 100J and 147J of impact, as mentioned, the 147J impact resulted in full penetration and the 100J of impact shows a four-split crack.

Gun middle indent

For the Gun Mid - type 4 coupons, only 100J shows back cracking, a four-split crack. The 50J does not show cracking on the back of the substrate.

Gun side indent

For the side impact the back crack is seen for the 65J, 85J, and 100J of impact. For all a four-split crack is seen.

Cowling

The back side of the Cowling only shows cracks for the 100J of impact, the cracks do show a characteristic four-split as for the other coupons but the cracks grow in multiple directions.

Thresholds

The back crack threshold is plotted in Figure 5.40 together with the threshold for visible cracks with the naked eye. Following the graph, the back cracking did not occur particularly before or after cracks are visible at the surface with the naked eye.

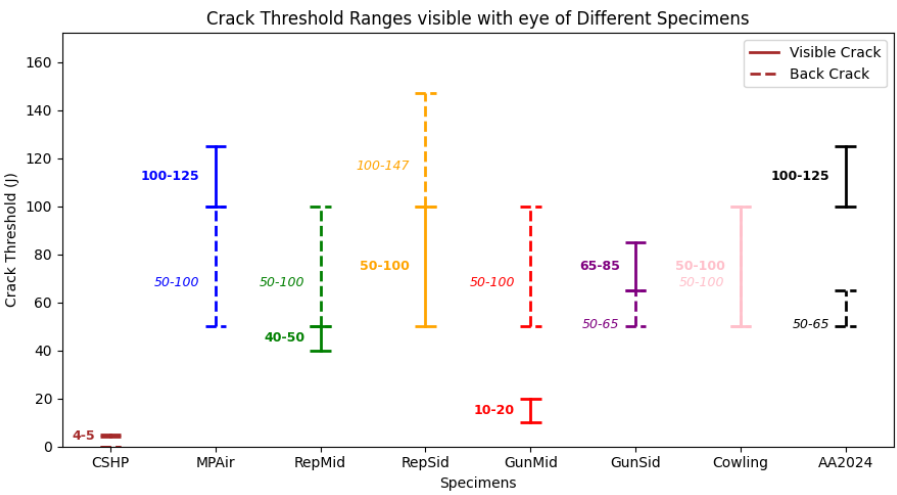


Figure 5.40: Visible crack and back crack threshold

The geometry of the back cracking is characteristic, the cross-section area shows this, Figure 5.41. The angle of the cracks appears approximately between 13-25° from the vertical line, parallel to the line of impact.

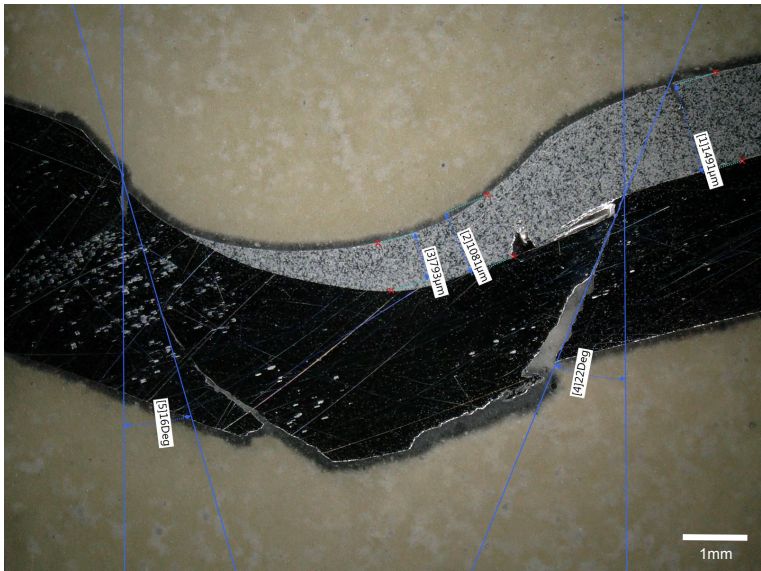


Figure 5.41: Shear plug failure angle - 30x

The longest crack length of the the four-split crack are listed below per coupon type and impact energy in Table 5.2. The values on the right side are the back crack lengths of the reference plate AA2024. No data is present for the AA2024 50J coupon, because no back cracking is observed. As can be seen in the table, the substrates acts differently according to the length of the back crack compared to impact subjected to the reference plate. Adding a cold spray coating on top of the substrate (MPAir) decreases the back crack length. As for the RepAir, Gun and Cowling coupons, the back crack length increases.

The crack lengths were measured using the software of the Keyence 1000, despite using the measurements software, errors could potential be there. These include parallax errors due to the viewing angle, limited resolution of the measuring tool and human estimation when crack boundaries were not clearly defined. Additionally, variations in lighting and surface conditions may have affected the visibility and extent of the cracks. As a results, small discrepancies of 0.1mm in the measured lengths are expected.

To minimize the uncertainty, all measurements were taken using the same method. Nonetheless, the recorded values should be interpreted with an awareness of the inherent measurement limitations.

Table 5.2: Back cracking coupons

Coupon	Crack length [mm]	Reference plate [mm]
MPAir 157J	14.2	15.3
MPAir - 140J	12.8	12.8
MPAir - 125J	10.2	13.2
MPAir - 100J	6.8	9.11
RepAir Mid - 100J	11.8	9.11
RepAir Mid - 50J	8.6	0
RepAir Side - 147J	16.9	13
RepAir Side- 100J	8.7	9.11
Gun Mid - 100J	12.6	9.11
Gun Side - 100J	10.7	9.11
Gun Side -85J	9.02	7.8
Gun Side - 65J	6.5	4.1
Cowling - 100J	10.4	9.11

5.4. Impact behavior: Data-driven perspective

5.4.1. Dent width and depth

The data retrieved from the QSI and LVI tests conducted on coupon type 1 were evaluated separately from the other coupons due to their significantly lower impact energy values. Figure 5.42 shows the results of the CSHP impact tests. When comparing the QSI and LVI tests to the reference AA2024 plate, both impact methods resulted in reduced dent depths, yet displayed greater dent widths. This indicates that plastic deformation primarily occurred laterally, in the direction of shock wave propagation. While the LVI and reference AA2024 samples showed a relatively linear width-depth relationship, the QSI test results exhibited greater variability, lacking consistent linear behavior.

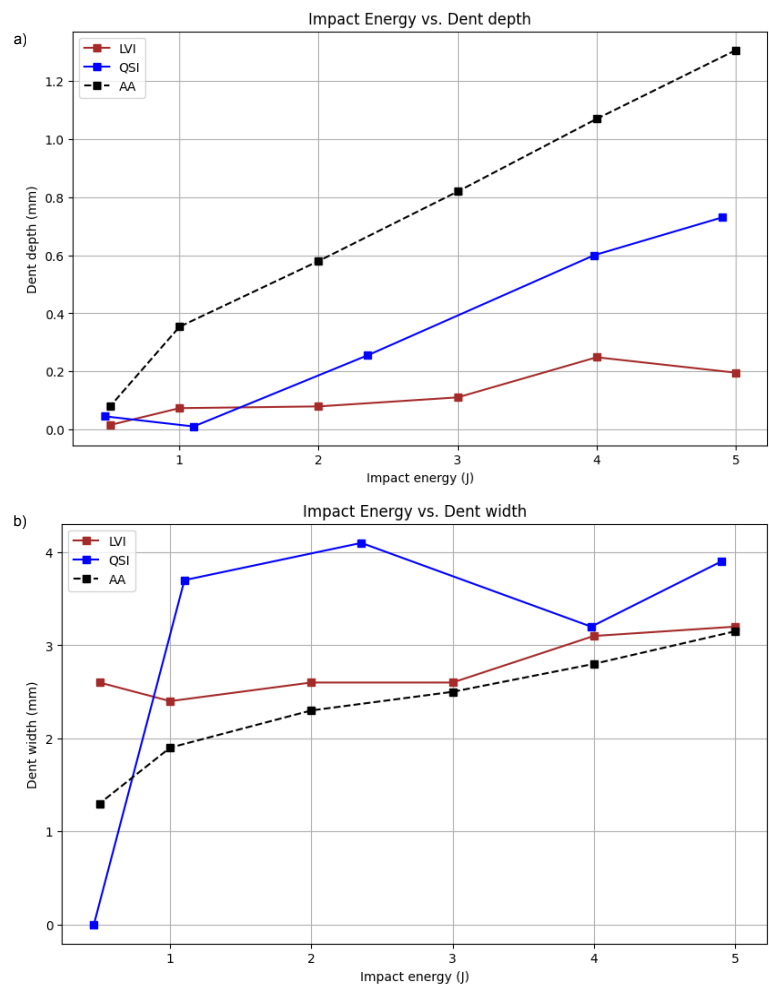


Figure 5.42: CSHP coupons: Impact energy vs a) Dent depth, b) Dent width

Figure 5.43 presents the dent depth and width data for the remaining coupon types. The overall trend reveals consistent behavior between depth and width for each coupon type, particularly at higher impact energies. At impact energies exceeding 40J, the measurements showed more linearity and similarity between samples. Among all tested configurations, the RepAir middle indent coupon exhibited the highest dent depth and width, followed closely by the Gun middle indent and the RepAir side indent. Although the Gun side indent results varied, they remained within range of the Gun middle and RepAir side indent results. In terms of dent width, the Gun side indent fell slightly below these values and aligned more closely with the reference AA2024 plate. The MPAir coupons consistently exhibited the lowest dent depths and widths, in some cases even lower than the reference material, indicating increased impact resistance. The Cowling samples displayed a unique trend: while their dent depths remained low and consistent with the overall pattern, their dent widths ranked second highest after the RepAir middle indent, suggesting a material or geometric influence affecting lateral deformation behavior. These findings underscore the variation in deformation behavior across cold spray repair configurations.

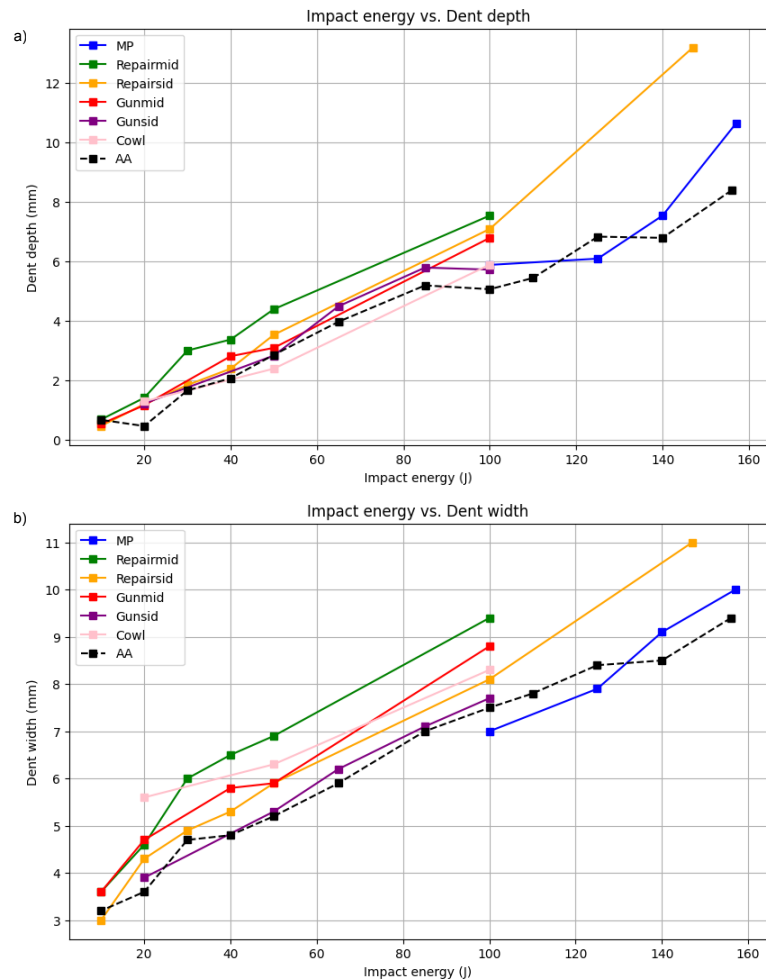


Figure 5.43: Coupons 2-5: Impact energy vs a) Dent depth, b) Dent width

5.4.2. Absorbed energy

The absorbed energy for the QSI and LVI tests on coupon type 1 was similar and closely aligned with that of the reference AA2024 plate, shown in Figure 5.44.

However, at an impact energy of 5J, the hand-held tower test showed a significantly higher absorbed energy, causing a higher difference in the pre- and post impact velocity, 0.6m/s for the 5J of impact, compared to the 0.3–0.4 m/s differences observed for the other impact energies. The percentage absorbed energy is not significantly higher than the other values, the value is very close to the reference coupon AA. The dent depth and width are also not significantly higher. The 5J coupon did show multiple cracks, which could be the primary reason for the high amount of absorbed energy, the energy does not dissipated more into plastic deformation but may contribute to the more crack initiation and propagation.

For both the LVI and AA reference plate, the 0.5J of impact had almost 100% absorbed energy, causing a minimal bounce back of the indenter. A very little bounce back was observed with the high-speed camera for the LVI 0.5J coupon. The AA reference plate did not have any visible bounce back. When examining the percentage of energy absorbed, the LVI and reference coupons again displayed comparable values, while the QSI tests showed a more linear trend but consistently lower absorption percentages.

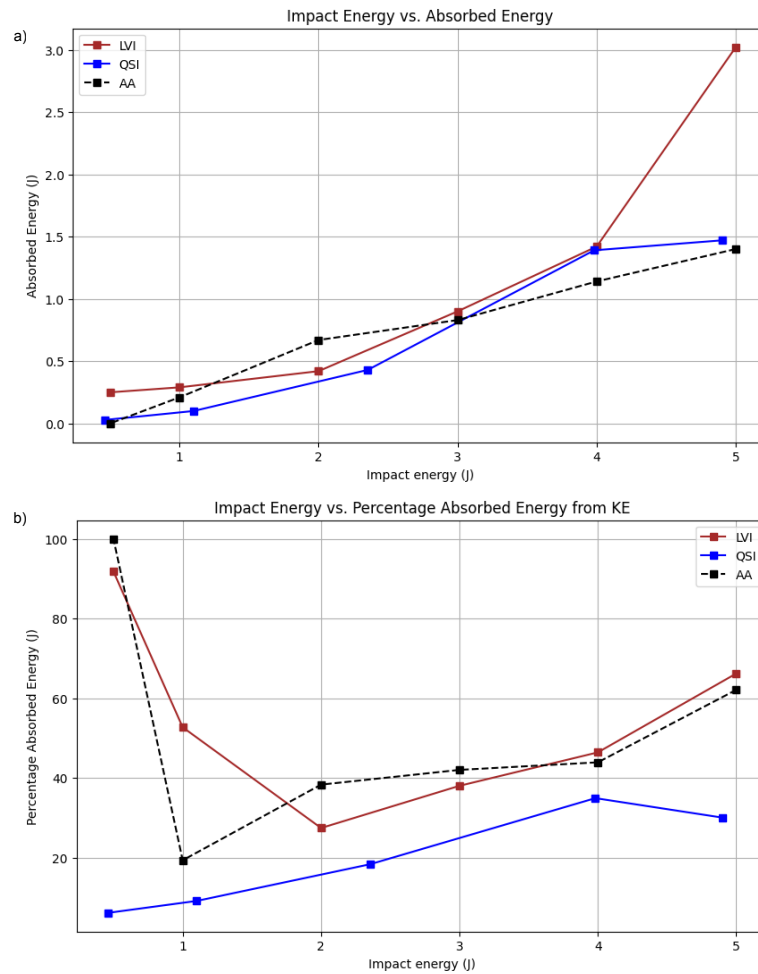


Figure 5.44: CSHP coupons: Impact energy vs a) absorbed energy, b) percentage absorbed energy

Overall, all cold sprayed coupons absorbed more energy than the reference AA2024 coupon, see Figure 5.45a. This trend is consistent with the mechanical properties of AA1XXX, which is softer, more ductile, and possesses higher fracture toughness compared to AA2024. These characteristics enable AA1XXX depositions to undergo more deformation and absorb more energy before failure, whereas the more brittle AA2024 substrate absorbs less.

Among the tested coupons, the MPAir configuration absorbed the most energy, which also has the highest impact energies tested. The values were slightly higher than the other coupons and may also be partially attributed to its greater overall coupon thickness. For the RepAir coupons, the absorbed energy was nearly identical for both middle and side indent locations, with slightly lower values recorded for the side indent. Since side indent impacts partially contact the substrate, they absorb slightly less energy. The Gun middle and side indent coupons exhibited nearly identical absorbed energy levels, both closely matching the reference AA2024 coupon. Cowling coupons followed this trend as well, with energy absorption values falling just below those of the RepAir and Gun coupons. Interestingly, both RepAir and Gun coupons exhibited elevated absorbed energy values at an impact energy of 30J. This peak was particularly noticeable in contrast to the 40J and 50 J impact levels.

Figure 5.45b displays the percentage of energy absorbed relative to impact energy. A wide spread in results was observed, especially for lower impact energies (<100J), where absorption percentages varied significantly. This variability made it difficult to identify a clear trend line. Notably, for the RepAir type 3 coupons, both mid and side indentations demonstrated higher absorption percentages at 30J compared to 40J and 50J, whereas the Gun coupons exhibited a more linear absorption behavior across increasing impact energies. These results suggest that localized material behavior, geometry, and interaction between the deposition and substrate significantly influence how energy is absorbed

during impact across different cold spray repair strategies.

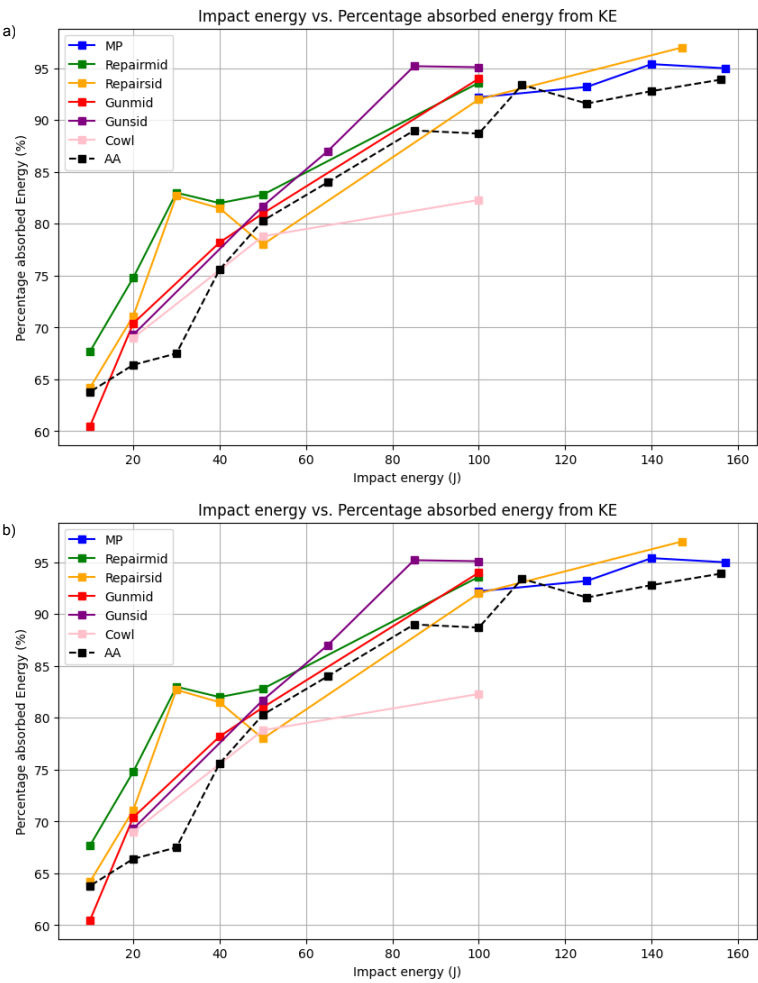


Figure 5.45: 2-5 coupons: Impact energy vs a) absorbed energy, b) percentage absorbed energy

Impact velocity

The velocity of the impact right before impact is plotted in the graph below, Figure 5.46, the velocity increases nearly linear. The velocity increases with impact energy for every coupon.

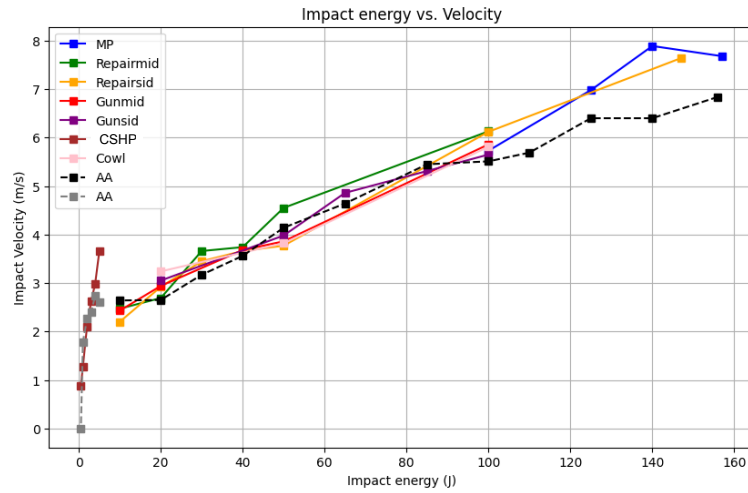


Figure 5.46: Impact energy vs velocity before impact per coupon

5.5. Normalization

The results from the four different graphs, dent depth and width, absorbed energy and percentage absorbed energy are normalized by the coupon thickness, in order to compare the data results accordingly.

5.5.1. CSHP

The absorbed energy values are normalized over the thickness for a better analysis with the reference plate AA2024 and plotted in Figure 5.47. The normalized values of LVI and QSI compared to the reference plate stayed nearly the same, the values are slightly increased compared to the normal values. Two values changed significantly, the dent depth for the 2J LVI impact, the depth surpasses the depth of the reference plate. The absorbed energy also increased significantly for the 1.1J of QSI test, again surpassing the reference plate.

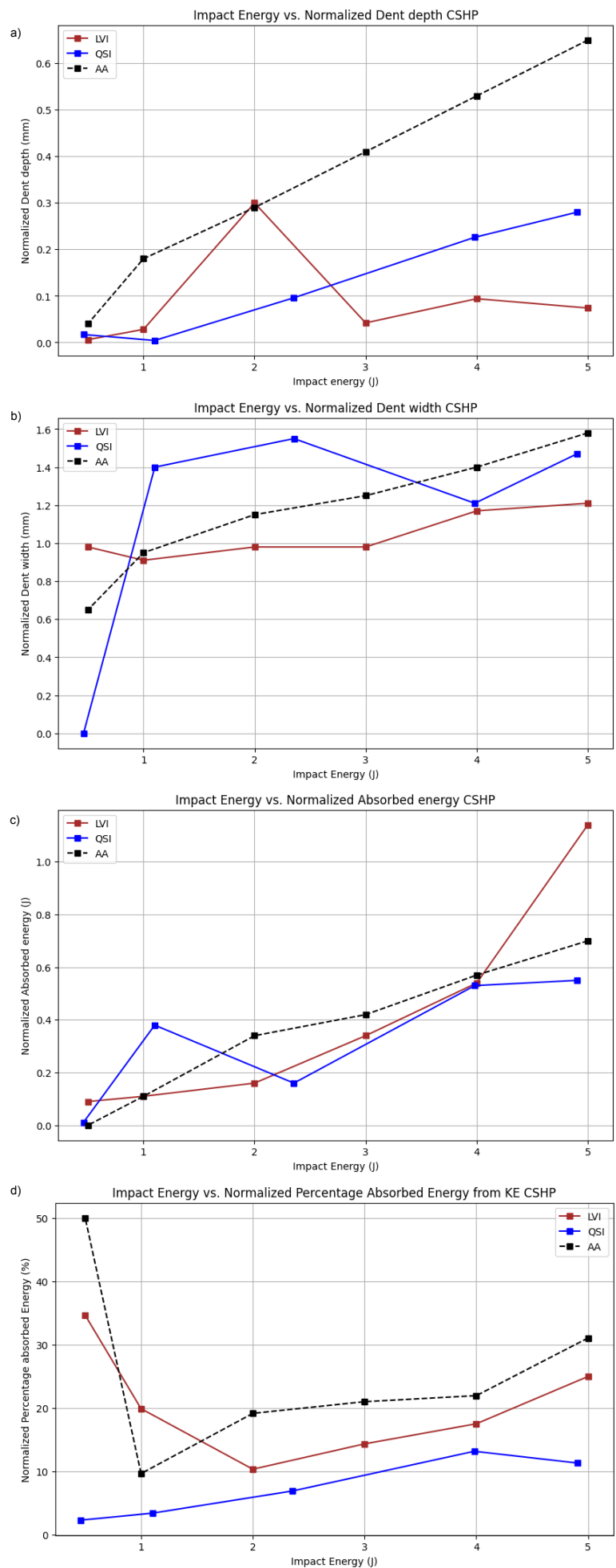


Figure 5.47: Normalized (over thickness) graphs CSHP a) Dent depth, b) Dent width, c) Absorbed Energy, d) Percentage Absorbed Energy.

5.5.2. Coupons 2-5

Normalization of the test results for dent depth, dent width, absorbed energy, and percentage of absorbed energy are shown in Figure 5.48 and revealed notable deviations from the trends observed in the absolute values. In the case of dent depth, the Cowling coupon values shifted upward on the graph, indicating the highest normalized dent depth among all coupons. This can be attributed to the Cowling's relatively low thickness; although its absolute dent depth was moderate, the thinner structure resulted in a higher normalized value. Conversely, the MPAir coupons, which have the greatest thickness and comparatively low absolute dent depth, demonstrated significantly lower normalized values—falling even below those of the reference AA2024 plate. A similar pattern was observed for the normalized dent width and percentage of absorbed energy. The Cowling values increased substantially in both metrics, reinforcing the influence of coupon thickness on normalized deformation behavior. On the other hand, the MPAir coupons again displayed a reduction in normalized values, dropping below the reference plate. Despite these shifts, the overall trend lines for the other coupons remained consistent with the non-normalized data, indicating reliable behavior across most configurations. For absorbed energy, normalization also caused the Cowling coupon values to rise. While the MPAir values did not fall below the reference plate in this category, their normalized trend became non-linear. Nonetheless, they remained in the upper region of the graph, suggesting that the ductile nature of the coating still enabled it to absorb considerable energy relative to its thickness.

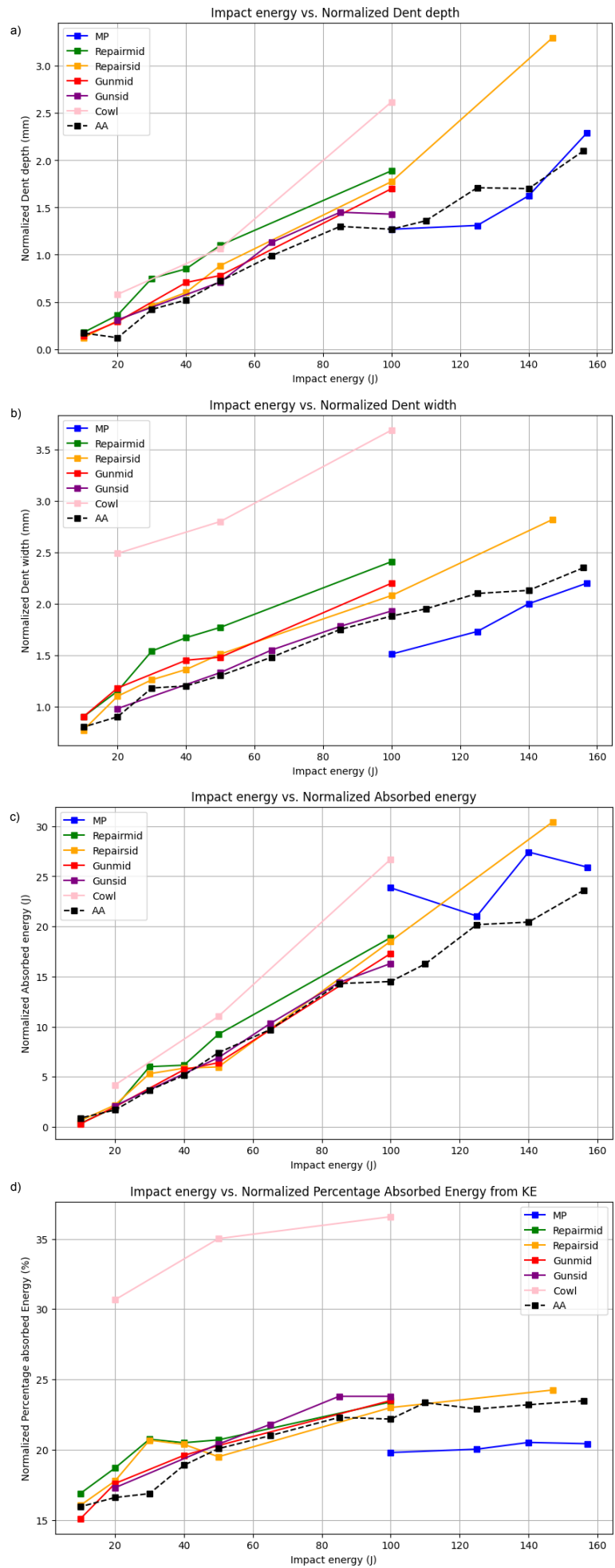


Figure 5.48: Normalized (over thickness) graphs coupons 2-5 a) Dent depth, b) Dent width, c) Absorbed Energy, d) Percentage Absorbed Energy.

The cowling absorbs the most amount of energy, mainly in the form of plastic deformation (dent depth and width). The RepAir mid and Gun mid absorb more energy compared to their side indents, in which the impact is partially on the substrate. The MPAir coating absorbs the least amount of energy.

5.6. Flowability

5.6.1. Rheometer

The results on the Rheometer test are listed in the Table below, 5.3.

Table 5.3: Rheometer Analysis

Parameter	AA2024	AA1XXX
Compressability	3.83%	21.9%
BFE	211 mJ	129mJ
Flow Rate Index	1.3	1.57

The AA1XXX has a higher compressibility, which means the powder is more prone to deform and densify under stress. The BFE value is lower for AA1XXX, meaning there is less resistance to the particle flow. The FRI is higher for the AA1XXX, reducing the interparticle contact, also allowing the particles to compress more. For detailed results of the Rheometer analysis, see A.1, A.2, A.2 and A.3 in Appendix A.3.

5.6.2. LDA

The particle size distribution of the two cold spray powder is measured with the LDA. The results of the flowability test of AA2024 and AA1XXX are listed in Table 5.4. The full results are shown in Table A.4 in the Appendix A.3.

Table 5.4: LDA Analysis

Parameter	AA2024	AA1XXX
D[4,3]	31.2 μm	17.2 μm
Span	1.088 μm	13.1 μm
Dx (50)	19.8 μm	7.68 μm

The AA2024 had an overall larger particle size and a more uniform distribution, compared to the AA1XXX. The AA1XXX powder caused some difficulties during the test, the powder was shown to agglomerate during the test and had some difficulties entering the feeder. The original and measured particle size is shown in Table 5.5.

Table 5.5: Particle size

Powder	Datasheet Titomic	D[4,3]
AA2024	5-30 μm	31.2 μm
AA1XXX	5-50 μm	17.2 μm

Comparing the particle size distribution from the LDA with the particle size which is on the datasheet of the powder delivery, the AA2024 particles are slightly larger than they should be. As the D[4,3] value is the average, particles are larger than this value. For the AA1XXX the D[4,3] value is within the particle size range of the expected particle size.

5.7. Model dent depth

The Johnson-Cook model is used to predict the yield strength value, using the material parameters presented in [19]. See Appenix A.4.6 for the exact values. The yield strength calculated with Formula 2.2 is 138.15MPa. This value is used in optimizing the dent depth. The results of the dent depth

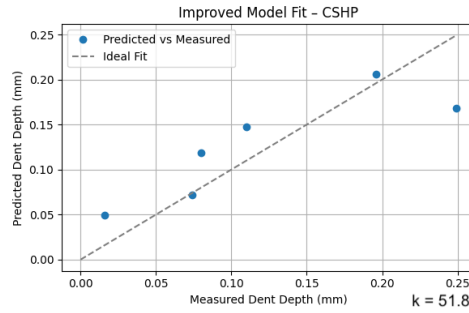


Figure 5.49: Depth prediction vs measured depth CSHP

model following Formula 4.11 and optimizing the value for k are shown in the graphs below. The fitting parameter is optimized for every coupon type separately. The outcomes of the optimization are visualized in Figures 5.49, 5.50, 5.51 and 5.52. A full overview is given in the Appendix A.4.1, Table A.6.

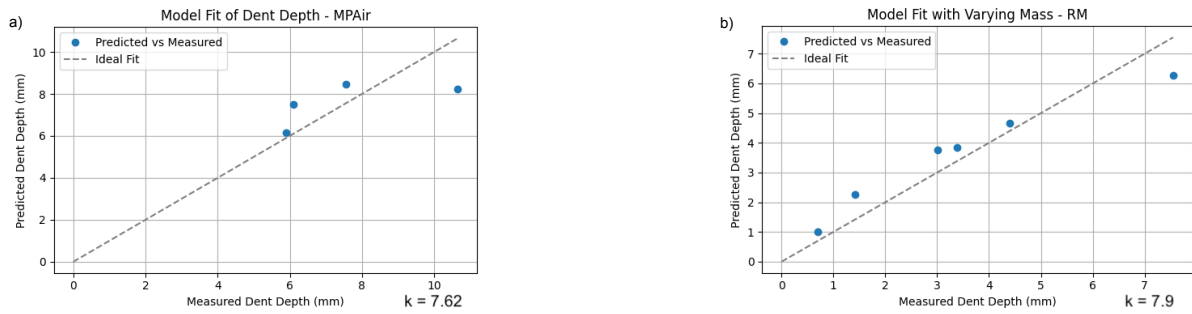


Figure 5.50: Depth prediction vs measured depth a) MPAir, b) RepAir mid indent

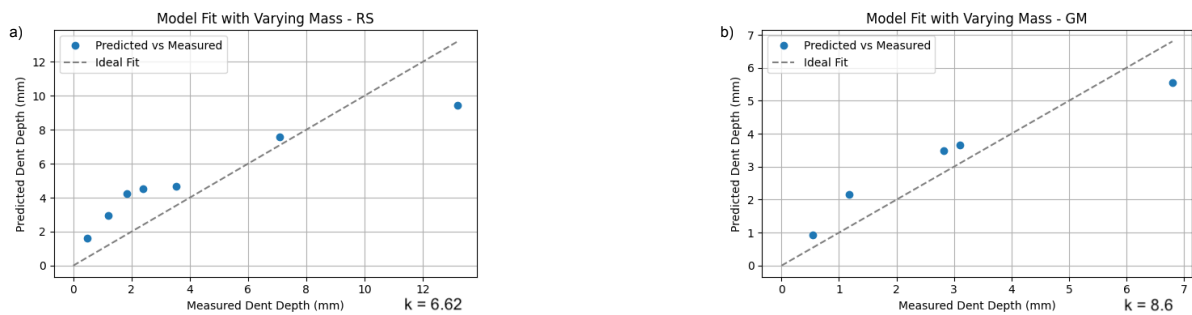


Figure 5.51: Depth prediction vs measured depth c) RepAir side indent, b) Gun mid indent

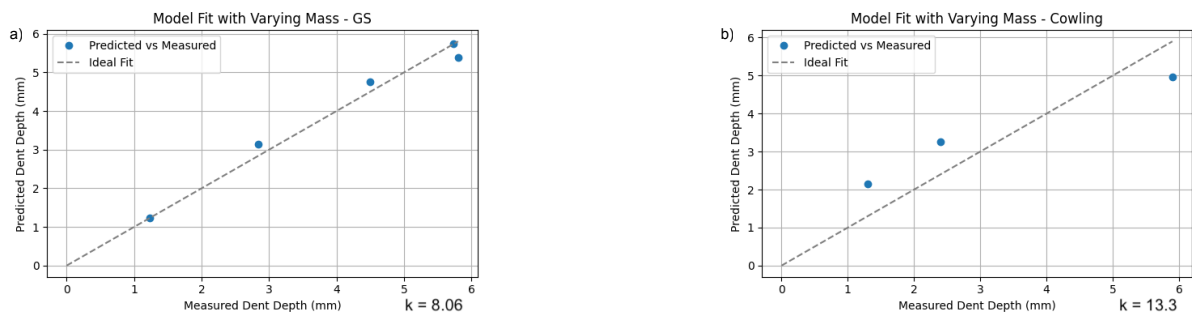


Figure 5.52: Depth prediction vs measured depth a) Gun side indent, b) Cowling

The dent depth model developed for hail impact on metal plates aligns closely with the experimental data for certain cold spray coupons, particularly the Gun side indent, CSHP, RepAir, and Gun mid indent samples, which are near the fitting line. However, other samples, including the MPAir, RepAir side, and cowling coupons, deviate significantly from the expected fit. While the fitting parameters, as shown in Table 5.6, exhibit some similarities, the variations remain substantial, indicating inconsistencies in the model's applicability across different cold spray configurations.

Table 5.6: Fitting parameter k

Coupon type	k value
CSHP	51.78
MPAir	7.62
RepAir mid	7.9
RepAir sid	6.62
Gun Mid	8.6
Gun side	8.06
Cowling	13.3

5.8. Quasi static indentation test

Two distinct energy regions can be derived from the force-deflection curves by integration: one corresponding to the total impact energy, and the other to the absorbed energy. The total impact energy is represented by the entire area under the upward curve of the graph (loading phase), as seen in Figure 5.54. The absorbed energy equals the area between the upward and downward curves, as shown in Figure 5.53. The test begins at zero force ($F = 0$) and zero time ($t = 0$) at point P1. From this point, the force increases gradually, and all curves initially follow a steep linear slope—referred to as the upward line—indicating elastic deformation of the coupon. For the 2.3J, 4J, and 5 J impact energy coupons, the curve transitions from linear to non-linear, which marks the onset of plastic deformation. In the 4J curve, a noticeable kink or drop is observed in the upward slope. This irregularity likely corresponds to internal failure mechanisms such as delamination or crack propagation. In fact, post-test inspection revealed a large crack on the left side of the 4J coupon, supporting the hypothesis that the kink represents sudden energy release due to damage initiation. As the force reaches its peak, the curve plateaus at a maximum value before transitioning into the downward slope—representing the unloading phase—as the indenter retracts. The downward line ends when the indenter is no longer in contact with the specimen, returning to $F = 0$ at point P2. The slope of the downward curve is consistently lower than that of the upward curve, signifying energy dissipation within the material. The distance between P1 and P2 on the x-axis (deflection) indicates permanent plastic deformation; this residual deflection represents the final dent depth left in the coupon after impact. These features are visualized and labeled in the force-deflection curve corresponding to the 5J impact case in Figure 5.53. This representation clearly outlines the elastic and plastic regions, energy absorption behavior, and mechanical response characteristics relevant to different failure modes observed in the tested coupons.

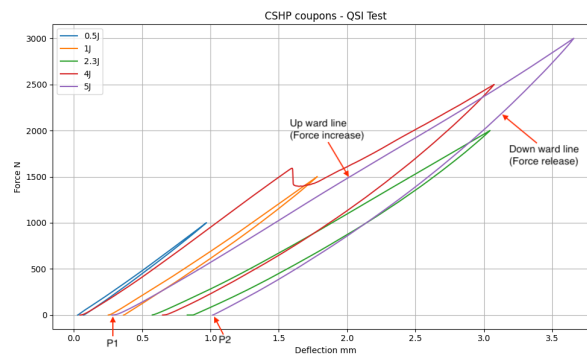


Figure 5.53: Coupon 1 Force Deflection curve

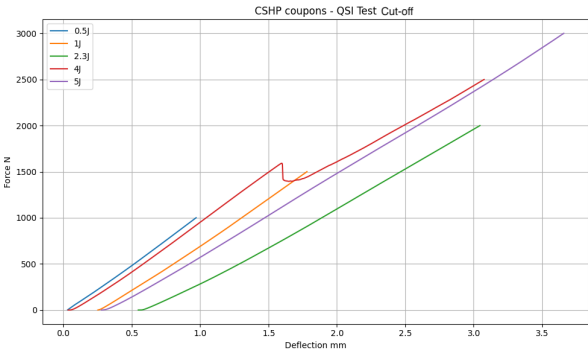


Figure 5.54: Coupon 1 Force Deflection curve - peak value

6

Discussion

This section discusses the outcome of the experimental work and compares the results of the different coupons. Phenomena occurring within the coupons due to impact testing are discussed and related to the found literature.

6.1. Deposition

6.1.1. Deposition quality cold spray AA2024

The substrate and deposition material is the same for the CSHP and CSMP coupons, however, the presence of the copper precipitates is substantially lower in both the depositions. This could be due to the spraying characteristics of cold spraying process. The process does not involve melting of the deposition material; the feedstock powder remains in solid solution, which suppresses the formation of intermetallic precipitation, resulting in finer and more dispersed copper precipitates, making them invisible or indistinct under optical microscopy. In thermal spraying processes, in which the feedstock material melts, the copper precipitates can dissolve into the matrix and diffuse. The intermetallic formation and coarsening of the material make the copper precipitates visible with the microscope. If no thermal exposure occurs, the particles remain in their as-sprayed state, which is typically free of large intermetallic precipitates [57, 58].

6.2. Crack threshold

6.2.1. CSHP coupons

The CSHP coupons, manufactured by Titomic with the high-pressure cold spray system have a significantly lower crack and delamination threshold compared to all the other coupons. No surface treatment on the substrate was performed, which played an important role in the quality of the bonding between substrate and deposition. Having a smooth substrate surface weakens the bonding between the cold spray particles and substrate, resulting in failure of the coupon. Secondly, pores are observed in the CSHP coating from the side view. Pores act as stress concentrators, initiating microcracks. Pores also reduce the amount of deposition material in the coating itself, less material results in a lower tensile and compressive strength. Pores along the interface of the substrate and deposition can also induce delamination between substrate and coating. Lastly, the coupons were not milled before impact testing was done. The very thin layer of deposition, in combination with the weak bonding did not allow for milling to be completed. On one CSHP coupon, the deposit delaminated during milling steps, leaving behind very little of the previously sprayed deposition. As explained in section 3.2.4 Milling, milling could improve the mechanical properties of the deposition, thus not milling the CSHP coupons could have played a role in the lower crack threshold compared to the other coupons.

6.2.2. Gun Side indent threshold

The Gun coupons with an impact location on the side of the repair showed a big difference in the crack threshold compared to the Gun Mid and RepAir coupons (both impact locations). The Gun coupons

were sprayed by AX with a hand gun, which is different from spraying with the robotic arm. By manually spraying, it is difficult to keep the spray distance, speed, and angle. This differs slightly for every coupon, but also within the coupon itself. Having a slower/faster (non-constant) traverse speed results in more or less localized heating. The longer the gun is held at one point, the more the temperature increases at that point, changing the deposition characteristics. Observation of the Gun coupons showed that the repair (after milling) was no longer circular. The repair had an egg-like form, see Figure 6.1; the exact geometry is different for every coupon sprayed with the gun. For the coupons sprayed by the robot, this geometry change is not visible. The egg form deposition results in a difference in stress distribution. From visual inspection by the author, it appears as though the deposition is expanded, pushing harder against the substrate and resulting in a higher pressure on the edges. This increases the compressive stresses at the interface of the substrate and deposition. Higher compressive stresses improve adhesion. The egg form deposition could also result in a more gradual stress transition and transfer between the deposition and the substrate, improving the impact resistance of both materials.

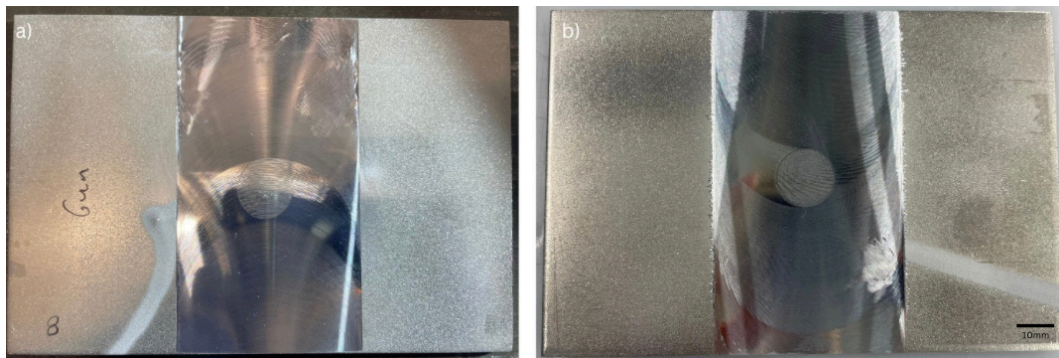


Figure 6.1: Deposition geometry after milling a) Gun sprayed (AX), b) Robotic sprayed (Titomic)

The egg form deposition could be a result of the non-constant traverse speed of the nozzle/gun. If the gun is held longer in one place, the temperature increases. If the temperature exceeds $0.4T_m$ (T_m : melting temperature), recrystallization is induced and grain refinement occurs. As the grain refinement is increased, at certain areas a difference in grain orientation is present, because of the non-constant traverse speed. The difference in grain orientation causes bridging connections between connection points, having multiple connection points next to each other, at the interface with the substrate for example, long interlocked recrystallized grain are formed, which enhances impact resistance [59].

By spraying manually, the deposition is not constant/uniform and the spray angle could deviate slightly from 90 degrees, which is wanted. This causes the deposition material to accumulate more in certain areas, pushing the circumference of the blend out outward unevenly, as a result of the compressive stresses building up in the cold spray. Further this would result in an elongated or asymmetric shape instead of a uniform buildup.

6.2.3. RepAir Mid indent and Cowling Threshold

The RepAir Mid indent and Cowling both showed cracks for 20J but not for one impact energy level above this, 30J and 50J respectively. For impact energies from 30J and above, the indenter weight is set to 4.3 kg. To increase the impact energy the height is increased. For impact energies below 30J, the mass of the indenter had to be decreased since the impact tower had reached its limits in terms of minimal height. For 20J and 10J of impact, the mass is decreased to 2.6kg and 1.58kg respectively. Altering the system's mass slightly affects the energy transferred to the coupon. Different stress states can be produced, even when the nominal energy is the same, but having a different indenter mass. Reducing the impact mass can alter the shape, duration, and localization of the impact load on the coupon, this could be compared to having a sharper indentation. The lighter impact mass tends to produce more localized deformation, due to a shorter (more impulsive) impact duration. Higher local strain rates are present, which promotes brittle cracks and decreases the crack threshold [27, 28].

6.2.4. Substrate vs deposition cracks

For the Side indent location, the location of the cracks due to the impact differed for the RepAir Side indent and Gun Side indent. For the RepAir Side indent showed cracks mainly in the substrate material for low impact energies 30-40J, Figure 6.2. This is due to the difference in the mechanical properties of the substrate and deposition material. During impact, compressive waves travel through the material from the impacted to the non-impacted side (vertically). At the back of the aluminium plate, the waves are reflected back as tensile waves. Tensile waves are more damaging to brittle materials and therefore the impact causes cracks in the brittle substrate before the ductile deposition. The Gun Side indent coupons only showed cracks in the deposition/repaired part. This could be happening due to the small geometry change of the repair due to the manual spraying as explained in the previous section. This builds up higher stress concentration around the edges of the repair, stress concentrations are prone to crack initiation. The higher stress concentration around the edges of the repair itself could be so high that it fails in this region before the substrate fails.

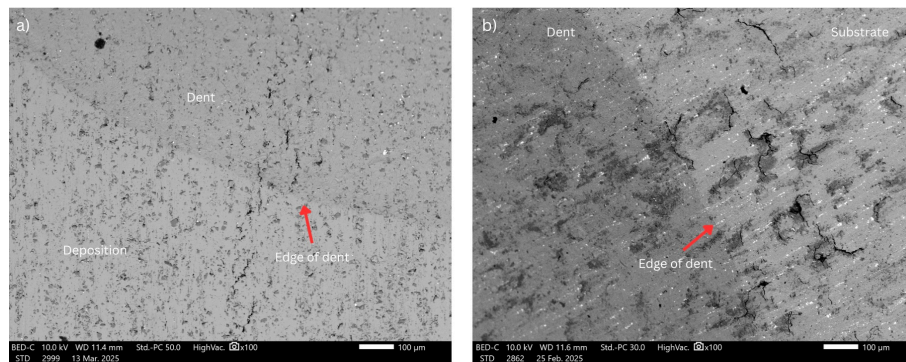


Figure 6.2: Different locations of cracks a) RepAir Mid coupon - 100x, b) RepAir Side coupon - 100x

6.2.5. Type of cracks

Interparticle and transparticle

The distinction between interparticle and transparticle cracking is difficult to see with the SEM. The impacted coupons are highly deformed, resulting in uneven height, especially within cracks. This makes it difficult to focus the SEM completely on the crack to examine the type of crack. The analysis and thus the answers to the 3rd sub-research question could thus not fully be answered for each coupon type.

Radial and tangential

For all the coupon types, tangential cracks were only visible at higher impact energy levels. The tangential cracks were always ring-like for the highest impact energy levels and in combination with radial cracks, except for the CSHP coupons. The CSHP coupons showed a severe tangential crack for the hand held 5J of impact, and one tangential crack for the QSI at 4J. As radial cracks are more likely to initiate in brittle materials and thin coatings, it would be expected to see radial cracks in the brittle CSHP deposition. However, the LVI 5J and QSI 4J impact coupons both showed delamination, which could induce tangential cracking.

For coupon type 2-4, the highest impact energy levels all had radial cracks in combination with ring-like tangential cracks. For the lower impact energies only radial cracks were visible. The type of cracks is in line with the theory that radial cracks are frequently the primary cracks upon impact, following from [54]. The milling of the coupons could also have induced radial cracks due to impact, since extensive milling could change the residual stresses from compressive to tensile. The severity of the milling on the residual stresses is not measured in this research, but could have an effect on the crack type and crack threshold found in this research. The formation of ring-like tangential cracks for the higher impact energies could also be due to the difference in the expansion coefficient of the substrate and deposition material, causing anisotropic behavior as the material expands unevenly.

For the cowling, only radial cracks were visible for 100J of impact, while radial and straight-line tangential cracks are visible for the 20J. The type of cracks compared to impact energy differed from the other

coupon types. The milling process for the cowling was different compared to the flat coupons (2-4), the mill head used for the cowling differs. This resulted in a very small height difference in the repair, which could have influenced the residual stresses in the material and thus the type of cracks.

The location of the cracks regarding the dent are in line with the theory discussed in Section 4.3.4 Analysis - Crack type. Large ring-like cracks are visible in the walls of the dent, where the material is trying to resist the outward movement of the material. Radial cracks are seen around the indent edge, especially in the substrate, which has lower ductility.

6.2.6. Delamination

There is a clear difference in the delamination threshold for the coupons, coupon type 1 (CSHP) showed delamination for 4J and 5J of impact, which is likely caused due to the non-roughened substrate surface.

For the coupons sprayed by Titomic (2 and 3), roughened with Al_2O_3 particles, the delamination threshold is above 100J, indicating a strong bond between the substrate and deposition. The MPAir coating started to delaminate at the same impact energy as cracks start to appear, between 100J-125J. The RepAir Side coupon of 147J did show delamination under the microscope, however, the damage on the coupon was so severe that it was impossible to make a cross-sectional area of the exact spot of the delamination. For the RepAir coupons, 125J and 140J of impact were not tested, so it can not be said that the delamination threshold of the RepAir coupons are the same as the MPAir coupons. Both coupon types did have the same surface treatment and R_a value, which has a big influence on the occurrence of delamination so the reasoning can also not be excluded.

Both the Gun Mid and Side coupons showed delamination at 100J of impact, near the part where the substrate failed with a vertical crack. No delamination is seen for 50J and 65J for the Mid and Side impact respectively. The delamination threshold range is closer to the crack threshold compared to the RepAir coupons. However, the delamination threshold is much lower, this could be due to the differing surface treatment and lower surface roughness values. The R_a and R_z values of coupons 4 were two to three times lower compared to coupon 3. Less roughening could decrease the bonding strength, thereby initiating delamination earlier. Figure 5.4 shows the interface line of the bonding between deposition and substrate. The MPAir and RepAir bonding both show a wider range of penetration depth, which could indicate more plastic deformation and thus more strain hardening on the interface, resulting in a better bonding. Following the research from Blochet et al. [19], fine grit-blasting results in a different plastic deformation behavior of the substrate. Small peaks and valleys are vanished by the high kinetic impacts of the particles, especially due to large particles which may flatten the surface quickly.

Delamination in deposition

Delamination within the deposition is seen for one coupon, RepAir Mid indent of 50J, however, it can not be excluded that delamination inside the deposition did not occur for the other coupons. Cross-sections are made to find the threshold for delamination between the substrate and deposition. To find the thresholds, it was unnecessary to make a cross-section of all the coupons, thus not all coupons are analysed for delamination inside the deposition. Secondly, the cross-section is made of the middle section of the dent, having the highest dent depth value. Delamination is most likely to occur here due to the highest amount of deformation. However, delamination could also occur somewhere else, for both substrate-deposition and deposition delamination. For a complete examination of the presence of deposition delamination (but also substrate-deposition delamination) non destructive observation/technology (NDT) could be used.

6.2.7. Barely visible impact damage

Barely Visible Impact Damage does not apply for cold spray coatings and repairs (under impact testing). However the results show that the back cracking and internal damage does not always align with the visible damage at the surface. The material combination and mechanical properties of the substrate and deposition should be taken into account. Differing mechanical properties result in different material and damage behavior when subjected to low velocity impact. Besides the differing material properties of the deposition and substrate, the substrate itself does behave differently when a cold spray deposition is added. When cold spray deposition is added on top of the substrate (MPAir), the substrate back

crack length is reduced, which could be due to the overall higher thickness. Thicker coupons absorb more energy before cracks occur. The RepAir, Gun and Cowling coupons show more severe damage compared to the reference plate. This indicates that the replacement of substrate material (AA2024) for cold spray material (AA1XXX) changes the stress transfer and distribution over the coupon due to impact loading.

6.2.8. Allowable damage limits

Recalling the allowable damage limits set by the OEMs for a cowling inlet lip to operate with; Crack length: maximum of 76.2 mm and delamination: maximum of 24.5mm separation between substrate and deposition. The damage found during this research is smaller than the allowable damage limits, the longest crack found is for the RepAir side indent, around 14 mm and the largest delamination observed is around 3200 μm long in the Gun Mid coupon. However the size of the dents are not within the allowable limits, the maximum allowable dent width is 127 mm, the dent depth must be equal or smaller than 10% of the dent width. The largest dent found in this research is 11 mm wide and 13.2 mm in depth, corresponding to the RepAir side coupon with 147J of impact. This coupon got fully penetrated by the indenter, so the dent is not a 'dent' anymore but a hole. The largest dent corresponds to the MPAir 157J of impact, 10 mm width with 10.65 mm depth, this is still surpassing the limits and thus a repair should be made immediately. For all the coupons types, except the CSHP coupons, the dent depth is more than 10% of the dent width, meaning all the damage made due to LVI in this research should be repaired before the cowling inlet lip is serviceable again. Since the cowling inlet lip is not a structural component, the damage can be repaired by placing a sealing patch of aluminium sealing tape. The repair patch should be checked and examined every 'A' check and the damage should be fully repaired during a 'C' check.

6.3. Energy Absorption

6.3.1. Depth and width

The dent depth and dent width graphs (against impact energy), showed a similar behavior, comparing the different coupon types. The dent depth and width increased with impact energy; the higher the impact energy, the larger the difference in dent depth and width between the different coupons. For both the depth and width and RepAir and Gun coupons, the Mid impact location had higher values compared to the side impact location. For impact on both the substrate and deposition (Side coupons), the impact energy was spread over the substrate and deposition, constraining the deformability. The substrate (AA2024) had lower ductility, carrying more load, deforming less, and absorbing less energy, which resulted in lower dent depth and width. The middle impact location was only on the repair (AA1XXX), which was high in ductility, absorbing more energy and therefore deforming more, which resulted in a higher dent depth and width.

6.3.2. MPAir

When comparing the normalized results of the MPAir coating with the RepAir and Gun repaired coupons, it becomes evident that the MPAir values are consistently lower than those of the repaired configurations, including the Cowling. Specifically, the MPAir coupons absorb a smaller percentage of energy per unit of deposition thickness. This reduced energy absorption may be attributed to differences in deposition geometry. The MPAir coating has a maximum thickness of 0.65 mm, whereas the RepAir and Gun repairs feature depositions up to 1.8 mm thick.

Thicker depositions, as in the repaired coupons, are likely to delay the arrival of stress waves at the substrate interface, allowing greater energy dissipation within the deposition before transferring stress into the substrate. This increased energy dissipation may contribute to a higher degree of plastic deformation. In contrast, the thinner MPAir coating may allow stress waves to reach the substrate more rapidly, potentially increasing the load transmitted to the substrate and limiting the energy absorbed within the coating layer. However, this assumption would benefit from further validation through numerical or experimental stress wave analysis.

Another factor influencing the mechanical response is the relative placement of the deposition. In the MPAir configuration, the coating is applied on top of the substrate, whereas in the repaired coupons, the deposition is embedded within a recessed cavity. This embedded geometry promotes better me-

chanical interlocking and may result in more effective interaction between the deposited material and the substrate. During deposition, minor thermal expansion of the deposited material can induce compressive residual stresses at the interface, enhancing bonding and potentially acting as a barrier to crack propagation.

In contrast, the MPAir coating is only bonded to the substrate on one face, allowing greater lateral expansion during impact. The repaired geometries, being more constrained by the surrounding substrate, limit lateral expansion and promote more localized energy dissipation.

Despite their thinner deposition and lower normalized energy absorption, the MPAir coupons exhibited a higher threshold for crack initiation. This can be attributed to the overall greater thickness of the MPAir coupons, which allows the impact load to be distributed over a larger volume, delaying the onset of fracture. However, a complete comparison between absorbed energy and deposition thickness remains limited due to differences in the applied impact energy ranges for each configuration.

6.3.3. Cowling

The Cowling coupons exhibited significantly higher energy absorption compared to the other coupon types, both the dent depth and width show higher values in the normalized impact results. This increased energy absorption can be attributed to several factors. Firstly, the substrate material of the Cowling coupons is AA2XXX, which has a lower Vickers hardness (98 HV) than AA2024 (137 HV), the substrate used in the RepAir and Gun coupons. The lower hardness indicates a greater capacity for plastic deformation, which aligns with the observed increase in dent size and energy dissipation.

Secondly, the geometry of the repair plays a critical role. The Cowling repair area is substantially larger than that of the RepAir and Gun coupons, providing a greater volume of ductile material (AA1XXX) to deform under impact. AA1XXX itself has an even lower Vickers hardness (typically below 80 HV), which further contributes to the enhanced plasticity and energy absorption capacity of the Cowling system.

Furthermore, the Cowling coupons impacted at 20 J showed crack lengths that were three to four times greater than those observed in the RepAir coupons at the same energy level. The extended crack propagation and larger plastic zones both contribute to the increased energy absorption. However, it should be noted that the total number of cracks was not quantified in this analysis, which may also influence the total absorbed energy.

6.3.4. 30J Impact

Both the RepAir Mid and Side coupons showed a higher value of absorbed energy for the 30J of impact compared to the 40J of impact, which resulted in a non-linear trend from 10-30J and a more linear line from 40J on. The MPAir, Gun and Cowling coupons were not tested at 30J and 40J. Comparing the absorbed energy values with normalized the normalized values, the 30J values drop below 40J but just slightly, still showing a non-linear behavior. As for the percentage of absorbed energy from the kinetic energy, both 30J (normal and normalized values) are above the 40J. The reason for this could be that, at lower impact energy and velocity, insufficient kinetic energy is produced to plastically deform the material, reducing the absorbed energy. The strain rate is also reduced due to the low velocity, and thus less energy is absorbed.

Another possible explanation for this could be the change in indenter weight blow impact energies of 30J, along with a steady state reached at 30J of impact. The energy absorption and percentage of energy absorption graphs are non-linear before 40J, suggesting differing behavior upon impact, i.e. cracking and plastic deformation. The non linear damage behavior could be a result of the changing indenter mass for the 10J and 20J of impact (indenter radius is the same) compared to the 30J and 40J. The lower impact mass, could cause a shorter impact duration and thus more bounce back from the indenter. Above 30J the material behavior becomes more stable, suggesting that the material has entered a steady-state deformation regime. However, the graphs are not fully steady-state, a few fluctuations are seen, suggesting minor instabilities in the energy absorption.

6.4. Dent Behavior

6.4.1. Shear plug

The coupons show a characteristic back side, cracks in the substrate start to appear from approximately 50J of impact on. Material is pushed out and a three or four split crack is visible. From the cross-section pictures in Figure 6.4 it can be seen that the push out looks like a plug. Shear plugging is a phenomenon that has been researched for reinforced concrete beams and is also seen in metals [60, 61, 62]. Shear failure plays a critical factor during impact loading. By increasing the impact energy, as done in this research, the shear force can transform from minor vertical cracks into global flexural or shear damage. Flexural failure is ductile and provides warnings while shear failure is brittle and sudden. Local shear failure initiates at the point of impact and grows outwards with a 45 degree angle. By further increasing the impact rate, the cracks will propagate downward from the impacted side, due to the downward bending [31].

As the stress concentration around the edges of the impactor causes the material to shear off and the inertial forces contribute to the outward movement, a plug is formed, called shear plugging. Shear plugging happens when the shear stress around the impact zone exceeds the shear strength of the material, forming a nearly cylindrical or slightly tapered 'plug' that is ejected from the impact site. The process is dominated by high strain rates, so the material has no time to deform plastically. Shear plugging is the most preferable fracture mode for tensile and shear loading [60, 61].

Adiabatic shear bands (ASB) also play a role in the crack formation and shear plugging. Shear bands represent high strain regions and heterogeneous deformation, the adiabaticity defines the level of localized heating which builds-up during the high strain rate deformation [24]. Impact testing is hard and fast, generating heat as a result of the deformation occurring. The heat can not escape as quickly and softens the material locally. As the material softens, more local deformation can happen. Eventually the deformation becomes unstable and leads to cracking. The weak region created by the material softening is called a shear band, and all the deformation is concentrated at that location. As the indenter in this research has a round geometry, the indenter leaves a circular dent, with high strain rates in the walls of the circle. The material in the walls of the circle loses strength due to the ASB and circular plug is pushed out, called shear plugging [62].

6.4.2. Second dent

In some of the coupons, a second dent is visible, attached to the side of the main indent, see Figure 6.3. The second dent does differ in size and is not completely circular, only a part of the circle is visible. There is no correlation found between the size of the second indent and the size or impact energy of the main indent. However, the coupons that do have a second 'child' indent, were tested in the same batch/day, only visible for some of the RepAir Mid and RepAir Side batches. A possible explanation for this could be that a second, short impact was made. Since the child indent is smaller and less deep than the main indent. The reason for the second indent could be due to the safety that did not work properly. A safety is set on the impact tower which catches the indenter after the first impact, however if the safety doesn't catches the indenter properly or too low after the first indent, a small second indent can be made.

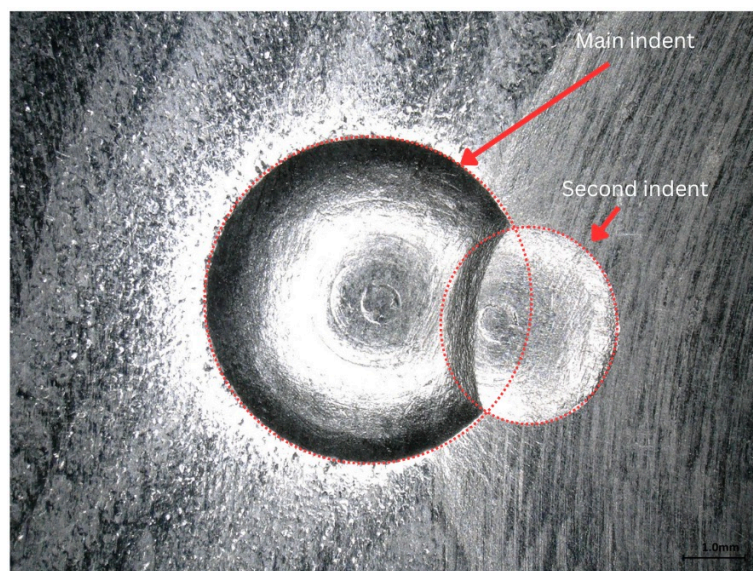


Figure 6.3: Two dents after impact - 30x

6.4.3. Elongation and accumulation

Elongation of the deposition material is observed in multiple coupons, the red arrows in Figure 6.4 show a very clear elongation of the cold spray on the sides of the coating. The substrate cracked on both sides on the indent while the deposition is still in one piece. Pure aluminium (AA1XXX) has a ductile nature, however by cold spraying, materials become more brittle, especially if the AA1XXX is mixed with brittle Al_2O_3 particles. The severe elongation was thus not expected to be happening. Literature research showed a contradicting behavior of AA1XXX repairs, a very brittle behavior during tensile testing, having elongation values below 1%. Impact testing does induce more compressive stresses, especially at the impacted side, compared to tensile testing. The spraying direction, longitudinal or transverse could also have an effect on the mechanical properties as literature suggests an anisotropic behavior of cold spray depositions.

For the MPAir coupons, with a cold spray coating, the deposition not only elongated but also thickened at the center of impact, blue arrows in Figure 6.4, surpassing the original thickness of the coating from 0.65 mm to 0.8 mm, see Figure 6.5. Simply said, thickening of the deposition happens if the back (non-impact side) increases in length while the impact side length stays the same, to conserve volume, the deposition must thicken. However, measuring the length of the deformed deposition, both the impacted and non-impacted side of the deposition increase in length, so this theory does not clarify the accumulation. The local buildup could be attributed to plastic deformation under high compressive stresses combined with a restriction for the deposition to expand sideways caused by the surrounding substrate. As the material cannot flow outward due to geometric constraints, it is forced to flow vertically, resulting in a bulging or pile-up effect [63, 64].

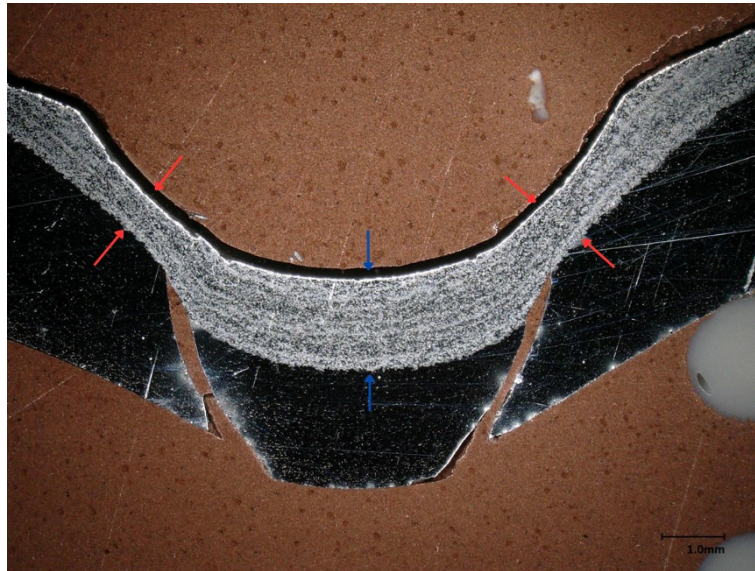


Figure 6.4: Elongation and Accumulation - 30x

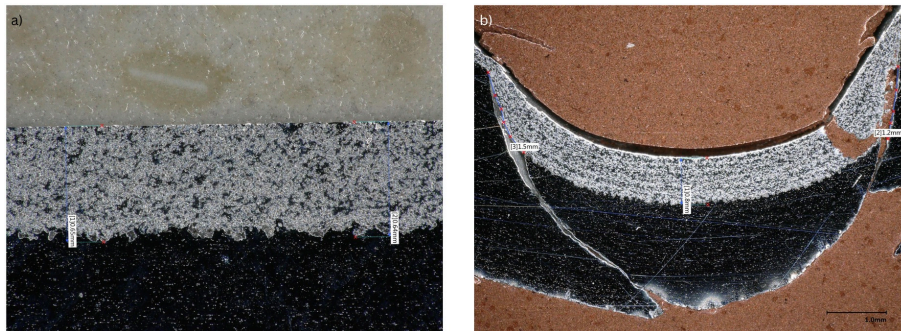


Figure 6.5: Accumulation in MPAir coupons, a) original deposition thickness -30x , b) thickness after impact -30x

6.4.4. Separation Al_2O_3

For every coupon, three or four layers of aluminium oxide are present in the horizontal direction. The lines are visible in Figure 6.6. The number of passes made by the robot arm during spraying does not correspond to the number of Al_2O_3 layers. The coupons were milled after spraying so this does not exclude the possibility of the number of Al_2O_3 layers with the spraying passes. However, in both the coating deposition (MPAir) coupons and the repair depositions (RepAir and Gun), the number of Al_2O_3 layers is three or four but there is a difference in the amount deposition that has been removed between the two types of deposition. For the coating, only one layer of approximately 0.15mm is removed, while for the repair deposition much more material had to be removed, around 1.7mm. The segregation lines are not clearly visible in every coupon, some coupons show a very clear distinction while others do not show the lines, this observed in all coupon types, MPAir, RepAir and Gun.

The separation of the Al_2O_3 particles and aluminium particles into horizontal layers could have occurred during the deposition process. The gas flow dynamics is sensitive to the size and mass of the particles. As seen for the RepAir and Gun coupons, the separation is present in the pre-impacted coupons. Al_2O_3 has a higher density compared to AA1XXX, 2.99 g/cm^3 vs 2.7 g/cm^3 respectively, the density affects the terminal velocity of the gas stream in the nozzle.

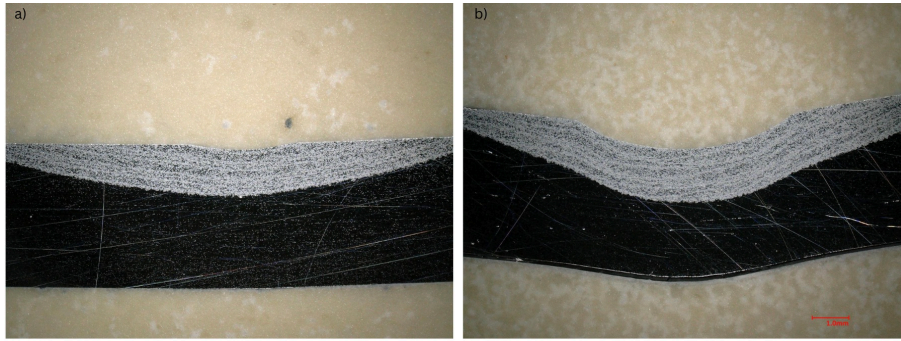


Figure 6.6: Segregation lines of Al_2O_3 and AA1XXX particles 30x

The lighter AA1XXX particles accelerate more easily, resulting in different arrival times on the substrate compared to heavier Al_2O_3 particles. The mass-based segregation could lead to the layered build up visible. The ductility of the material could also play a role; AA1XXX is highly ductile and deforms plastically upon impact, bonding well and filling the gaps in between particles. Al_2O_3 is a brittle ceramic, which cannot bond by deformation. These particles can become embedded or trapped between aluminium splats [42, 65].

However, in the MPAir coating, the separation lines are not visible before impact, but after impact the lines are visible. The Al_2O_3 and AA1XXX separation is not seen for every coupon. This doesn't mean that the segregation occur during the impact, but there is a possibility this happens due to the impact. The following theory might describe this. This Al_2O_3 free layer could correspond to a localized shear band, formed as a result of intense shear strain under high strain rates. Within this narrow zone, the adiabatic nature of deformation leads to localized heating, which lowers the flow stress of the ductile matrix and promotes material flow. Consequently, the brittle Al_2O_3 particles could be mechanically displaced or fractured, resulting in a visibly cleaner, oxide-free region. This combination of thickening and oxide redistribution highlights the complex interplay between plastic flow, shear localization, and material heterogeneity in cold sprayed coatings subjected to dynamic impact [63].

6.5. Flowability

During the research, it became clear that the AA2024 did not give the required cold spray deposition quality using the medium pressure system. High enough particle velocity and temperatures were not reached, resulting in a deposition efficiency of 1%. Most of the powder particles did not bond on the substrate or previous sprayed layers and bounced off/eroding the surface. Looking at the results from the LDA, the particle size of the AA2024 is more favorable than the AA1XXX particle size, suggesting the larger particles of the AA2024 would achieve the critical velocity easier. However, the rheometer results say different. The energy of the AA2024 is significantly higher, 211mJ vs 129mJ of the AA1XXX. The higher the energy, the more resistance to particle flow which is unwanted. The Flow Rate Index of the AA2024 is higher, meaning particle interlocking is more likely, as adjacent particles nestle together, forming big particle chunks. This aligns with the LDA results in which the particle size of the AA2024 is bigger than the AA1XXX. As large particles accelerate more easily, excessively large particles are difficult to accelerate due to their higher weight and higher resistance. The AA2024 clogged particles might be too large to be accelerate to the required critical velocity and thus not bond the substrate. As for the compressability, the AA1XXX has a higher compressibility percentage. The powder is able to compress more upon stress, which could be due to a porous structure, loosely packed structure or density. Both the AA1XXX and AA2024 have the FCC lattice structure with close packed planes. AA1XXX does have a slightly lower density compared to AA2024, 2.71 vs 2.78 g/cm^3 . The higher flow rate also allows the material to be more compressible, both reducing the energy required to produce a stable flow.

No data was found in the literature for compressibility and flowability measurements. The results of this research could thus not be compared with other research. However, the results of the rheometer, the higher energy and higher flow rate numbers of the AA2024 compared to the AA1XXX could explain the low deposition efficiency. The higher flow rate also explains the larger AA2024 particles found in

the LDA, due to the particle interlocking.

6.6. Dent depth model

The dent depth model proposed by Emerson and Souter, which uses yield strength and a fitting parameter k , did not fully align with the experimental dent depth measurements obtained in this study. This discrepancy can be attributed to several factors:

- **Material Composition:** The model is designed for monolithic materials, whereas the test coupons in this study consist of two distinct layers—a deposition and a substrate. The mechanical interaction between these layers is complex and not accounted for in the model.
- **Particle Interactions:** Cold spray depositions involve numerous particle-particle and particle-substrate interactions, leading to unique microstructural characteristics. These interactions influence the mechanical response under impact but are not considered in the model's framework.

Furthermore, certain assumptions inherent in the model do not hold true for cold spray applications:

- **Assumption:** The dent depth (w) is small compared to the radius (r) of the plastically deformed region.
Observation: In many of the tested coupons, the dent depth was at least 50% of the dent width, indicating that w is not small relative to r .
- **Assumption:** The deformation is purely plastic and irreversible and fully resisted by the membrane forces.
Observation: While the absorbed energy is partitioned into plastic deformation and crack/delamination formation, the presence of cracks and delaminations suggests that other factors, such as interfacial bonding and material heterogeneity, play significant roles.
- **Assumption:** All the kinetic energy of the impactor is expended in the straining of the plate.
Observation: In reality, the kinetic energy is distributed among various mechanisms, including the bounce back of the indenter, plastic deformation, and the initiation and propagation of cracks or delamination.

Despite these discrepancies, the k -values for five of the coupons fell within a narrow range of 6.6 to 8.6. However, the CSHP coupon exhibited a notably higher k -value of 51.78, indicating significantly different mechanical behavior. This could be attributed to factors such as variations in deposition material, increased porosity, or inferior bonding quality.

6.7. QSI vs LVI

Even though the quasi static indentation test can be used as a low velocity impact test, differences are observed in the results of the QSI and LVI. The impact behavior of the LVI coupons is similar to that of the reference AA plate, except for the depth of the dent. However, the LVI does differ slightly from the QSI test. The depth and width of the dent are higher for the QSI test compared to the LVI test, which is a result of the difference in the strain rate. Higher strain rates in the LVI test which restrict dislocations from moving, resulting in less ductile behavior and a stiffer material. Another factor is the energy dissipation, in LVI some of the energy of impact energy goes into wave propagation and vibrations of the coupon, which increases the amount of energy absorbed. In QSI no shock waves or rapid internal motion is present, and thus less energy is needed to reach the same amount of deflection. This also explains the slightly higher value for energy absorption in the LVI coupons. As the absorbed energy could be divided into two types, plastic deformation and crack formation/delamination, LVI coupons should thus have more cracks, since plastic deformation is lower. The crack threshold for the LVI is lower compared to QSI, so more energy is indeed dissipated to cracks; also, the amount of cracks per coupon is higher for the LVI, leading to a higher amount of energy going to the formation of cracks.

6.8. Experimental Issues

During the experimental work, some issues were encountered which could have influenced the results of this thesis.

6.8.1. Impact tower

The impact tower at the Aerospace Engineering Faculty of the TU Delft does have some limitations which could have effected the actual impact energy, following from the Formula 4.1. The height sensor is not very accurate; while the indenter was brought to a certain height, the value on the software still changed over time, while the indenter is kept static at a certain height. The actual height compared to the software height is also not the same, the height has to be corrected by a value which is set manually by measuring the height of the indenter with a ruler. For large impact heights, the actual height could not be measured with a ruler because it was simply too high, $> 2m$.

The software attached to the impact tower creates a force-deflection curve after impact is made, the maximum force and acceleration of the indenter are also given, valuable data for the analysis of the impact. During testing of the RepAir coupons, the software responsible for capturing force-deflection data encountered accuracy issues. Specifically, the measured force-deflection values did not reflect the actual behavior of the material, showing unrealistically low readings. Fixing this software malfunction would have significantly delayed the experimental schedule. Consequently, it was decided to proceed without relying on the software-generated force-deflection data. Fortunately, the primary research objectives could still be effectively met using alternative data sources, the footage captured by the high-speed camera. This visual data provided sufficient data to analyze the performance of different coupons and allowed for an accurate comparison of absorbed energy between coupons. By omitting the software-based force-deflection measurements, the quasi static indentation test—initially intended to provide supplementary data for coupon type 1—became redundant. Given that the primary reason to use the QSI test setup and the impact tower used for other coupon types was to retrieve more data. Therefore, the continuation of experiments with the hand held impact tower alone was deemed fully adequate to address the research objectives.

The accuracy of the impact location of the indenter is not stable. The indenter does fluctuate slightly during impact and thus does not always impact on the exact same spot. For the RepAir and Gun coupons this could have had an influence on the result. If the impact is not on the exact same spot repetitively, the ratio of deposition and substrate thickness underneath the impact is different, resulting in a different stress distribution. This could have had small effects on the damage mechanisms and thresholds researched in this thesis. Another issue that was caused by the fluctuating indenter was the spillage of the three coupons. The indenter did not impact the location set before impact, resulting in three impacts fully on the substrate for the RepAir side and Gun side coupons. One default hit for the RepAir side and two default hits for the Gun side. These coupons could not be used.

6.8.2. Coupon preparation

The cutting process of the coupons could have influenced the presence of cracks and or delamination around the dent. To cut the metal coupons properly, the coupons had to be clamped on two sides in order to not break the saw. During the cutting of the clamped system, stresses could be induced in the coupons. Pictures of the dent were taken before cutting the coupons, in order to capture the visible cracks by eye in case the coupons were damaged during cutting. No damage was observed by the cutting process, however, small cracks are not visible with the Keyence 1000 and it could thus not be excluded that cracks appeared in the coupons due to the cutting.

The preparation of the cross-sectional samples did not result in the intended quality required for detailed microstructural analysis. Specifically, the goal of obtaining a clean, scratch-free surface for the investigation of delamination between the substrate and the deposition was not fully achieved. During the sanding and polishing processes of the embedded coupons, it was challenging to produce a surface suitable for clear optical microscopy. The preparation protocol was carefully followed, beginning with coarse sanding and progressing to fine polishing. Despite this stepwise approach, scratches remained visible under microscopic inspection. A likely explanation for the surface damage is that cold spray powder particles were pulled out the coupon during sanding or etching. These particles may have adhered to the rotating sanding or etching equipment and subsequently scratched the sample surfaces during continued operation.

To overcome this issue and improve surface quality, manual sanding and etching could be done as an alternative. This method reduces the risk of particle entrapment and uncontrolled abrasion. However, manual preparation must be performed in a controlled environment due to the use of chemical

agents and the risk of contamination, which requires access to a designated laboratory area with safety regulations.

Given that the scratched surfaces did not obstruct the interpretation of bonding characteristics, it was unnecessary to repeat the preparation using manual sanding and polishing techniques. Although manual preparation could potentially yield a higher quality surface, the process is very time-consuming. As the existing images provided sufficient clarity for the intended analysis, the decision was made to proceed without reprocessing the samples manually.

7

Conclusion

7.1. Research Questions

The overall aim of this master thesis is to *evaluate the damage mechanisms in cold spray repairs subjected to low velocity impact*. This was explored by 4 sub-questions, from which based on the presented work the following conclusions can be drawn:

1. *At which impact energy level does the cold spray deposition begin to crack?* The cold spray depositions start to crack at the following thresholds:

Table 7.1: Crack threshold

Coupon	Type of deposition	Crack threshold
CSHP	Cold spray coating	1J-2J
MPAir	Cold spray coating	100J-125J
RepAir Mid	Cold spray repair	10J-20J
RepAir Mid	Cold spray repair	10J-20J
Gun Mid	Cold spray repair	10J-20J
Gun Mid	Cold spray repair	65J-85J
Cowling	Cold spray repair	0J-20J

2. *Does Barely Visible Impact Damage occur in the repair? If so, at what impact energy level does it start?*

The concept of Barely Visible Impact Damage (BVID) does not apply to cold spray depositions under low-velocity impact, as the impact consistently produces a visible dent, indicating the presence of damage mechanisms. However, the combination of substrate and deposition material should be chosen carefully. Because differing mechanical properties, ductility, yield strength, and thermal expansion could cause different damage mechanisms. The damage behavior of the substrate, especially the back side of the substrate can not be inspected by visual inspection. Due to the difference in mechanical properties the substrate could damage different or earlier compared to the visible dent in the cold spray deposition.

3. *Do interparticle and transparticle cracks appear? Does one type occur before the other, or do they occur simultaneously?*

Interparticle and transparticle cracks do appear both. Interparticle is the main cracking type as this is seen in all the cracks. Transparticle cracks are seen in two coupons, however, the distinguishing between inter- and transparticle cracking is difficult using the SEM. The height difference of the coupons

due to impact makes it difficult to focus and thus analyse the particles at high magnification, required for the analysis.

4. Does delamination between the substrate and deposition occur? If so, at what impact energy level does it happen?

The cold spray depositions show delamination of the substrate at the following thresholds:

Table 7.2: Delamination threshold

Coupon	Type of deposition	Crack threshold
CSHP	Cold spray coating	3J-4J
MPAir	Cold spray coating	100J-125J
RepAir Mid	Cold spray repair	> 100J
RepAir Mid	Cold spray repair	> 100J
Gun Mid	Cold spray repair	50J-100J
Gun Mid	Cold spray repair	65J-85J
Cowling	Cold spray repair	n.d.

This study has provided new information regarding the damage mechanisms and impact behavior of cold spray depositions. The experimental results confirm that cold spray repairs offer a promising solution against impact from low velocity foreign objects, demonstrating their potential as a viable repair method in aerospace applications. The crack lengths and delamination lengths created by the impact are far within the allowable damage limits following the maintenance manual. The dent width and depth are not within the allowable limits, however since the cowling inlet lip is a non-structural component, the damage can be repaired by placing an aluminium sealing patch. The large dent depth and width values can be attributed to the ductile material behavior of AA1XXX, absorbing large amounts of energies during impact load. The dominant damage mechanisms for most of the tested coupons is the initiation and propagation of cracks, which is the preferable damaging mechanisms compared to delamination. For two coupon types the cracking and delamination initiate at the same threshold. Crack initiation being the dominant damage mechanism is a positive outcome since delamination poses a particularly critical risk, as it may result in complete separation between the substrate and deposited layer. If such a delaminated section detaches during operation, it could be sucked into the engine, potentially causing severe damage. The primary damage mechanism observed for each coupon type is summarized in Table 7.3.

Table 7.3: Damage threshold

Coupon	Leading Damage type	Threshold
CSHP	Cracking	1J-2J
MPAir	Cracking and Delamination	100J-125J
RepAir Mid	Cracking	10J-20J
RepAir Mid	Cracking	10J-20J
Gun Mid	Cracking	10J-20J
Gun Mid	Cracking and Delamination	65J-85J
Cowling	Cracking	0J-20J

However, the variation in crack threshold values observed in different coupon types reveals that repair performance is highly dependent on several factors. These include the geometry of the deposition, the age and quality of the feedstock powder, the surface treatment prior to deposition, and the type of spraying system used. These parameters directly influence the bonding quality, uniformity, and mechanical response of the final repair and thus the damage thresholds.

7.2. Additional Findings

In addition to findings aligned with the main research objectives, several additional conclusions were drawn. A particularly clear contrast was observed between the RepAir and Gun coupons (Robotic vs

Gun sprayed), despite both using a blend-out repair geometry. The following factors are likely responsible for the differences in performance:

- **Surface Treatment Quality:** The bonding strength between the deposition and the substrate is highly influenced by the surface preparation method. Coarse grit-blasting creates deeper valleys and sharper peaks, improving mechanical interlocking and increasing the delamination threshold. In contrast, a finer or inconsistent roughening results in weaker bonding, inducing delamination between substrate and deposition.
- **Deposition uniformity from hand-held spraying:** The use of a manual cold spray gun introduces variability in nozzle speed, angle, and stand-off distance. This leads to non-uniform layer thickness, local heating, and inconsistent bonding across the surface. This results in expansion of the deposition, creating high compressive stresses around substrate-deposition interface.

Other additional findings are:

- **Ductile behavior of AA1XXX:** The deposition material AA1XXX behaves as a ductile material, with visible elongation and accumulation of material near the center of the indent. This contrasts with the results of tensile tests in which the material appeared more brittle.
- **Influence of post-treatment (Milling):** The milling process used to flatten the surface after spraying alters the mechanical properties of the deposition. It removes weaker surface layers and introduce residual compressive stresses, thereby affecting the deposition's performance.
- **Shear plug formation:** A distinct shear plug failure mode was observed on the back the of higher impact energy coupons, particularly in the substrate material. This was likely caused by localized shear stresses that exceed the material's strength, leading to plug-like fracture features.
- **Geometry and configuration effects:** The overall geometry of the coupon and the relative positioning of the deposition within or on top of the substrate significantly affected the energy absorption capacity. Blend-out repairs tended to dissipate more energy than surface coatings.
- **Quasi static indentation test** showed lower energy absorption compared to low velocity impact testing with the hand held tower. The lower strain rate sensitivity of the QSI plays a critical role, as strain rate effects delay or advance plastic flow and fracture initiation in aluminium.
- **The dent depth model** from Emerson and Souter can not be used to predict the dent depth due to low velocity impact on cold spray depositions.

These findings highlight the critical role of process control, material selection, and surface preparation in achieving reliable cold spray repairs—especially when using manual cold spray systems for in-field aerospace applications.

7.3. Final Remark

By combining the findings for the sub-objectives with the additional findings, this master thesis can be concluded by evaluating the main research objective:

The dominant failure mode in cold spray repair subjected to low velocity impact is interparticle-radial cracking. The first crack initiation is mainly observed between 10-20J of impact and the crack lengths and delamination observed are within the allowable damage limits for operation. The dent depth and width are not within the limits, but are allowed to be repaired with a fast method, placing an aluminium sealing patch. From a low velocity impact testing point of view, cold spray can be called a feasible technology to repair dents in the cowling inlet lips.

The conclusion regarding the applicability of the manual cold spray gun is as follows:

The manual cold spray gun is suitable for repairing cowling inlet lip damage, provided that the deposition uniformity is optimized. When combined with a coarse roughed substrate surface, the resulting layer can withstand low-velocity impacts from foreign objects.

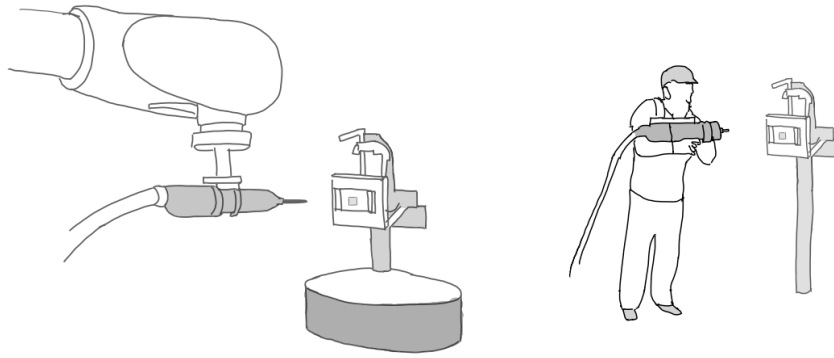
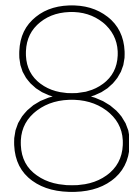


Figure 7.1: Robotic vs Manual gun cold spray



Recommendations

Based on the experimental results and observed failure mechanisms, the following recommendations and outlook are proposed to improve the performance and reliability of cold spray repairs in aerospace structures:

- Investigate the nature and mechanical impact of material accumulation observed in the deposition, and its influence on stress distribution and plastic deformation during impact.
- Study the phase segregation behavior of Al_2O_3 and pure AA1XXX during the deposition process, and how it affects bonding and damage initiation mechanisms.
- Analyze the effect of reducing the Al_2O_3 content in the AA1XXX + Al_2O_3 feedstock mixture on the ductility and crack resistance of the final repair.
- Evaluate the influence of the indenter geometry (specifically the radius) on stress concentration and distribution during low velocity impact testing.
- Further investigate the effect of the deposition geometry, repair vs coating on the crack threshold of the cold spray.
- Develop a model to analyze stress transfer at the substrate–deposition interface, as well as particle–particle interactions under dynamic loading.
- Further investigate the influence of milling-induced stresses and the severity of post-processing on residual stress fields and mechanical performance of the cold spray deposition.

To support the certification and real-world application of cold spray as a repair method for aircraft engine cowlings, the following topics are recommended to investigate:

- Explore the effect of preheating cold spray powder on particle softening and bonding quality to enhance deposition strength and cohesion.
- Optimize the AA1XXX + Al_2O_3 mix feedstock by reducing the proportion of Al_2O_3 , aiming to increase ductility without significantly compromising bonding.
- Develop support accessories or guiding tools to improve the uniformity and consistency of the manual sprayed depositions, mimicking the controlled parameters used in robotic spraying.
- Integrate a traverse speed monitoring system into the hand-held gun to maintain a constant nozzle speed, reduce localized heat buildup, and prevent blister formation—especially in curved geometries like the cowling backside.
- Investigate the feasibility of using the handheld gun to perform in-situ grit-blasting with Al_2O_3 , increasing substrate surface roughness and promoting stronger mechanical interlocking between particles and the substrate.
- Investigating the possibility repairing cold spray dents with cold spray.

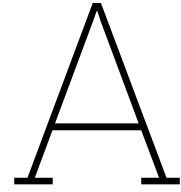
References

- [1] V. Champagne, M. H. Gangaraj, and D. Helfritsch. *Advances in Cold Spray*. 2nd ed. -. Sawston, United Kingdom: WoodHead Publishing, 2023.
- [2] M. van Hecking Colenbrander. "Impact on Cold Spray Repairs". In: -.1 (2024). DOI: -.
- [3] Anatolii Papyrin. "Cold Spray Technology". In: *Advanced Materials and Process* -. (2001), pp. 49–51. DOI: -.
- [4] V. Champagne, A. Nardi, and O. Ozdemir. *Practical Cold Spray*. 1st ed. -. Cham, Switzerland: Springer, 2021.
- [5] M. Kumar, H. Singh, and R. Singh. "An overview of various applications of cold spray coatings process". In: *Materialstoday: Proceedings* 56.5 (2022). -, pp. 2826–2830. DOI: <https://doi.org/10.1016/j.matpr.2021.10.160>.
- [6] South Dakota Mines. *Cold Spray*. 2024. URL: <https://www.sdsmt.edu/Research/Research-Laboratories/AMP/Capabilities/Cold-Spray/>.
- [7] H. Farhat. *Operation, Maintenance and Repair of Land-Based Gas Turbines*. 1st. Rome, Italy: Elsevier, 2021.
- [8] S. Bagherifard et al. "Deposit shape control for local repair and welding by cold spray". In: *Journal of Manufacturing Processes* 112.28 (2024). -, pp. 45–59. DOI: <https://doi.org/10.1016/j.jmapro.2024.01.023>.
- [9] S. Yin et al. "Towards high-strength cold spray additive manufactured metals: Methods, mechanisms, and properties". In: *Journal of Materials Science Technology* 170.20 (2024). -, pp. 47–64. DOI: <https://doi.org/10.1016/j.jmst.2023.05.047>.
- [10] Gunther Reinhart. *CIRP Encyclopedia of Production Engineering*. 1st. -. Berlin, Heidelberg: Springer Berlin, 2014.
- [11] E.Z. Liu and Yu. "Formation of refined grains below 10nm in size and nanoscale interlocking in the particle–particle interfacial regions of cold sprayed pure aluminum". In: *Scripta Materialia* 177.- (2020), pp. 96–100. DOI: <https://doi.org/10.1016/j.scriptamat.2019.09.018>.
- [12] G. Prashar and H. Vasudev. "A comprehensive review on sustainable cold spray additive manufacturing: State of the art, challenges and future challenges". In: *Journal of Cleaner Production* 310.10 (2021). -. DOI: <https://doi.org/10.1016/j.jclepro.2021.127606>.
- [13] Xiawei Yang et al. "Study on relieving residual stress of friction stir welded joint of 2219 aluminum alloy using cold spraying". In: *Materials Characterization* 206.- (2023). DOI: <https://doi.org/10.1016/j.matchar.2023.113417>.
- [14] Christopher M. Sample et al. "Factors governing static properties and fatigue, fatigue crack growth, and fracture mechanisms in cold spray alloys and coatings/repairs: A review". In: *Additive Manufacturing* 36.- (2020), pp. -. DOI: <https://doi.org/10.1016/j.addma.2020.101371>.
- [15] Qian Wang et al. "Measurement and analysis of cold spray residual stress using arbitrary Lagrangian–Eulerian method". In: *Additive Manufacturing* 35.- (2020). DOI: <https://doi.org/10.1016/j.addma.2020.101296>.
- [16] Silvano Rech et al. "Different Cold Spray Deposition Strategies: Single- and Multi-layers to Repair Aluminium Alloy Components". In: *Journal of Thermal Spray Technology* 23.8 (2014), pp. 1237–1250. DOI: <https://doi.org/10.1007/s11666-014-0141-y>.
- [17] C. Ziemian et al. "Effect of substrate surface roughening and cold spray coating on the fatigue life of AA2024 specimens". In: *Materials Design* 54.- (2014), pp. 212–221. DOI: <https://doi.org/10.1016/j.matdes.2013.08.061>.

- [18] M. Sharma, T. Eden, and B. Golesich. "Effect of Surface Preparation on the Microstructure, Adhesion, and Tensile Properties of Cold-Sprayed Aluminum Coatings on AA2024 Substrates". In: *Journal of Thermal Spray Technology* 24.- (2015), pp. 410–422. DOI: <https://doi.org/10.1007/s11666-014-0175-1>.
- [19] Q. Blochet et al. "Effect of the Cold-Sprayed Aluminum Coating-Substrate Interface Morphology on Bond Strength for Aircraft Repair Application". In: *Journal of Thermal Spray Technology* 26.- (2017), pp. 671–686. DOI: <https://doi.org/10.1007/s11666-017-0548-3>.
- [20] Patrick E. Morrison et al. "Evaluating the damage tolerant behavior of cold spray repaired aluminum alloys". In: *International Journal of Fatigue* -. (2024). DOI: <https://doi.org/10.1016/j.ijfatigue.2024.108607>.
- [21] Ondrej Kovarik et al. "Fracture Toughness of Cold Sprayed Pure Metals". In: *Journal of Thermal Spray Technology* 29.- (2020), pp. 147–157. DOI: <https://doi.org/10.1007/s11666-019-00956-z>.
- [22] Trevor Bond et al. "Fatigue and delamination of 6061 aluminum cold spray on a similar wrought substrate". In: *Materials Science and Engineering: A* 913.- (2024). DOI: <https://doi.org/10.17632/j3bvsd6bmk.1>.
- [23] Scott E. Julien et al. "Bulk fracture anisotropy in Cold-Sprayed Al 6061 deposits". In: *Engineering Fracture Mechanics* 263.- (2022). DOI: <https://doi.org/10.1016/j.engfracmech.2022.108301>.
- [24] G. Bae et al. "Bonding features and associated mechanisms in kinetic sprayed titanium coatings". In: *Acta Materialia* 57.19 (2009), pp. 5654–5666. DOI: <https://doi.org/10.1016/j.actamat.2009.07.061>.
- [25] Mohammed Jawaid, Mohamed Thariq, and Naheed Sada. *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*. 1st. Cambridge: Woodhead Publishing, 2019, pp. 1–12.
- [26] S. Nguyen et al. "Parametric analysis of runway stone lofting mechanisms". In: *International Journal of Impact Engineering* 37.5 (2010), pp. 502–514. DOI: <https://doi.org/10.1016/j.ijimpeng.2009.11.006>.
- [27] Z. Li et al. "Effects of impactor mass on the low-velocity impact behaviour of thick GFRP pultruded laminates". In: *Construction and Building Materials* 279.- (2021), pp. -. DOI: <https://doi.org/10.1016/j.conbuildmat.2021.122491>.
- [28] B. Aryal et al. "Effects of impact energy, velocity, and impactor mass on the damage induced in composite laminates and sandwich panels". In: *Composite Structures* 266.- (2019), pp. -. DOI: <https://doi.org/10.1016/j.compstruct.2019.111284>.
- [29] J. Artero-Guerrero et al. "Experimental study of the impactor mass effect on the low velocity impact of carbon/epoxy woven laminates". In: *Composite Structures* 133.- (2015), pp. 774–781. DOI: <http://dx.doi.org/10.1016/j.compstruct.2015.08.027>.
- [30] H. Wang et al. "Analytical study on the low-velocity impact penetration of the fully-clamped foam-core composite sandwich panels". In: *Composites Part B: Engineering* 224.- (2021). DOI: <https://doi.org/10.1016/j.compositesb.2021.109214>.
- [31] G. Gholipour, A. Mousavi, and C. Zhang. "Loading rate effects on the responses of simply supported RC beams subjected to the combination of impact and blast loads". In: *Engineering Structures* 201.- (2019). DOI: <https://doi.org/10.1016/j.engstruct.2019.109837>.
- [32] Y. Li and Y. Xuenfeng A. Xiaosu. "Comparison with Low-Velocity Impact and Quasi-static Indentation Testing of Foam Core Sandwich Composites". In: *International Journal of Applied Physics and Mathematics* 2.1 (2012), pp. 58–62. DOI: <https://doi.org/10.7763/IJAPM.2012.V2.54>.
- [33] Z. Wang et al. "Quasi-static and low-velocity impact behaviors of steel-aluminum foam sandwich beams". In: *Structures* 64 (2024). DOI: <https://doi.org/10.1016/j.istruc.2024.106549>.
- [34] T. Allen et al. "A comparison of quasi-static indentation and low-velocity impact on composite overwrapped pressure vessels". In: *Journal of Composite Materials* 52.29 (2018), pp. 4051–4060. DOI: <https://doi.org/10.1177/0021998318774401>.

- [35] W. Wang et al. "Strain rate effect on tensile behavior for high specific strength steel: From quasi static to intermediate strain rates". In: *Metals* 8.1 (2017). DOI: <https://doi.org/10.3390/met8010011>.
- [36] G. Bae et al. "General aspects of interface bonding in kinetic sprayed coatings". In: *Acta Materialia* 56.17 (2008), pp. 4858–4868. DOI: <https://doi.org/10.1016/j.actamat.2008.06.003>.
- [37] General Electric. *SPM 70-71-04 Metallographic evaluation of thermal spray coatings*. -. Commercial Engine standard practical Manual. -: General Electric, 2020.
- [38] General Electric. *SPM 70-49-01 Thermal spraying pure aluminum (Powder)*. -. Commercial Engine standard practical Manual. -: General Electric, 2007.
- [39] INC ROHR. *Structural Repair Manual*. -. Inlet Cowl Allowable Damage. -: Goodrich Aerostructures, 2024.
- [40] MatWeb. *MatWeb*. n.d. URL: https://www.matweb.com/search/datasheet_print.aspx?matguid=67d8cd7c00a04ba29b618484f7ff7524.
- [41] MatWeb. *MatWeb*. n.d. URL: <https://www.matweb.com/search/DataSheet.aspx?MatGUID=38e1c167c7ea4dfebf80778b29ae71cf&ckck=1>.
- [42] E. Irissou et al. "Investigation of Al-Al₂O₃ Cold Spray Coating Formation and Properties". In: *Journal of Thermal Spray Technology* 16.5 (2007), pp. 661–668. DOI: <http://dx.doi.org/10.1007/s11666-007-9086-8>.
- [43] MatWeb. *MatWeb*. n.d. URL: <https://www.matweb.com/search/DataSheet.aspx?MatGUID=4e4e4fc28bbe405882c789e8b2fd3817>.
- [44] M. Rokni et al. "An investigation into microstructure and mechanical properties of cold sprayed 7075 Al deposition". In: *Materials Science and Engineering: A* 625.- (2015), pp. 19–27. DOI: <https://doi.org/10.1016/j.msea.2014.11.059>.
- [45] J. Aurich et al. "Experimental study on the effect of the milling condition of an aluminum alloy on subsurface residual stress". In: *The International Journal of Advanced Manufacturing Technology* 127.- (2023), pp. 5487–5501. DOI: <https://doi.org/10.1007/s00170-023-11921-0>.
- [46] M. El-Khabeery and M. Fattouh. "Residual stress distribution caused by milling". In: *International Journal of Machine Tools and Manufacture* 29.3 (1989), pp. 391–401. DOI: [https://doi.org/10.1016/0890-6955\(89\)90008-4](https://doi.org/10.1016/0890-6955(89)90008-4).
- [47] Uddeholm. *Uddeholm Impax Supreme*. 2025. URL: <https://www.uddeholm.com/netherlands/nl/products/uddeholm-impax-supreme-voor-kunststof/>.
- [48] C. Cheung et al. "Cracking behavior during scratching brittle materials with different-shaped indenters". In: *International Journal of Mechanical Sciences* 268.- (2024). DOI: <https://doi.org/10.1016/j.ijmecsci.2024.109041>.
- [49] Z. Lou et al. "Towards understanding the influence of structured indenters geometry on material deformation behavior of indentation process". In: *Precision Engineering* 88.- (2024), pp. 401–414. DOI: <https://doi.org/10.1016/j.precisioneng.2024.03.002>.
- [50] G. Nilakantan and S. Nutt. "Effects of clamping design on the ballistic impact response of soft body armor". In: *Composite Structures* 108.- (2014), pp. 137–150. DOI: <https://doi.org/10.1016/j.istruc.2024.106549>.
- [51] S. Saatci and F. Vecchio. "Effects of Shear Mechanisms on Impact Behavior of Reinforced Concrete Beams". In: *ACI Structural Journal* 106.1 (2009), pp. 78–86. DOI: <https://doi.org/10.14359/56286>.
- [52] J. Emerson and R. Souter. *Summary of available hail literature and the effect of hail on aircraft in flight*. 1st. Langley Field, VA: NACA, 1952, pp. 20–22.
- [53] ThermoFischers. *SEM: Types of Electrons and the information They Provide*. 2019. URL: <https://www.thermofisher.com/blog/materials/sem-signal-types-electrons-and-the-information-they-provide/>.
- [54] H. Al-Emrani, R. Haghani, and M. Heshmati. "Fatigue-Prone Details in Steel Bridges". In: *buildings* 2.4 (2012), pp. 456–476. DOI: <http://dx.doi.org/10.3390/buildings2040456>.

- [55] D. Sandberg and O. Soderstrom. "Crack formation due to weathering of radial and tangential sections of pine and spruce". In: *Wood Material Science Engineering* 1.1 (2006), pp. 12–20. DOI: <https://doi.org/10.1080/17480270600644407>.
- [56] P. Cavaliere and A. Silvello. "Crack Initiation and Growth Behavior of Cold-Sprayed Ni Particles on IN718 Alloy". In: *Journal of Materials Engineering and Performance* 26.- (2017), pp. 1929–1937. DOI: <https://doi.org/https://doi.org/10.1007/s11665-017-2620-z>.
- [57] H. Bu et al. "Effect of heat treatment on the intermetallic layer of cold sprayed aluminum coatings on magnesium alloy". In: *Surface and Coatings Technology* 205.19 (2011), pp. 4665–4671. DOI: <https://doi.org/10.1016/j.surfcoat.2011.04.018>.
- [58] A. Sabard, H. Villiers Lovelock, and T. Hussain. "Microstructural Evolution in Solution Heat Treatment of Gas-Atomized Al Alloy (7075) Powder for Cold Spray". In: *Journal of Thermal Spray Technology* 27.- (2018), pp. 145–158. DOI: <https://doi.org/10.1007/s11666-017-0662-2>.
- [59] S. Jian, Z. Li, and H. Zhou. "Effect of gas temperature on the interfacial bonding of cold-spray additive-manufactured Ti6Al4V". In: *Surfaces and Interfaces* 44.- (2024). DOI: <https://doi.org/10.1016/j.surfin.2023.103676>.
- [60] H. Hao and T. Pham. "Prediction of the Impact Force on RC Beams from a Drop Weight". In: *Advances in Structural Engineering* -.- (2016), pp. 1–13. DOI: <http://dx.doi.org/10.1177/1369433216649384>.
- [61] A. Kubit et al. "Analysis of the mechanical properties and of micrographs of refill friction stir spot welded 7075-T6 aluminium sheets". In: *Archives of Civil and Mechanical Engineering* 18.1 (2018), pp. 235–244. DOI: <http://dx.doi.org/10.1016/j.acme.2017.07.005>.
- [62] P. Jena et al. "An experimental study on the ballistic impact behavior of some metallic armour materials against 7.62 mm deformable projectile". In: *Materials Design* 31.7 (2010), pp. 3308–3316. DOI: <https://doi.org/10.1016/j.matdes.2010.02.005>.
- [63] K. Karantza and D. Manolakos. "A Review on the Adiabatic Shear Banding Mechanism in Metals and Alloys Considering Microstructural Characteristics, Morphology and Fracture". In: *Metals* 13.12 (2023). DOI: <https://doi.org/10.3390/met13121988>.
- [64] Y. Liu et al. "Simulations of Effects of Geometric and Material Parameters on the Interfacial Stress of the Thermal Barrier Coatings with Free Edges". In: *Coatings* 13.8 (2023). DOI: <https://doi.org/10.3390/coatings13081378>.
- [65] R. Fernandez and B. Jodoin. "Cold Spray Aluminum–Alumina Cermet Coatings: Effect of Alumina Content". In: *Journal of Thermal Spray Technology* 27.2 (2018). DOI: <http://dx.doi.org/10.1007/s11666-018-0702-6>.



Appendix

A.1. Additional found literature

A.1.1. Dendritic microstructure

The rapid solidification of the powder particles during the deposition process lead to a variety of non-equilibrium microstructures. The high cooling rates combined with the temperature gradient present during solidification result in a cellular dendritic microstructure. Small dendritic cells, between 1-4 μm are observed with optical microscopy. The growth of dendrites is accompanied by a solute rejection, solute elements segregate on the sides of the dendrites, together forming dendritic cells which are visible in Figure 2.3. The wide range of cooling rates leads to the differing distribution and shapes of the cells visible. Dendrites propagate through the material and release heat. The formation of dendrites also contributes to localized segregation of alloying elements in the material. The temperature gradient in the material is partially related to the difference in powder particle size, smaller particles cool faster due to their larger surface area-to-volume ratio [58].

The formation of dendritic arms also influences the segregation seen in the coupons. When the deposition does not cool down quickly enough, diffusion occurs during the solidification itself and solute atoms migrate toward the grain boundaries. The inconsistent and non-equilibrium microstructure of the deposition leads to a lack of predictability and reproducibility for the cold spray deposition.

A.1.2. Heat treatment

One of the recommendations for using cold spray as a repair method for engine cowling inlet lips is to investigate the effect of pre-heating the powder particles before spraying. This in order to enhance the deposition strength and cohesion and could possibly lead to more ductility. Since this report does not go into the effect of pre-heating, an explanation of this suggested process will be given below, based on information found in the literature.

The recrystallized grains exhibit different orientation due to heat treatment. The difference in grain orientation increase the amount of bridging connections between local contact points, forming interlocked recrystallized grains, promoting the interface bonding [59]. Solution heat treatment of cold sprayed aluminium alloys can homogenize the microstructure of the deposition. The dendritic structure is eliminated and the solute atoms can be dissolved leading to a uniform solid solution. The redistribution of the alloying elements reduce the microhardness of the powder, allowing for greater plastic deformation during the deposition process and increasing the deposition efficiency.

The inconsistent microstructure in the cold spray deposition, explained in the previous section, effects the response of the powder particles to heat treatments. Post-spray annealing of the colds spray could enhance the mechanical properties of deposition. However, grain growth was found to be limited in the cold spray deposition during the post-spray annealing due to the presence of the solute segregation in coatings. The non-uniform distributed alloying elements in the grain structure are expected to redissolve in solid solution during the heat treatment, homogenizing the microstructure and decreasing the

hardness [58].

Another possible treatment is pre-heating the powder particles. Pre-heating the powder particles results in more deformed particles after deposition, flattening the particles and reducing the pores. A more intimate bonding is also seen in the preheated powders by Bae et al., due to activated surfaces and thermally softened. The pre-heating of the powder also affect the fracture modes, the material fractures more ductile when the treatment is applied, causing more transparticle cracks, compared to the non treated powder [24].

A.2. Compliance test QSI

Table A.1: Compliance values for QSI test

$F_{max}[N]$	$Compliance(C)$	Stiffness	$\delta_{max}[mm]$
500	$1.91 * 10^{-10}$	$523 * 10^7$	$9.58 * 10^{-8}$
750	$1.74 * 10^{-10}$	$574 * 10^7$	$1.31 * 10^{-7}$
1000	$1.66 * 10^{-10}$	$603 * 10^7$	$1.66 * 10^{-7}$
1250	$1.61 * 10^{-10}$	$623 * 10^7$	$2.01 * 10^{-7}$
1500	$1.57 * 10^{-10}$	$638 * 10^7$	$2.35 * 10^{-7}$
2000	$1.51 * 10^{-10}$	$662 * 10^7$	$3.02 * 10^{-7}$
2500	$1.48 * 10^{-10}$	$677 * 10^7$	$3.69 * 10^{-7}$
3000	$1.44 * 10^{-10}$	$691 * 10^7$	$4.34 * 10^{-7}$
3500	$1.42 * 10^{-10}$	$703 * 10^7$	$4.98 * 10^{-7}$

A.3. Flowability

Below the results of the Rheometer measurement is shown. Besides the AA2024 and AA1XXX powder, used in this research, AA6061 is tested as well. This in order to compare the results with. AA6061 is also used for cold spray and currently under investigation at the TU Delft. Two types of AA6061 are measured, the two different AA6061 powder show different deposition efficiencies, comparable to the difference between the AA2024 and AA1XXX.

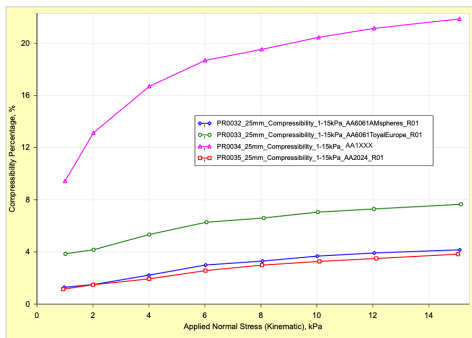


Figure A.1: Compressibility results

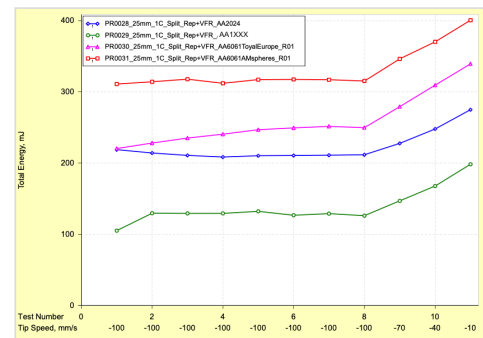


Figure A.2: Flowability results

Table A.2: Compressibility measurement

Material and Batch	CBD, g/ml	CPS, % @ 15.0kPa
AA6061AMspheres	1.35	4.16
AA6061Toyaleurope	1.42	7.65
AA1XXX	1.29	21.87
AA2024	1.54	3.83

Table A.3: Flowability measurement

Material and Batch	BFE, mJ	SI	FRI	SE, mJ/g	CBD, g/ml
AA2024	211.07	0.96	1.30	2.80	1.56
AA1XXX	129.00	1.23	1.57	3.02	1.64
AA6061Toyaleurope	251.57	1.14	1.36	3.64	1.37
AA6061AMspheres	317.01	1.02	1.27	4.19	1.32

Table A.4: LDA measurement

Sample Name	D [4,3]	D [3,2]	Span	Dx (10)	Dx (50)	Dx (90)
AI1XXX_250312	17.2	13.1	1.266	7.68	16.2	28.2
AI2024_250312	36.6	31.4	1.084	19.9	34.1	56.9
AI2024_250312	36.4	31.2	1.091	19.8	33.8	56.7
AI2024_250312	36.3	31.1	1.088	19.8	33.8	56.5

For the LDA results, an average value of the three AA2024 tests is taken. For the AA1XXX sample, only one out of the five tests was approved and shown.

A.4. Database results

Table A.5: Database testing

Sample	Tower used	Indenter	Mass kg	Impact energy J	V_in m/s	Absorbed energy	Absorbed/Ek	Delamination	Dent visible	Dent width (mm)	Dent Depth (mm)	Back crack
CSHP6	Hand tower	1	0.668	5	3.65	3.02	66.2	Yes	Yes	3.2	0.196	No
CSHP7	Hand tower	1	0.668	4	2.99	1.42	46.4	Yes	Yes	3.1	0.249	No
CSHP8	Hand tower	1	0.668	3	2.62	0.9	38	No	Yes	2.6	0.111	No
CSHP9	Hand tower	1	0.668	2	2.1	0.42	27.4	No	Yes	2.6	0.08	No
CSHP10	Hand tower	1	0.668	1	1.28	0.29	52.7	No	Yes	2.4	0.074	No
CSHP11	Hand tower	1	0.668	0.5	0.88	0.25	91.8	No	Yes	2.6	0.016	No
CSHP12	QSI	2	-	4.9	-	1.47	30	No	No	3.9	0.73	No
CSHP13	QSI	2	-	3.98	-	1.39	34.9	No	No	3.7	0.6	No
CSHP14	QSI	2	-	2.35	-	0.43	18.3	No	Yes	4.1	0.256	No
CSHP15	QSI	2	-	1.1	-	0.1	9.09	No	Yes	3.2	0.011	No
CSHP16	QSI	2	-	0.46	-	0.028	6.09	No	Yes	3.9	0.046	No
MPAir4 156	Impact tower	3	4.3	156	7.68	120.52	95	Yes	Yes	10	10.65	Yes
MPAir7 140	Impact tower	3	4.3	140	7.89	127.5	95.4	Yes	Yes	9.1	7.55	Yes
MPAir5 125	Impact tower	3	4.3	125	6.98	97.8	93.2	Yes	Yes	7.9	6.1	Yes
MPAir3 100	Impact tower	3	4.3	100	5.73	64.4	92.2	No	Yes	7	5.89	Yes
RepAir_mid 11 100	Impact tower	3	4.3	100	6.13	75.5	93.6	No	Yes	9.4	7.55	Yes
RepAir_mid 10 50	Impact tower	3	4.3	50	4.55	36.9	82.8	No	Yes	6.9	4.4	Yes
RepAir_mid 13 40	Impact tower	3	4.3	40	3.74	24.6	82		Yes	6.5	3.38	No
RepAir_mid 12 30	Impact tower	3	4.3	30	3.66	23.9	83		Yes	6	3.01	No
RepAir_mid 14 20	Impact tower	3	2.6	20	2.69	7.77	74.8		Yes	4.6	1.42	No
RepAir_mid 22 10	Impact tower	3	1.58	10	2.47	1.38	67.7		Yes	3.7	0.69	No
RepAir_sid 15 147	Impact tower	3	4.3	147	7.64	121.7	97	Yes	Yes	11	13.2	Yes
RepAir_sid 17 100	Impact tower	3	4.3	100	6.12	74.1	92	No	Yes	8.1	7.1	Yes
RepAir_sid 16 50	Impact tower	3	4.3	50	3.77	23.9	78		Yes	5.9	3.54	No
RepAir_sid 18 40	Impact tower	3	4.3	40	3.66	23.4	81.5		Yes	5.3	2.4	No
RepAir_sid 19 30	Impact tower	3	4.3	30	3.45	21.2	82.7		Yes	4.9	1.85	No
RepAir_sid 20 20	Impact tower	3	2.88	20	2.92	8.72	71.1		Yes	4.2	1.21	No
RepAir_sid 20 10	Impact tower	3	1.58	10	2.2	2.45	64.2		Yes	3	0.47	No
Gun_mid	Impact tower	3	4.3	100	5.86	69.3	94	Yes	Yes	9	9	Yes
Gun_mid	Impact tower	3	4.3	50	3.86	25.9	81		Yes	5.9	5.9	No
Gun_mid	Impact tower	3	4.3	40	3.68	22.8	78.2	No	Yes	5.8	2.82	No
Gun_mid	Impact tower	3	2.6	20	2.94	7.9	70.4		Yes	4.7	4.7	No
Gun_mid	Impact tower	3	1.58	10	2.43	1.2	60.5	No	Yes	3.6	0.54	No
Gun_sid	Impact tower	3	4.3	100	5.65	65.2	95.1	Yes	Yes	7.7	5.73	Yes
Gun_sid	Impact tower	3	4.3	85	5.31	57.7	95.2	Yes	Yes	7.1	5.8	Yes
Gun_sid	Impact tower	3	4.3	65	4.86	41	87	No	Yes	6.2	4.5	Yes
Gun_sid	Impact tower	3	4.3	50	3.98	27.8	81.7		Yes	5.3	2.84	Yes
Gun_sid	Impact tower	3	2.6	20	3.05	8.4	69.3		Yes	3.9	1.23	No
AA_7 5	Hand tower	2	0.668	5	2.6	1.4	62.1		Yes	3.15	1.305	No
AA_8 4	Hand tower	2	0.668	4	2.74	1.14	43.9		Yes	2.8	1.069	No
AA_9 3	Hand tower	2	0.668	3	2.4	0.83	42		Yes	2.5	0.819	No
AA_10 2	Hand tower	2	0.668	2	2.26	0.67	38.3		Yes	2.3	0.58	No
AA_11 1	Hand tower	2	0.668	1	1.78	0.21	19.3		Yes	1.9	0.354	No
AA_12 0.5	Hand tower	2	0.668	0.5	0.00038	0	100		Yes	1.3	0.08	No
AA10 156	Impact tower	3	4.3	156	6.84	94.4	93.9		Yes	9.4	8.4	Yes
AA9 140	Impact tower	3	4.3	140	6.4	81.7	92.8		Yes	8.5	6.8	Yes
AA5 125	Impact tower	3	4.3	125	6.4	80.7	91.6		Yes	8.4	6.84	Yes
AA8 110	Impact tower	3	4.3	110	5.69	65	93.4		Yes	7.8	5.45	Yes
AA4 100	Impact tower	3	4.3	100	5.51	58	88.7		Yes	7.5	5.072	Yes
AA 85	Impact tower	3	4.3	85	5.45	57.1	89		Yes	7	5.2	Yes
AA65	Impact tower	3	4.3	65	4.64	38.9	84		Yes	5.9	3.98	Yes
AA3 50	Impact tower	3	4.3	50	4.41	29.6	80.3		Yes	5.2	2.866	No
AA1 40	Impact tower	3	4.3	40	3.56	20.55	75.6		Yes	4.8	2.077	No
AA2 30	Impact tower	3	4.3	30	3.17	14.6	67.5		Yes	4.7	1.668	No
AA6 20	Impact tower	3	2.88	20	2.65	6.7	66.4		Yes	3.6	0.679	No
AA7 10	Impact tower	3	1.58	10	2.64	3.5	63.8		Yes	3.2	0.473	No
Cowling2	Impact tower	3	4.3	100	5.81	60.1	82.3	-	Yes	8.3	4.9	Yes
Cowling1	Impact tower	3	4.3	50	3.82	24.8	78.8	-	Yes	6.3	2.4	No
Cowling3	Impact tower	3	2.6	20	3.24	9.4	69	-	Yes	5.6	1.3	No

Table A.6: Dent depth values predicted and measured

Sample	Measured depth [mm]	Predicted depth [mm]
CSHP6	0.196	0.206
CSHP7	0.249	0.168
CSHP8	0.111	0.148
CSHP9	0.08	0.118
CSHP10	0.074	0.072
CSHP11	0.016	0.05
MPAir 4	10.65	8.244
MPAir7	7.55	8.47
MPAir 5	6.1	7.493
MPAir 3	5.89	6.151
RepAir_mid 11	7.55	6.279
RepAir_mid 10	4.4	4.668
RepAir_mid 13	3.38	3.837
RepAir_mid 12	3.01	3.755
RepAir_mid14	1.42	2.25
RepAir_mid 22	0.69	0.997
RepAir_sid 15	13.2	9.433
RepAir_sid 17	7.1	7.556
RepAir_sid 16	3.54	4.655
RepAir_sid 18	2.4	4.519
RepAir_sid 19	1.85	4.26
RepAir_sid 20	1.21	2.951
RepAir_sid 21	0.47	1.639
Gun_mid5	6.8	5.557
Gun_mid2	3.1	3.661
Gun_mid	2.82	3.49
Gun_mid12	1.17	2.168
Gun_mid9	0.54	0.922
Gun_sid3	5.73	5.739
Gun_sid7	5.8	5.393
Gun_sid8	4.5	4.753
Gun_sid6	2.84	3.136
Gun_sid11	1.23	1.239
Cowl1	2.4	3.263
Cowl2	5.9	4.963
Cowl3	1.3	2.152

A.4.1. Dent depth model values

A.5. Python codes

A.5.1. Graphs Absorbed Energy

Listing A.1: Absorbed Energy graphs

```

1
2 plt.figure(figsize=(10, 6))
3 plt.plot(ImpactMP, Absorbed_MP, marker='s', linestyle='--', label= 'MP', color = '
  blue')
4 plt.plot(Impactrepmid, Absorbed_RepAir_mid, marker='s', linestyle='--', label= '
  Repairmid', color = 'green')
5 plt.plot(Impactrepsid, Absorbed_RepAir_sid, marker = 's', linestyle='--', label= '
  Repairsid', color = 'orange')
6 plt.plot(ImpactGun_mid, Absorbed_Gun_mid, marker='s', linestyle='--', label= '
  Gunmid', color = 'red')

```



```

7 plt.plot(ImpactGun_sid, Absorbed_Gun_sid, marker='s', linestyle='-', label= '
  Gunsid', color ='purple')#
8 plt.plot(ImpactCowl, Absorbed_Cowl, marker='s', linestyle='-', label= 'Cowl',
  color ='pink')
9 plt.plot(ImpactAA, Absorbed_AA, marker='s', linestyle='dashed', label= 'AA', color
  ='black')
10 plt.xlabel('Impact energy (J)')
11 plt.ylabel('Absorbed energy (J)')
12 plt.title('Impact energy vs. Absorbed energy')
13 plt.grid(True)
14 plt.legend()
15 plt.show()

```

A.5.2. Graphs Threshold

Listing A.2: Threshold graphs

```

1 bfseriesimport matplotlib.pyplot as plt
2 bfseriesimport numpy as np
3
4 # Data for crack threshold ranges of different specimens
5 specimens = ['CSHP', 'MPAir', 'RepMid', 'RepSid', 'GunMid', 'GunSid', 'Cowling']
6 thresh_min = [3, 100, 10, 10, 10, 65, 0] # Minimum threshold values
7 thresh_max = [4, 125, 20, 20, 20, 85, 20] # Maximum threshold values
8
9 colors = ['brown', 'blue', 'green', 'orange', 'red', 'purple', 'pink'] # Assigned
  colors
10
11 # Create a figure
12 plt.figure(figsize=(8, 5))
13
14 # Plot error bars with specified colors for front cracks
15 bfseriesfor i bfseriesin bfseriesrange(bfserieslen(specimens)):
16     plt.plot([i, i], [thresh_min[i], thresh_max[i]], color=colors[i], linewidth=2,
17         label='Crack' bfseriesif i == 0 bfserieselse "")
18     plt.hlines(thresh_min[i], i - 0.1, i + 0.1, color=colors[i], linewidth=2) #
  Small horizontal line at min
19     plt.hlines(thresh_max[i], i - 0.1, i + 0.1, color=colors[i], linewidth=2) #
  Small horizontal line at max
20
21 # Labels and title
22 plt.xlabel('Specimens')
23 plt.ylabel('Crack Threshold (J)')
24 plt.title('Crack Threshold Ranges of Different Specimens')
25 plt.xticks(bfseriesrange(bfserieslen(specimens)), specimens)
26 plt.ylim(0, bfseriesmax(thresh_max) + 20) # Adjust y-limit for better
  visualization
27
28 # Display values on top of front crack lines
29 bfseriesfor i, (min_val, max_val) bfseriesin bfseriesenumerate(bfserieszip(thresh_min,
  thresh_max)):
30     plt.text(i, max_val + 2, f'{min_val}-{max_val}', ha='center', fontsize=10,
31         color=colors[i])
32
33 # Add legend
34 plt.legend()
35
36 # Show chart
37 plt.show()

```

A.5.3. Normalized values

Listing A.3: Normalized values

```

1 #normalized values absorbed energy
2 bfseriesfor i bfseriesin Absorbed_MP:
3     Norm_abs_MP = i/4.65
4     bfseriesprint('Abs MP', Norm_abs_MP)
5
6 bfseriesfor i bfseriesin Absorbed_RepAir_sid:
7     Norm_abs_RepAir_sid = i/4
8     bfseriesprint('Abs repsid', Norm_abs_RepAir_sid)
9
10 bfseriesfor i bfseriesin Absorbed_RepAir_mid:
11     Norm_abs_RepAir_mid = i/4
12     bfseriesprint('Abs repmid', Norm_abs_RepAir_mid)
13
14 bfseriesfor i bfseriesin Absorbed_AA:
15     Norm_abs_AA = i/4
16     bfseriesprint('Abs AA', Norm_abs_AA)
17
18 bfseriesfor i bfseriesin Absorbed_HP:
19     Norm_abs_HP = i/2.65
20     bfseriesprint('Abs HP', Norm_abs_HP)
21
22 bfseriesfor i bfseriesin Absorbed_AA2:
23     Norm_abs_AA2 = i/2
24     bfseriesprint('Abs AA2', Norm_abs_AA2)
25
26 bfseriesfor i bfseriesin Absorbed_Gun_mid:
27     Norm_abs_Gun_mid = i/4
28     bfseriesprint('AbsGunMid', Norm_abs_Gun_mid)
29
30 bfseriesfor i bfseriesin Absorbed_Gun_sid:
31     Norm_abs_Gun_sid = i/4
32     bfseriesprint('AbsGunSid', Norm_abs_Gun_sid)
33
34 bfseriesfor i bfseriesin Absorbed_Cowl:
35     Norm_abs_Cowl = i/2.25
36     bfseriesprint('Abs Cowl', Norm_abs_Cowl)
37
38 bfseriesfor i bfseriesin Absorbed_QSI:
39     Norm_abs_QSI = i/2.65
40     bfseriesprint('AbsQSI', Norm_abs_QSI)

```

A.5.4. QSI results

Listing A.4: QSI - Full

```

1 bfseriesimport pandas as pd
2 bfseriesimport matplotlib.pyplot as plt
3 bfseriesdef plot_multiple_graphs(file_path, sheets, Standard_travel, Standard_force
4     , labels=None):
5     """
6     Plot multiple graphs from different sheets in an Excel file on one figure.
7
8     Parameters:
9     file_path (str): Path to the Excel file.
10    sheets (list): List of sheet names to extract data from.
11    x_column (str): Column name for the x-axis data.
12    y_column (str): Column name for the y-axis data.
13    labels (list): List of labels for the graphs (optional).
14    """
15    plt.figure(figsize=(10, 6))

```

```

15
16 # Plot data from each sheet
17 bfseriesfor i, sheet bfseriesin bfseriesenumerate(sheets):
18     # Read data from the sheet
19     data = pd.read_excel(file_path, sheet_name=sheet)
20
21     # Extract x and y data
22     x = data[Standard_travel]
23     y = data[Standard_force]
24
25     # Use the sheet name or provided labels as the legend
26     label = labels[i] bfseriesif labels bfserieselse sheet
27
28     x = pd.to_numeric(x, errors='coerce')
29     y = pd.to_numeric(y, errors='coerce')
30
31     # Plot the data
32     plt.plot(x, y, label=label)
33
34     # Customize the plot
35     plt.xlabel('Deflection mm')
36     plt.ylabel('Force N')
37     plt.title('CSHP coupons - QSI Test')
38     plt.legend()
39     plt.grid(True)
40     plt.tight_layout()
41
42     # Show the plot
43     plt.show()
44
45 # Example usage
46 file_path = '/content/drive/MyDrive/cold spr/Impact Data - Force graphs/Quasi
    Static CS/QuasiStaticCSHP_full.xlsx'
47 # Path to your Excel file
48 sheets = ["CSHP#12", "CSHP#13", "CSHP#14", "CSHP#15", "CSHP#16"] # Replace with
    your sheet names
49 x = "Compliance standard travel" # Replace with your x-axis column name
50 y = "Standard force" # Replace with your y-axis column name
51 labels = ["0.5J", "1J", "2.3J", "4J", "5J"] # Optional: Labels for the graphs
52
53 plot_multiple_graphs(file_path, sheets, x, y, labels)

```

Listing A.5: QSI - cut off

```

1 bfseriesimport pandas as pd
2 bfseriesimport matplotlib.pyplot as plt
3 bfseriesimport numpy as np
4
5 bfseriesdef extract_energies_from_tabs(file_path, sheets, x, y):
6     # Read the Excel file
7     energies = {}
8
9     bfseriesfor i, sheet bfseriesin bfseriesenumerate(sheets):
10         # Read data from the sheet
11         data = pd.read_excel(file_path, sheet_name=sheet)
12
13         # Extract x and y data, converting to numeric and handling errors
14         deflection = pd.to_numeric(data[x], errors='coerce').to_numpy()
15         force = pd.to_numeric(data[y], errors='coerce').to_numpy()
16
17

```

```

18     # Remove NaN values to ensure proper sorting and calculation
19     valid_indices = np.isfinite(deflection) & np.isfinite(force)
20     deflection = deflection[valid_indices]
21     force = force[valid_indices]
22
23     # Calculate the area under the curve using the trapezoidal rule (in N·mm)
24     energy_nmm = np.trapz(force, deflection, dx=0.01)
25
26     # Convert N·mm to Joules (1 N·mm = 0.001 J)
27     energy_joules = energy_nmm * 0.001
28
29     # Store the result in the dictionary
30     energies[sheet] = energy_joules
31
32     bfseriesreturn energies
33
34 # Example usage
35 # Replace `tabs` with your dictionary of DataFrames (one for each tab)
36 # Replace 'Deflection' and 'Force' with your actual column names
37 # Example usage
38 file_path = '/content/drive/MyDrive/cold spra/Impact Data - Force graphs/Quasi
    Static CS/QuasiStaticCSHP_cutoff.xlsx'
39 # Path to your Excel file
40 sheets = ["CSHP#12", "CSHP#13", "CSHP#14", "CSHP#15", "CSHP#16"] # Replace with
    your sheet names
41 x = "Compliance standard travel" # Replace with your x-axis column name
42 y = "Standard force" # Replace with your y-axis column name
43 labels = ["0.5J", "1J", "2.3J", "4J", "5J"] # Optional: Labels for the graphs
44 plot_multiple_graphs(file_path, sheets, x, y, labels)
45
46 # Extract energies from all tabs
47 energies = extract_energies_from_tabs(file_path, sheets, x, y)
48
49 # Print the calculated energies
50 bfseriesfor sheet, energy bfseriesin energies.items():
51     bfseriesprint(f"Sheet: {sheet}, Energy: {energy:.4f} Joules")

```

A.5.5. Dent depth model - Optimization

Listing A.6: Optimization of dent depth model

```

1 bfseriesimport numpy as np
2 bfseriesfrom scipy.optimize bfseriesimport least_squares
3 bfseriesimport matplotlib.pyplot as plt
4
5 # --- Input data ---
6 v_inMP = np.array([5.73, 6.98, 7.89, 7.68]) # velocities (m/s)
7 dent_depthMP = np.array([5.89, 6.1, 7.55, 10.65]) # actual dent depths (mm)
8
9 mass = 4.3 # kg
10 ys = 138.15e6 # Pa (yield strength)
11 t = 0.000465 # m (thickness)
12
13 # --- Model Function ---
14 bfseriesdef model_w(k, v):
15     """Computes predicted dent depth w in mm"""
16     bfseriesreturn v * np.sqrt(mass) / (k * np.sqrt(ys * t)) * 1000
17
18 # --- Residual Function for Optimization ---
19 bfseriesdef residuals(k, v, w_measured):
20     w_pred = model_w(k, v)
21     bfseriesreturn w_pred - w_measured

```

```

22
23 # --- Run Least Squares Optimization ---
24 initial_guess = [6.0]
25 bounds = (0.1, 100.0)
26
27 result = least_squares(residuals, initial_guess, bounds=bounds, args=(v_in,
    dent_depthMP))
28
29 # --- Extract Optimal k ---
30 k_opt = result.x[0]
31 w_fit = model_w(k_opt, v_in)
32
33 # --- Output Results ---
34 bfseriesprint(f"    Optimized k: {k_opt:.4f}")
35 bfseriesprint("\nPredicted vs Measured Dent Depths (in mm):")
36 bfseriesfor i, (pred, actual) in bfseriesenumerate(bfserieszip(w_fit,
    dent_depth)):
37     bfseriesprint(f"Test {i+1}: Predicted = {pred:.3f}, Measured = {actual:.3f},
        Error = {pred - actual:.3f}")
38
39 # --- Optional: Plot Results ---
40 plt.figure(figsize=(6,4))
41 plt.plot(dent_depthMP, w_fit, 'o', label='Predicted vs Measured')
42 plt.plot([0, bfseriesmax(dent_depthMP)], [0, bfseriesmax(dent_depthMP)], '--', color
    ='gray', label='Ideal Fit')
43 plt.xlabel('Measured Dent Depth (mm)')
44 plt.ylabel('Predicted Dent Depth (mm)')
45 plt.title('Model Fit of Dent Depth - MPAir')
46 plt.legend()
47 plt.grid(True)
48 plt.tight_layout()
49 plt.show()

```

A.5.6. Johnson-Cook model

Listing A.7: Johnson-Cook model

```

1 ##Johnson cook model bron
2 bfseriesimport numpy as np
3
4 # Example values for a typical aluminum alloy
5 A = 110e6          # Pa
6 B = 150e6          # Pa
7 n = 0.36
8 C = 0.014
9 m = 1.0
10 eps_dot_0 = 1.0    # 1/s
11 T_room = 293       # K
12 T_melt = 931       # K (e.g., aluminum)
13 eps = 0.1          # plastic strain
14 eps_dot = 1000     # strain rate
15 T = 473            # temperature (200°C in Kelvin)
16
17
18 bfseriesdef johnson_cook_yield_strength(eps, eps_dot, T, A, B, n, C, m, eps_dot_0,
    T_room, T_melt):
19     """
20     Calculate yield strength using the Johnson-Cook model.
21
22     Parameters:
23     - eps: plastic strain (dimensionless)
24     - eps_dot: strain rate (1/s)

```

```

25     - T: current temperature (K)
26     - A: yield strength at reference (Pa)
27     - B: strain hardening coefficient (Pa)
28     - n: strain hardening exponent
29     - C: strain rate sensitivity coefficient
30     - m: thermal softening exponent
31     - eps_dot_0: reference strain rate (1/s)
32     - T_room: room temperature (K)
33     - T_melt: melting temperature (K)
34
35     Returns:
36     - Yield strength _y in Pascals
37     """
38     # Normalize temperature
39     T_star = (T - T_room) / (T_melt - T_room)
40     T_star = bfseriesmax(0.0, bfseriesmin(T_star, 1.0)) # Clamp to [0,1]
41
42     # Johnson-Cook equation
43     sigma_y = (A + B * eps**n) * \
44               (1 + C * np.log(eps_dot / eps_dot_0)) * \
45               (1 - T_star**m)
46
47     bfseriesreturn sigma_y
48
49 sigma_y = johnson_cook_yield_strength(eps, eps_dot, T, A, B, n, C, m, eps_dot_0,
50                                     T_room, T_melt)
51 bfseriesprint(f"Johnson-Cook Yield Strength: {sigma_y/1e6:.2f} MPa")

```