



CHALMERS
UNIVERSITY OF TECHNOLOGY



Material Selection and Characterisation of Sustainable Low Voltage Busbars

Master's thesis in Materials Engineering

GEETIK MAMILLAPALLI

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2026

www.chalmers.se

MASTER'S THESIS 2026

Material Selection and Characterisation of Sustainable Low Voltage Busbars

GEETIK MAMILLAPALLI



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Industrial and Material Science
Division of Materials and Manufacture
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026

Material Selection and Characterisation of Sustainable Low Voltage Busbars

GEETIK MAMILLAPALLI

© GEETIK MAMILLAPALLI, 2026.

Supervisor: Niclas Fogelberg, ABB

Examiner: Sheng Guo, Industrial and Material Science

Master's Thesis 2026

Department of Industrial and Material Science

Division of Materials and Manufacture

Chalmers University of Technology

SE-412 96 Gothenburg

Telephone +46 31 772 1000

Cover: ABB CDC 40 low-voltage distribution assembly, the phase rail system investigated in this thesis.

Typeset in L^AT_EX, template by Kyriaki Antoniadou-Plytaria

Printed by Chalmers Reproservice

Gothenburg, Sweden 2026

Material Selection and Characterisation for Sustainable Low Voltage Busbars
In Co-operation with ABB
GEETIK MAMILLAPALLI
Department of Industrial and Material Science
Chalmers University of Technology

Abstract

Title: Material Selection and Characterisation for Sustainable Low Voltage Busbars.

Abstract: Low-voltage busbars are critical current-carrying components in switchgear systems, and growing pressure to reduce lifecycle environmental impact has motivated interest in sustainable conductor material alternatives. This thesis investigates material substitutes for the incumbent Al 6063-T6 phase rail used in the ABB CDC 40 switchgear system, aiming to maintain electrical and mechanical performance while reducing carbon footprint.

An Ashby-based material selection methodology was applied, translating functional requirements into constraints, performance indices, and a multi-objective penalty function weighting material cost and cradle-to-grave carbon footprint. Five candidates were shortlisted after systematic screening: C11000 (ETP Cu), C18100 (Cu-CrZr), Al 1350-H12, Al 6101-T6, and the baseline Al 6063-T6. Finite element analysis in ANSYS Mechanical under combined thermal (IEC 61439, Temperature Rise = 70°C) and static loading established mechanical feasibility constraints, with peak support stresses of 103 MPa disqualifying Al 1350-H12. Copper alloys were eliminated on cost-weighted penalty function grounds. Al 6101-T6 emerged as the primary sustainable alternative, offering slightly higher conductivity (55% vs. 52% IACS) and a marginally lower carbon footprint than the incumbent.

Characterisation of new and aged (10-year service) busbar samples via SEM and EDS revealed formation of oxides at grain boundaries around pore sites, irregular Sn plating and oxide cracking at surface, and Ni diffusion into the Sn layer in aged samples; none of which were present in new samples. Limitations such as this sample being representative of all conditions and effects of sample preparation on the morphology information were also discussed. Al-Si-Mg (6000 series) alloys are concluded to be the most viable sustainable pathway for this application.

Keywords: Material selection, Low voltage, Busbars, Aluminum alloys, Ashby method, Material indices, Electrical conductivity, Carbon footprint

Acknowledgements

I would like to extend my gratitude to Niclas Fogelberg, Ida Nylander, David Lindell, Su Zhao and Erik Johansson from ABB for their support and expertise that helped me throughout this project. I would also like to thank Sheng Guo, Antonio Mulone and Sahith Kokkiralala from Chalmers University of Technology for guiding and providing me with the essential tools and training to access the laboratory equipment efficiently. I would lastly like to thank my parents and family for their constant support and motivation.

Geetik Mamillapalli, Gothenburg, June 2026

Nomenclature

Below is the nomenclature of roman symbols, greek symbols, and abbreviations that have been used throughout this thesis.

Roman Symbols

A	Cross-sectional area of the conductor
C_{cost}	Material cost
C_{CO_2}	Cradle-to-grave carbon footprint
E	Elastic modulus
I	Electrical current
k	Thermal conductivity
L	Conductor length
M_1	Material index for thermal performance under electrical loading (σ_E/α_T)
M_2	Material index for resistance to elastic cyclic thermal stress during current conduction ($\sigma_Y \cdot \sigma_E$)
P	Power dissipated as Joule heat
R	Electrical resistance
T	Temperature

Greek Symbols

α	Penalty function weighting factor
α_T	Coefficient of thermal expansion
ΔT	Temperature rise
ε_{th}	Thermally induced strain
ρ	Density

ρ_e	Electrical resistivity
σ_E	Electrical conductivity
σ_T	Tensile strength
σ_{th}	Cyclic thermal stress
σ_Y	Yield strength (elastic limit)
$\tilde{\Phi}$	Multi-objective penalty function

Abbreviations

BSE	Backscattered Electron (imaging)
CDC	ABB CDC 40 low-voltage distribution assembly
CES	Cambridge Engineering Selector (EduPack materials database)
CTE	Coefficient of Thermal Expansion
EDS	Energy-Dispersive X-ray Spectroscopy
EPD	Environmental Product Declaration
FEM	Finite Element Method
IACS	International Annealed Copper Standard
IEC	International Electrotechnical Commission
LV	Low Voltage
PA11	Polyamide 11
SEM	Scanning Electron Microscopy

Contents

Nomenclature	ix
List of Figures	xiii
List of Tables	xvii
1 Introduction	1
1.1 Overview	1
1.2 Problem Statement	2
1.3 Aims and Objectives	2
1.4 Scope and Limitations	3
2 Background	5
2.1 The ABB CDC 40 Phase Rail System	5
2.2 Conductor Materials for Low-Voltage Busbars	5
2.3 Methodology Overview	7
3 Methodology	9
3.1 Overview	9
3.2 Material Selection	9
3.2.1 Selection Strategy	9
3.2.2 Functional Requirements and Baseline Constraints	10
3.2.3 Material Indices	11
3.2.3.1 Index M_1 : Thermal Performance under Electrical Loading	11
3.2.3.2 Index M_2 : Resistance to Elastic Cyclic Thermal Stress during Current Conduction	13
3.2.4 Penalty Function and Final Ranking	13
3.2.5 Database Limitations	14
3.3 Finite Element Analysis	14
3.3.1 Model Description	14
3.3.2 Boundary Conditions	15
3.3.3 Mesh	15
3.4 Sample Preparation and Characterisation	15
3.4.1 Sample Selection	15

3.4.2	Metallographic Preparation	17
3.4.3	SEM and EDS Analysis	18
3.5	Limitations	19
4	Results	21
4.1	Overview	21
4.2	FEM Results	21
4.2.1	Thermal Analysis	21
4.2.2	Static Structural Analysis	23
4.3	Material Screening Results	25
4.3.1	Baseline Material Properties	25
4.3.2	Ashby Plot Analysis	25
4.3.3	Hard Constraint Screening	27
4.3.4	Performance Index Ranking and Penalty Function	27
4.4	SEM and EDS Results	28
4.4.1	Scope and Representativeness	28
4.4.2	BSE Imaging — New Sample	29
4.4.3	BSE Imaging — Aged Sample	29
4.4.3.1	Rail End Section	30
4.4.3.2	Middle Section — Connector Mounting Point	31
4.4.4	EDS Analysis — New Sample	35
4.4.5	EDS Analysis — Aged Sample	37
4.4.6	Summary of Characterised Samples	41
5	Discussion	43
6	Conclusion	47
	Bibliography	49
A	Appendix	I
A.1	Appendix 1: Thesis Planning Report	I

List of Figures

2.1	ABB CDC 40 low-voltage distribution assembly.	5
2.2	IEC 61439 standard defining the environment conditions taken as assumptions for testing and validation	6
2.3	CDC 40 phase rail: front view showing multi-bar arrangement and cross-sectional profile with C-shaped extruded geometry (cross-sectional area 200 mm ² , material Al 6063-T6).	6
3.1	Four-stage Ashby screening process for CDC 40 conductor material selection.	10
3.2	Conductivity vs. CTE after Stage 2 screening. Dashed lines: constant $M_1 = \sigma_E / \alpha_T$	12
3.3	yield strength vs. conductivity after Stage 2 screening. Dashed lines: constant $M_2 = \sigma_Y \cdot \sigma_E$	12
3.4	Thermal BC: 95 °C at connector contact surfaces ($\Delta T = 70$ °C, IEC 61439). 15	
3.5	Static BC: fixed support (B), connector loads 2 N (C), fusegear loads 25 N (D).	15
3.6	Mounted specimens after preparation: cross-sectional and longitudinal orientations for new (top) and aged (bottom) rails.	16
3.7	Labelled rail sections prior to cutting. Top: new (1CN, 1FN); middle/bottom: aged. C = connector point; F = rail end.	17
3.8	Precision abrasive saw for initial rail sectioning.	17
3.9	Metallographic cutting machine for cross-sectional and longitudinal slicing.	17
3.10	Struers TegraForce-5 polisher used for SiC grinding and diamond/OPS polishing.	18
3.11	Zeiss Leo 1550 FEG-SEM used for BSE imaging and EDS mapping.	19
3.12	Mount setup while venting SEM before Analysis	19
4.1	Steady-state temperature distribution in the CDC 40 phase rail (Al 6063-T6, length 500 mm). Peak temperature of 95 °C is localised at the connector region; temperature dissipates rapidly along the rail length. 22	
4.2	Total heat flux distribution. Peak flux of 1.69 W/mm ² is concentrated at the connector contact surface; the bulk of the rail operates at near-zero flux.	22

4.3	Von Mises equivalent stress distribution in the CDC 40 phase rail under combined thermal ($\Delta T = 70^\circ\text{C}$) and static loading. Peak stress of 103 MPa is localised at the fixed support regions; this value defines the minimum yield strength constraint applied in Stage 3 material screening.	23
4.4	Equivalent elastic strain distribution corresponding to the Von Mises stress field. Peak strain is co-located with the peak stress at the fixed support regions, confirming elastic behaviour of the Al 6063-T6 incumbent under the design loading condition.	24
4.5	Total deformation of the CDC 40 phase rail under combined thermal and static loading. Peak cumulative elongation of 0.2 mm is distributed across both supported ends, consistent with free longitudinal thermal expansion about the fixed support boundary condition. . . .	24
4.6	Ashby plot of electrical conductivity vs. thermal expansion coefficient. Dashed lines indicate constant $M_1 = \sigma_E/\alpha_T$ index values. ($M_1 = 2.22$)	26
4.7	Ashby plot of tensile strength vs. electrical conductivity. Dashed lines indicate constant $M_2 = \sigma_T \cdot \sigma_E$ index values. ($M_2 = 11,180$)	27
4.8	New sample cross-section (1CN_CS). Uniform Ni-Sn bilayer with sharp interface; no oxide or porosity.	29
4.9	New sample longitudinal section (1CN_LONG_01). Continuous coating along current-flow direction; no delamination or cracking.	29
4.10	New sample longitudinal section (1CN_LONG_02). Uniform Sn layer thickness across the contact surface.	29
4.11	New sample overview (1CN_PL). Low void density and intact coating across the full field of view.	29
4.12	Aged sample longitudinal overview at rail end (1CO_LONG_01). Discolouration at pore sites visible in BSE contrast.	30
4.13	Aged longitudinal section at higher magnification (1CO_LONG_07). Grain boundaries visible around oxidised pore regions.	30
4.14	Pore site 1 (1CO_pore1). Dark BSE contrast at pore boundary consistent with Al_2O_3	30
4.15	Pore site 2 (1CO_pore2). Oxidised boundary with visible discolouration extending into surrounding matrix.	30
4.16	Pore site 3 (1CO_pore3). Elevated void density with Al_2O_3 at boundaries compared to new sample.	31
4.17	Pore site 4 (1CO_pore4). Larger oxidised region; grain boundaries traceable around the pore.	31
4.18	Fusegear region, left side (2FO_FUSEGEAR_L_04). Irregular Sn plating thickness visible on the top contact surface.	31
4.19	Fusegear region, left side (2FO_FUSEGEAR_L_08). Locally thinned Sn layer with evidence of surface oxidation.	31
4.20	Fusegear region, left side (2FO_FUSEGEAR_L_18). Variation in Sn layer continuity along the bottom contact surface.	32
4.21	Fusegear region, right side (2FO_FUSEGEAR_R_02). Irregular electroplating layer compared to the uniform Sn seen in the new sample.	32

4.22	Fusegear region, right side (2FO_FUSEGEAR_R_03). Elevated void density at the coating–substrate interface with no oxidation in the Al core.	32
4.23	Fusegear region, right side (2FO_FUSEGEAR_R_10). Ni signal broadening at the Ni–Sn interface indicative of solid-state interdiffusion.	32
4.24	Preparation scratch visible on sample surface (1SEM_Scratch). Introduced during OPS polishing for attempted etched finish; sample was repolished before final imaging.	33
4.25	Electron Image 1 (new sample). Spectra 1–3 identify AlFeSi precipitates (bright contrast) and Al matrix in the substrate bulk.	35
4.26	Electron Image 1 (new sample). Spectra 1,2,3 acquired at each inclusion for characterisation	35
4.27	Electron Image 9 (new sample). Spectra 24–27 establish the baseline composition at the Sn–Ni–Al coating interface in the as-manufactured condition.	36
4.28	Electron Image 9 (new sample). Spectra 24–27 acquired at the Sn, Ni, and Al layers establish the reference spectra for each layer in the as-manufactured condition.	36
4.29	EDS elemental maps of new sample (Al, Sn, C, Ni, O, Mg). Ni and Sn layers are sharply defined with no oxygen enrichment at any interface. AlFeSi precipitates visible as localised Al-depleted regions in the substrate.	37
4.30	Electron Image 5 (aged sample). Spectra 8–13 acquired at the cracked Sn layer confirm oxygen co-localised with Sn (SnO_x).	38
4.31	Electron Image 5 (aged sample). Spectra 8–13 acquired at the cracked Sn layer confirm oxygen co-localised with Sn (SnO_x).	38
4.32	EDS elemental maps of aged sample (Al, Sn, Mg, Ni, C, O). Oxygen enrichment at pore boundaries (Al_2O_3) and co-localised with Sn layer (SnO_x); Ni signal extends into the Sn-rich region. Compare with Figure 4.29.	39
4.33	Electron Image 6 (aged sample). Spectra 16–19 confirm oxygen enrichment at pore boundaries and Ni diffusion into the Sn layer, the aged-sample counterpart to the precipitate characterisation in Electron Image 1.	39
4.34	Electron Image 6 (aged sample). Spectra 16–19 acquired at the inclusions found in the aged sample for characterisation.	40

List of Tables

3.1	Baseline material properties of the incumbent Al 6063-T6 conductor [1].	10
4.1	Full property comparison of incumbent and candidate busbar materials grouped by category. Values at 20 °C unless stated. Al 6063-T6 shown as baseline (rightmost column). Red-boxed values indicate properties that led to elimination or disadvantage during screening. .	25
4.2	Consolidated performance index, penalty function, and volumetric cost and environmental impact for all candidates ($\alpha = 0.5$, normalised to Al 6063-T6 baseline). Al 1350-H12 eliminated at Stage 3 ($\sigma_y < 103$ MPa). Vol. cost = $\rho_d \cdot C_{\text{cost}}$ (norm.); Vol. CO ₂ = $\rho_d \cdot C_{\text{CO}_2}$ (norm.).	28
4.3	Summary of all samples examined by SEM and EDS, including busbar region, sectioning orientation, and principal observation for each specimen.	41

1

Introduction

1.1 Overview

The increasing electrification of industrial processes, transportation systems, and energy infrastructure has led to a growing demand for reliable electrical power distribution systems. Low-voltage cable distribution cabinets and their equipment forms a critical part of this infrastructure, ensuring the safe and efficient delivery of electrical power to downstream components and end users. Within these systems, busbars serve as the primary current-carrying elements and are required to maintain high electrical performance while operating under varying thermal and mechanical conditions.

The manufacturing sector is simultaneously facing increasing pressure to reduce the environmental impact of products throughout their lifecycle. As a result, material selection has become an important aspect of engineering design, requiring consideration not only of functional performance but also of sustainability metrics such as embodied carbon and resource consumption. This has motivated the exploration of alternative materials capable of delivering equivalent performance while reducing environmental impact.

This study was conducted in collaboration with an industrial partner: ABB, focuses on phase rails used within low-voltage distribution units. These components, hereafter referred to as busbars, are manufactured using an aluminum alloy conductor with electroplated contact surfaces and an insulating polymer coating. The current material system has demonstrated reliable performance in service and is widely used within industry. However, opportunities may exist to reduce the environmental impact associated with material production through the identification of suitable alternative materials.

To investigate these opportunities, an Ashby-based material selection methodology was employed. Functional requirements were translated into quantitative constraints and material indices, allowing candidate materials to be screened and ranked according to both performance and sustainability criteria. In parallel, experimental characterization was performed on end-of-life busbar samples to investigate the degradation mechanisms present in the current material system. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were used to examine the microstructural condition and elemental composition of the samples after service exposure.

The combination of material selection and experimental characterization provides both a forward-looking assessment of potential material alternatives and an improved understanding of the performance of the existing material system under operational conditions.

1.2 Problem Statement

The current busbar design satisfies the electrical, thermal, and mechanical requirements associated with low-voltage distribution applications. The aluminum alloy conductor provides an effective balance between conductivity, strength, corrosion resistance, and manufacturability, while the nickel–tin electroplated contact surfaces ensure reliable electrical contact and wear resistance. Consequently, any alternative material must demonstrate equivalent functional performance before it can be considered a viable replacement.

At the same time, the environmental impact associated with material production is becoming an increasingly important design consideration. Reducing the carbon footprint of electrical distribution equipment requires the identification of materials that can satisfy demanding engineering requirements while offering improved sustainability performance. Material selection therefore becomes a multi-objective problem involving trade-offs between electrical performance, mechanical integrity, thermal behavior, manufacturability, and environmental impact.

A further challenge is the limited availability of experimental validation for candidate materials within the timeframe of the project. While alternative materials can be identified through systematic selection methodologies, experimental testing and qualification often require significant lead times. Consequently, a complementary approach is required to support material selection decisions, by understanding the loadcase it is required to withstand using FEM simulations. Characterization of end-of-life busbar samples can provide valuable insight into degradation mechanisms and long-term service behavior, thereby improving the understanding of material performance in practical applications.

1.3 Aims and Objectives

The aim of this study is to investigate sustainable material alternatives for low-voltage busbar applications while characterizing the degradation behavior of the currently employed material system.

The objectives of the study are:

- Identify the functional requirements of busbar conductor and insulation materials used in low-voltage distribution systems.
- Establish quantitative constraints and performance metrics using an Ashby-based material selection methodology.

- Derive material indices that account for electrical, thermal, mechanical, and sustainability requirements.
- Screen and rank candidate materials according to the defined selection criteria.
- Characterize end-of-life busbar samples using SEM, and EDS techniques.
- Investigate the morphological and compositional changes present after service exposure.
- Relate the observed degradation mechanisms to the evaluation of alternative material systems.

1.4 Scope and Limitations

This study focuses on material selection for busbar applications used within low-voltage electrical distribution systems. The investigation is primarily concerned with the conductor material, as it constitutes the largest proportion of the component mass and therefore represents the greatest opportunity for reducing environmental impact.

The existing nickel–tin electroplated contact system is retained throughout the study and is not considered for further optimization. This decision is based on its widespread industrial adoption and established performance in electrical contact applications. Similarly, the geometric design of the busbar is assumed to remain unchanged, allowing the study to focus exclusively on material substitution.

Material selection is conducted using published material property data, literature sources, manufacturer datasheets, and the CES EduPack materials database. Candidate materials are evaluated using Ashby material selection principles and sustainability-related metrics. Gaps between theoretical and practical applications of material selection methods can create limitations for the material choices.

Although alternative materials are identified and ranked, experimental validation of these materials was not performed within the duration of the project due to procurement lead times and project constraints. Instead, experimental work was limited to the characterization of end-of-life samples of the current material system. The findings obtained from SEM and EDS analyses are therefore used to improve understanding of the degradation behavior of the incumbent material rather than to validate the performance of proposed alternatives directly.

2

Background

2.1 The ABB CDC 40 Phase Rail System

The ABB CDC 40 is a low-voltage (LV) distribution assembly rated for 400 A continuous current duty, governed by the requirements of IEC 61439 [2]. As shown in Figure 2.1, the assembly houses multiple outgoing circuits served by fusegear and protective devices. Current is distributed to these circuits through a set of extruded phase rails — referred to hereafter as busbars — which run the length of the assembly and provide direct mounting interfaces for fusegear and connectors (Figure 2.3).

Each phase rail has a cross-sectional area of approximately 200 mm^2 and is manufactured from Al 6063-T6, an Al–Mg–Si alloy with an electrical conductivity of 52 %IACS [1]. The conductor is coated with a nickel–tin electroplated contact surface at electrical interfaces and encapsulated in a Polyamide 11 (PA11) insulation layer applied by powder coating. While this material system has demonstrated reliable in-service performance, rising regulatory and industry pressure to reduce the lifecycle environmental impact of electrical products [3] motivates the investigation of alternative conductor materials capable of delivering equivalent performance with a lower carbon footprint.

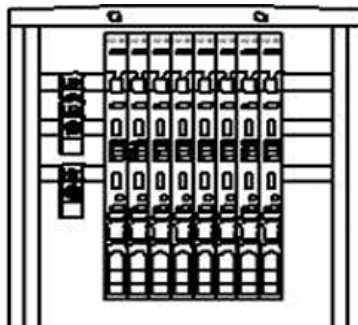


Figure 2.1: ABB CDC 40 low-voltage distribution assembly.

2.2 Conductor Materials for Low-Voltage Busbars

Busbar conductors must simultaneously satisfy electrical, thermal, mechanical, and sustainability requirements, making material selection a multi-objective problem [4].

Environmental conditions for outdoor installation

Tabella 3.2

Relative humidity	Ambient air temperature	Altitude
100% temporarily (at the maximum temperature of 25° C))	Maximum temperature $\leq 40^{\circ}\text{C}$	Not higher than 2000 m
	Maximum temperature average over a period of 24 h $\leq 35^{\circ}\text{C}$	
	Minimum temperature $\geq -25^{\circ}\text{C}$	

Figure 2.2: IEC 61439 standard defining the environment conditions taken as assumptions for testing and validation

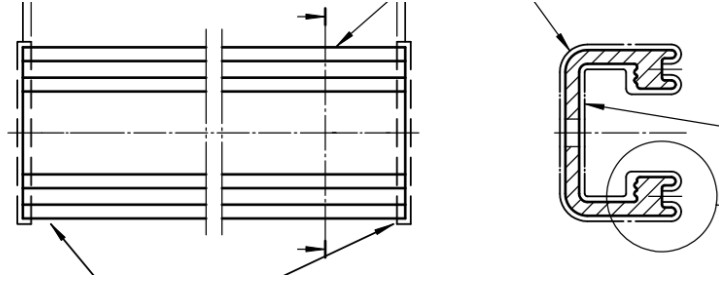


Figure 2.3: CDC 40 phase rail: front view showing multi-bar arrangement and cross-sectional profile with C-shaped extruded geometry (cross-sectional area 200 mm², material Al 6063-T6).

Copper and aluminum alloys have historically dominated LV electrical conductor applications [5, 6]. Copper offers near-ideal electrical conductivity ($\sim 100\%$ IACS) and excellent thermal performance, the two properties being coupled through the Wiedemann–Franz relationship, which can be considered an accurate approximation for metals although it does not include the contribution of thermal conductivity changes due to phonons. Wiedemann–Franz law also assumes minimal electron scattering which is not the case in this condition, but can be a good approximation for good thermal/electrical conductors as its effects amplify for insulators [7]. However, its high density and cost are significant disadvantages at the scale of distribution equipment [5].

Aluminum, with roughly one-third the density of copper, enables comparable current-carrying capacity through geometric compensation and has become the standard choice for LV busbars [8, 6]. Within the Al–Mg–Si (6000 series) family, electrical conductivity and mechanical strength are governed by the precipitation state of Mg₂Si phases [9, 10]. Strengthening precipitates enhance mechanical performance but increase electron scattering. This phenomenon causes a tradeoff between electrical conductivity and mechanical strength in conductors. It is also interesting to note that ageing helps these alloys form precipitates that help in converging the elements dispersed in the solid solution of the conductor matrix which causes lattice distortions that reduce the conductivity [11]. Al 6101-T6 was developed specifically to achieve a more favorable balance for electrical conductor applications, while Al 1350-H12 maximizes conductivity at the expense of reduced mechanical strength [12, 13].

Environmental performance has become an additional selection criterion. Primary aluminum production is energy-intensive, though high recyclability and ongoing process improvements have progressively reduced lifecycle emissions [14]. Treating carbon footprint as a quantitative design objective alongside conductivity, strength, and cost therefore requires a structured multi-criteria framework rather than single-property optimization.

2.3 Methodology Overview

Three complementary methods are employed in this thesis to evaluate candidate materials.

Ashby material selection. Design requirements are translated into constraints, performance indices, and a multi-objective penalty function weighting material cost and cradle-to-grave CO₂ footprint [4, 15]. Candidate materials are screened and ranked using the CES EduPack materials database, enabling transparent comparison across electrical, mechanical, and environmental property domains [16].

Finite element analysis. A FEM model of the three-busbar assembly is developed in ANSYS Mechanical to establish mechanical feasibility constraints under combined thermal loading (IEC 61439 temperature rise of $\Delta T = 70^\circ\text{C}$) as shown in 2.2 and static loading from mounted connectors and fusegear [2]. Results define minimum yield strength requirements that constrain the shortlisted candidates.

SEM and EDS characterisation. Aged (10-year service) and new phase rail samples are examined using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) [17] to characterise degradation mechanisms in the Ni-Sn coating system. This provides experimental evidence on the in-service behaviour of the incumbent material system and informs coating-related design constraints for any replacement material.

3

Methodology

3.1 Overview

This study employs a three-part methodology to evaluate sustainable material alternatives for the CDC. First, an Ashby-based material selection framework is applied to screen and rank candidate conductor materials against electrical, thermal, mechanical, and sustainability criteria. Second, a finite element model of the busbar assembly is developed in ANSYS Mechanical to derive the mechanical loading constraints required by the selection framework. Third, scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) are used to characterise degradation in aged phase rail samples, establishing experimental evidence on the failure modes of the incumbent system.

3.2 Material Selection

3.2.1 Selection Strategy

The material selection strategy follows the framework proposed by Ashby [4], in which functional requirements are translated into constraints and objectives, candidate materials are screened against the constraints, and the surviving candidates are ranked using performance indices and a multi-objective penalty function [15]. The four-stage screening process applied in this study is summarised in Figure 3.1 and described in detail in the following subsections.

The geometry of the CDC 40 phase rail in Figure 2.3 is treated as fixed throughout the selection process. The existing extruded C-profile (cross-sectional area 200 mm², length 500 mm) is retained as the design envelope, so the objective reduces to identifying an alternative conductor *material* that satisfies the same functional requirements as Al 6063-T6 while lowering lifecycle environmental impact.

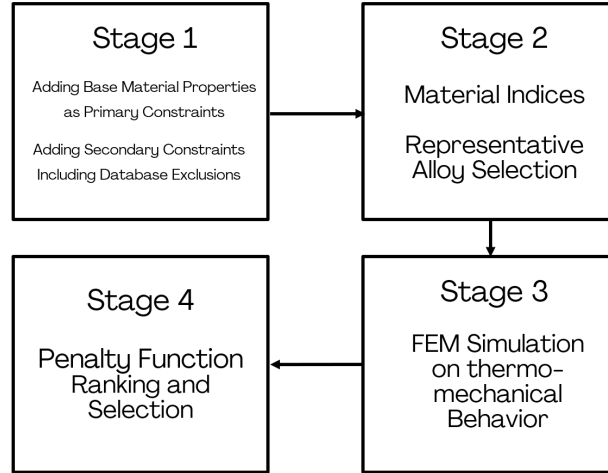


Figure 3.1: Four-stage Ashby screening process for CDC 40 conductor material selection.

3.2.2 Functional Requirements and Baseline Constraints

The phase rail serves two simultaneous functions: it distributes 400 A of continuous current between incoming and outgoing circuits, and it provides mechanical mounting interfaces for fusegear and connectors [18, 5]. The current material system consists of an Al 6063-T6 conductor, a nickel–tin electroplated contact surface, and a PA11 insulation coating [1]. The Ni–Sn plating and PA11 insulation are retained unchanged; only the core conductor is subject to substitution.

The baseline properties of Al 6063-T6 define the minimum acceptable performance thresholds for candidate materials and are summarised in Table 3.1.

Stage 1 screening applies bounds to limit power losses generated. The calculated power losses of the current material were taken as the baseline and the idea is to not compromise on power losses with the alternatives whatsoever.

For a conductor of fixed cross-sectional area A and length L , the electrical resistance is:

$$R = \frac{\rho_e L}{A} \quad (3.1)$$

where $\rho_e = 1/\sigma_E$ is the electrical resistivity. Since the geometry is fixed, minimising

Table 3.1: Baseline material properties of the incumbent Al 6063-T6 conductor [1].

Property	Symbol	Baseline value
Electrical conductivity	σ_E	52 %IACS
Thermal conductivity	k	200 W/m·K
Yield strength	σ_Y	215 MPa
Density	ρ	2690 kg/m ³
Thermal expansion coeff.	α_T	23.4×10^{-6} strain/°C

R is equivalent to maximising conductivity σ_E . Power dissipated as Joule heat is:

$$P = I^2 R = \frac{I^2 \rho_e L}{A} = m C v \Delta T \quad (3.2)$$

For a fixed geometry, the limits we have to ensure to minimise becomes the temperature rise allowed in the conductor. dealing with a constant volume approach would also change the dependency of density ρ from the material index to the cost calculation in the penalty function. This method has been taken using the design guide for a busbar in terms of material and performance requirements [5]

Stage 2 introduces secondary constraints from the CES EduPack database, including exclusion of materials with known processing incompatibilities or insufficient extrudability for the existing profile geometry [6].

3.2.3 Material Indices

Following the Ashby methodology, performance indices are derived by combining the governing physics of each functional requirement into a single material group [4]. Two indices are used in this study: the first captures thermal performance under electrical loading, and the second captures resistance to elastic cyclic thermal stress during current conduction.

3.2.3.1 Index M_1 : Thermal Performance under Electrical Loading

A busbar carrying current I dissipates Joule heat that raises its temperature above ambient. For a conductor of fixed cross-section A and length L , the steady-state temperature rise ΔT is governed by the balance between heat generated and heat conducted away. The heat generated per unit volume is proportional to the electrical resistivity $\rho_e = 1/\sigma_E$, while the ability of the material to conduct that heat longitudinally is characterised by its thermal conductivity λ . The magnitude of the resulting thermal expansion, and therefore the thermally induced strain, scales with the coefficient of thermal expansion α_T :

$$\varepsilon_{th} = \alpha_T \Delta T \quad (3.3)$$

A material that performs well thermally under electrical loading must maximise electrical conductivity σ_E (to minimise heat generation) while minimising α_T (to minimise the resulting dimensional change). Combining these two requirements, the thermal performance index is:

$$M_1 = \frac{\sigma_E}{\alpha_T} \quad (3.4)$$

where σ_E is the electrical conductivity (%IACS) and α_T is the coefficient of thermal expansion (strain/°C). A higher M_1 identifies materials that conduct current efficiently while remaining dimensionally stable under the associated temperature rise. Figure 4.6 shows the Ashby plot of electrical conductivity versus thermal expansion coefficient used to screen candidates on this index, with dashed guide lines of constant M_1 .

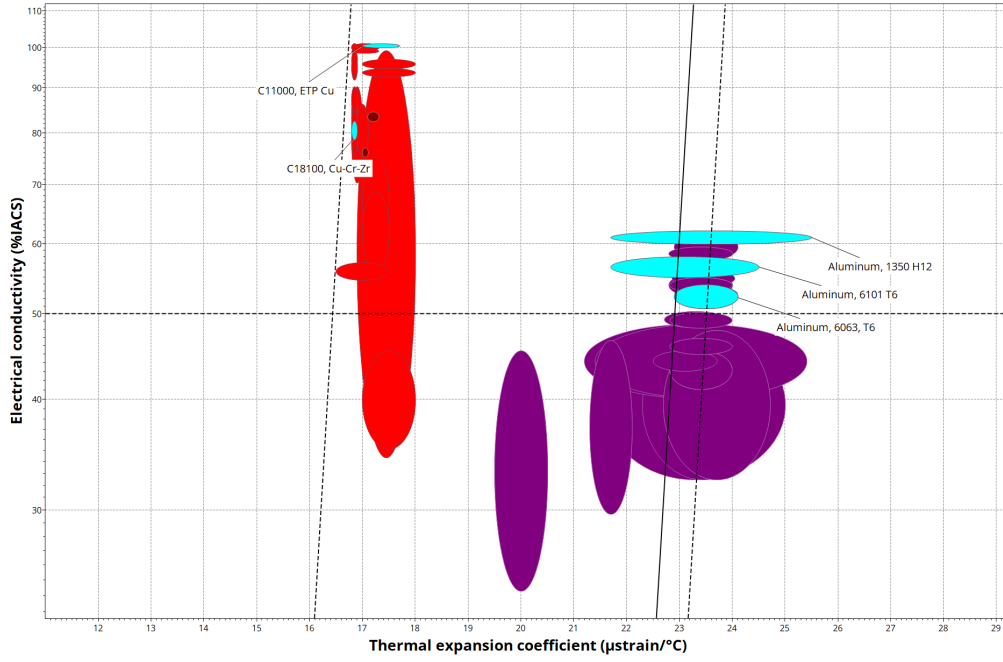


Figure 3.2: Conductivity vs. CTE after Stage 2 screening. Dashed lines: constant $M_1 = \sigma_E/\alpha_T$.

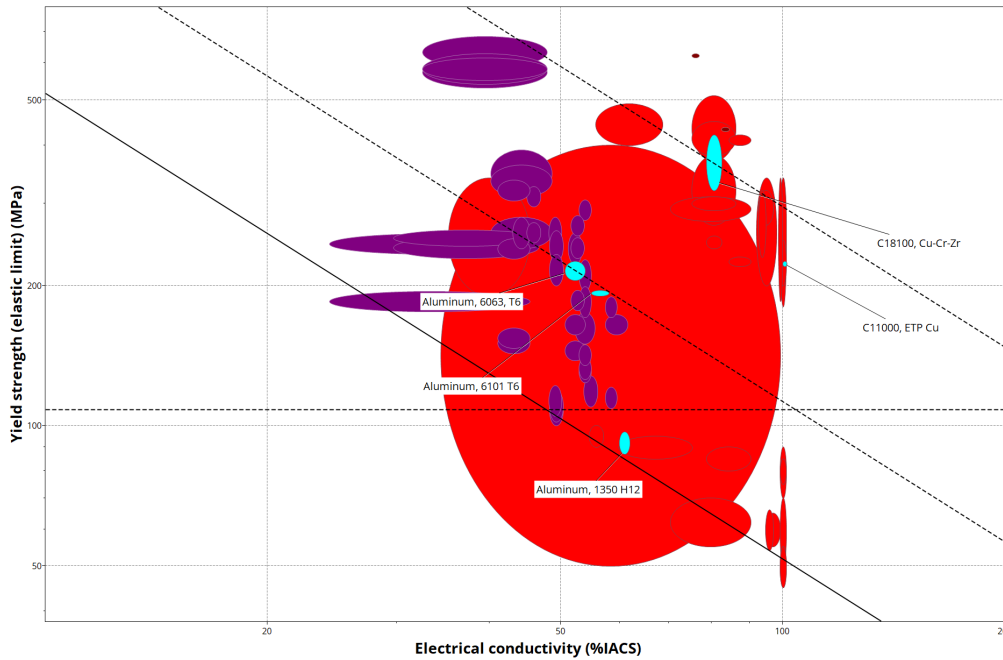


Figure 3.3: yield strength vs. conductivity after Stage 2 screening. Dashed lines: constant $M_2 = \sigma_Y \cdot \sigma_E$.

3.2.3.2 Index M_2 : Resistance to Elastic Cyclic Thermal Stress during Current Conduction

During operation, repeated current loading cycles impose cyclic thermal strains on the busbar. If the conductor is constrained — for example at mounting and connector interfaces — the thermal strain generates a cyclic stress:

$$\sigma_{th} = E \alpha_T \Delta T \quad (3.5)$$

where E is the elastic modulus. For the component to remain in the elastic regime and avoid low-cycle fatigue, the yield strength σ_Y must exceed σ_{th} . At the same time, the material must conduct current efficiently, requiring high electrical conductivity σ_E .

The CDC unit also mounting several components undergoes mechanical load along with thermal and that is the reason the index should be strength limited to find equivalent stress limitations in working conditions

A material that satisfies both requirements simultaneously maximises both σ_Y and σ_E . The combined index for elastic cyclic thermal stress with electrical conduction is therefore:

$$M_2 = \sigma_Y \cdot \sigma_E \quad (3.6)$$

where σ_Y is the Yield Strength at elastic limit (MPa) and σ_E is the electrical conductivity (%IACS). A higher M_2 identifies materials that are mechanically robust against thermal fatigue while remaining electrically efficient. Figure 4.7 shows the Ashby plot of yield strength versus electrical conductivity used to screen candidates on this index.

3.2.4 Penalty Function and Final Ranking

After Stage 3 screening using M_1 and M_2 , five to six candidates should survive together with the baseline Al 6063-T6. Since the problem involves two competing objectives — minimising cost and minimising carbon footprint — the cost and carbon footprint are first normalised with respect to the baseline material:

$$\tilde{C}_i = \frac{C_i}{C_{\text{baseline}}}, \quad i \in \{\text{cost, carbon}\}, \quad (3.7)$$

where C_{cost} is the material cost (SEK/kg), C_{carbon} is the cradle-to-grave CO₂ footprint (kg CO₂/kg), and C_{baseline} denotes the corresponding value for the baseline material Al 6063-T6. The normalised quantities $\tilde{C}_{\text{cost}}$ and $\tilde{C}_{\text{carbon}}$ are therefore dimensionless.

A linear weighted penalty function is then introduced following Ashby [4] and Jahan et al. [15]:

$$\tilde{\Phi} = \alpha \tilde{C}_{\text{cost}} + (1 - \alpha) \tilde{C}_{\text{carbon}} \quad (3.8)$$

where $\alpha \in [0, 1]$ is a weighting factor controlling the relative importance of cost and environmental impact. Since both $\tilde{C}_{\text{cost}}$ and $\tilde{C}_{\text{carbon}}$ are dimensionless, the penalty function $\tilde{\Phi}$ is also dimensionless. Setting $\alpha = 0.5$ gives equal weight to cost and environmental impact. A lower $\tilde{\Phi}$ indicates a more sustainable and economically viable candidate relative to the baseline.

Environmental footprint data are taken from the European Aluminium industry EPD [14] and manufacturer datasheets for the individual candidates: C11000 [19], C18100 [20], Al 6101-T6 [12], and Al 1350-H12 [13]. Cost data for Al 6063-T6 are sourced from the CES EduPack database [1], for C18100 from the CES EduPack database [20], and for C11000, Al 6101-T6, and Al 1350-H12 from the corresponding manufacturer datasheets [19, 12, 13].

3.2.5 Database Limitations

The CES EduPack (ANSYS Granta) database did not include all relevant electrical-grade materials. In particular, Al 6101-T6 and Al 1350-H12 were not available as standard entries and were supplemented from published datasheets: Al 6101-T6 from [12] and Al 1350-H12 from [13]. These datasheets did not provide carbon emission data for the materials. This problem was tackled by taking carbon emission values of alloys with closest composition, properties and heat treatment processes. Some external databases were used to verify these values although they gave an overview of alloy groups and not individual values [14]. Where database ranges were broad, representative mid-range values were selected consistently across all candidates to avoid bias in the screening outcome.

3.3 Finite Element Analysis

3.3.1 Model Description

A finite element model of a single CDC 40 phase rail (length 500 mm, Al 6063-T6) is developed in ANSYS Mechanical 2024 R2 to establish the mechanical and thermal loading conditions that candidate materials must satisfy. The model geometry replicates the extruded C-profile cross-section and includes connector and fusegear attachment regions as load application surfaces.

Two analyses are performed sequentially:

1. A steady-state thermal analysis to determine the temperature distribution under the IEC 61439 rated temperature rise of $\Delta T = 70^\circ\text{C}$ above an ambient of 25°C (i.e. a peak connector surface temperature of 95°C).
2. A static structural analysis with the thermal field applied as a pre-load, supplemented by the mechanical loads from mounted components.

3.3.2 Boundary Conditions

The thermal boundary condition is applied as a uniform temperature of 95 °C at the connector contact surfaces, as shown in Figure 3.4. This represents the worst-case operating condition specified in IEC 61439 [2].

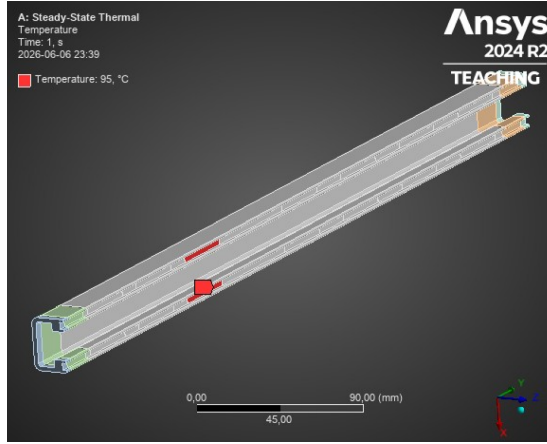


Figure 3.4: Thermal BC: 95 °C at connector contact surfaces ($\Delta T = 70$ °C, IEC 61439).

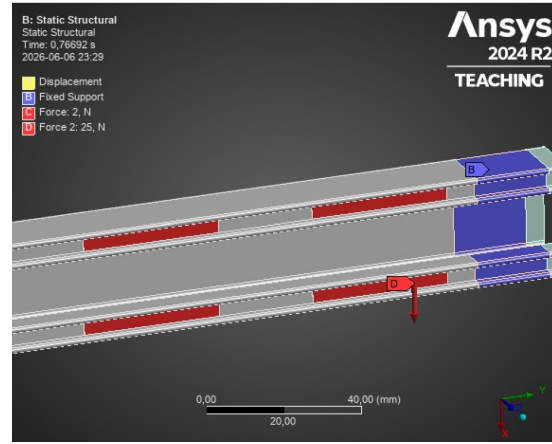


Figure 3.5: Static BC: fixed support (B), connector loads 2 N (C), fusegear loads 25 N (D).

For the structural analysis, one end of the rail is assigned a fixed support, while the opposite end uses a displacement support that permits deformation along the longitudinal axis to avoid over-constraint from thermal expansion. Applied loads are:

- Connector loads: 2 N per connector surface (3 connectors per busbar)
- Fusegear loads: 25 N per fusegear attachment (4/3 of a fusegear unit per busbar)

The load arrangement and boundary conditions are illustrated in Figure 3.5.

3.3.3 Mesh

An automatic mesh with a global element size of 1 mm (ANSYS prime mesh) is applied to the full model geometry. The mesh is refined at connector contact regions where peak heat flux and stress concentrations are expected.

3.4 Sample Preparation and Characterisation

3.4.1 Sample Selection

Characterisation was carried out on three busbar sections taken from the CDC 40 assembly:

- One *new* (unaged) phase rail (sample series 1N), used as a reference baseline.

- Two *aged* phase rails (sample series 1O and 2O–3O) removed after approximately 10 years of in-service operation.

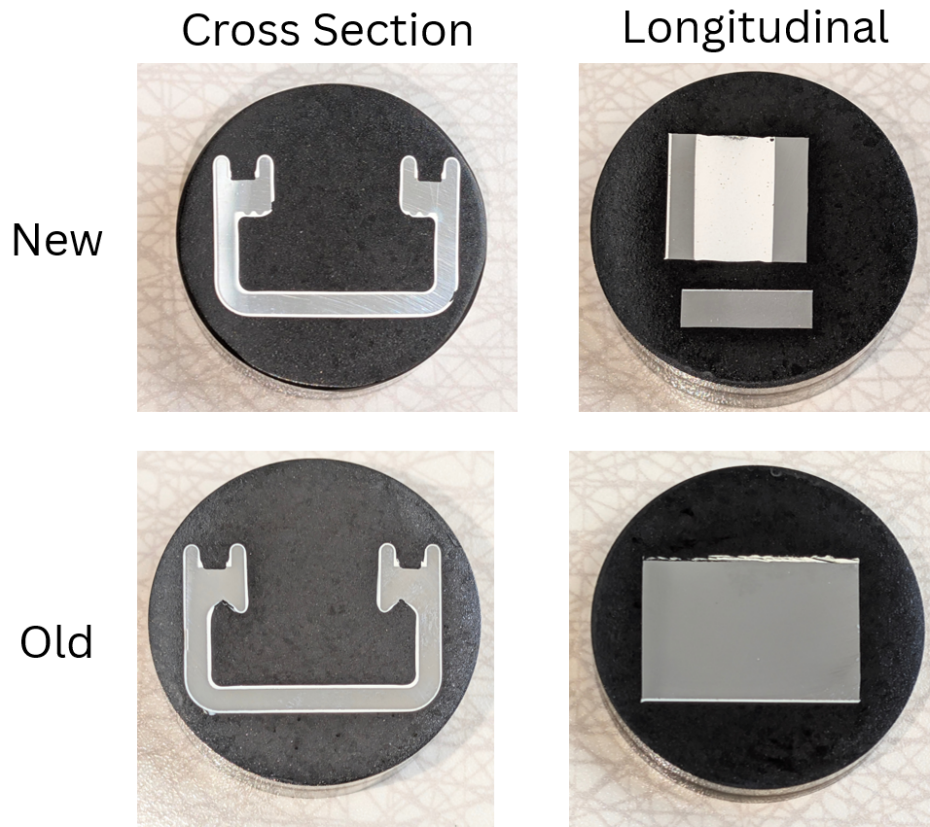


Figure 3.6: Mounted specimens after preparation: cross-sectional and longitudinal orientations for new (top) and aged (bottom) rails.

From each rail, sections were cut at two locations: at a *mounting point* (connector interface region, suffix C) and at a *rail end* (suffix F). Both longitudinal (along the current flow direction) and cross-sectional orientations were prepared from each location, yielding a total of twelve mounted samples. The labelled rail sections prior to cutting are shown in Figure 3.7, and the resulting mounted cross-sectional and longitudinal specimens for new and aged rails are shown in Figure 3.6.

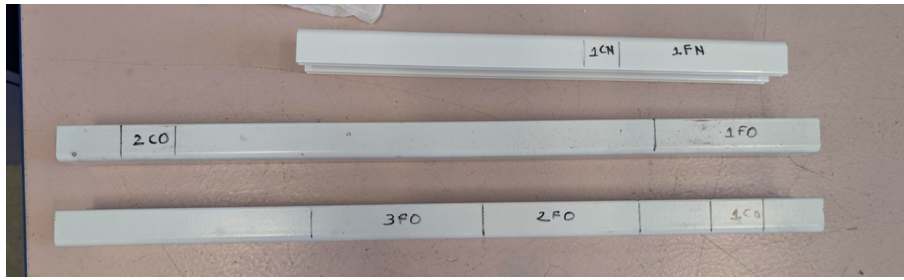


Figure 3.7: Labelled rail sections prior to cutting. Top: new (1CN, 1FN); middle/bottom: aged. C = connector point; F = rail end.

3.4.2 Metallographic Preparation

Rail sections were cut to length using a precision abrasive saw (Figure 3.8) under continuous coolant flow to avoid thermal damage to the Ni-Sn coating. Cross-sectional and longitudinal slices were then sectioned on a water-cooled metallographic cutting machine (Figure 3.9) before cold mounting in conductive resin.



Figure 3.8: Precision abrasive saw for initial rail sectioning.



Figure 3.9: Metallographic cutting machine for cross-sectional and longitudinal slicing.

Mounted samples were ground through successive SiC abrasive papers (P320 to P4000), followed by diamond suspension polishing to a $1\mu\text{m}$ finish on a Struers TegraForce-5 semi-automatic polisher (Figure 3.10), following standard procedures for aluminium alloys [21]. Final polishing used colloidal silica ($0.04\mu\text{m}$ OPS) to produce a deformation-free surface suitable for microstructural imaging and elemental mapping.

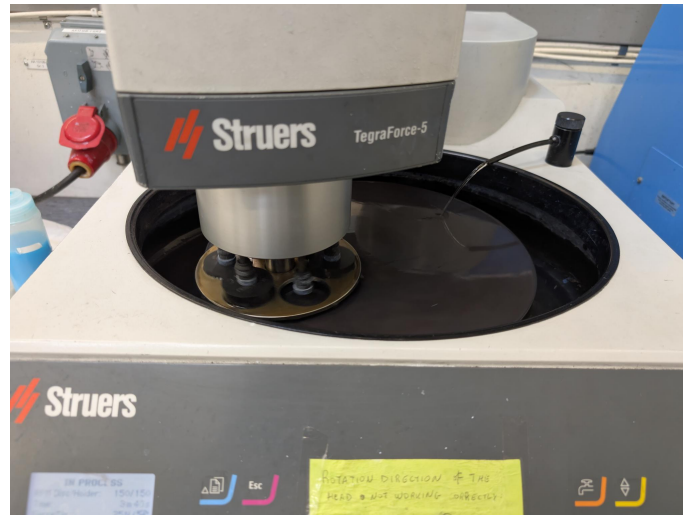


Figure 3.10: Struers TegraForce-5 polisher used for SiC grinding and diamond/OPS polishing.

3.4.3 SEM and EDS Analysis

Scanning electron microscopy was performed on a Zeiss Leo 1550 FEG-SEM (Figure 3.11) equipped with an Oxford Instruments X-Max EDS detector (Figure 3.12) [17]. Imaging was carried out in backscattered electron (BSE) mode to maximise compositional contrast between the Al substrate, Ni interlayer, Sn plating, and any oxide phases. BSE imaging is particularly sensitive to atomic number (Z) contrast, enabling the Ni–Sn coating layers and any Al_2O_3 or SnO_x phases to be distinguished from the surrounding matrix without the need for chemical etching.

Energy-dispersive X-ray spectroscopy (EDS) elemental mapping was performed at connector interface regions on both new and aged samples to identify the spatial distribution of Al, Ni, Sn, and O. EDS maps were used to confirm the presence and extent of oxidation at pore sites and to characterise any interdiffusion between the Ni and Sn layers after service exposure.

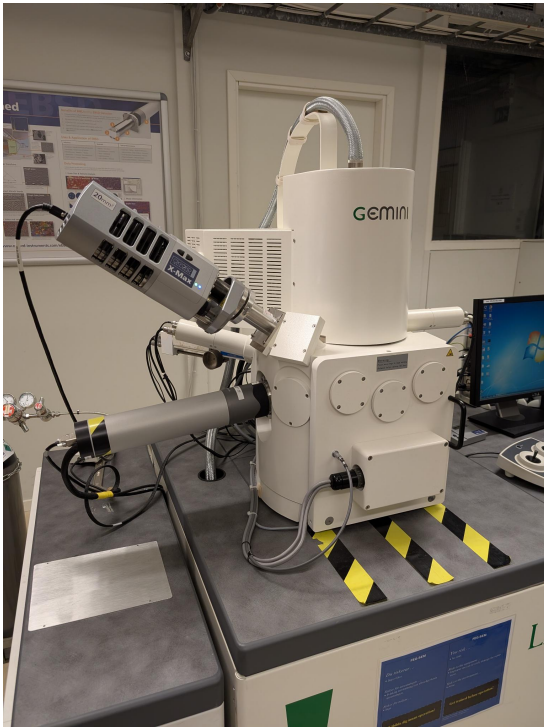


Figure 3.11: Zeiss Leo 1550 FEG-SEM used for BSE imaging and EDS mapping.

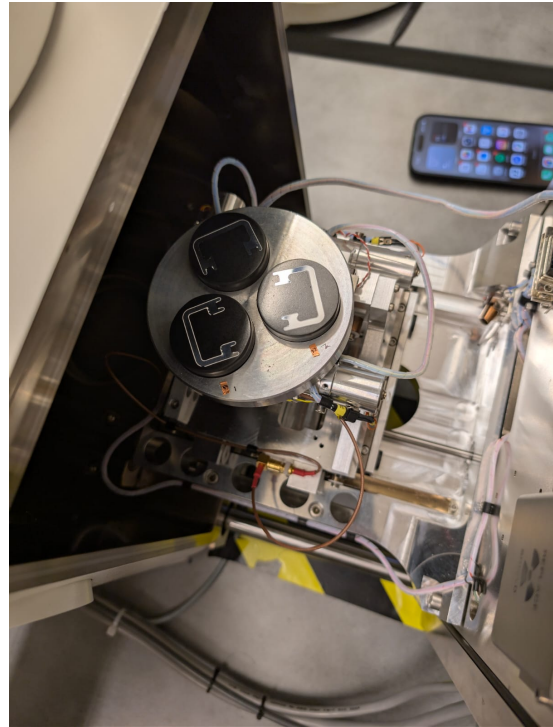


Figure 3.12: Mount setup while venting SEM before Analysis

3.5 Limitations

Several limitations constrain the scope of the methodology. Physical load-cycle and power loss testing of alternative extruded profiles was not possible within the project timeframe, as procurement of purpose-extruded Al 6101-T6 or Al 1350-H12 profiles matching the CDC 40 C-section geometry was not feasible at the prototype scale. Consequently, mechanical and electrical performance conclusions for candidate materials rely on the FEM model and published material property data rather than direct experimental measurement.

Additionally, the ANSYS Granta database did not include all electrical-grade alloys considered, requiring supplementary data from published datasheets. Where database property ranges were broad, representative values were selected to maintain consistency, but this introduces uncertainty in the ranking of closely competing candidates.

SEM imaging quality is dependent on sample preparation; polishing and etching artefacts are visible in certain micrographs and are identified where relevant in the results.

4

Results

4.1 Overview

This chapter presents the results of the material selection analysis and the experimental characterisation of the incumbent CDC 40 phase rail. Section 4.2 reports the finite element analysis results for the thermal and static loading conditions, which establish the mechanical feasibility constraint applied in material screening. Section 4.3 presents the material property data, Ashby chart analysis, hard-constraint screening, and performance index ranking and penalty function evaluation for the five candidate materials. Section 4.4 presents the SEM and EDS characterisation of the new and ten-year-aged phase rail samples; observations are treated as indicative of degradation mechanisms in this coating system and are not representative of product fleet performance.

4.2 FEM Results

4.2.1 Thermal Analysis

The steady-state thermal analysis was conducted with a connector surface temperature of 95 °C, corresponding to the IEC 61439 maximum allowable temperature rise of $\Delta T = 70$ °C above a 25 °C ambient [2]. The resulting temperature distribution (Figure 4.1) shows that the peak temperature is highly localised at the connector contact region and dissipates rapidly along the length of the rail. The total heat flux distribution (Figure 4.2) confirms that the peak heat flux of 1.69 W/mm² is concentrated at the connector contact surface, with the bulk of the rail operating at near-zero flux. This localisation confirms that the thermal loading applied in the static analysis is appropriately represented as a concentrated boundary condition rather than a uniform temperature field.

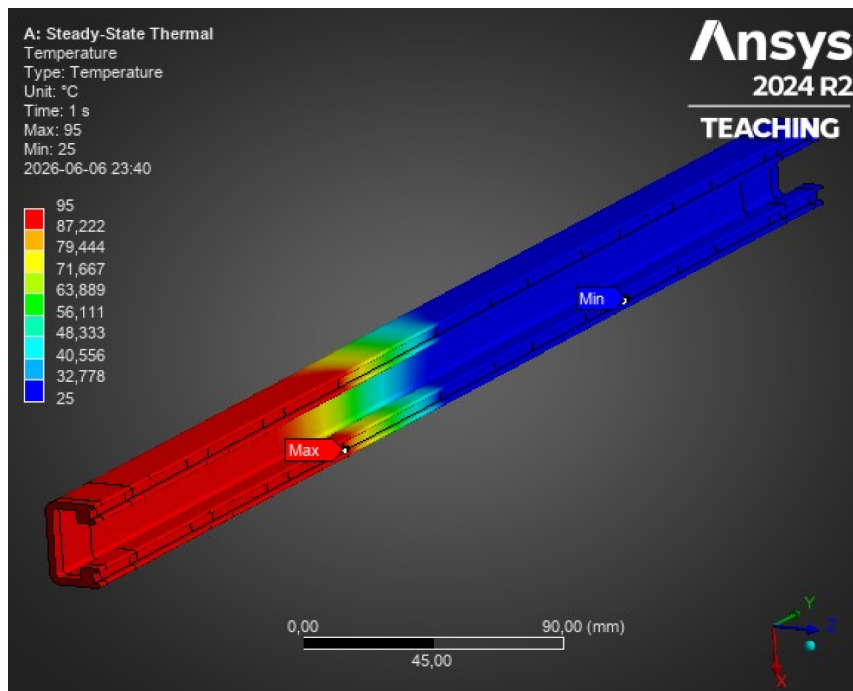


Figure 4.1: Steady-state temperature distribution in the CDC 40 phase rail (Al 6063-T6, length 500 mm). Peak temperature of 95 °C is localised at the connector region; temperature dissipates rapidly along the rail length.

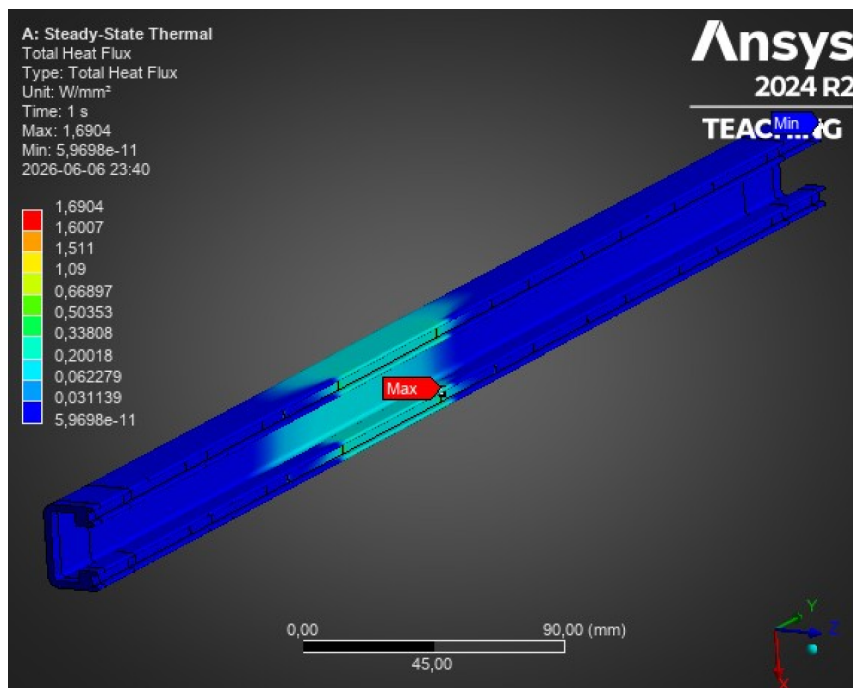


Figure 4.2: Total heat flux distribution. Peak flux of 1.69 W/mm² is concentrated at the connector contact surface; the bulk of the rail operates at near-zero flux.

4.2.2 Static Structural Analysis

The static structural analysis applied connector loads of 2 N per connector (3 connectors per rail) and fusegear loads of 25 N (4/3 fusegear unit per rail), superimposed on the thermal pre-load from the steady-state analysis. The most highly stressed regions are the fixed support sections at the rail ends, consistent with the bending moment distribution for a simply supported beam under distributed lateral loading.

The peak Von Mises equivalent stress at each support is 103 MPa. Since the assembly uses two supports, the resultant stress per support — after accounting for the symmetric load distribution — is 103 MPa. This value establishes the minimum yield strength constraint for candidate material screening: any substitute material must have $\sigma_y \geq 103$ MPa to remain elastic under the design loading. The peak total longitudinal elongation of the rail under combined thermal and static loading is 0.2 mm, distributed across both supported ends.

The Von Mises equivalent stress distribution, equivalent elastic strain, and total deformation are shown in Figures 4.3, 4.4, and 4.5 respectively.

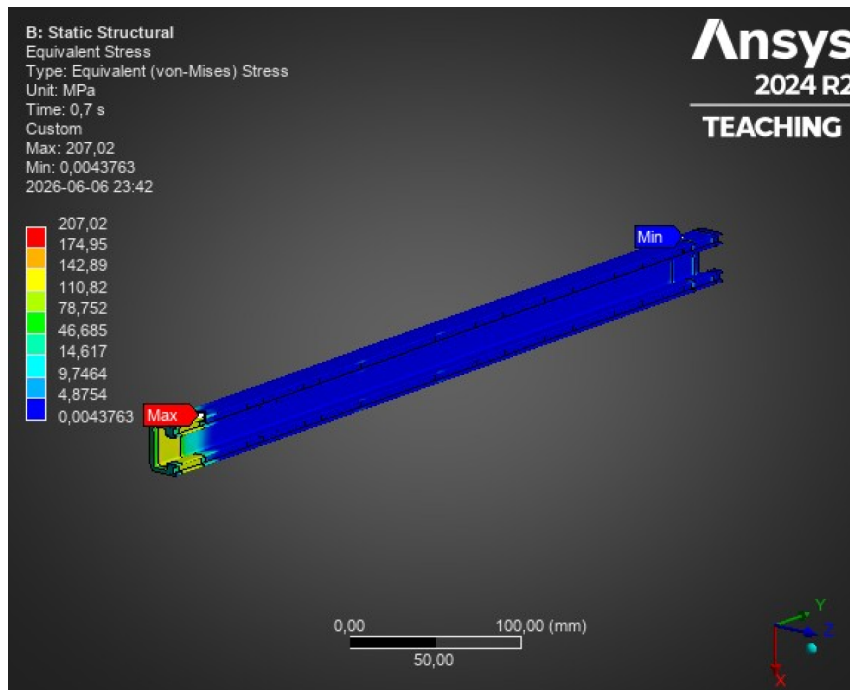


Figure 4.3: Von Mises equivalent stress distribution in the CDC 40 phase rail under combined thermal ($\Delta T = 70$ °C) and static loading. Peak stress of 103 MPa is localised at the fixed support regions; this value defines the minimum yield strength constraint applied in Stage 3 material screening.

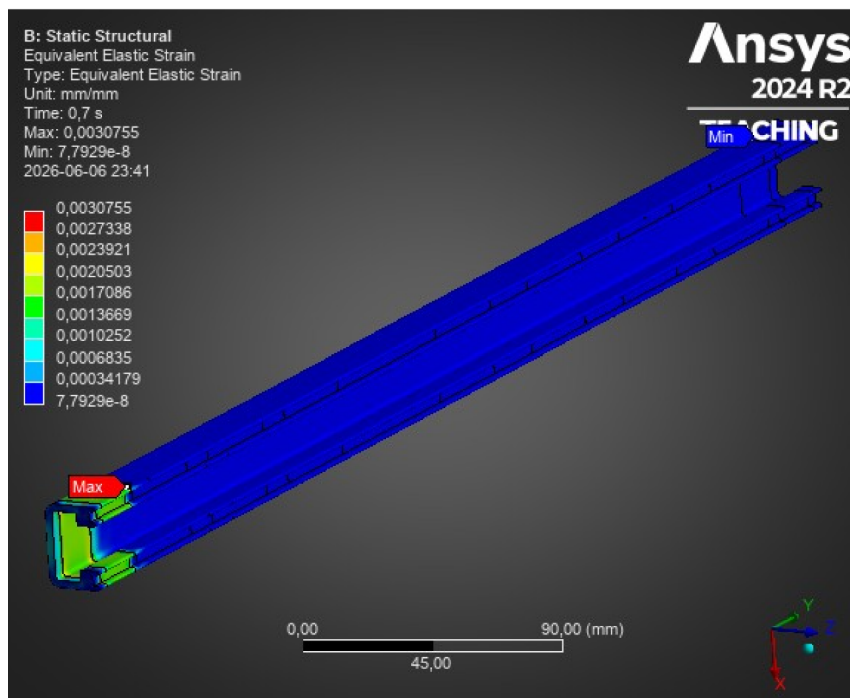


Figure 4.4: Equivalent elastic strain distribution corresponding to the Von Mises stress field. Peak strain is co-located with the peak stress at the fixed support regions, confirming elastic behaviour of the Al 6063-T6 incumbent under the design loading condition.

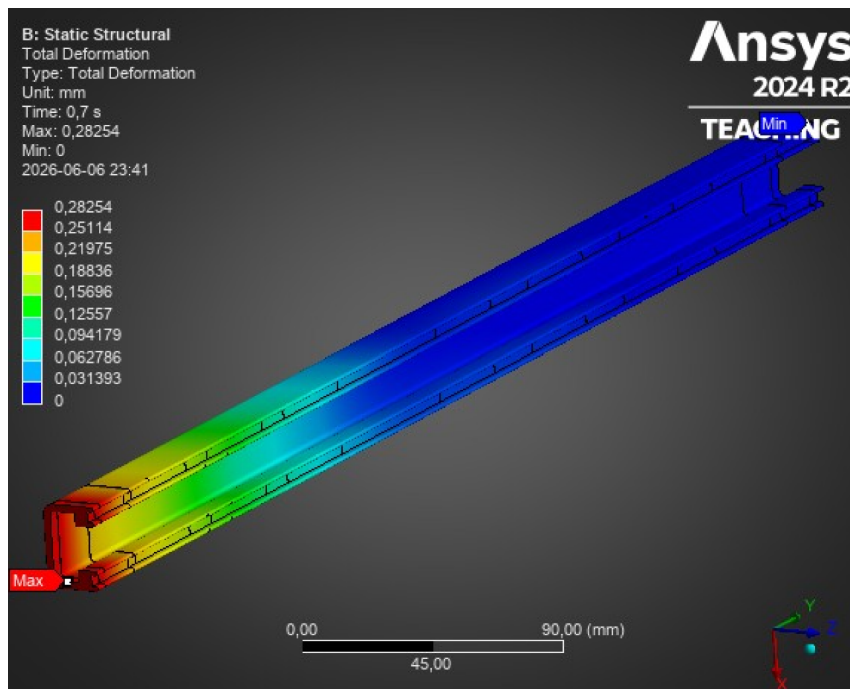


Figure 4.5: Total deformation of the CDC 40 phase rail under combined thermal and static loading. Peak cumulative elongation of 0.2 mm is distributed across both supported ends, consistent with free longitudinal thermal expansion about the fixed support boundary condition.

4.3 Material Screening Results

4.3.1 Baseline Material Properties

Table 4.1 summarises the key properties of the five candidate materials alongside the incumbent Al 6063-T6. Values for Al 6063-T6 are drawn from the CES EduPack materials database [1]; values for C18100 from the CES EduPack materials database [20]; values for C11000 from the manufacturer datasheet [19]; and values for Al 6101-T6 and Al 1350-H12 from the corresponding manufacturer datasheets [12, 13]. Table 4.1 presents the full property comparison grouped by category, matching the ranking and selection data used in the screening process.

Table 4.1: Full property comparison of incumbent and candidate busbar materials grouped by category. Values at 20 °C unless stated. Al 6063-T6 shown as baseline (rightmost column). Red-boxed values indicate properties that led to elimination or disadvantage during screening.

Category	Property	Unit	C18100	C11000	Al 1350-H12	Al 6101-T6	Al 6063-T6
Electrical	Electrical conductivity	% IACS	80	101	61	55	52
	Electrical resistivity	nΩ·m	2.14	1.70	2.83	2.99	3.30
Thermal	Thermal conductivity	W/m·K	394	390	234	218	200
	Specific heat capacity	J/kg·K	385	385	900	895	900
	Temperature rise at load	°C	70	70	70	70	70
Mechanical	Yield strength	MPa	370	220	55*	193	215
	Fatigue strength	MPa @ 10 ⁷	115	~100	~30	~70	83
	Formability (extrudability)	qualitative	Excellent	Excellent	Excellent	Excellent	Excellent
Environmental	CO ₂ footprint (cradle-to-grave)	kg CO ₂ /kg	~5.7	~5.4	~10.7	~11.25	~11.33
	Density	kg/m ³	8950 [†]	8940 [†]	2705	2700	2690
Economic	Material cost	SEK/kg	13,444 [†]	13,444 [†]	4300	4170	4170

*Fails FEM-derived yield strength constraint of 103 MPa; eliminated at Stage 3.

[†]High density amplifies per-kg cost and CO₂ to ≈10× aluminium on a volumetric basis; eliminated by penalty function.

CTE values for the aluminium alloys are similar ($\approx 23 \times 10^{-6}$ strain/°C) owing to their near-pure aluminium matrix; the copper alloys exhibit substantially lower CTE ($\approx 17 \times 10^{-6}$ strain/°C), making M_1 a meaningful discriminator between the two material families [5, 7]. The specific heat capacity contrast between copper (≈ 385 J/kg·K) and aluminium (≈ 900 J/kg·K) is noteworthy: despite copper’s higher conductivity, aluminium’s greater thermal mass means it stores more heat per unit mass during transient overload events, moderating peak temperatures at a given current surge [7].

4.3.2 Ashby Plot Analysis

Figure 4.6 plots electrical conductivity σ_E against thermal expansion coefficient α_T . Lines of constant performance index $M_1 = \sigma_E/\alpha_T$ appear as straight lines of slope M_1 through the origin on a linear–linear plot. The incumbent Al 6063-T6 performance line ($M_1 = 2.22$, dashed) demarcates the minimum acceptable region; all materials above this line represent an improvement on the primary index. The copper alloys occupy the high- M_1 region by virtue of their lower CTE, despite moderate conductivity relative to aluminium. Among the aluminium candidates, Al 6101-T6 and Al 1350-H12 both lie above the incumbent line with $M_1 = 2.57$ and $M_1 = 2.58$ respectively.

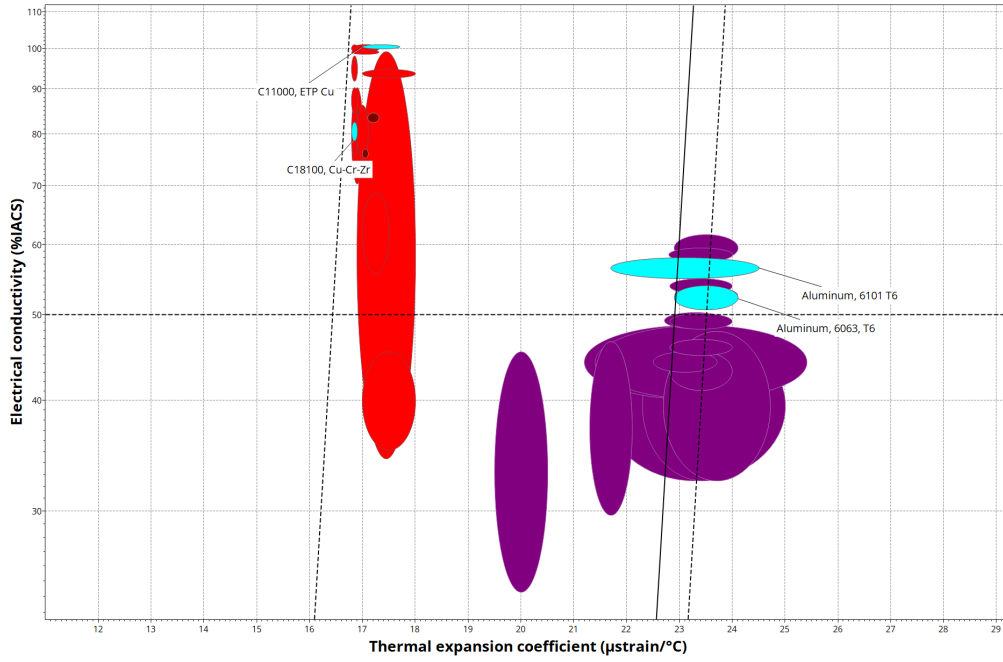


Figure 4.6: Ashby plot of electrical conductivity vs. thermal expansion coefficient. Dashed lines indicate constant $M_1 = \sigma_E/\alpha_T$ index values. ($M_1 = 2.22$)

Figure 4.7 plots tensile strength σ_T against electrical conductivity σ_E , used to evaluate the secondary index $M_2 = \sigma_T \cdot \sigma_E$. Copper alloys occupy the upper-right region of high strength and high conductivity. Among the aluminium candidates, Al 6101-T6 achieves a higher M_2 than the baseline Al 6063-T6 owing to its superior conductivity, while Al 1350-H12 is displaced significantly to the lower right owing to its very low yield strength (55 MPa), placing it below the 103 MPa FEM-derived constraint.

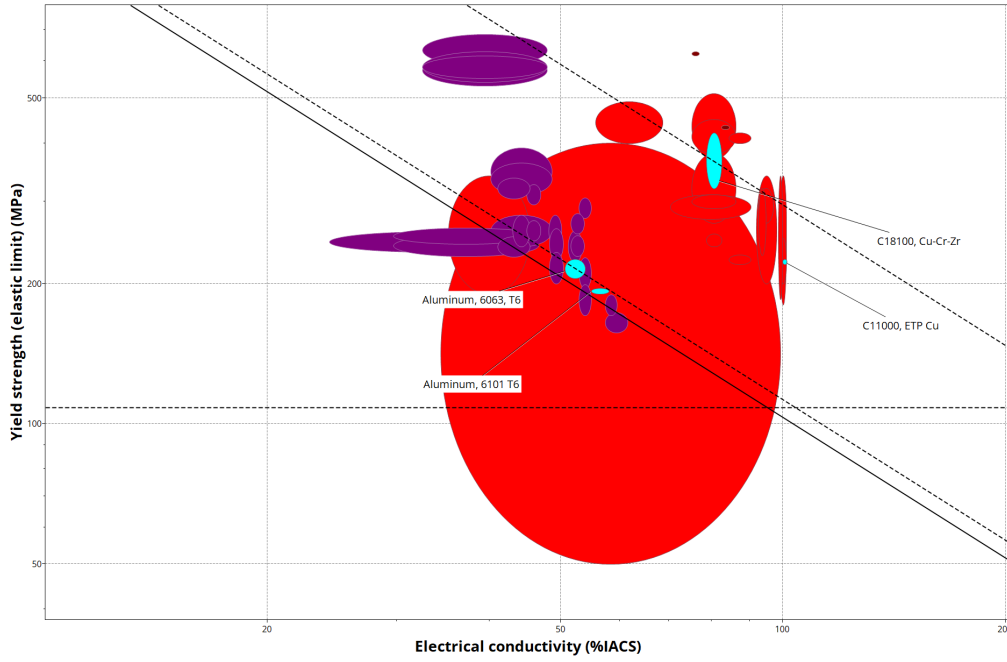


Figure 4.7: Ashby plot of tensile strength vs. electrical conductivity. Dashed lines indicate constant $M_2 = \sigma_T \cdot \sigma_E$ index values. ($M_2 = 11, 180$)

4.3.3 Hard Constraint Screening

Following the Stage 1 and Stage 2 Ashby screening, the FEM-derived yield strength constraint of $\sigma_y \geq 103$ MPa is applied as a Stage 3 hard constraint. Al 1350-H12 ($\sigma_y = 55$ MPa) fails this constraint and is eliminated from further consideration. The four remaining candidates — C11000, C18100, Al 6101-T6, and Al 6063-T6 (baseline) — all satisfy the mechanical feasibility requirement and proceed to the penalty function ranking.

4.3.4 Performance Index Ranking and Penalty Function

Table 4.2 consolidates the performance index evaluation, penalty function ranking, and volumetric cost and carbon data for all candidates. The penalty function $\tilde{\Phi} = \alpha \tilde{C}_{\text{cost}} + (1 - \alpha) \tilde{C}_{\text{carbon}}$ is evaluated at equal weighting ($\alpha = 0.5$), with cost and carbon normalised to the Al 6063-T6 baseline. To account for the fixed cross-section constraint of this application — meaning that equal volume of each material is consumed regardless of density — the cost and cradle-to-grave CO₂ footprint are also expressed on a per-unit-volume basis ($\rho_d \cdot C_{\text{cost}}$ and $\rho_d \cdot C_{\text{CO}_2}$ respectively). This is the physically meaningful basis for comparison: a given rail section requires the same volume of material regardless of which alloy is selected.

C11000 and C18100 achieve the highest M_1 values (5.94 and 4.55 respectively) owing to copper’s substantially lower CTE ($\approx 17 \times 10^{-6}$ strain/°C) compared to aluminium ($\approx 23 \times 10^{-6}$ strain/°C), and the highest M_2 values owing to copper’s high tensile strength combined with high conductivity. On a per-kilogram basis, copper also carries a lower carbon footprint ($\tilde{C}_{\text{carbon}} = 0.48\text{--}0.50$), reflecting the energy intensity of

Table 4.2: Consolidated performance index, penalty function, and volumetric cost and environmental impact for all candidates ($\alpha = 0.5$, normalised to Al 6063-T6 baseline). Al 1350-H12 eliminated at Stage 3 ($\sigma_y < 103$ MPa). Vol. cost = $\rho_d \cdot C_{\text{cost}}$ (norm.); Vol. CO₂ = $\rho_d \cdot C_{\text{CO}_2}$ (norm.).

Material	M_1 (σ_E/α_T)	M_2 ($\sigma_T \cdot \sigma_E$)	$\tilde{C}_{\text{cost}}$ (norm.)	$\tilde{C}_{\text{carbon}}$ (norm.)	$\tilde{\Phi}$ ($\alpha=0.5$)	Vol. cost (norm.)	Vol. CO ₂ (norm.)
C11000 (ETP Cu)	5.94	22,220	3.22	0.48	1.85	10.72	1.58
C18100 (CuCrZr)	4.55	29,600	3.22	0.50	1.86	10.73	1.67
Al 1350-H12	2.58	3,355	<i>eliminated</i>	$\sigma_y = 55 \text{ MPa} < 103 \text{ MPa}$ (FEM constraint)			
Al 6101-T6	2.57	11,387	1.00	0.99	1.00	1.00	1.00
Al 6063-T6 (baseline)	2.22	11,180	1.00	1.00	1.00	1.00	1.00

primary aluminium production. However, the penalty function eliminates copper on cost grounds: $\tilde{C}_{\text{cost}} = 3.22$ drives $\tilde{\Phi}$ to 1.85–1.86, substantially above the aluminium baseline of 1.00.

Furthermore, evaluating cost and environmental impact on a volumetric basis — the physically correct basis for a fixed-geometry application [14] — reveals that copper’s per-kilogram CO₂ advantage is neutralised by its high density ($\rho_d \approx 8,940 \text{ kg/m}^3$ vs. $\approx 2,700 \text{ kg/m}^3$ for aluminium): the volumetric CO₂ factor rises to 1.58–1.67 $\times$ the aluminium baseline, while the volumetric cost reaches $\approx 10.7\times$ the aluminium baseline. The cumulative effect of high volumetric cost and elevated volumetric carbon makes copper impractical for this application.

Among the aluminium candidates, Al 6101-T6 achieves $M_1 = 2.57$ — a 16% improvement over the incumbent ($M_1 = 2.22$) — and $M_2 = 11,387$ vs. 11,180 for Al 6063-T6, with a marginal reduction in carbon footprint (0.99 normalised) and equal cost per kilogram. **Al 6101-T6 is therefore identified as the primary sustainable alternative** to Al 6063-T6 for the CDC 40 phase rail application, with the Al 6000 series alloys proving the most economical and sustainable option overall [6, 10].

4.4 SEM and EDS Results

4.4.1 Scope and Representativeness

The SEM and EDS characterisation was conducted on one new (unaged) phase rail and one ten-year-aged phase rail retrieved from a single decommissioned CDC 40 assembly. These samples were not selected through a statistically controlled sampling procedure, and the specific load history, ambient environment, and installation conditions of the aged unit are unknown. The observations reported below therefore reflect the state of a single aged example and should not be interpreted as characteristic of the broader population of in-service CDC 40 busbars. Results are treated as *indicative* of the degradation mechanisms accessible to the Ni–Sn coating system under service conditions, not as quantitative evidence of product performance.

4.4.2 BSE Imaging — New Sample

BSE cross-sections of the new sample (Figures 4.8 and 4.9) showed a uniform Ni–Sn bilayer coating of consistent thickness across both the top and bottom contact surfaces of the C-profile. The Al 6063 substrate exhibited a fine grain structure consistent with the extruded and artificially aged condition. Pore density was low, and no oxide layer was resolved at the coating–substrate interface. The Ni–Sn interface was sharp and continuous with no evidence of interdiffusion or delamination.

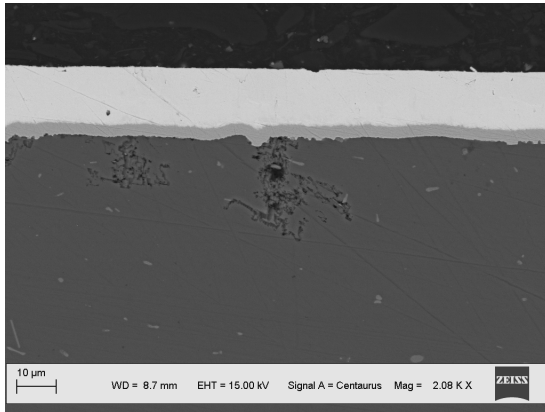


Figure 4.8: New sample cross-section (1CN_CS). Uniform Ni–Sn bilayer with sharp interface; no oxide or porosity.

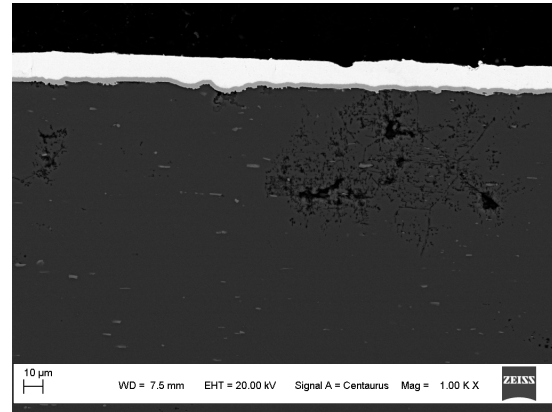


Figure 4.9: New sample longitudinal section (1CN_LONG_01). Continuous coating along current-flow direction; no delamination or cracking.

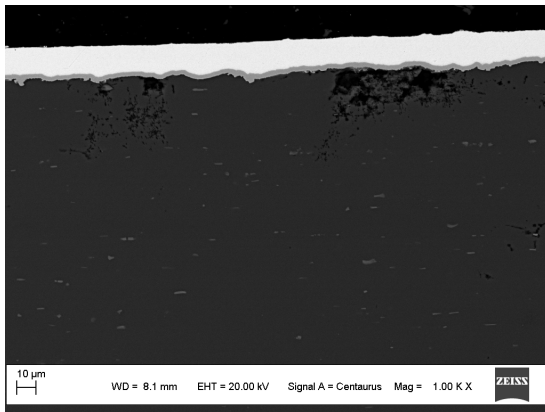


Figure 4.10: New sample longitudinal section (1CN_LONG_02). Uniform Sn layer thickness across the contact surface.

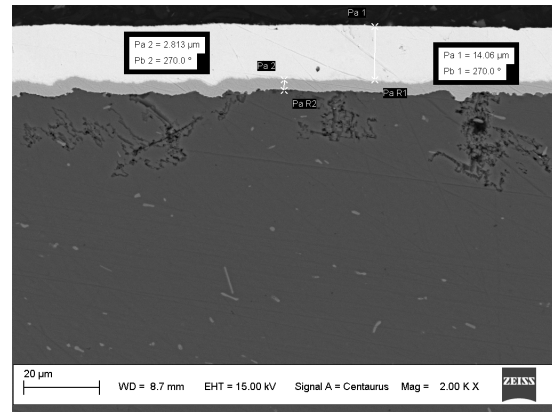


Figure 4.11: New sample overview (1CN_PL). Low void density and intact coating across the full field of view.

4.4.3 BSE Imaging — Aged Sample

The aged sample cross-sections exhibited markedly different morphology at both the rail end and the middle fusegear mounting section, as shown in Figures 4.12–4.23.

4.4.3.1 Rail End Section

At the rail end (Figure 4.12), pore sites were visibly discoloured in BSE contrast. The approximate grain size can be estimated around the oxidised regions. EDS (Section 4.4.5) confirms that the darker discolouration at pore boundaries corresponds to oxygen enrichment, consistent with Al_2O_3 formation driven by localised galvanic activity at trapped moisture sites [6].

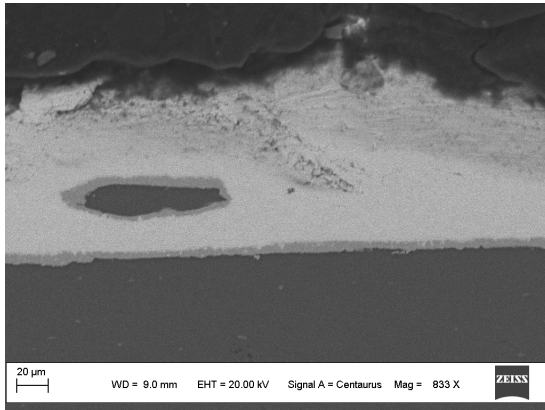


Figure 4.12: Aged sample longitudinal overview at rail end (1CO_LONG_01). Discolouration at pore sites visible in BSE contrast.

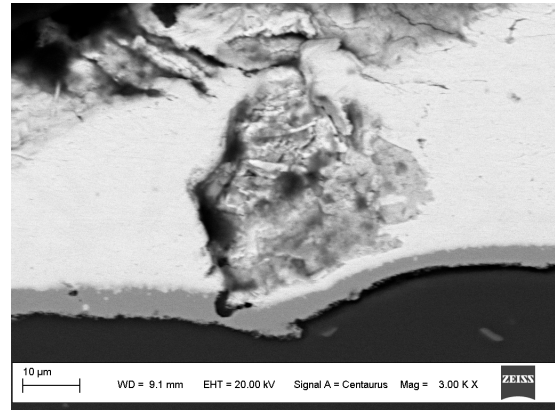


Figure 4.13: Aged longitudinal section at higher magnification (1CO_LONG_07). Grain boundaries visible around oxidised pore regions.

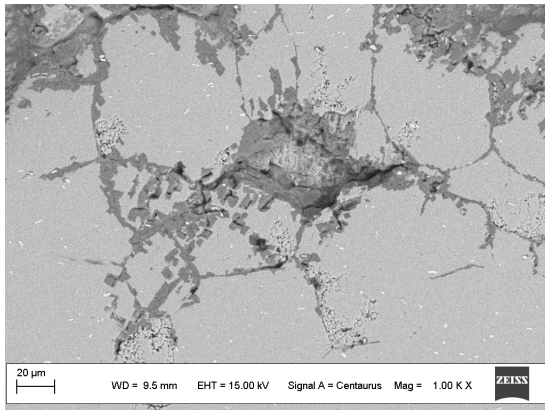


Figure 4.14: Pore site 1 (1CO_pore1). Dark BSE contrast at pore boundary consistent with Al_2O_3 .

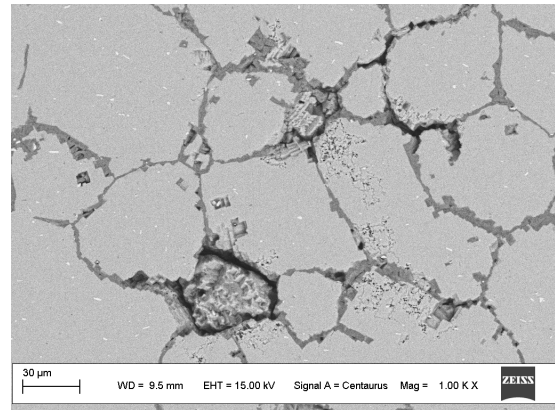


Figure 4.15: Pore site 2 (1CO_pore2). Oxidised boundary with visible discolouration extending into surrounding matrix.

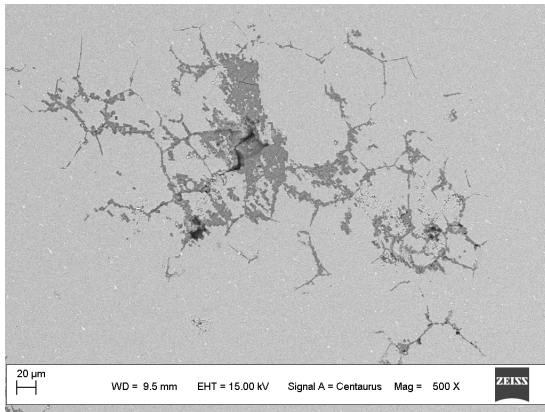


Figure 4.16: Pore site 3 (1CO_pore3). Elevated void density with Al_2O_3 at boundaries compared to new sample.

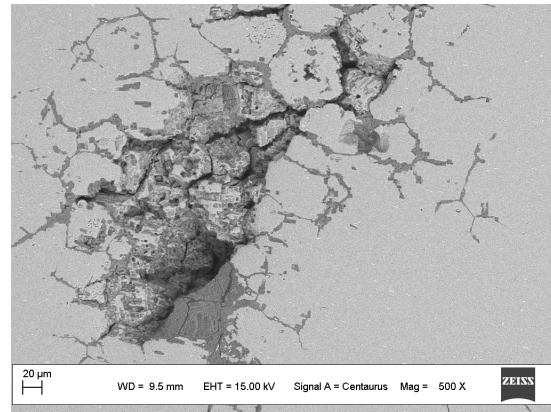


Figure 4.17: Pore site 4 (1CO_pore4). Larger oxidised region; grain boundaries traceable around the pore.

4.4.3.2 Middle Section — Connector Mounting Point

At the connector mounting point (Figures 4.18–4.23), the top and bottom surfaces of the phase rail showed an irregular Sn plating thickness, in contrast to the uniform layer observed in the new sample. The fusegear contact regions on both left and right sides of the rail exhibited localised Sn thinning and surface oxidation in BSE contrast. Void density at the coating–substrate interface was elevated relative to the new sample, though no oxidation was detected within the core of the Al substrate away from the surface. Ni signal broadening at the Ni–Sn interface indicates partial diffusion of Ni into the Sn layer as a result of accumulated thermal cycling [7, 6].

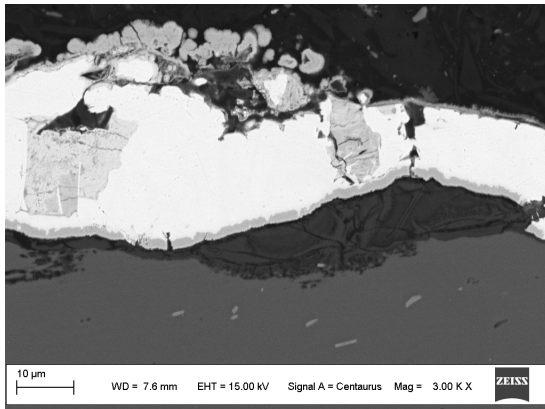


Figure 4.18: Fusegear region, left side (2FO_FUSEGEAR_L_04). Irregular Sn plating thickness visible on the top contact surface.

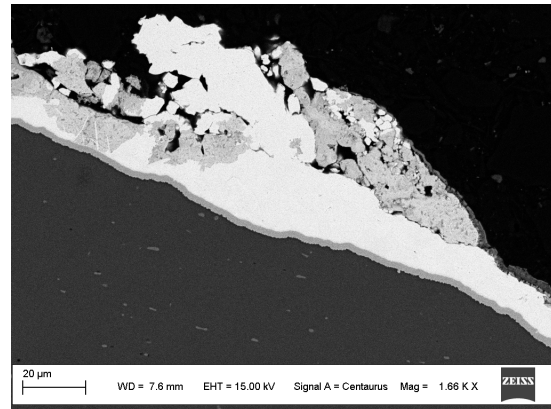


Figure 4.19: Fusegear region, left side (2FO_FUSEGEAR_L_08). Locally thinned Sn layer with evidence of surface oxidation.

The spatial correlation between pore sites and oxide formation, and the irregular Sn plating observed at connector regions, provide a microstructural explanation for contact resistance increase at connector interfaces over service life. It is emphasised that this mechanistic link is drawn from a single aged specimen; its prevalence across

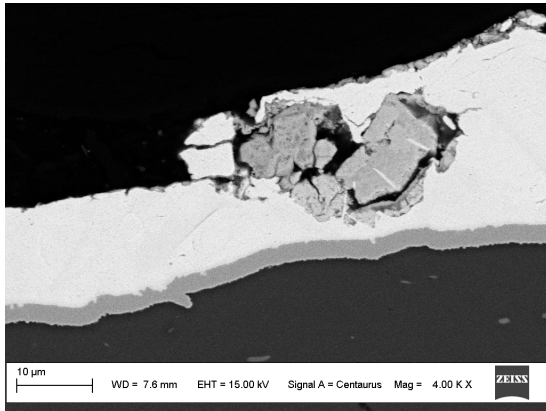


Figure 4.20: Fusegear region, left side (2FO_FUSEGEAR_L_18). Variation in Sn layer continuity along the bottom contact surface.

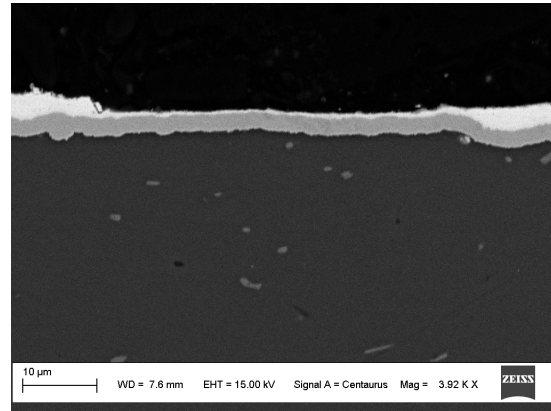


Figure 4.21: Fusegear region, right side (2FO_FUSEGEAR_R_02). Irregular electroplating layer compared to the uniform Sn seen in the new sample.

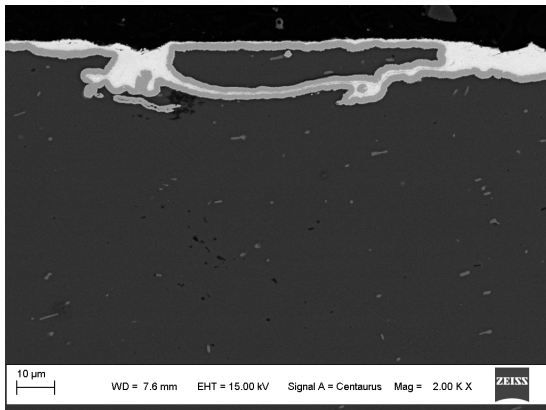


Figure 4.22: Fusegear region, right side (2FO_FUSEGEAR_R_03). Elevated void density at the coating–substrate interface with no oxidation in the Al core.

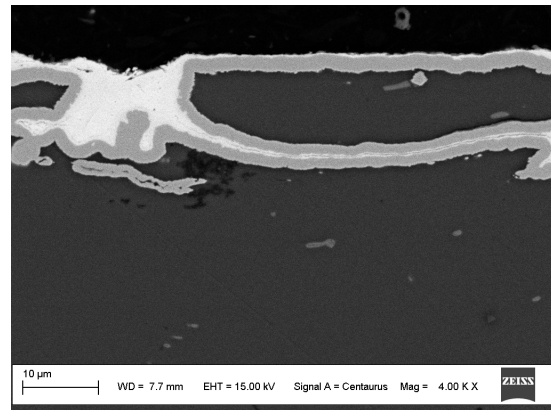


Figure 4.23: Fusegear region, right side (2FO_FUSEGEAR_R_10). Ni signal broadening at the Ni–Sn interface indicative of solid-state interdiffusion.

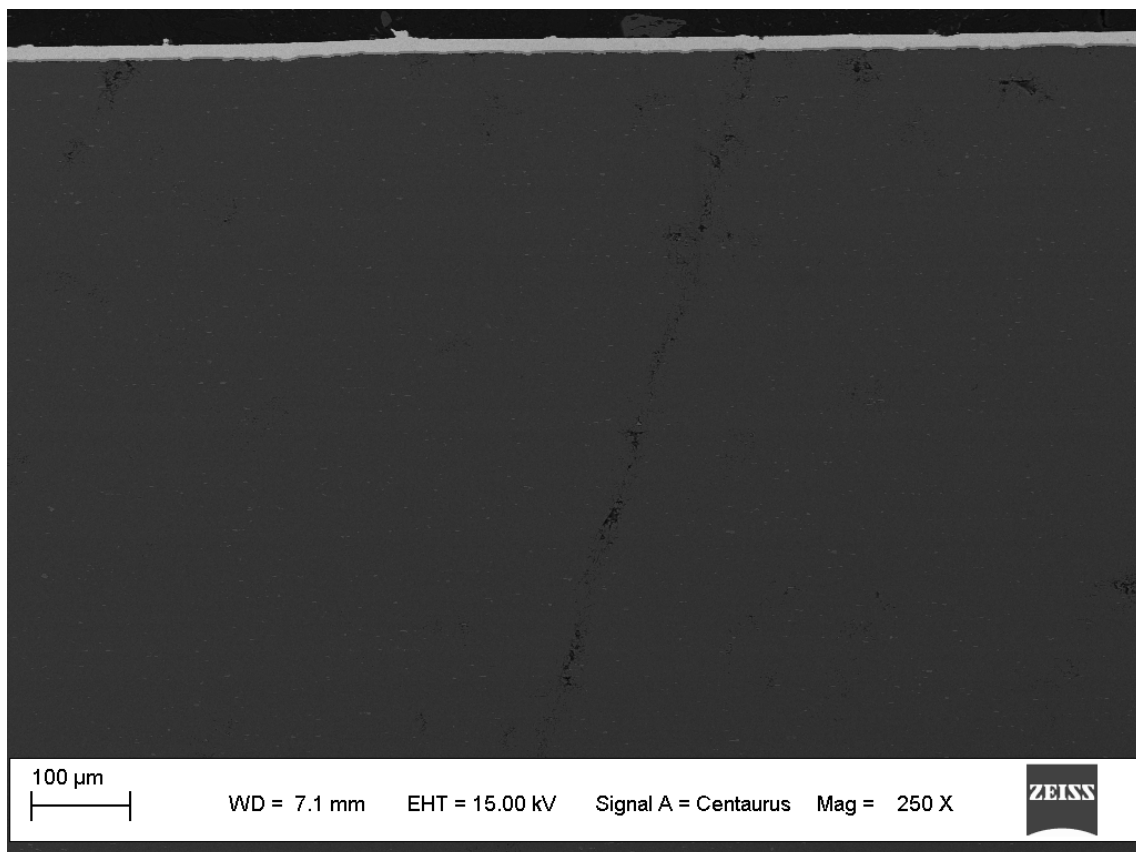


Figure 4.24: Preparation scratch visible on sample surface (1SEM_Scratch). Introduced during OPS polishing for attempted etched finish; sample was repolished before final imaging.

4. Results

the wider CDC 40 fleet cannot be established from this study alone.

4.4.4 EDS Analysis — New Sample

Point EDS spectra were acquired from the new sample at locations identified in Electron Images 1 and 9 (Figures 4.25 and 4.27). Spectra 1–3 (Electron Image 1) confirm the composition of the Al 6063 substrate matrix and identify bright-contrast AlFeSi intermetallic precipitates distributed throughout the bulk. Spectra 24–27 (Electron Image 9) provide the baseline layer-by-layer composition at the Sn–Ni–Al coating interface, characterising the Sn plating, Ni interlayer, and Al core in their as-manufactured condition. No oxygen signal was detected at any point in the new sample substrate or at the coating interface. The composite elemental map (Figure 4.29) shows sharply defined Al, Sn, Ni, and C layers with no oxygen enrichment, confirming the integrity of the as-manufactured Ni–Sn bilayer. These maps serve as the baseline reference for interpreting the aged sample.

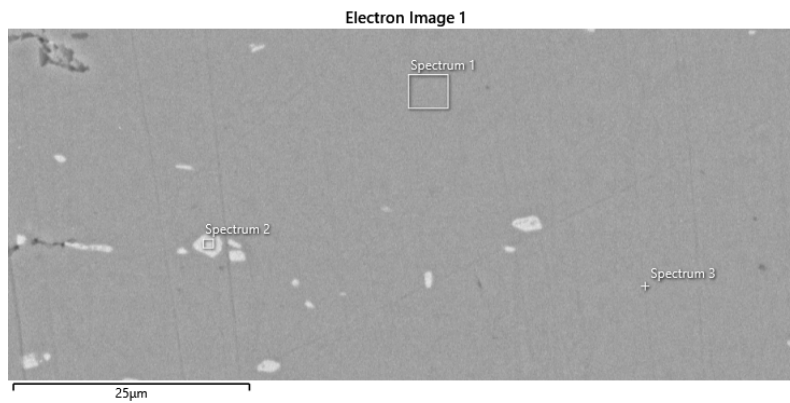


Figure 4.25: Electron Image 1 (new sample). Spectra 1–3 identify AlFeSi precipitates (bright contrast) and Al matrix in the substrate bulk.

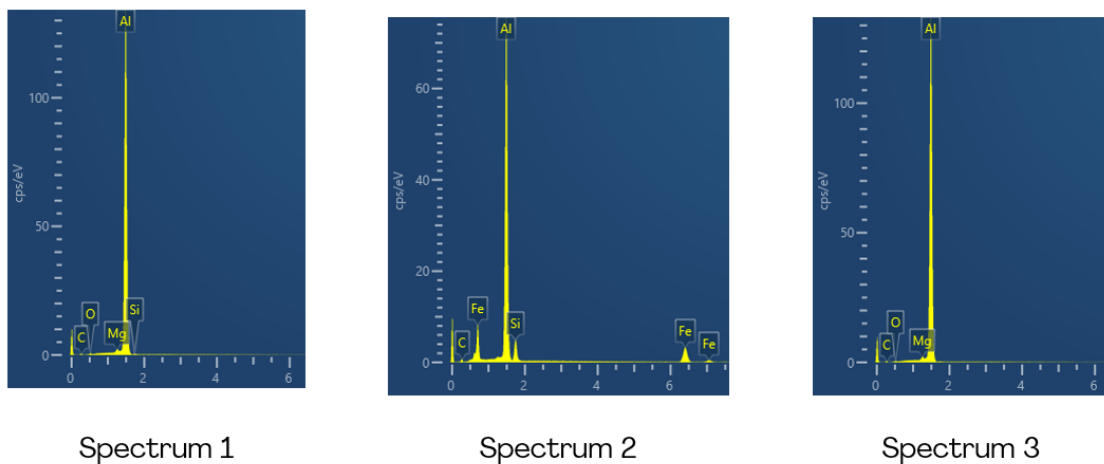


Figure 4.26: Electron Image 1 (new sample). Spectra 1,2,3 acquired at each inclusion for characterisation

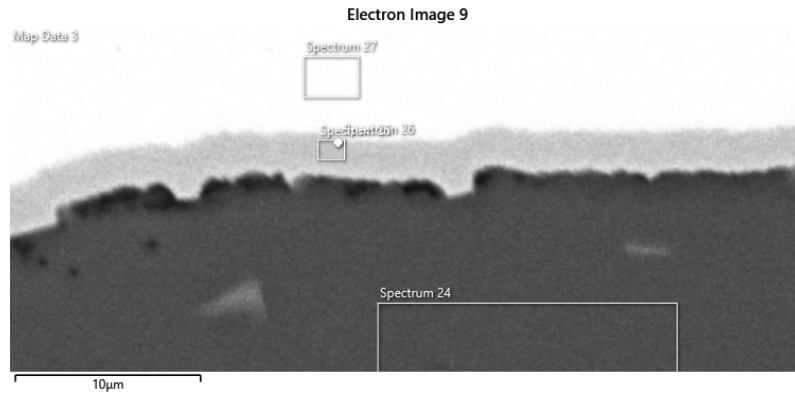


Figure 4.27: Electron Image 9 (new sample). Spectra 24–27 establish the baseline composition at the Sn–Ni–Al coating interface in the as-manufactured condition.

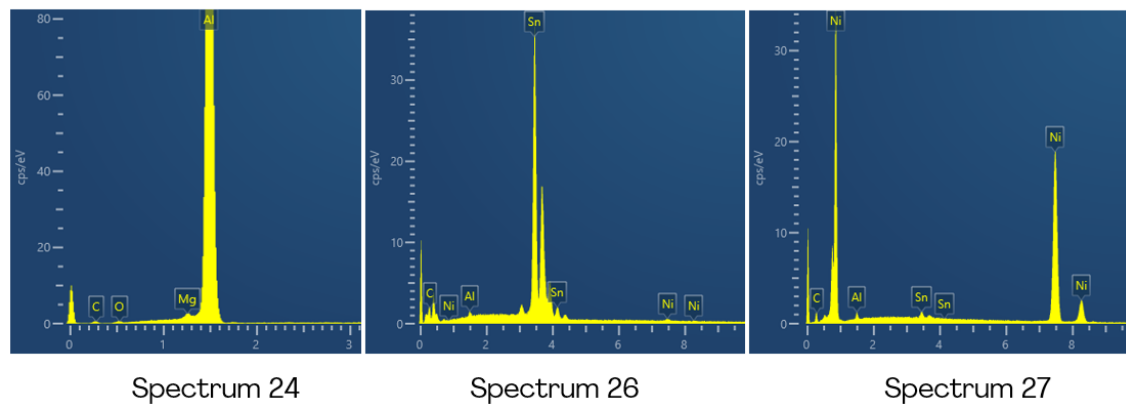


Figure 4.28: Electron Image 9 (new sample). Spectra 24–27 acquired at the Sn, Ni, and Al layers establish the reference spectra for each layer in the as-manufactured condition.

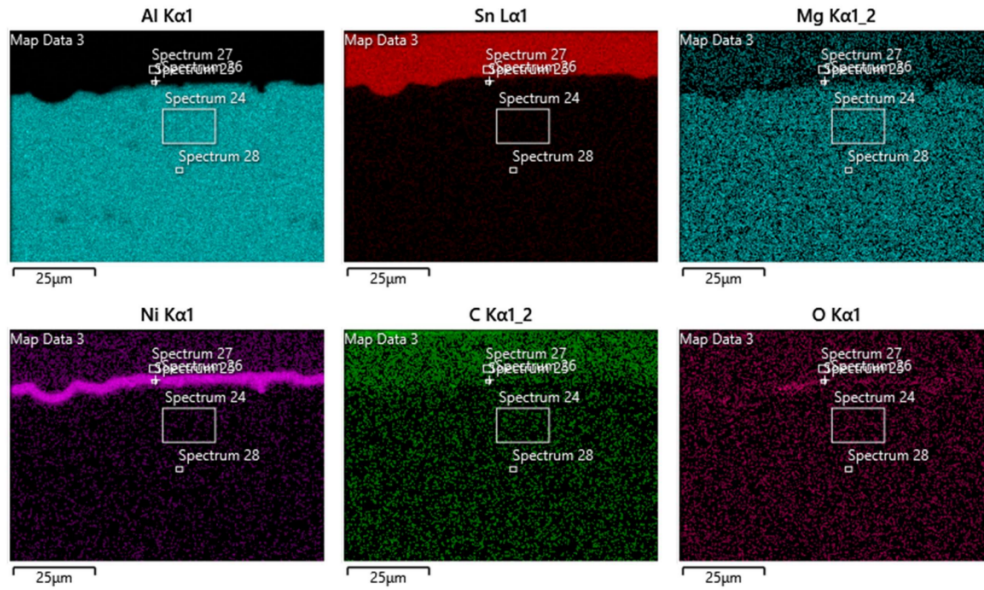


Figure 4.29: EDS elemental maps of new sample (Al, Sn, C, Ni, O, Mg). Ni and Sn layers are sharply defined with no oxygen enrichment at any interface. AlFeSi precipitates visible as localised Al-depleted regions in the substrate.

4.4.5 EDS Analysis — Aged Sample

Point EDS spectra were acquired from the aged sample at locations identified in Electron Images 5 and 6 (Figures 4.30 and 4.33). Electron Image 5 targets the Sn–Ni–Al coating interface at regions where the layer composition departs from the new-sample baseline established in Electron Image 9; spectra acquired at the cracked region (Spectra 8, 10, 12) and at the Sn layer surface (Spectra 9, 11, 13) confirm the presence of oxygen co-localised with Sn, consistent with SnO_x formation, while regions away from these anomalies return spectra consistent with the new sample baseline. Electron Image 6 provides the aged-sample counterpart to the precipitate characterisation of Electron Image 1; Spectra 16–19 confirm oxygen enrichment at pore boundaries in the substrate, while the Ni–Sn interface spectrum shows Ni signal extending into the Sn-rich region, providing direct evidence of solid-state Ni–Sn interdiffusion. The composite elemental map (Figure 4.32) reveals three key differences relative to the new sample baseline:

1. **Sn layer oxidation:** oxygen signal (O K α 1) is co-localised with the Sn layer, consistent with SnO_x formation at the exposed contact surface following prolonged service exposure.
2. **Al₂O₃ at pore sites:** oxygen enrichment is concentrated at pore boundaries in the Al substrate, consistent with Al₂O₃ formation driven by localised anodic oxidation at trapped moisture sites, as observed in BSE imaging (Section 4.4.3).
3. **Ni diffusion into the Sn layer:** the Ni signal (Ni K α 1) extends beyond the sharp bilayer interface seen in the new sample, indicative of solid-state Ni–Sn

interdiffusion accumulated over ten years of thermal cycling [7].

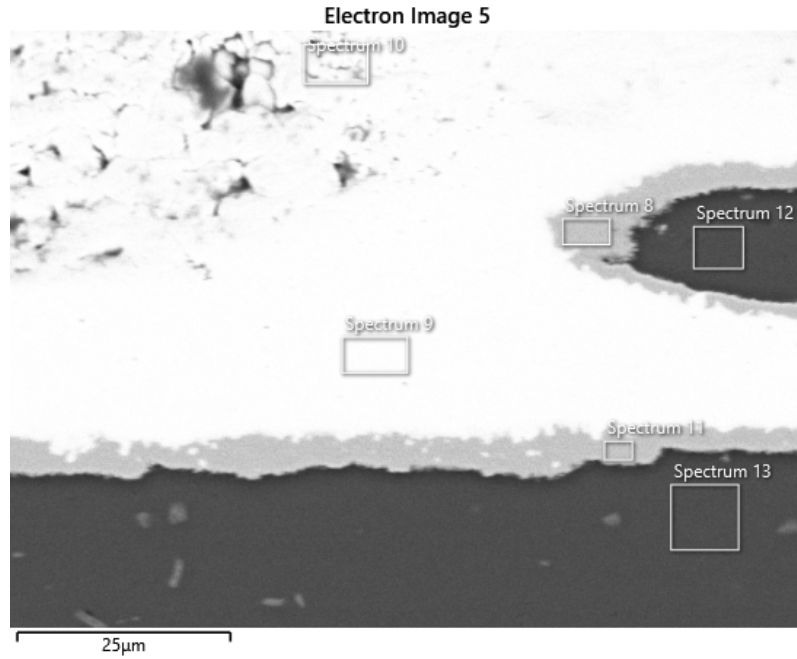


Figure 4.30: Electron Image 5 (aged sample). Spectra 8–13 acquired at the cracked Sn layer confirm oxygen co-localised with Sn (SnO_x).

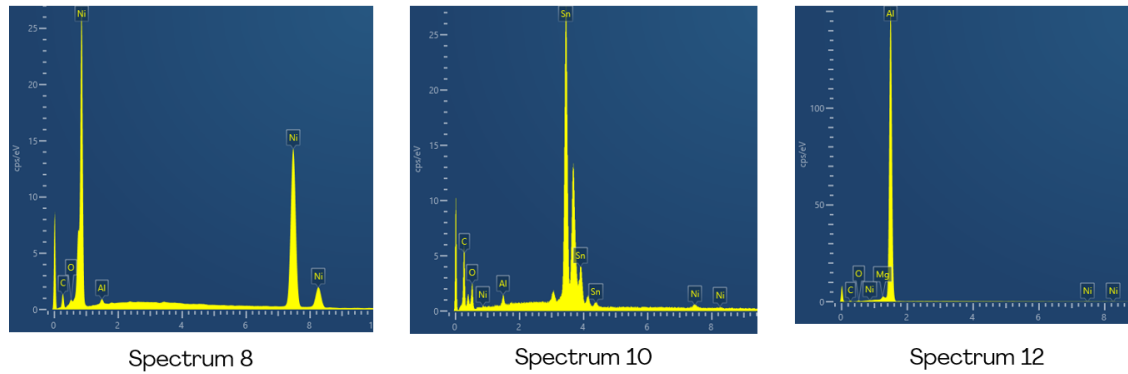


Figure 4.31: Electron Image 5 (aged sample). Spectra 8–13 acquired at the cracked Sn layer confirm oxygen co-localised with Sn (SnO_x).

These EDS observations are consistent with the degradation sequence expected for a Ni–Sn coated aluminium conductor subjected to repeated thermal cycling: Ni–Sn interdiffusion progresses with cumulative thermal exposure, the Sn surface undergoes progressive oxidation, and moisture-trapping at substrate pores drives localised Al_2O_3 formation that compromises the contact interface. It is reiterated that these observations derive from a single aged sample of unknown load history and should be treated as qualitative indicators of the degradation mechanisms operating in this coating system, not as statistically validated product performance data.

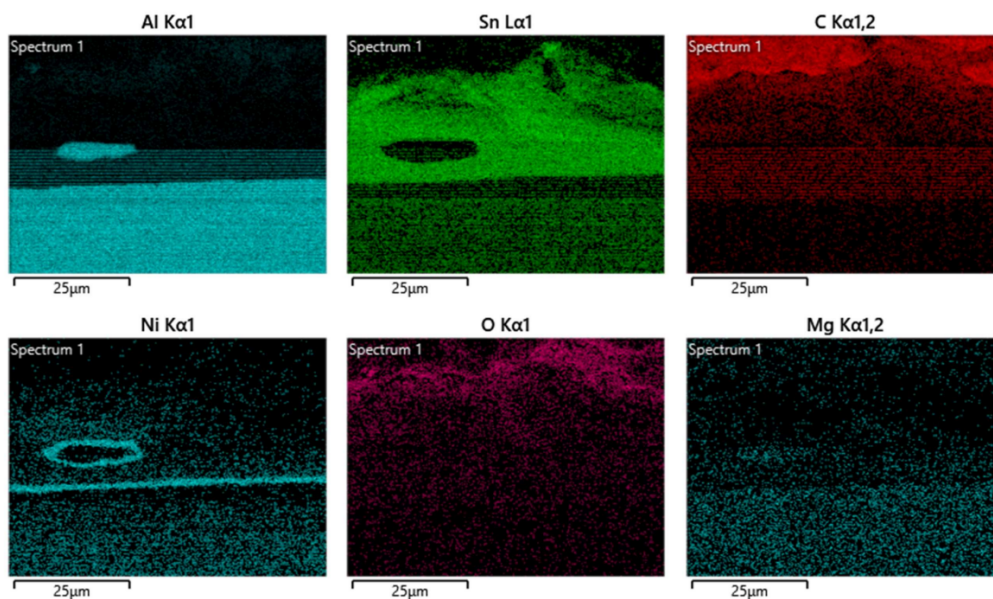


Figure 4.32: EDS elemental maps of aged sample (Al, Sn, Mg, Ni, C, O). Oxygen enrichment at pore boundaries (Al_2O_3) and co-localised with Sn layer (SnO_x); Ni signal extends into the Sn-rich region. Compare with Figure 4.29.

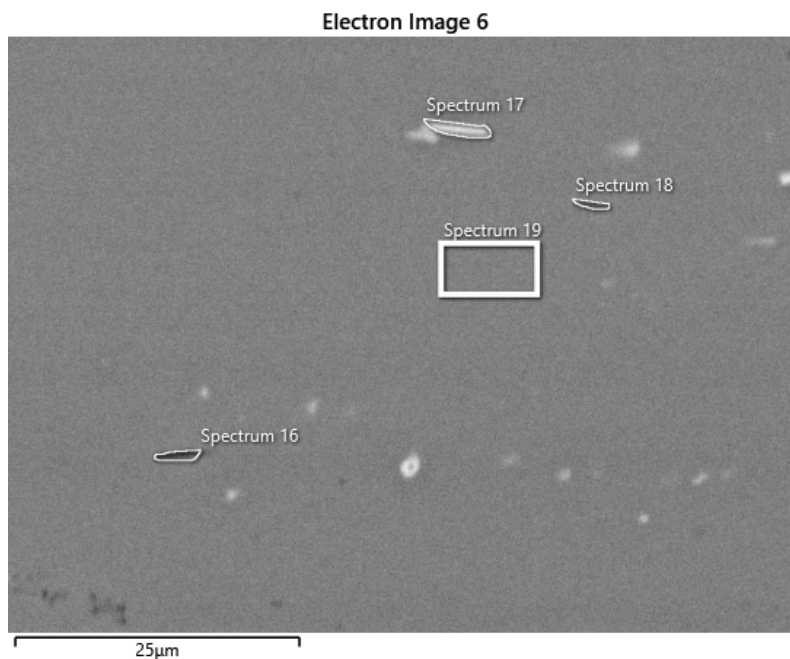
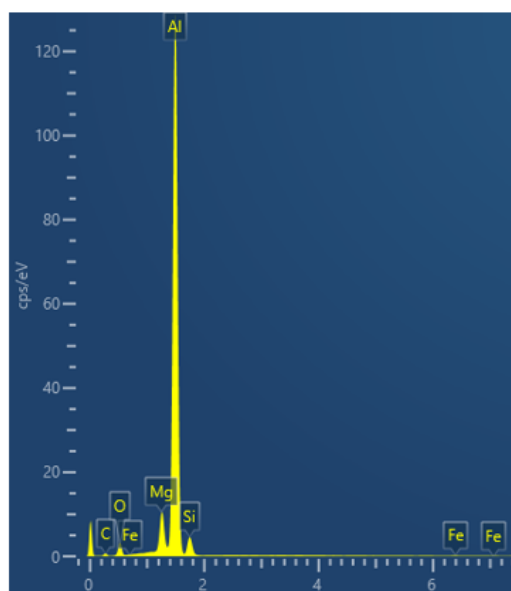
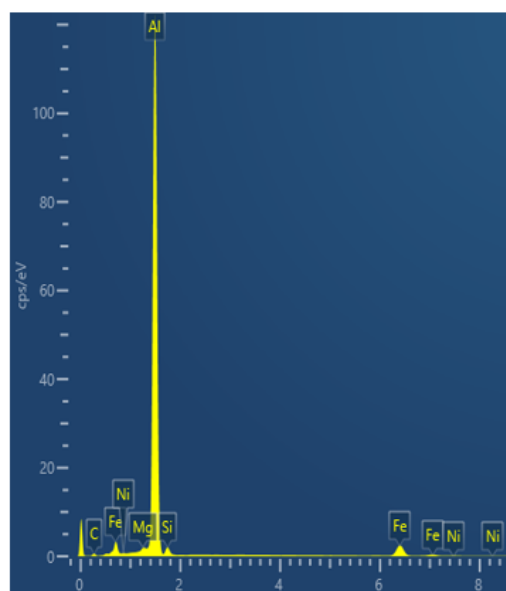


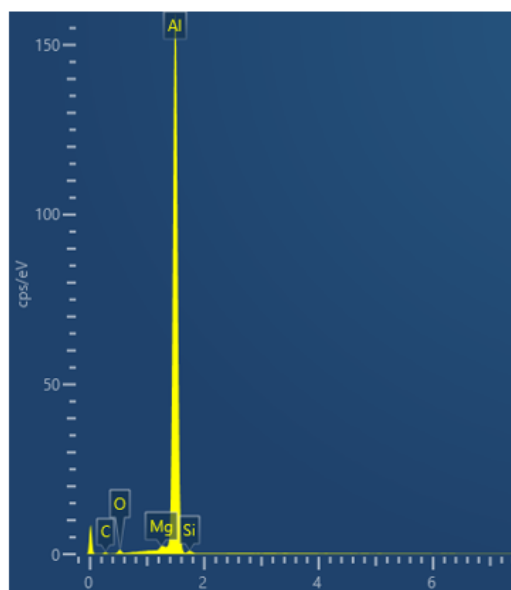
Figure 4.33: Electron Image 6 (aged sample). Spectra 16–19 confirm oxygen enrichment at pore boundaries and Ni diffusion into the Sn layer, the aged-sample counterpart to the precipitate characterisation in Electron Image 1.



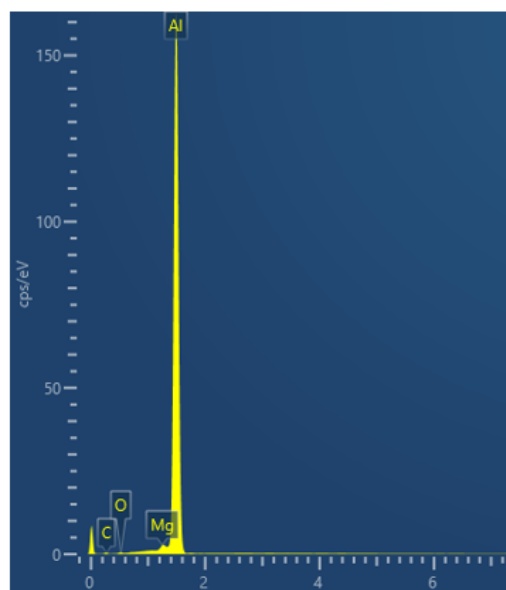
Spectrum 16



Spectrum 17



Spectrum 18



Spectrum 19

Figure 4.34: Electron Image 6 (aged sample). Spectra 16–19 acquired at the inclusions found in the aged sample for characterisation.

4.4.6 Summary of Characterised Samples

Table 4.3 consolidates the full set of samples examined by SEM and EDS, identifying the busbar region and sectioning orientation of each specimen alongside the principal observation recorded. N denotes the new (unaged) rail and O denotes the ten-year-aged rail, consistent with the sample naming convention introduced in Section 4.4.1.

Table 4.3: Summary of all samples examined by SEM and EDS, including busbar region, sectioning orientation, and principal observation for each specimen.

Sample Name	Busbar Region	Section	Observation
1FN	End	Cross Section	No oxidation; inclusions' EDS and elemental map
1CN	Middle	Longitudinal	Scratching in polishing step
1FO	End	Cross Section	Oxidation at pore sites
1CO	End	Cross Section	Inclusions' EDS and elemental map
2CO	End	Longitudinal	Sn oxidation and Ni diffusion into Sn
2FO	Middle	Cross Section	Non-uniform Ni/Sn layer on top and bottom rail
3FO	Middle	Cross Section	Non-uniform Ni/Sn layer at top and bottom rail

5

Discussion

The Ashby-based material selection framework developed in this study provides a structured and transparent basis for evaluating sustainable conductor alternatives for the CDC 40 phase rail. By translating the functional requirements of a fixed-geometry, 400 A rated busbar into quantitative performance indices and a multi-objective penalty function, the framework moves beyond single-property comparisons and captures the trade-offs between electrical performance, mechanical integrity, cost, and lifecycle carbon footprint simultaneously. The four-stage screening process, grounded in IEC 61439 constraints and validated by FEM-derived mechanical thresholds, represents a methodologically sound approach to this class of material substitution problem [4, 15].

The elimination of Al 1350-H12 at Stage 3 illustrates the importance of integrating FEM results directly into the selection framework rather than relying on nominal datasheet values alone. Al 1350-H12 offers the highest electrical conductivity among the aluminium candidates (61 %IACS) and a marginally lower cradle-to-grave carbon footprint (10.70 kg CO₂/kg), yet its yield strength of 55 MPa falls well short of the 103 MPa threshold established by the static structural analysis under combined thermal ($\Delta T = 70^\circ\text{C}$) and mechanical loading. This constraint is not arbitrary: the FEM results show that peak stresses concentrate at the fixed support regions where the rail is clamped to the switchgear frame, and any material that yields at these locations would compromise both the mechanical integrity of the assembly and the stability of the electrical connections it supports. The near-pure aluminium matrix that gives Al 1350-H12 its conductivity advantage is precisely what prevents it from meeting this threshold, reflecting the fundamental Mg₂Si precipitation strengthening trade-off inherent to the 6000 series alloy family [10, 11].

Among the surviving candidates, the case for Al 6101-T6 as the primary sustainable alternative is robust. Its primary performance index $M_1 = \sigma_E / \alpha_T = 2.57$ represents a 16 % improvement over the incumbent Al 6063-T6 ($M_1 = 2.22$), driven by a higher electrical conductivity (55 vs. 52 %IACS) at a near-identical coefficient of thermal expansion (23.0×10^{-6} vs. 23.4×10^{-6} strain/ $^\circ\text{C}$). The secondary index $M_2 = \sigma_T \cdot \sigma_E = 11,387$ also marginally exceeds the incumbent value of 11,180, confirming that the conductivity improvement does not compromise cyclic thermal stress resistance. Crucially, these gains are achieved at an identical material cost (4,170 SEK/kg) and a slightly lower carbon footprint (11.25 vs. 11.33 kg CO₂/kg),

yielding a penalty function of $\tilde{\Phi} = 1.00$ — matching the baseline — while delivering measurably better electrical performance. This combination of properties makes Al 6101-T6 a compelling drop-in candidate: it requires no change to the existing rail geometry, coating system, or manufacturing process.

The copper alloys C11000 and C18100 rank highest on both M_1 (5.94 and 4.55) and M_2 (22,220 and 29,600), and their per-kilogram carbon footprint is genuinely lower (≈ 5.4 – 5.7 vs. 11.3 kg CO₂/kg for aluminium). A surface-level reading of these figures might suggest that copper is the more sustainable choice. However, the fixed-geometry constraint of this application demands that the comparison be made on a volumetric basis: the rail cross-section is fixed at 200 mm^2 , so each metre of rail consumes the same volume of material regardless of alloy. Copper’s density of $\approx 8,940\text{ kg/m}^3$ — more than three times that of aluminium — reverses its per-kilogram environmental advantage entirely, producing a volumetric CO₂ factor of 1.58 – $1.67\times$ the aluminium baseline. Combined with a volumetric material cost of $\approx 10.7\times$ the aluminium baseline, the penalty function conclusively eliminates copper from practical consideration. This outcome underlines a general principle relevant to fixed-geometry electrical applications: the density ratio between copper and aluminium means that per-kilogram environmental metrics systematically misrepresent the true lifecycle impact of copper conductors, and volumetric normalisation is essential for a fair comparison [14, 5].

The SEM and EDS characterisation of the aged phase rail provides qualitative insight into the degradation mechanisms that develop in the incumbent Ni–Sn coating system over extended service. Three features distinguish the aged sample from the new baseline: Al₂O₃ formation concentrated at pore boundaries in the Al substrate, irregular and locally thinned Sn plating on the top and bottom contact surfaces, and solid-state diffusion of Ni into the Sn layer. These observations form a coherent degradation sequence: repeated thermal cycling progressively disrupts the sharp Ni–Sn bilayer interface, while moisture trapped in substrate pores sustains localised anodic oxidation of the Al matrix, producing Al₂O₃ nodules that increase interfacial contact resistance at device clamp locations [6]. The elevated void density in the aged sample relative to the new baseline is consistent with Kirkendall-type vacancy condensation associated with differential Ni–Sn diffusion rates [7].

It is essential, however, to place these microstructural observations in their proper evidential context, as discussed in Section 4.4.1: the characterisation reflects a single aged phase rail of unknown load history, and the degradation features reported should be read as indicative of mechanisms accessible to this coating system rather than as a representative or quantitatively predictive failure mode for the wider CDC 40 fleet.

An additional practical limitation of the characterisation concerns sample preparation quality. During attempts to achieve an etched surface finish for grain structure study using colloidal silica (OPS) final polishing, scratches were introduced on several samples, necessitating repolishing through the full SiC and diamond suspension sequence before a satisfactory surface could be obtained. This constrained the num-

ber of regions available for imaging and may have introduced minor residual surface deformation in samples where the repolishing cycle was not completed in full. As a result, the grain structure analysis intended to complement the BSE and EDS observations could not be carried out to the standard required, and microstructure-level conclusions regarding grain size evolution between new and aged samples are not drawn in this thesis.

Within these limitations, the qualitative agreement between the observed degradation features and the mechanisms predicted by the literature lends confidence that the findings reflect genuine service-induced phenomena rather than preparation artefacts, and the observations are therefore useful as a starting point for understanding coating system behaviour. The finding that Ni–Sn interdiffusion and surface oxidation are detectable after ten years of service suggests that the long-term contact resistance of the busbar system is more sensitive to the condition of the plated contact surface than to the bulk conductivity of the core conductor. This has a direct implication for the material substitution question: if contact surface degradation dominates system losses over time, then improvements in bulk conductor conductivity — such as those offered by Al 6101-T6 — will be progressively offset by rising contact resistance as the rail ages, and the sustainability and performance case for alternative conductor materials should be evaluated in conjunction with, rather than independently of, the coating system employed.

6

Conclusion

This thesis investigated sustainable material alternatives for the Al 6063-T6 phase rail used in the ABB CDC 40 low-voltage switchgear assembly, combining an Ashby-based multi-objective material selection framework with finite element analysis and microstructural characterisation of in-service samples.

An Ashby material selection framework was developed integrating electrical, thermal, mechanical, and sustainability criteria for a fixed-geometry, 400 A rated busbar application. Two performance indices were derived from first principles: $M_1 = \sigma_E/\alpha_T$, capturing thermal performance under electrical loading, and $M_2 = \sigma_T \cdot \sigma_E$, capturing resistance to elastic cyclic thermal stress during current conduction. A four-stage screening process, constrained by IEC 61439 requirements and a FEM-derived yield strength threshold of 103 MPa, reduced an initial candidate pool to four viable materials. Al 1350-H12 was eliminated on mechanical grounds ($\sigma_y = 55$ MPa); copper alloys C11000 and C18100 were eliminated by the penalty function, as their material cost of 13,444 SEK/kg and high density ($\approx 8,940$ kg/m³) produce a volumetric cost and carbon impact of approximately 10.7 $\times$ and 1.6 $\times$ the aluminium baseline respectively when evaluated on the volumetric basis appropriate to this fixed-geometry application.

Al 6101-T6 was identified as the primary sustainable alternative to the incumbent Al 6063-T6. It achieves a primary performance index of $M_1 = 2.57$ compared to 2.22 for the baseline — a 16 % improvement — driven by higher electrical conductivity (55 vs. 52 %IACS) at a near-identical coefficient of thermal expansion. It satisfies all mechanical constraints, matches the incumbent on cost, and carries a marginally lower cradle-to-grave carbon footprint (11.25 vs. 11.33 kg CO₂/kg). As an alloy within the same 6000 series family, it is compatible with the existing extrusion geometry, Ni–Sn coating system, and PA11 insulation without modification.

SEM and EDS characterisation of a ten-year-aged phase rail revealed Al₂O₃ formation concentrated at pore sites in the Al substrate, irregular Sn plating thickness at connector mounting surfaces, and solid-state diffusion of Ni into the Sn layer. These features are consistent with progressive coating degradation driven by thermal cycling over service life. As discussed in Section 4.4.1, these observations are drawn from a single sample of unknown load history and cannot be generalised to the broader CDC 40 fleet; they remain indicative of the degradation mechanisms

accessible to this coating system rather than a characteristic failure mode.

The findings of this thesis support the conclusion that Al–Mg–Si (6000 series) alloys represent the most viable and sustainable conductor material family for this application. Future work should include physical testing of extruded Al 6101-T6 profiles under representative electrical load cycles to validate the predicted conductivity and mechanical performance, grain structure analysis to quantify microstructural evolution over service life, and investigation of alternative coating systems with lower environmental impact to complement the conductor material improvements identified here.

Bibliography

- [1] ANSYS Granta. Aluminum alloy 6063-T6: Materials data for simulation. CES EduPack database entry, 2024.
- [2] IEC 61439: Low-voltage switchgear and controlgear assemblies, 2011. Replaces IEC 60439.
- [3] Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS recast), 2011.
- [4] Michael F. Ashby. *Materials Selection in Mechanical Design*. Butterworth-Heinemann, 4 edition, 2011.
- [5] David Chapman and Toby Norris. *Copper for Busbars: Guidance for Design and Installation*. Copper Development Association, 2014. CDA Publication No. 22; European Copper Institute Publication No. Cu0201.
- [6] Frank Czerwinski. Aluminum alloys for electrical engineering: a review. *Journal of Materials Science*, 59:14847–14892, 2024.
- [7] Charles Kittel. *Introduction to Solid State Physics*. Wiley, 8 edition, 2005.
- [8] Devender Nath. Indian experience with aluminum busbars, links, and cable terminations for use on low-voltage systems up to 1000 V. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, CHMT-9(1):30–36, 1986.
- [9] Jiayi Zhang and Jing Peng. A review on aluminum alloy conductors influenced by alloying elements and thermomechanical treatments: microstructure and properties. *Journal of Materials Research*, 38(6):557–591, 2023.
- [10] J. K. Sunde, C. D. Marioara, S. Wenner, and R. Holmestad. On the microstructural origins of improvements in conductivity by heavy deformation and ageing of Al–Mg–Si alloy 6101. *Materials Characterization*, 176:111073, 2021.
- [11] Y. Han, D. Shao, B. A. Chen, Z. Peng, Z. X. Zhu, Q. Zhang, X. Chen, G. Liu, and X. M. Li. Effect of Mg/Si ratio on the microstructure and hardness–conductivity relationship of ultrafine-grained Al–Mg–Si alloys. *Journal of Materials Science*, 52:4445–4459, 2017.

- [12] Aluminum Association. Aluminum 6101-T6 datasheet. Aluminum Association, Arlington, VA, 2023.
- [13] Aluminum Association. Aluminum 1350-H12 datasheet. Aluminum Association, Arlington, VA, 2023.
- [14] European Aluminium. Environmental profile report for the European aluminium industry. Technical report, European Aluminium, 2019.
- [15] A. Jahan, K. L. Edwards, and M. Bahraminasab. *Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design*. Butterworth-Heinemann, 2 edition, 2016.
- [16] M. F. Ashby and Y. J. M. Bréchet. Designing hybrid materials. *Acta Materialia*, 51(19):5801–5821, 2003.
- [17] Joseph I. Goldstein, Dale E. Newbury, Joseph R. Michael, Nicholas W. M. Ritchie, John Henry J. Scott, and David C. Joy. *Scanning Electron Microscopy and X-Ray Microanalysis*. Springer, 4 edition, 2018.
- [18] D. W. Pryer, editor. *Electrical Engineer’s Reference Book*. Newnes, Oxford, UK, 16 edition, 2003. Chapter on cables by P. F. Gale.
- [19] Copper Development Association. Copper alloy C11000 (electrolytic tough pitch): Material data. CDA Technical Data, 2022.
- [20] ANSYS Granta. Copper–Cr–Zr alloy C18100: Materials data for simulation. CES EduPack database entry, 2024.
- [21] Struers ApS. Application notes: Preparation of aluminium and aluminium alloys. Struers Technical Documentation, 2022. Preparation method for aluminium–silicon alloys; TegraPol/TegraForce procedures.

A

Appendix

A.1 Appendix 1: Thesis Planning Report

Master's Thesis Planning Report



Project Title: Material Selection for Electrical Applications
of Busbars in Low Voltage Distribution Systems

Student Name: Geetik Mamillapalli
Program: MSc in Materials Engineering (MPAEM)
University: Chalmers University of Technology
Supervisor: Niclas Fogelberg
Examiner: Sheng Guo
Company: ABB AB
Date: 06-03-2026

Table of Contents

1. Introduction
 - 1.1 Background
 - 1.2 Aim
 - 1.3 Objectives
 - 1.4 Limitations
 - 1.5 Specification of the Issue Being Investigated
2. Methodology
 - 2.1 Research Approach
 - 2.2 Data Collection Methods
 - 2.3 Tools and Technologies
 - 2.4 Workflow / Project Process
 - 2.5 Reliability and Validity
3. Project Schedule
 - 3.1 Timeline Overview
 - 3.2 Gantt Chart
4. References

1. Introduction

1.1 Background

Low voltage electrical distribution systems are widely used in industrial facilities, commercial buildings, and infrastructure projects to distribute electrical power safely and efficiently. One of the key components in these systems is the busbar, which serves as a conductor that distributes electrical power from incoming feeders to outgoing circuits within switchgear, distribution boards, and power panels.

Busbars are typically made from conductive materials and must be designed to handle high currents while minimizing electrical losses and thermal stress. The choice of material plays a critical role in determining the electrical performance, mechanical strength, thermal behavior, and overall cost of the system.

In many industrial applications, selecting the appropriate busbar material requires balancing several factors including electrical conductivity, thermal conductivity, corrosion resistance, weight, mechanical strength, and economic cost. However, improper material selection may result in excessive power losses, overheating, reduced reliability, or increased maintenance requirements in electrical distribution systems.

With the UNSDGs in mind, industries are constantly trying to push boundaries and implement more sustainable products that help reduce the overall carbon footprint. Carbon emissions for the entire lifecycle of a product should be one of the primary factors as well when selecting materials. Therefore, it is important to systematically analyze and compare different materials to determine their suitability aspects as a crucial factor for busbars.

This project investigates the criteria involved in selecting busbar materials and evaluates the performance of commonly used materials to identify optimal choices for electrical applications.

1.2 Aim

The aim of this project is to analyze and evaluate different materials used in busbars for low voltage electrical distribution systems to determine the most suitable material based on electrical performance, thermal characteristics, mechanical properties, and cost considerations.

The project will focus on sustainability as its primary objective while ensuring the material selected fulfills the functional requirements of the busbar and examining how material properties affect current carrying capacity, power losses, and overall system efficiency.

1.3 Objectives

The following objectives will guide the project:

1. Conduct a literature review on busbar design and material selection in low voltage distribution systems.
2. Identify the key electrical, thermal, and mechanical requirements for busbar materials.
3. Compare the physical, electrical and environmental properties of commonly used busbar materials such as copper and aluminum alloys.
4. Evaluate the thermal performance of different busbar materials under electrical loading.
5. Analyze how material selection influences current carrying capacity and power losses.
6. Investigate economic and ecological cost considerations associated with different busbar materials.
7. Propose recommendations for optimal material selection in low voltage busbar applications.

1.4 Limitations

This project will focus primarily on the material selection aspect of busbar design in low voltage electrical distribution systems.

Several limitations apply to the scope of the project.

First, the design of the switchgear interface cannot be changed. It is designed in accordance with other related ABB products. This limitation sets the constraints on design changes and relies mainly on the material.

Second, the project will rely mainly on theoretical calculations, available technical data and nested screening rather than full-scale experimental testing of busbar systems. The final shortlisted materials will be tested to verify. The number of material options to be tested depends on the Timeline.

Third, the study will consider standard operating conditions in low voltage systems and will not investigate extreme environmental conditions such as high humidity, corrosive environments, or high-altitude installations.

Finally, the project will analyze electrical and thermal properties of materials and their performance but will not include detailed structural or mechanical design optimization of busbar supports and enclosures.

1.5 Specification of the Issue Being Investigated

The investigation into this project will be guided by the following research questions:

RQ1: What are the key material properties required for busbars in low voltage electrical distribution systems?

RQ2: How do current busbar materials compare in terms of electrical conductivity, thermal performance, mechanical properties and environmental effects at EoL?

RQ3: How does the choice of material affect current carrying capacity and electrical losses in busbar systems?

RQ4: What economic factors influence the selection of busbar materials in industrial applications?

These questions will guide the analysis and evaluation conducted throughout the project.

2. Methodology

2.1 Research Approach

This project follows a comparative analytical research approach, focusing on the evaluation and comparison of different materials used in busbar applications.

The research will involve studying existing literature, engineering standards, and technical specifications related to electrical conductors and busbar design. Based on this information, key material properties will be analyzed and compared to determine their suitability for use in low voltage distribution systems.

The research will also include electrical and thermal calculations to estimate current carrying capacity, resistive losses, and temperature rise in busbars made from different materials.

2.2 Data Collection Methods

Several methods will be used to collect relevant data for the project.

Literature Review

A literature review will be conducted using textbooks, academic papers, and engineering standards related to electrical distribution systems and conductor materials.

Technical Standards

Relevant electrical standards and guidelines will be reviewed to identify recommended practices for busbar design and material selection.

Material Property Data

Material properties such as electrical conductivity, thermal conductivity, density, and mechanical strength will be collected from engineering databases and manufacturer documentation.

Analytical Calculations

Electrical and thermal performance will be evaluated using standard electrical engineering formulas for resistance, power loss, and heat generation.

2.3 Tools and Technologies

The project will use several analytical and documentation tools.

Engineering Calculation Tools

- ANSYS Granta EduPack 2023 for Material property charts and data
- Microsoft Excel for electrical and thermal calculations
- MATLAB (if applicable) for analytical modeling

Technical Documentation Tools

- Microsoft Word and LaTeX for report writing
- Microsoft Excel, MATLAB or Python (if applicable) for data analysis and charts

Reference Databases

- Engineering handbooks (e.g. Material Selection in Mechanical Design by M. Ashby)
- Technical standards (e.g. IEC 61439)
- Manufacturer datasheets (e.g. Rilsan PA11 datasheet)

2.4 Workflow / Project Process

The project will follow a structured process consisting of several stages.

Stage 1: Literature Review

Review existing research and technical documentation related to busbar design and material selection.

Stage 2: Identification of Material Requirements

Determine the key electrical, thermal, and mechanical properties required for busbar materials.

Stage 3: Function, Objective, Constraint and Variable Definition

Determine specific values of the important properties and define the problem statement necessary for Material Index. This includes definition of objective function.

Stage 4: Material Screening

Perform calculations to define material index and screen the materials according to constraints defined in Stage 3 to get a pool of candidates

Stage 6: Cost Evaluation

Analyze economic and environmental costs related to material and installation. Adjust pool of materials such that the penalty function can compare over substantial data by iterating value limiters on constraints

Stage 7: Result Analysis and Discussion

Compare the performance of different materials and identify advantages and disadvantages.

Stage 8: Final Documentation

Prepare the final report summarizing the findings and recommendations.

2.5 Reliability and Validity

To ensure reliability, the analysis will be based on well-established electrical engineering principles and standard formulas used in power distribution system design. The procedures and the tests should be compliant with IEC standards.

Material property data will be obtained from ANSYS Granta and will be the standard throughout the project. It is important to note that the Cost analysis might not be accurate to real world costs as in Granta the current prices might not be updated. For cost data, an exception might be considered.

Additionally, the calculations and comparisons will be performed using consistent assumptions and clearly defined parameters to ensure that results can be reproduced and verified.

3. Project Schedule

3.1 Timeline Overview

The Thesis is being targeted to be completed before summer, tentatively by Mid-June. The project itself is broadly divided into 3 phases:

1. The Problem Definition Phase: This phase carries on till mid-March, as the objective function, material constraints and free variables are defined
2. The Testing and Validation Phase: This is the most crucial phase as Screened materials will be tested according to standards, for feasibility as alternative needs to be verified
3. The Ranking and Comparison Phase: The Final candidates in the pool will be ranked with more detailed properties which needed to be excluded in the index but is still relevant (e.g. Corrosion Resistance). This phase will ensure more data is available while making the final selection metrics of material.

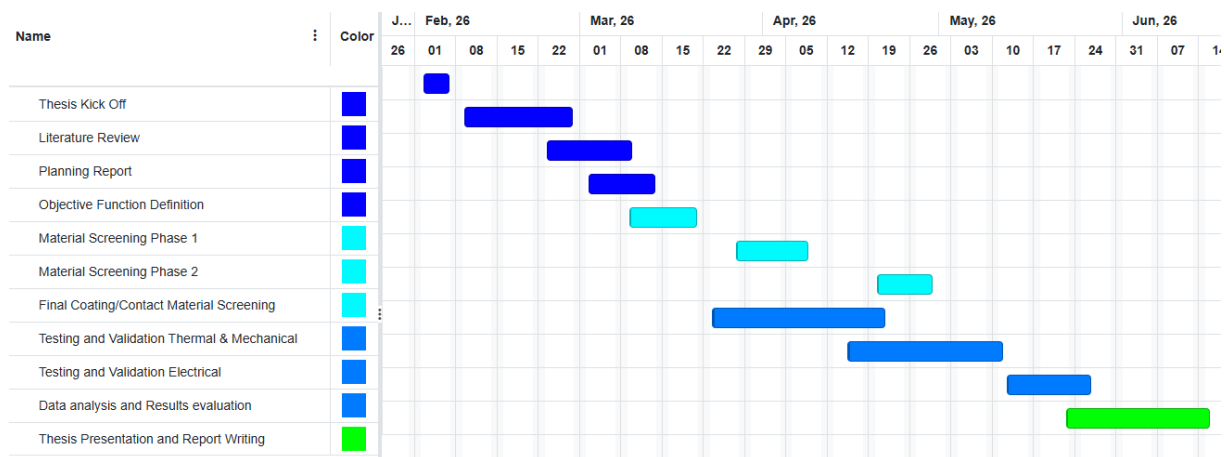
Name	Color	Start Date	End Date	Duration
Thesis Kick Off		Feb 02, 2026	Feb 06, 2026	5 days
Literature Review		Feb 09, 2026	Feb 27, 2026	15 days
Planning Report		Feb 23, 2026	Mar 09, 2026	11 days
Objective Function Definition		Mar 02, 2026	Mar 13, 2026	10 days
Material Screening Phase 1		Mar 09, 2026	Mar 20, 2026	10 days
Material Screening Phase 2		Mar 27, 2026	Apr 08, 2026	9 days
Final Coating/Contact Material Screening		Apr 20, 2026	Apr 29, 2026	8 days
Testing and Validation Thermal & Mechani...		Mar 23, 2026	Apr 21, 2026	22 days
Testing and Validation Electrical		Apr 15, 2026	May 11, 2026	19 days
Data analysis and Results evaluation		May 12, 2026	May 26, 2026	11 days
Thesis Presentation and Report Writing		May 22, 2026	Jun 15, 2026	17 days

The testing period is still ambiguous based on what material is presented post initial screening, which determines the steps needed to test and verify the alternative is as effective for the 20-40 year lifecycle of the product. The testing might also vary based upon which current rating busbar is selected for tes

ting as test durations or iterations might vary in each case. The idea, however, is to conduct the thesis for a singular category out of the ABB Kabeldon range of busbars for benchmarking the comparisons.

3.2 Gantt Chart

The projected timeline has been shown here. It is important to note this is just to set deadlines and streamline the workflow from phase to phase.



It is possible that a situation calling for extra testing/lesser screening etc. can arise and the final timeline would be added to the thesis report. In such a case, the tentative durations of each phase will be adjusted to the schedule.

4. References

- [1] Ashby, Michael F.. (2011). *Materials Selection in Mechanical Design (4th Edition)*. Elsevier. Retrieved from <https://app.knovel.com/hotlink/toc/id:kpMSMDE022/materials-selection-in/materials-selection-in>
- [2] IEC 61439-1:2020 Standard

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY