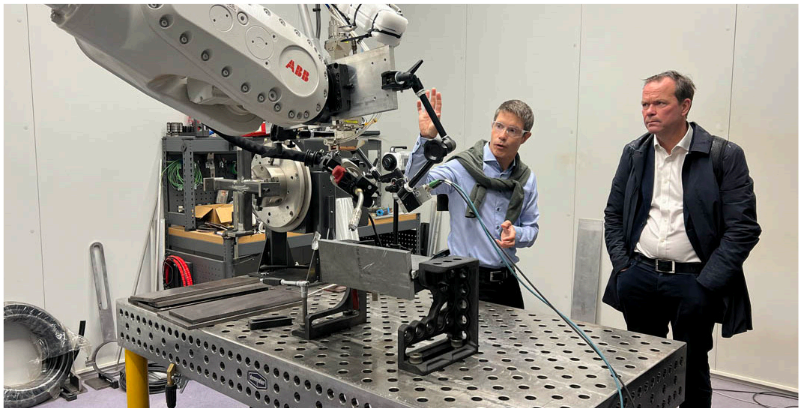
Centre for Sustainable and Competitive Metallurgical and Manufacturing Industry

ANNUAL REPORT 2024

SFI PHYSMET



PhysMet

Norwegian Centre for Research-based Innovation

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Frontpage:
Top: Group photo from the guided tour to Elkem Fiskaa in Kristiansand, Credit: NTNU

Bottom left: Magnus Eriksson is showing the Hydro CEO Eivind Kallevik the laser welding machine in Perleporten. Credit: Photo: Silje Grytli Tveten

Bottom right: Group photo from the Consortium meeting in Kristiansand. Credit: NTNU

Layout and production: Monika Wist Solli, NTNU Grafisk senter

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ANNUAL REPORT 2024
SFI PHYSMET

SUMMARY

BY CENTRE MANAGER
KNUT MARTHINSEN, NTNU

Yet a busy and productive year for SFI PhysMet has passed. The scientific results and achievements have been documented in a significant number of internationally renowned scientific journals and presented at national and international scientific conferences and relevant meetings, including our bi-annual consortium meetings in Kristiansand (hosted by Elkem) in April and in Trondheim in November. SFI PhysMet is now half way into its 8 year funding period. In 2024, a lot pf preparatory work was carried out to document and report the activities and achievement so far, as basis for the 'Half-way Assessment' organized by the Research Council in Norway (RCN). This will also continue into 2025 and end with a final decision from RCN, whether the center can continue as planned or will be imposed changes of some kind.

Some factual numbers of what we have achieved so far are: (i) ~60 Journal papers (directly or partly funded through the SFI); (ii) ~110 Conference and scientific presentations; (iii) Several tens of MSc students have been educated through the centre (on topics initiated in the center, and often in collaboration with the user partners 2021-2024); (iv) Organized / co-organized 1 International Conference (LightMat 2023) + 1 National Conference (NMT 2024), as well as several national and international workshops. Most of these numbers are well ahead of the targets for the whole center period.

An important objective of SFI PhysMet is to generate new knowledge and skills and provide useful results that the partners can use in their internal R&D and innovation activities for value creation and increased competitiveness. Indeed, SFI PhysMet has also made important contributions in this context, with some examples given below.

Hydro has high ambitions about increasing the amount of recycled metal in their processing chains, partly to make their production more cost efficient and to significantly reduce the CO2 footprint of their production and partly driven by market requirements of 'greener' metal into their products. However, replacing primary metal with post-consumer scrap inevitably increase the amount of trace elements and widening the window of alloying elements that will impact processability, microstructure and properties. SFI PhysMet contributes with advanced characterization and modelling (of microstructure and properties) to understand these effects (and the underlaying mechanisms) as well as means that can possibly mitigate negative effects. An import objective of Hydro is also to back-up their alloy and process development by modelling and simulations. SFI PhysMet provide both nano-scale experimental and modelling results that Hydro can use as input, for validation and further development of their own modelling portfolio. More generally, SFI PhysMet develops multi-scale modelling tools, enabling alloy & process development for more efficient manufacturing and that allows for more use of recycled metal, relevant e.g. for Benteler and Raufoss Technology.

Similarly, SFI PhysMet provides results and knowledge (also through advanced characterization and modelling) of the effects of trace elements in cast iron(such as B, Mn, Cr etc), originating from recycled materials. These effects are known, but not understood, which are important to possible neutralize the negative effects of these elements in Elkem's product development: Elkem uses this knowledge to optimize the use of existing products as well as design of new products. Elkem is also producing silicon-based powder materials for additive manufacturing. SFI PhysMet has provided electron microscopy characterization of AlSi and NiSi powders made by Elkem's new gas atomizer. NiSi powder is currently tested for metal dusting protections at Equinor's facility at Tjeldbergodden, made possible by the partnership of both Equinor and Elkem in SFI PhysMet.

Innovative processing and joining methods are critical enabling technologies for several key Norwegian industry sectors, e.g., offshore wind, battery production and aluminium structures. Significant research activities are related to laser-arc hybrid-welding (LAHW) of thick steel (45 mm). LAHW can lead to significant cost reductions and productivity enhancement for e.g., bridges and offshore wind turbines, of high interest and relevance to Equinor and Statens Vegvesen. Controlling the microstructure (martensite/bainite vs. acicular ferrite) is challenging but has been achieved by introduction of preplaced filler wires at the weld interface. Other emerging solutions with pre-deposition of inoculation phases for acicular ferrite is currently ongoing. The PhD work by Dr. Trond Arne Hassel on "Additive manufacturing of duplex stainless steels with coaxial laser directed energy deposition", provided important knowledge for the use of additive manufacturing (AM) in repair of large metal components, of great interest to Equinor.

Finally, Benteler, has developed a new process to improve Intergranular Corrosion (ICG) resistance in aluminium 6000-series alloys. At the same time there is an increased use of recycled aluminium in their products, and there is a strong need for knowledge on how recycled aluminium with increased amounts of trace elements influence the corrosion properties. With support from SFI PhysMet, both in terms of expertise and advanced analytical facilities, we have successfully identified potential critical chemical elements related to ICG, important for Benteler's alloy and process development activities.

An important objective of SFI PhysMet is the training and education of master and PhD candidates with state-of-the art competence and skills in the field of physically metallurgy in general and on the focus areas of SFI PhysMet in particular. Currently 9 PhD students (3 female and 6 male students) are doing their PhD projects within SFI PhysMet, several in close collaboration with one or more of the industrial partners. Of these, 7 are directly funded by SFI PhysMet, while 2 are funded by SINTEF and Statens Vegvesen, respectively. Three of these are close to finishing (in 2025), while two new students started their PhD studies in 2024, Inga Konow working on aluminium, and Jan Konkel on steels. One PhD candidate, Trond Arne Hassel, as the first one, finished his PhD in 2024. He is now working at Equinor. A number of master student projects were also in 2024 carried out in close collaboration with the industrial partners, as listed later in the Report.

An important and popular communication platform has been the monthly SFI PhysMet webinars, which typically attracts several tens of attendees, where internationally renowned researchers or colleagues from NTNU/SINTEF/IFE/Industry give overview and expert presentations within their respective fields. Also, in 2024 we organized 10 well attended webinars, covering different aspects of the SFI PhysMet research areas.

VISION AND RESEARCH STRATEGY

Vision: *SFI PhysMet aims to be a world leading research centre in the field of physical metallurgy, required to accelerate the transformation of the national metal industry towards more sustainable and cost-efficient production and future material products, solutions and improved processing methods.*

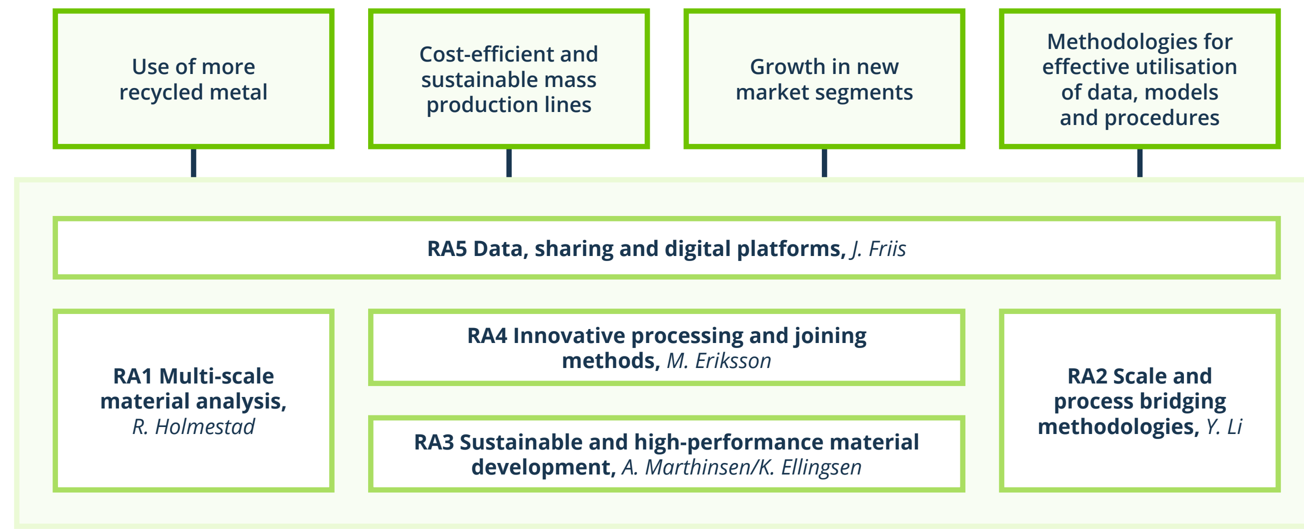
RESEARCH STRATEGY

The energy-demanding land-based industry sectors in Norway, i.e., *the metallurgical and manufacturing industry* have been of vital importance for Norwegian export and national value creation. However, *their presence and future sustainable growth in Norway depend on a competitive advantage in terms of high-technology competence and superior quality in their businesses*. In order to secure their position and prepare for further growth, four main industrial technology challenges that need to be solved to enable future new jobs, competitiveness and sustainable growth have been identified, and described in detail in the SFI PhysMet project description:

- **Use of more recycled metal**
- **Cost-efficient and sustainable mass production lines**
- **Growth in new market segments**
- **Methodologies for effective utilisation of data, models and procedures**

Even though these four main industrial challenges are comprehensive, requiring new innovative alloys, materials and processes, their basic knowledge needs are overlapping and generic. Extensive knowledge is required, about the mechanisms for formation and evolution of microstructures, and about the underlying principles. Then processing routes can be designed or improved, to provide the desired properties at a low cost. Progress and innovations are accelerated when the knowledge and associated methodologies, models and data are efficiently stored and made available to academic and industrial researchers and engineers in the Centre.

The figure above illustrates the structure of SFI PhysMet, for which five *Research Areas* (RA1-RA5) are designed to meet the targeted industrial knowledge needs. Material characterisation in RA1 and modelling in RA2 represent the basic research required for developing the desired material design in RA3 and innovative processing in RA4. A separate RA5 is dedicated for developing a platform for storage and sharing of data and



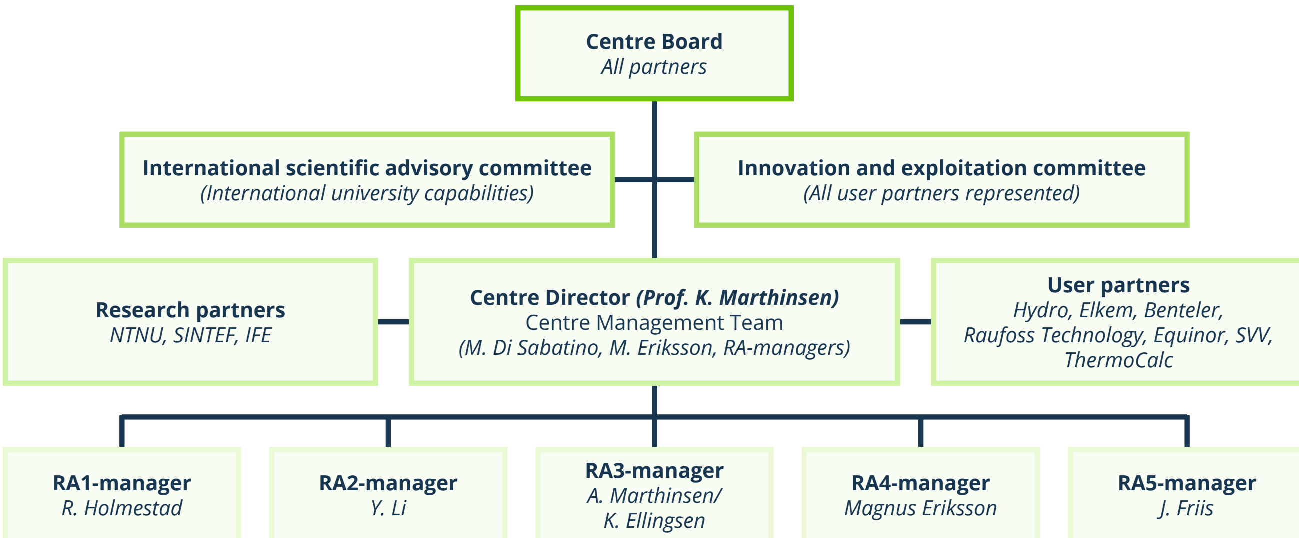
models, facilitating accelerated progress in RA1-RA4 and making results available for exploitation.

The targeted industrial knowledge needs serve as the basis for the specific research activities in each Research Area as further described later in this report.

SFI PhysMet has now passed half-way through its funding period (2020-2028), and the over-all objectives, as stated above are still valid. However, how to realize them involves some changes in priorities and adaption of the original project plans, influenced by the progress and achievements in the first period of the centre, industrial priorities and also influenced by recent trends in materials science and engineering relevant to SFI PhysMet, which will be accounted for in the plans for the remaining period of the Centre. Important trends and aspects are:

- Increased focus on sustainability and materials with a high content of post-consumer scrap and low carbon footprint and how this influences microstructure, processability and properties.
- In the last years, additive manufacturing (AM) has been developing rapidly in Norway. A Norwegian AM eco-system has been established, e.g., Norwegian AM cluster. Driven by the digital inventory and urgent need from the energy sector, AM can play a vital role in realizing on-demand and in-time manufacturing of spare parts, as well as AM-based repair and refurbishment. This calls for new development of materials, - processes and digital solutions to ensure first-time-right operation and high quality.
- Norway has set up an ambitious target for green energy transition, e.g., 30 GW offshore wind within 2040. Further development and implementation of joining technologies such as laser beam welding and hybrid laser-arc welding can contribute to substantial cost reduction.
- Elkem has invested in a full-scale atomizer for powder production. The structure and properties of the powders produced should be explored.
- Impact of machine learning is growing, especially surrogate models (models trained to reproduce the results of physical-based models). These models are important for overcoming current issues in through scale and process modelling since a surrogate model is normally (i) very fast compared to the physical model that generated the results it is trained on and (ii) not restricted to be executed on a dedicated system, either due to performance (like a HPC cluster) or license restrictions. Another rapidly evolving trend is the use of the physics-informed machine learning (PINN) or scientific machine learning. Blending theory-driven and data-driven approaches help to model complex phenomena more accurately and also allows discovery of unknown underlying relations.
- It is expected that semantic technologies for knowledge integration and sharing between different disciplines will get increased recognition and attention in the coming years, due to the green transition, the new innovations based on holistic approaches and not at least training of AI models required to achieve the green transition. The centre will follow closely this evolution and evaluate the maturity level before integrating some tools in the platform. We will also closely follow the evolution in data documentation based on semantics and revise on a yearly basis the components and content of the platform to select the most relevant technologies becoming available.

ORGANIZATION



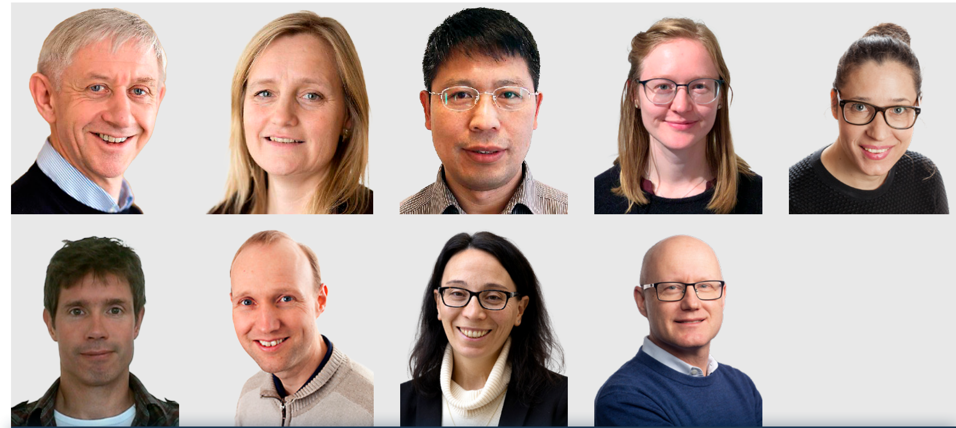
THE CENTRE BOARD

Board meetings are held at least twice a year. The board's main responsibility is to ensure that the intentions and plans underlying the contract for the establishment of the centre are fulfilled. The board is to ensure that cooperation proceeds smoothly between the centre, the host institution and the partners in the consortium.

MEMBERS OF THE BOARD ARE:
Nina Dahl, SINFEF Industry (Board leader)
Magnus Rønning, NTNU
Trond Furu, Hydro
Gro Eide, Elkem
Lars Lodgaard, Benteler
Gotthard Mälzer, Equinor
Jørgen Li, Raufoss Technology
Cato Dørum, Statens Vegvesen
Anders Engström, Thermo-Calc Software
Tanja Pettersen, SINTEF Manufacturing
Øyvind Jensen, IFE
Øystein Asphjell, NFR (observer)

THE CENTRE MANAGEMENT TEAM

The centre manager is Knut Marthinsen. Co-manager is Marisa Di Sabatino and administrative coordinator is Torleif Nordskog. Magnus Eriksson represents SINTEF in the management team. The five Research Area (RA) leaders are also part of the management team.



First row: Knut Marthinsen (NTNU, director), Randi Holmestad (NTNU, RA 1 manager), Yanjun Li (NTNU, RA 2 manager), Astrid Marthinsen and Kjerstin Ellingsen (SINTEF, RA 3 managers). Second row: Magnus Eriksson (SINTEF, RA 4 manager), Jesper Friis (SINTEF, RA 5 manager), Marisa Di Sabatino (NTNU, co-director) and Torleif Nordskog (NTNU, administrative coordinator).

PARTNERS

User partners: SFI PhysMet's user partners include metal and material producers, downstream material processing industries as well as end users of metals and alloys. The user partners are: Equinor, Hydro, Elkem, Benteler, Raufoss Technology, Thermo-Calc Software and The Norwegian Public Roads Administration

Research partners: NTNU, SINTEF and IFE

THE SCIENTIFIC ADVISORY COMMITTEE

In order to secure that the centre activities hold an excellent scientific standard and that we are closely connected with leading scientific groups in metallurgy around the world, we have appointed a scientific advisory committee (SAC). The members of SAC are:

Professor
Dierk Raabe,
Max Planck Institute for Iron Research, Düsseldorf, Germany

Professor
Aude Simar,
UC Lovain, Belgium

Professor
Dorte Juul Jensen,
DTU Technical university of Denmark

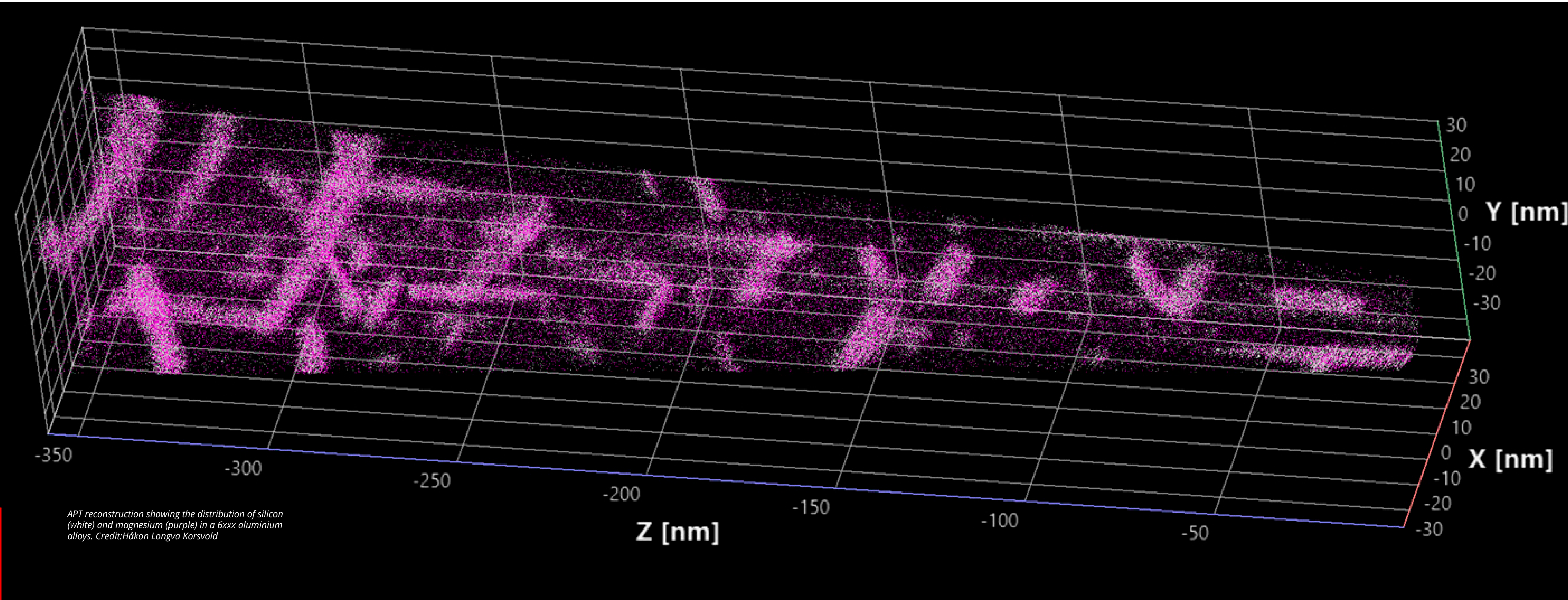
LOCATION

SFI PhysMet is hosted by NTNU, Department of Material Science and Engineering. The managers of the centre's five research areas work in Trondheim at campus Gløshaugen and at SINTEF Industry in Oslo. The centre is located at campus Gløshaugen, with offices available for all research- and industry partners. PhD candidates and Postdoctors recruited to the centre work closely together and with short distance to the project leaders and supervisors. The co-location in Kjemiblokk 1 ensures effective collaboration between the research groups.

Campus Gløshaugen, Trondheim

SCIENTIFIC ACTIVITIES AND RESULTS

The following pages give a brief overview of our Research Areas in terms of contributions to the centre objectives, main challenges to be met, research activities with focus on the specific activities performed in 2024. The scientific activities are performed at NTNU, SINTEF and IFE, in close collaboration with the user partners.



APT reconstruction showing the distribution of silicon (white) and magnesium (purple) in a 6xxx aluminium alloys. Credit:Håkon Longva Korsvold

RESEARCH AREA 1.
MULTI-SCALE MATERIAL ANALYSES

RESEARCH AREA LEADER:
RANDI HOLMESTAD
NTNU

CONTRIBUTIONS TO CENTRE OBJECTIVES
Production of advanced materials for the future requires detailed knowledge of the structure and chemical composition of materials at several length scales. NTNU hosts a world-class characterization infrastructure that is especially equipped to tackle metallurgical problems. The objective of RA1 is to utilize these instruments to the best for SFI PhysMet.

- Develop a world leading platform and corresponding methodologies for multiscale and multidimensional structure characterization and high-sensitivity chemical analysis of metals, alloys and advanced nanomaterials.
- Contribute to other RAs by providing detailed characterization information, revealing in-depth mechanisms, providing reliable experimental data, and validating through-process modelling.

MAIN CHALLENGES TO BE MET
- Develop correlative use of transmission electron microscopy (TEM) and atom probe tomography (APT). The techniques are complementary and provide experimental data on the crystal structure and chemistry down to the atomic scale - crucial for developing and validating atomic scale simulations and through-process models.
- Develop and establish a framework for multiscale studies of material joints. The multiscale microstructure and complicated chemistry created when materials are joined (by welding or AM) require use of the entire characterization toolbox.
- Establish in-situ characterization techniques. Advanced in-situ characterization tools will be utilized to quantify the kinetics of microstructure evolution during solidification, heat treatment and deformation, at several length and time scales.

ACTIVITIES AND RESULTS IN 2024
RA1 is organized into research tasks, and we had activities in eight of them in 2024. In addition, we contribute with characterization work for the other RAs. The results obtained in 2024 are described in the following.

Multiscale studies of materials joints
MIG-welded high-strength 7xxx (Al-Zn-Mg(-Cu) alloys are made by Benteler in collaboration with RA4. Master student Liesbeth Campbell has started to study a screw extruded 7108 alloy welded to 7075 with TiC nanoparticles. Liesbeth will finish her master in June 2026.

APT and TEM of precipitates with Zn in Cu-containing 6xxx alloys
Håkon L. Korsvold is a PhD student in RA1, supervised by Yanjun Li, studying structure and chemistry of grain boundaries in aluminium alloys,

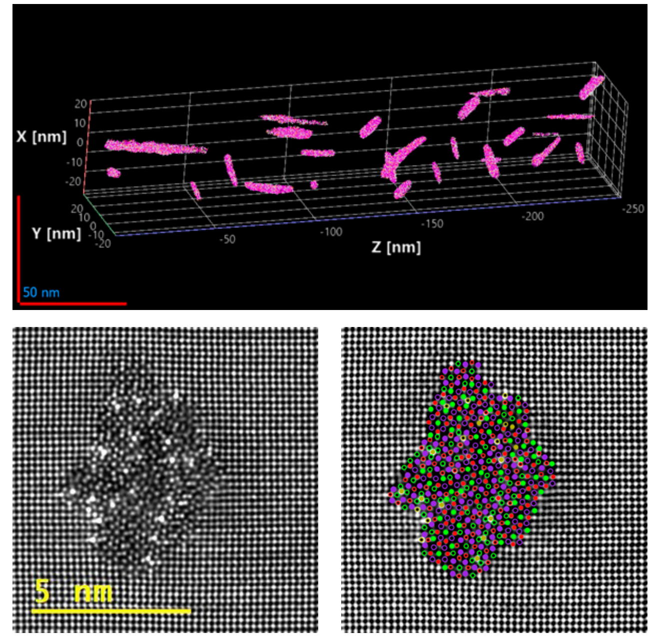
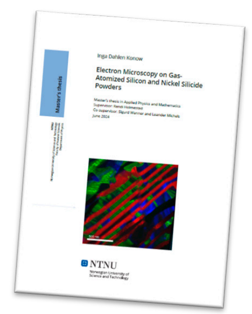


Figure 1. APT and high angle annular dark field scanning TEM images of precipitates in Cu-containing 6xxx alloy added Zn.

with a combined study of atom probe tomography (APT) and transmission electron microscopy (TEM). He has studied 6xxx (Al-Mg-Si) alloys with Cu and different contents of Zn. We know that Cu and Zn both reduce corrosion resistance individually and also see that addition of Zn to Cu-containing alloys seems to have some positive effects on intergranular corrosion. APT and TEM are used to understand how Zn and Cu affect the precipitates and grain boundary segregation. We see highly disordered precipitates regardless of Zn content. Figure 1 shows APT and TEM images of disordered precipitates in in Cu-containing 6xxx alloy added Zn. The alloys have similar precipitate density, composition and structure and the primary difference between the alloys is the grain boundary chemistry.

TEM analysis of gas-atomized silicon and nickel silicide powders
Silicon powders have a wide range of applications, from manufacturing of electronics and batteries to additives in metallurgy. For both traditional casting methods and additive manufacturing of metals, the properties of the added silicon powders are crucial for the



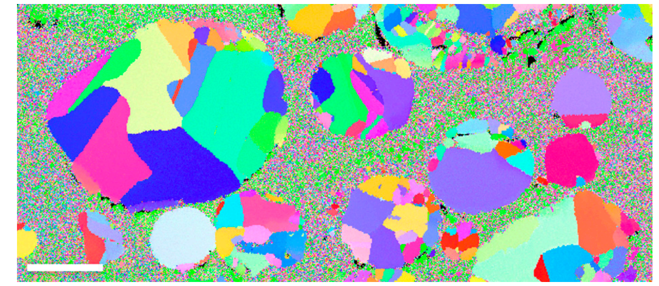
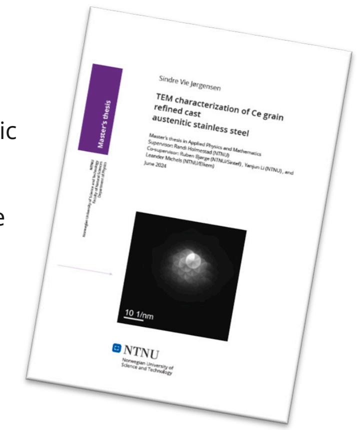


Figure 2. EBSD maps show that the silicon powders are mainly polycrystalline, even down to a few microns in diameter.

performance of the end product. In 2024 Inga Konow studied gas- atomized silicon and nickel silicide powders from Elkem in her MSc work. As seen from Figure 2, electron backscattered diffraction (EBSD) maps show that the silicon powders are mainly polycrystalline, even down to a few microns in diameter. Grain size and type of grain boundaries are controlled by solidification rate and impurities. In contrast to the silicon powder, the nickel silicide showed a complex eutectic microstructure.

TEM characterization of ferrous alloys



Sindre Vie Jørgensen did a MSc with Elkem on grain refinement of cast austenitic stainless steels. By adding a master alloy containing cerium into the melt before casting, particles which act as nucleation sites are created which facilitates a finer grain structure, and the mechanical properties are improved. Ce forms stable compounds with different crystal structures when reacting to elements in the steel melt. There are several inclusions which cerium can potentially form within the casting (cerium oxides, sulphides, aluminates and oxysulphides), but it is not experimentally known which specific compounds are formed or which one is the acting grain refiner. TEM was used to study samples of austenitic stainless steel to try to understand the role of Ce in the alloy. CeAlO$_3$ and Ce$_2$O$_2$S were found in addition to cerium oxides. The orientation relationship between CeAlO$_3$ and austenite was identified. This was used to find potential interface planes where nucleation might have taken place and theoretical estimations for interface misfits were found.

Nano-scale / TEM microstructure characterization of AM 7xxx alloys

Laser Powder Bed Fusion (LPBF) has been used to additive manufacture (AM) 7075 Al alloys in RA3. The following approaches were used to improve grain nucleation and avoid pores/cracking during AM of 7075 Al (Al-Zn-Mg-Cu) alloys:

- adding ZrH_2 nanoparticles by mechanical mixing
- adding Si by mechanical mixing
- with and without substrate pre-heating (250^{0}C)

Calin Marioara from SINTEF has studied the microstructure in of these alloys by TEM and found that solution heat treatment and artificial aging greatly change the phase composition and morphology, in addition to the elemental distribution of the printed material. Only the 1.6% ZrH_2 sample gave hardening AlZnMg precipitates.

Investigation of microstructure in forged aluminium parts

This is a SINTEF activity with Raufoss Technology. Two main processing routes were compared: Extrusion + forging, and direct forging. The microstructure was quantified on three different length scales, quantifying all primary + precipitating particles and how much Mg+Si are used to form them. By adjusting the heat treatment procedure, we obtain the same hardness in directly forged product as in extruded + forged (the standard process) product.

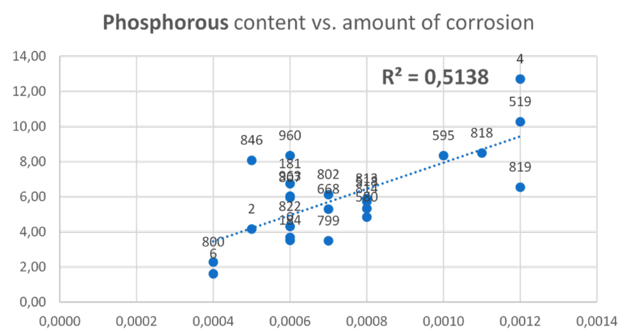


Figure 3. Phosphorous have a strong correlation with weight loss after corrosion in 6082 alloys.

Batch variations of intergranular corrosion in 6082 Al alloys

Intergranular corrosion in aluminium is a difficult problem, still not fully understood and requires therefore more fundamental research. Here, SINTEF has, in collaboration with Benteler, done a systematic study

Figure 4. Inga Konow at Hydro, Finspång in October 2024, checking how her aluminium samples are made. Co-supervisor Jan Halvor Nordlien to the left.

of trace element concentration vs. amount of corrosion in 23 batches, accounting for many variables. We found that iron and phosphor have the strongest correlation with weight loss after corrosion, as shown in Figure 3.

Microstructure studies of extruded 6xxx Al alloys

As the demand for aluminium alloys with higher recycled metal content continues to rise, it becomes increasingly important to understand how the inclusion of scrap metal affects the material properties of these alloys, particularly in different temper conditions. Inga Konow started her PhD in August 2024, working on extruded 6xxx alloys in T8 and T9 tempers. These tempers are a combination of plastic deformation and aging – for example, T8 is quenching from solution-heat treatment with subsequent stabilization before the alloy is deformed and then finally artificially aged. Inga receives her samples from Hydro and was in Finspång in October to see the production as shown in Figure 4. Her research will employ advanced microstructural characterization techniques, including TEM, to analyze and quantify the microstructural features. Statistical analysis will be used to establish correlations between microstructural characteristics and mechanical properties, providing insights into optimizing the processing conditions for these aluminium alloys.

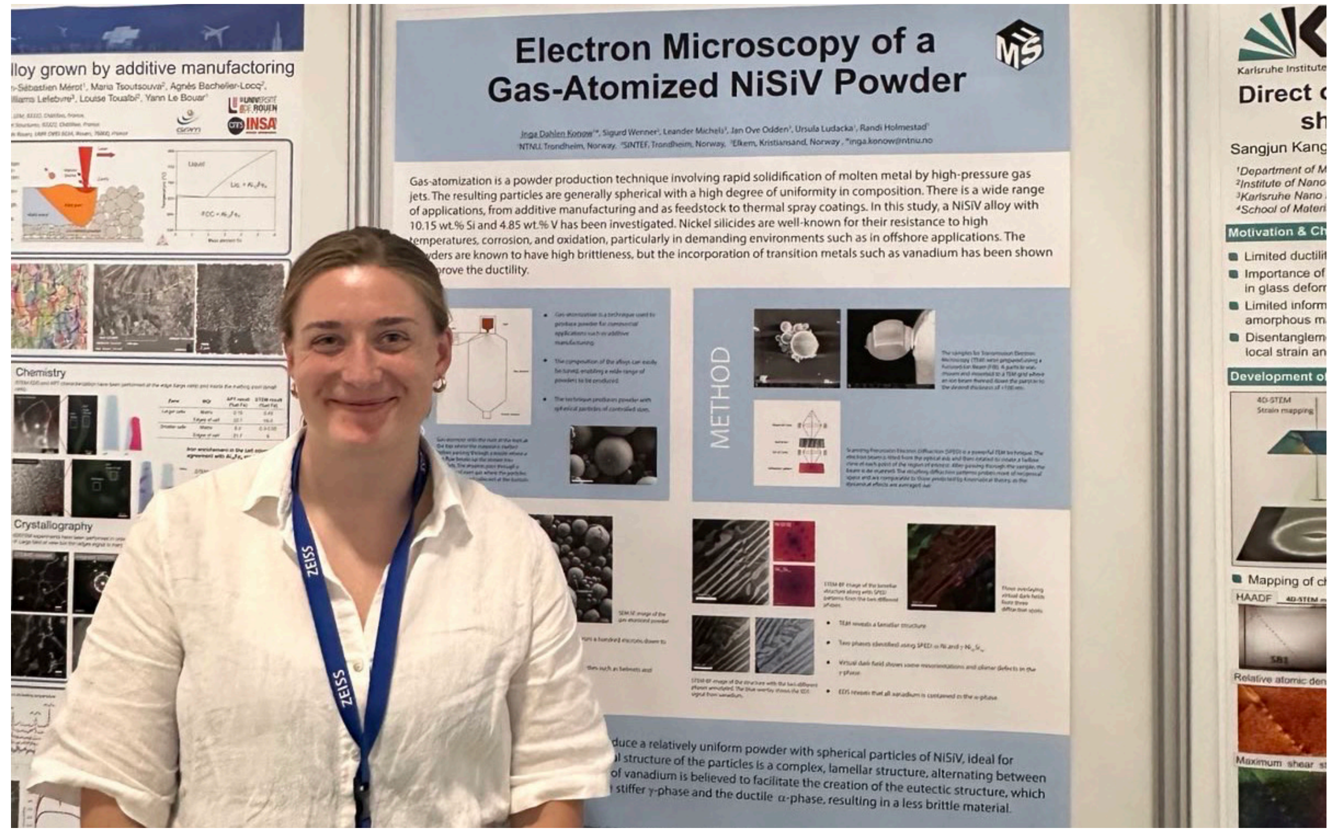


Figure 5. Inga Konow presenting her work on NiSiV powders at the European Microscopy conference in Copenhagen, August 2024.

Two more master students work on precipitation and aluminium alloys at the Physics department. Hannah Hareide studies precipitates in TEM with Hydro, Sunndalsøra and Kristian Bjørnes Thevik is using machine learning to extract precipitate statistics from TEM images.

Figure 5 and 6 show students in RA1 presenting their work, on conferences.

Figure 6. Master student Liesbeth Campbell, PhD student Inga Konow and Master student Kristian Thevik at the SFI consortium meeting in Trondheim in November 2024.

RESEARCH AREA 2.
SCALE AND PROCESS BRIDGING METHODOLOGIES

RESEARCH AREA LEADER:
YANJUN LI
NTNU

CONTRIBUTIONS TO CENTRE OBJECTIVES
- Provide fundamental material data and understanding through high-throughput calculations and simulations from atomistic to micro-structure scale.
- Develop and validate specific models for alloy recycling, AM and innovative processing.
- Establish and validate multiscale and multi process modelling framework and AI methods, providing smart design and developing tools of innovative alloys and products.

MAIN CHALLENGES TO BE MET
- How to reach a deeper understanding on the mechanisms and kinetics behind the physical metallurgical phenomena down to atomic scales.
- How to realize computational engineering based smart design of alloys and products with tailored properties.
- How to realize digitalization and automatization of the production in physical metallurgical industry.

Task RA2.1: Atomic scale calculation and simulation
The objective of this research task is to use first principles atomic scale calculations to generate thermodynamic and kinetic material data for atom clusters, precipitates and intermetallic phases, including bonding energy, formation enthalpy, interfacial energy, segregation energy and diffusivity of impurities in relevant alloys (aluminium, steel, cast iron).

In 2024, a kinetic Monte Carlo (KMC) simulation model has been developed and performed to study the early-stage atom clustering kinetics during natural ageing in 6xxx aluminium alloys. The vacancy migration barriers are determined on-the-fly in KMC simulations based on an improved kinetic resolved activation (KRA) method, which can offer accuracy comparable to the NEB (Nutged Elastic Band) method (cf. Figure 1). The formation enthalpies of atomic configurations are predicted by broken bond energies of atom-atom/vacancy pairs, which are trained on a recently developed neural network potential for Al-Mg-Si alloys. The interplay between solute clustering and vacancy trapping is carefully studied and compared with experimental measurements. In 2025, the KMC simulation framework will be further utilized to study the influence of alloy composition on atom clustering kinetics during NA, and therefore on the subsequent artificial ageing response.

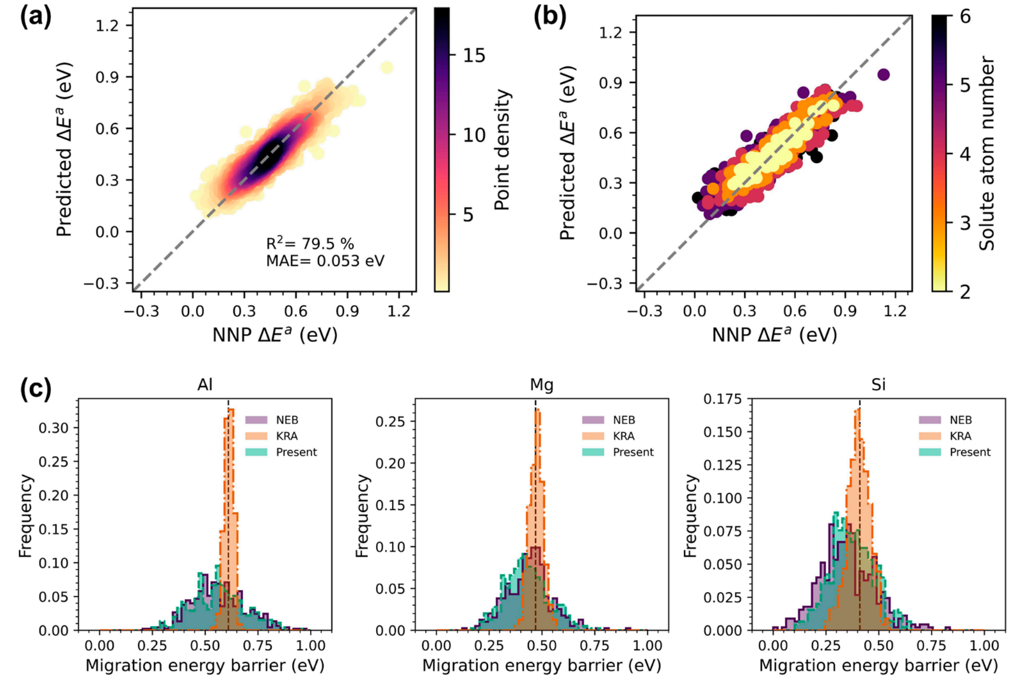


Figure 1. (a-b) Comparison between the vacancy migration barriers predicted by the improved KRA method and those calculated by the NEB method. The colormap in (a) represents the point density and in (b) the number of solute atoms surrounding the atom-vacancy pair. (c) Distribution of vacancy migration barriers towards Al, Mg and Si atoms calculated by conventional KRA, improved KRA and NEB methods. The grey dashed lines represent the values for vacancy migration towards corresponding atoms in dilute limit.

Task RA2.2: Development and further improvement of microstructure models for recycling-based alloys, AM and welding
The objective of this task is to develop microstructure prediction models for solidification and heat treatments of recycling based aluminium alloys, cast iron, AM alloys and welding of dissimilar metals.

Modelling the atom clustering process during natural aging of 6xxx alloys
The initial focus of this work is on development of precipitation models for age hardening aluminium alloys. By improving the atom clustering kinetics, the nucleation and growth of precipitates can be better predicted. The influences of impurity elements, excess vacancies, dislocations, and grain boundary precipitation/segregation are also addressed.

In 2024, a numerical model has been developed to simulate the atom clustering kinetics during natural ageing in 6xxx aluminium alloys. The vacancy evolution model developed in 2023 is fully coupled to consider the annihilation of excess vacancies at GB and dislocation sinks, the trapping of vacancy by solute atoms and atoms clusters, and the enhancement of solute diffusion mediated by vacancy exchange. The model is applied to understand the influences of quenching rate and alloy

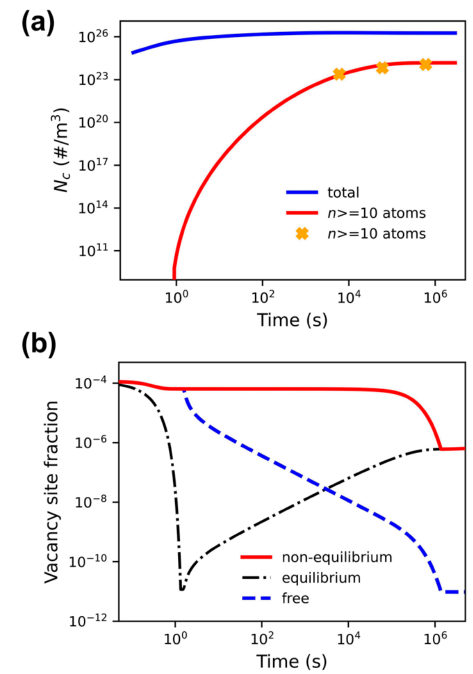


Figure 2. Time evolutions of (a) number density of solute clusters and (b) vacancy concentration during natural ageing at 300 K after quenching at 400 K/s from 835 K in an Al-0.46at%Mg-0.95%Si alloy.

chemical composition on the time evolution and size distribution of solute clusters. Figure 2 shows the simulated evolutions of atom clusters during natural aging of a 6xxx alloy and the corresponding evolution of vacancies. In 2025, the improvements and validations of the model will continue. The present model will be coupled with the conventional KWN model, which is specific for modelling the evolution of age hardening precipitates (such as β" and β') at the later stage of natural ageing or at artificial ageing.

Cast iron microstructure modelling

Ductile cast iron properties are mainly determined by the graphite nodules and the ratio of ferrite and pearlite. Additional chemical elements affect the development of the microstructure. For example, copper promotes pearlite formation and is beneficial for graphite formation, while small amounts of boron will cancel that effect. The boron contamination is mainly due to the recycling of high strength steel in the foundries. Numerical modelling in conjunction with advanced characterization (done in RA3) could help us understand the microstructure development and develop additives to ensure high quality products. In 2024, we established a set of reference

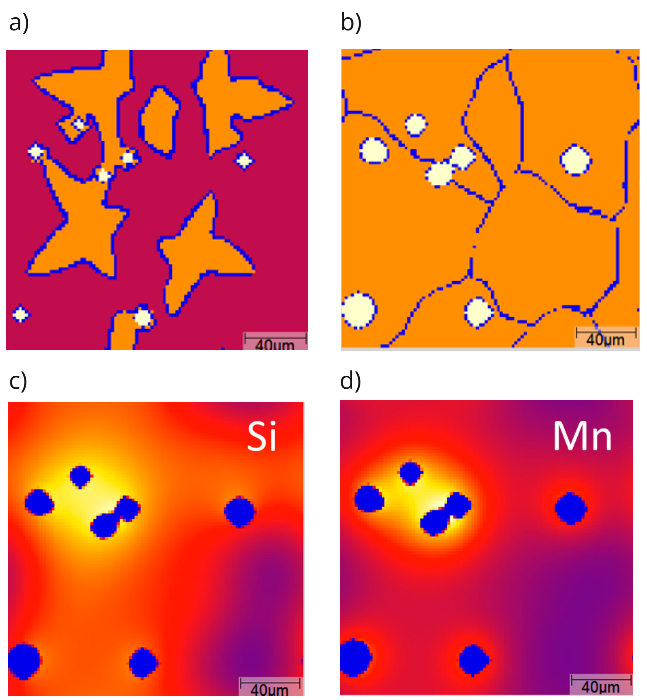


Figure 3. Austenite (orange) and graphite (white) nucleation (a) and final structure (b). Composition maps at the end of the solidification for Si (c) and Mn (d).

simulation cases using the commercial phase field software Micress, coupled with ThermoCalc to study the multi-component solidification of cast iron. The focus is on understanding the elements micro-segregation and the destabilization of the graphite interface. The results presented in Figure 3 illustrate the grain nucleation and growth and the segregation of Si and Mn. The simulations highlight the importance of numerical parameters and problems at the phases' interfaces which need to be addressed before the extension of the models with additional chemical elements.

Fast modelling of microstructure evolution in DED of DSS

During the direct energy deposition (DED) of duplex stainless steels (DSS), any point in the deposited part undergoes several cooling and heating cycles, as shown in Figure 4.

The history of temperature at each point determines the evolution of microstructure. Figure 5 shows a simplified temperature history of a point of the deposited part, and the corresponding evolution of austenite. Micress took 94 min to compute these results, which makes it not affordable for computing the microstructure of the whole piece. So, we propose to use Micress for

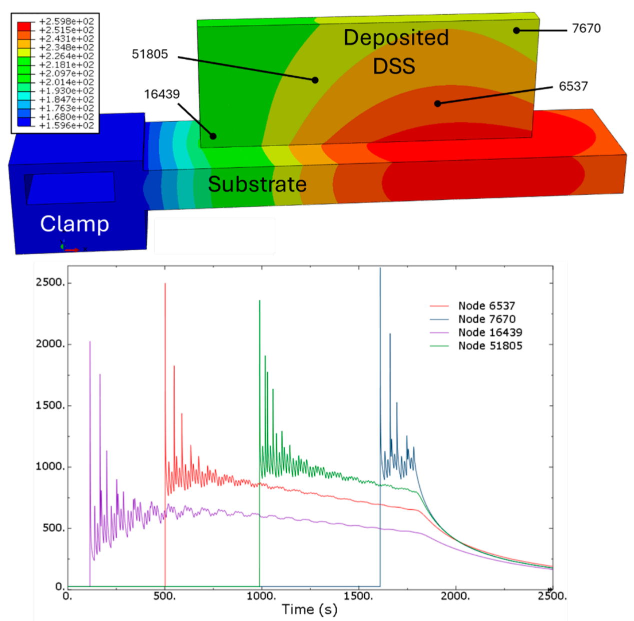


Figure 4. Top: Temperature field during cooling in DED of DSS. Bottom: Temperature histories at some nodes.

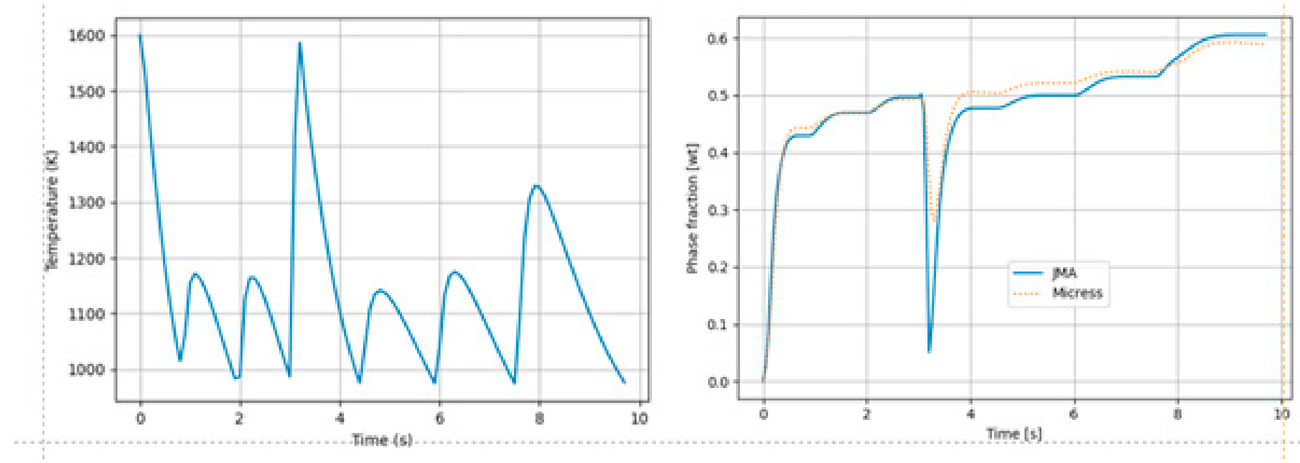


Figure 5. Left: temperature history. Right: corresponding evolution of austenite in DSS.

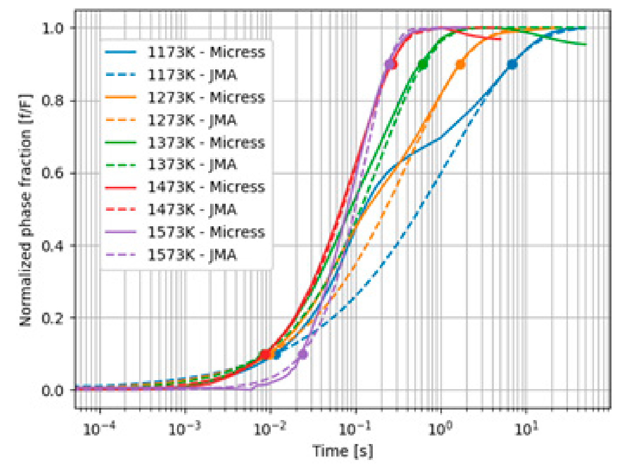


Figure 6. Isothermal ferrite-to-austenite transformations in DSS.

benchmark purposes, and to generate a few results for isothermal transformations in DSS, see Figure 6. Those curves are used to calibrate a metamodel based on the Johnson-Mehl-Avrami (JMA) equation . Using this metamodel, the microstructure evolution in Figure 6 took 0.06 s. As it can be seen in Figure 6, results from this metamodel are in satisfactory agreement with the Micress results taken as reference.

Task RA2.3: Through-process models under realistic industrial conditions

The objective is to generalize the existing and newly developed microstructure evolution models for heat treatment, recrystallization and work hardening. The objective is to use these models as sub-models in finite element simulation software to simulate the transient conditions experienced during complex thermomechanical processes and predict the material performance and failure behavior and properties of products.

Through processing microstructure modelling approach of AA6082 alloys

In this task, we have conducted through process microstructure modelling activities towards the fabrication process of an AA6082 alloy. This activity is in collaboration with RA1 with the support from the industrial partner Raufoss Technology. The objective is to investigate if the extrusion step could be skipped to forge this alloy during industrial fabrication process. The alloy composition is listed in the following table:

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ti
908230	1.20-1.30	0.15-0.25	0.07-0.10	0.55-0.65	0.80-0.90	0.15-0.20	0.01-0.10
Typical extruded 6082.54	1.26	0.21	0.09	0.54	0.91	0.16	0.01

The following (Figure 7) shows the thermal history that this alloy has experienced during the fabrication (up to quenching before aging treatment).

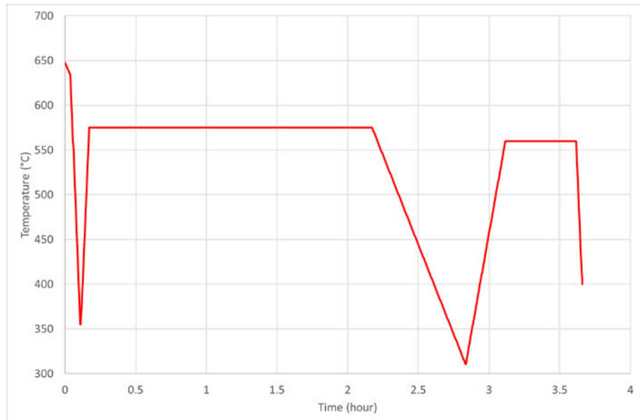


Figure 7. The quenching rate is not known yet but is estimated to be 10 to 100 °C/s, and the final aging treatment is 190 °C for two hours.

We have adopted the SINTEF In-house software PreciMS to predict microstructure evolution. PreciMS predict all the relevant microstructure features including primary (constituent) particles, dispersoids, and MgSi particles (non-hardening) formed during cooling, Hardening particles formed during artificial/natural aging, Solute Levels in Solid Solution (industrial alloys) and Precipitate Free Zone. The following table shows Mg and Si solid solution levels upon quenching to 400 °C:

SSSL	Before quenching (wt%)	Longer DAS (10 µm)	Shorter DAS (8 µm)
Cu	0.09	0.088	0.09
Mg	0.79	0.70	0.68
Si	1.02	0.92	0.89

It shows that larger dendrite arm spacings (DAS) lead to higher solid solution solute levels of Mg and Si and therefore is expected to provide a better hardening response during artificial aging. Extrusion would induce changes in grain size, dendrite arm spacing and the nucleation sites of MgSi particles. It would affect the microstructural response to quenching critically.

From this modelling activity, it is concluded that extrusion could be skipped. However, an adjusted quenching rate is needed to keep the required Mg and Si contents in solid solution. It is important to compensate for the reduced level of nucleation sites for hardening particles formed during ageing.

The following two research questions along this line are proposed:

1. What are the effects of extrusion on DAS, quenchability and aging response?
2. What are the optimized levels of Mg and Si in solid solution before aging treatment optimized levels of Mg and Si in solid solution before aging treatment? What are the optimized levels of Mg and Si in solid solution before aging treatment?

Task RA2.4: Development of AI methods for alloy design and process parameter optimisation

The objective is to develop machine learning techniques for big data analysis of alloy chemistry, process parameters, and mechanical properties to generate constitutive equations and quantitative correlations of chemistry-structure-process-properties of alloys with complex chemistry and processing step and parameters.

Bayesian Optimization of liquidus of Al-Mg-Si alloys

In this task, we trained a surrogate model to predict phase boundaries like the liquidus for various alloy systems with data from a "computationally expensive" CALPHAD model, as shown in Figure 8. This is done with machine-learning using Bayesian optimization which includes a measure of uncertainty. This uncertainty is used to efficiently sample the high dimensional space of an N-dimensional alloy system where the model is most uncertain. To test the methodology, we have chosen the Al-Mg-Si alloy system. During this year, we have updated the backend of the Bayesian optimization with standard unit testing and reduced technical debt. This will allow for easier modification and use in future projects.

During 2024, an initial investigation of the solute solubility of various alloying elements for β" phases in Al-Mg-Si alloys was started. This data could help predict which phases these alloying elements will interact with and predict how the phase diagram for the β" phases will change with a dilute amount of solute. The calculated substitutional energy of different impurity atoms in b"-AlMgSi precipitate is shown in Figure. 9.

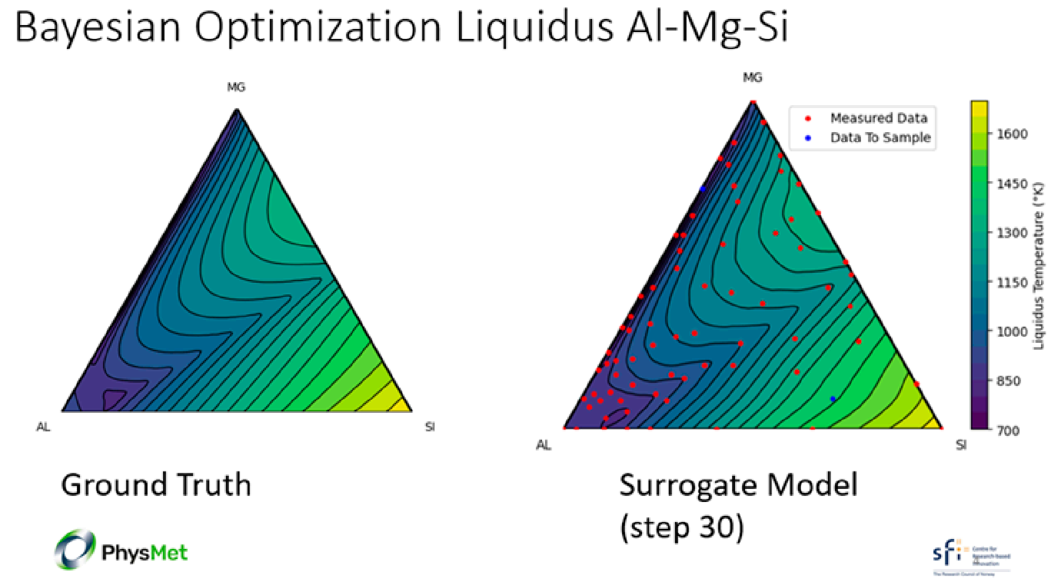
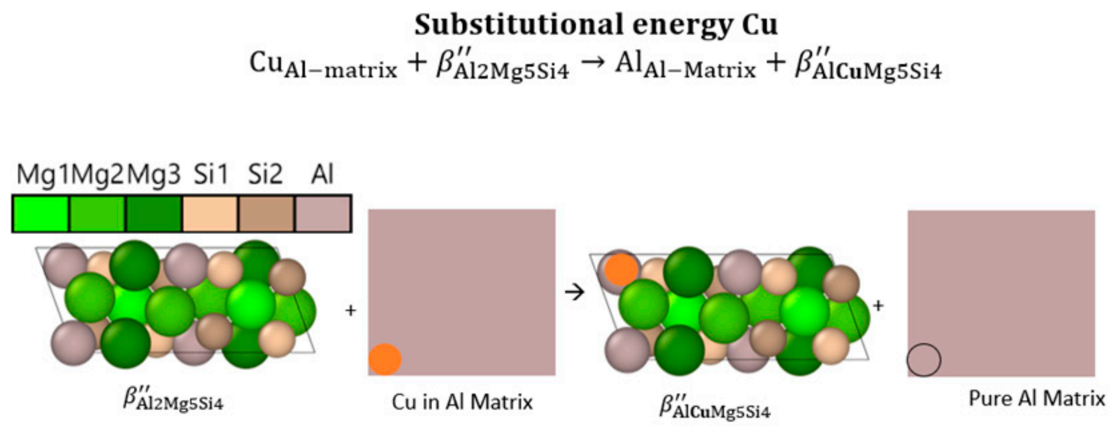


Figure 8. Liquidus surface of Al-Mg-Si alloys. Ground truth to the left and surrogate model to the right.



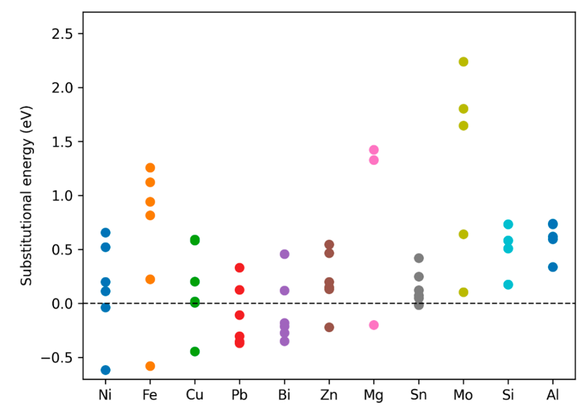


Figure 9. Calculated substitutional energy of different impurity atoms in β"- AlMgSi precipitates. The different dots for the respective impurities represent different substitutional positions in the β"-precipitate, cf. illustrations above

RESEARCH AREA 3.
SUSTAINABLE AND HIGH-PERFORMANCE MATERIAL DEVELOPMENT

RESEARCH AREA LEADERS:
ASTRID MARTHINSEN
KJERSTIN ELLINGSEN
SINTEF

CONTRIBUTIONS TO CENTRE OBJECTIVES
- The aim of RA3 is to establish fundamental knowledge and understanding of materials with recycled content and/or materials for new processes and applications (e.g. rapid solidification and additive manufacturing).
- To accelerate the design of new materials and alloys and/or industrial processes relationships will be systematized using modelling tools in collaboration with other Research Areas combined with experimental work.

MAIN CHALLENGES TO BE MET
- How to understand the effect of, and compensate for, elevated levels of trace elements from recycled materials and develop robust/novel alloys.
- How to develop and tailor the microstructure of AM/rapid solidification alloys.
- How to recover or improve material properties through post-processing.

ACTIVITIES AND RESULTS IN 2024
The research activities in this Research Area are organized in four main tasks. Main objectives, activities and results from 2024 are listed below for each task.

Task RA3.1: Solid-state mixing by screw extrusion
Due to a change in priorities of one of the main industry stakeholders remaining activities in this task has been put on hold.

Task RA3.2: Compensation metallurgy and alloy design
In 2024 the study of the effect of using post-consumer scrap (PCS) in Al-Si foundry alloys was continued. The motivation is to reduce the environmental impact of Al-alloys by replacing primary Al with recycled Al. The challenge is that secondary Al contains many impurity elements, and the effect on processability and properties of alloys made with PCS needs to be investigated. The strategy in RA3.2 is to build an efficient theoretical framework to understand, evaluate and compensate for any negative effects of elements from secondary Al. Supplementing the work from earlier years, the focus in 2024 was on the study of varying Fe levels ranging from 0.1 to 0.6 wt% on the microstructure of as-cast samples of AlSi10MnMg HPDC alloys at different cooling rates. Microstructural characterization (SEM-EDS) shows Fe-bearing phases of different types, e.g. α, ß, δ and π (Figure 1 and 2). The amount of α phases is increasing with increasing Fe content. The phases have script-like structures and grow large. The observation is in accordance with Thermo-Calc Scheil

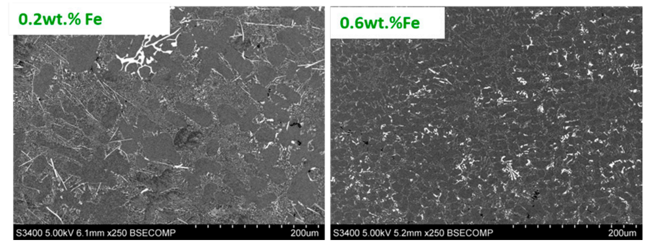


Figure 1. SEM Micrographs of AlSi10MnMg with 0.2 wt% Fe (left) and 0.6 wt% Fe (right).

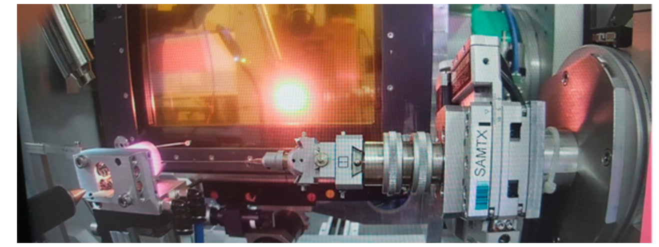


Figure 3. Experimental setup for the in-situ synchrotron X-ray experiments.

simulations that predicts this phase to form in the melt before the FCC phase and until the end of solidification. Such large phases can negatively influence castability and mechanical properties. The δ and ß phases are found in larger amounts for lower Fe levels, but δ is not predicted by Thermo-Calc.

Furthermore, work was started to investigate the effect of Cu and Zn on mechanical properties and corrosion on HPDC samples. The investigated levels of Cu and Zn were 0, 0.15, 0.3% and 0, 0.2 and 0.4%, respectively. The combination of these levels with two levels of Fe (0.15 and 0.6%), gave 18 different alloys, which were HPDC at Hydro plant in Sunndalsøra. The samples are currently under investigation. Tests are underway to allow selecting a few of these alloys to be further investigated.

The use of PCS in cast iron is an important contribution to the sustainability of the steel and cast-iron industries. A current trend in the automotive industry is to introduce more and more boron-containing steels, and when these components reach end-of-life, boron is introduced to cast iron. Small amounts of B (<70 ppm) have been shown to adversely affect the properties of spheroidal graphite iron (SGI) by promoting ferrite growth (ferrite is a softer phase). Knowledge of the pearlite promoting mechanisms of the common pearlite promoting elements in spheroidal graphite cast iron (SGI) is important for understanding the ferrite promoting effect of boron (B) in pearlitic SGI. The mechanism by which copper (Cu) promotes pearlite is not fully understood. In-situ synchrotron X-ray investigations (our experimental set up is shown in Figure 3) of the eutectoid transformation in cast iron show that Cu significantly retards the austenite-to-ferrite transformation kinetics, thereby allowing more of the austenite to transform to pearlite (Figure 4). These results are consistent with studies reported in the literature.

Task RA3.3: Powder materials and rapid solidification
One focus area of Task RA3.3 has been to develop numerical tools for microstructure prediction that account for the high cooling rates associated with AM. The models describing columnar-to-equiaxed transition as well as the solute trapping in multi-component alloys developed in this task was published in 2024.
Another focus area has been on the printability of the 6061 alloy in laser powder bed fusion (LPBF) additive

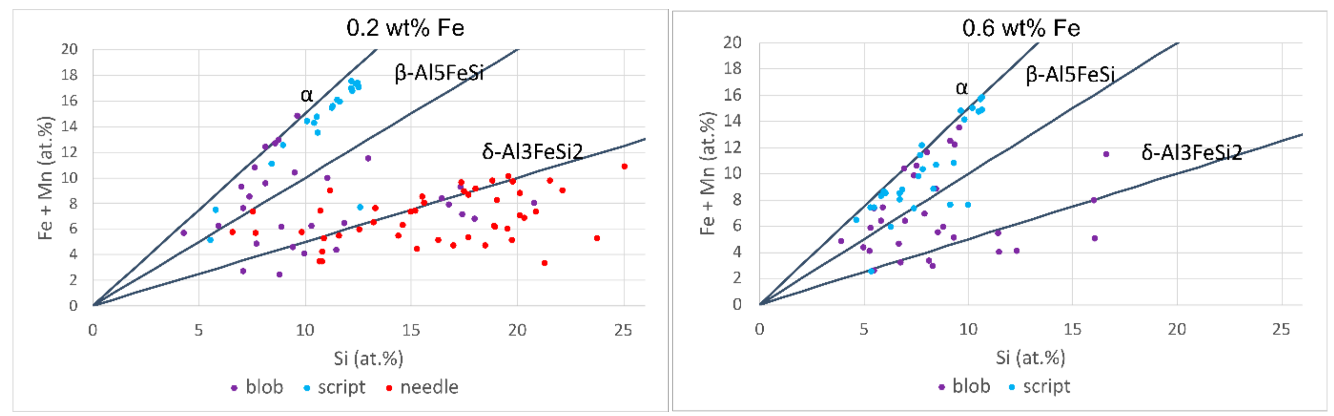


Figure 2. Left-Identification of Fe-bearing phases based on (Fe+Mn)/Si ratio for the alloy with 0.2 wt% Fe. Right- Identification of Fe-bearing phases based on (Fe+Mn)/Si ratio for the alloy with 0.6 wt% Fe.

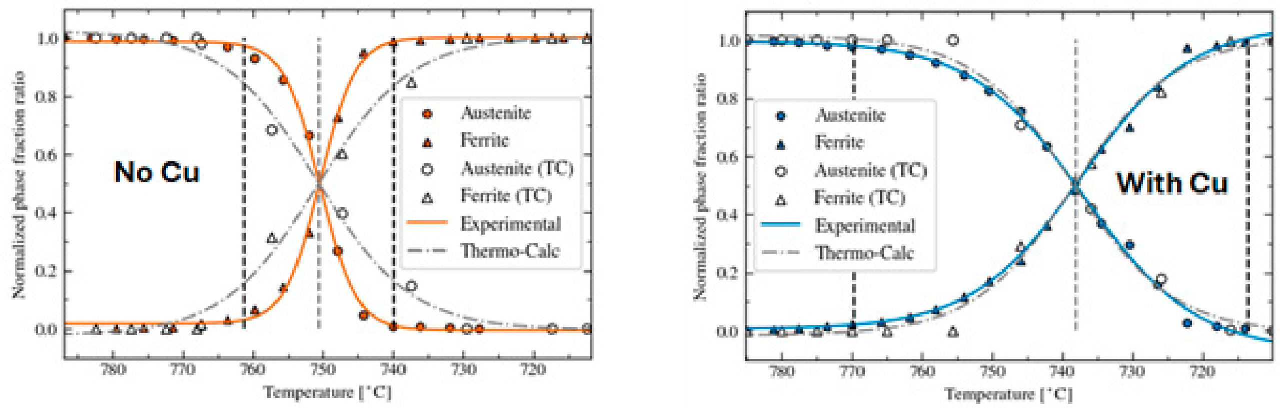


Figure 4. The fractions of austenite (circles) and ferrite (triangles) in an alloy without Cu (left) compared to an alloy with Cu (right). The mismatch between the experimental curves and the curves obtained at equilibrium by using Thermo-Calc for the alloy without Cu indicates that the experimental transformation is rapid compared to the simulated transformation. For the alloy with Cu, the experimental curves approach the equilibrium curves from Thermo-Calc, indicating that Cu has significantly retarded the austenite-to-ferrite transformation kinetics.

manufacturing. One of the main challenges are process induced defects such as micro cracks, which are often associated with a strong texture in a columnar microstructure. It is shown that grain refinement can mitigate these problems and selected nanoparticles that can act as grain-refiners, e.g. LaB6, ZrB2, TiB2 and VC were screened using arc melting. LaB6 and ZrB2 were selected as promising candidates for printing (Figure 5). The process window for LPBF was then determined using single track line scans combined with investigations of the melt-pool geometries and defect formation. Furthermore, printing of mixed powders was conducted by LPBF. The as-printed samples with ZrB2 appeared with less cracks and seem to be the most promising candidate. However, the quality of the 6061 commercial powder used in the printing was characterized and found not satisfactory for the LPBF, and further work needs to be done to firmly conclude.

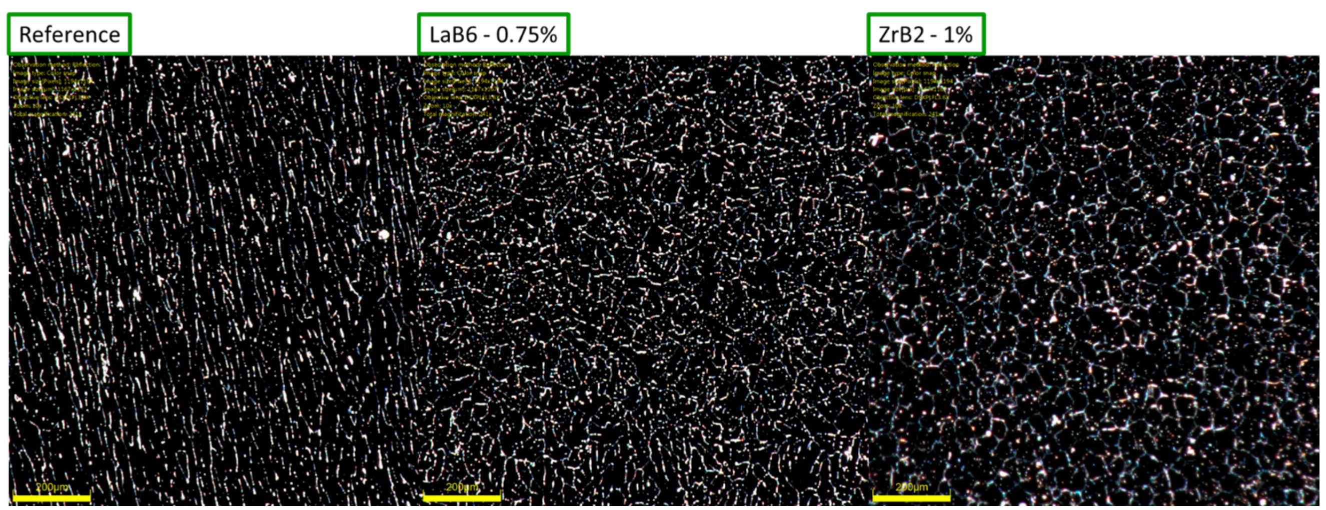


Figure 5. Grain morphology of aluminium alloy 6061 without (left) and with additions of LaB6 (mid) and ZrB2 (right) nanoparticles after Arc Melting.

In general, the investigation of silicon powders can bring important insights on their properties and applications. In 2024, a master student investigated SiOx formation and surface properties of several Si materials provided by Elkem. All samples were stored for more than 18 months prior to analyses at atmospheric conditions, then etched to remove SiOx layer, and finally re-oxidised by thermal treatment in controlled conditions. The results indicated the effect of natural environmental oxidation on SiOx surface consists in the hydrolysis of Si-H to Si-OH. This causes the agglomeration of Si, as observed by the increase of intraparticle porosity. Moreover, experimental data confirmed that oxidation was more severe in samples with smaller particle size distribution.

Task RA3.4: Tailored properties through post-processing

This task focuses on microstructure tailoring during heat treatments of Al products to compensate for unwanted detrimental secondary phases and precipitates and to promote desired phase transformations. Work was done to model phase transformation during post AM heat treatment of super duplex stainless steel and compared to experimental findings from experimental work in RA4 (Figure 6). ThermoCalc has been used to generate phase (sigma, austenite and ferrite) distribution plots and phase distribution tables for each grade based on the nominal wire composition as provided by the wire manufacturers. The effects of Cr, Ni and solution temperature have been predicted, which are in a reasonable agreement with experimental results (Figure 7).

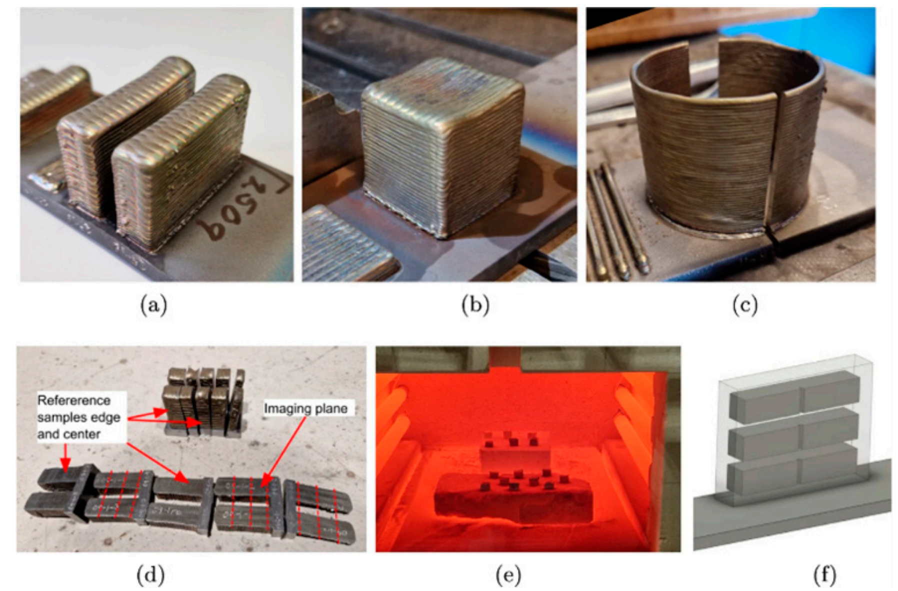


Figure 6. Specimen geometries, sectioning, solution heat treatment and Charpy specimen orientation and notch placement. The deposited material is transparent in (f).

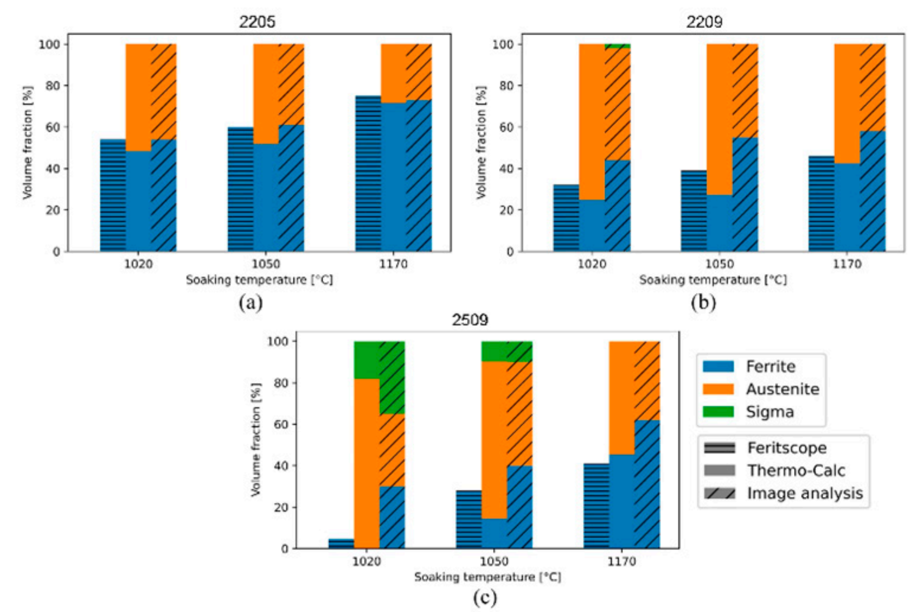


Figure 7. Comparison of phase balance for the three different materials measured with Feritoscope, measured with image analysis and simulated with Thermo-Calc[1]

[1] *Hassel, T.A., Marken, L.A., Arbo, S.M. et al. Microstructure Development in Duplex Stainless Steels from Additive Manufacturing with Coaxial Directed Energy Deposition and Heat Treatment. Metall Mater Trans A 56, 474–505 (2025). https://doi.org/10.1007/s11661-024-07560-z*

RESEARCH AREA 4.
INNOVATIVE PROCESSING AND JOINING METHODS

RESEARCH AREA LEADER:
MAGNUS ERIKSSON
SINTEF

CONTRIBUTIONS TO CENTRE OBJECTIVES

- Develop knowledge basis for welding of aluminium alloys to achieve full-strength integrity across the weld zone and heat affected zone.
- Develop new high-strength welding wire materials, including nano-particles, hypereutectic compositions and alloying elements for grain refinement and particle strengthening.
- Develop welding technologies of dissimilar metals (e.g. Al-Cu, Al-Fe, Al-Ti)
- Develop laser welding and Laser-arc hybrid welding for thick steel and aluminium alloys including numerical simulations using CFD approach.
- Develop laser assisted AM- and cladding processes, including new powders (e.g., silicides).
- ..and establish process-microstructure-properties relations and modeling technologies for these processing and joining methods.

MAIN CHALLENGES TO BE MET

- In welding of aluminium alloys, the low strength in weld metal and the heat affected zone (HAZ) represents one of the major challenges. To improve utilization of aluminium in welded structures as well as additive manufacturing (AM) there is therefore an urgent need for new high strength filler materials as well as new innovative welding methods e.g. laser welding, to minimize the width and the negative effect of the soft HAZ.
- Welding/joining of aluminium to steel, copper, titanium, and other aluminium alloys is desirable for weight reduction of components, e.g. busbars. However, a big challenge to achieve high quality welding is the formation of inert aluminium oxide films and intermetallic layers that form during solidification at the welding interface, and which strongly resist the formation of high strength metallic bonding. Innovative joining methods such as HYB and Friction Stir are therefore needed to overcome the above-mentioned challenges.
- Laser-arc hybrid welding of heavy steel provides both possibilities and challenges. Narrow and deep welds frequently provide excessive hardness in the root consisting of lath martensite and retained austenite in case of steels. Moreover, there are porosity and cracking issues. Numerical modelling and in-situ process monitoring e.g. high-speed imaging, are implemented to understand and control process behavior and minimize weld imperfections.
- Cladding: Silicides may have excellent corrosion and wear resistance but have very limited applications so far. More knowledge is needed on the processability of silicides as coating and exploring relevant coating processes is increasingly important.
- DED is one of the many additive manufacturing (AM) methods, using laser or arc as heating methods. There is increasing interest in applying DED methods for repair purposes, e.g., laser metal deposition (LMD) and wire arc additive manufacturing (WAAM). Applying these repair methods on a damaged component, including on-site repair, is very challenging due to uncertainties and variations of substrate material chemical composition, thickness, geometry, heat transfer etc.

ACTIVITIES AND RESULTS IN 2024

The research activities in this Research Area are organized into five main research tasks, listed below, together with their main results and highlights.

Task 4.1 New wires for welding of aluminium alloys

Welding of high-strength aluminium alloys are challenging as strengthening precipitates and dislocations are coarsened or annihilated due to the supplied heat. A weak heat affected zone (HAZ) is hence created which infer the overall mechanical properties of a welded structure. This task examines measures to reduce HAZ softening in aluminium by looking at the base materials, the welding wire and process technologies. Ultimately, the research will lead to improved material utilization and significant weight savings, followed by lower cost and CO2 emissions.

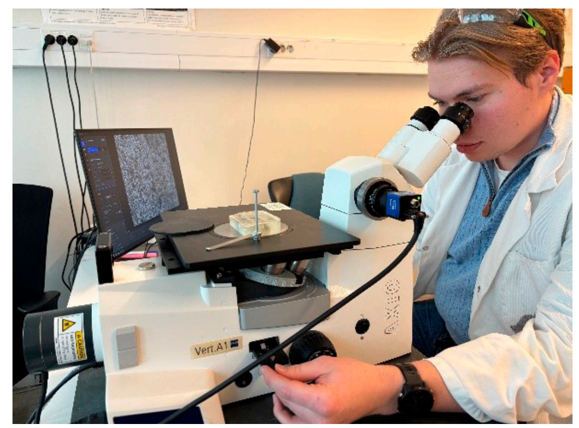
2024 was a year with extensive student activities in RA4.1; five master's student and one PhD candidate have performed their thesis wholly or partly related to this task. Supervision has been provided from NTNU, SINTEF and Benteler. PhD candidate Ingvild Runningen and MSc student Henrik Reberg have studied incorporation of TiC particles in aluminium during casting, with focus on the effect of salt fluxes and titanium stabilization. The survivability of TiC particles was further studied by TIG welding, showing promising results as to stabilize the ceramic phase. Results related to this work was presented at the ICAA19 conference in Atlanta, Georgia in June.

MSc student Henrik Elton has performed a screening study of heat-treatable welding wires from the 6xxx (Al-Mg-Si) - and 7xxx(Al-Zn-Mg(-Cu) series aluminium alloys for joining of 7108 profiles, cf. Figure 1. Elton started as a summer student in SFI Physmet, where he got the opportunity to participate in practical welding trials with Benteler at Raufoss.

Elkem and SINTEF have examined the applicability of ultra-hypereutectic aluminium-silicide (AlSi40) as high-strength joining material for 6082-T6 (peak-aged) base material. Initial testing with laser-powder deposition (Meltio) resulted in 40-50% hardness overmatch in the weld and a very narrow HAZ of just 2 mm. To improve the overall joint performance, new trials with laser metal deposition is scheduled in 2025.

Task 4.2: Welding of aluminium alloys and dissimilar metals

Solid-state welding, or low-heat input welding, technologies have been demonstrated to be the optimal choice for production of multi-material components. This minimizes the risk of intermetallic phase formation along the joint interface, promoting desirable properties such as strength and ductility. In 2024, a new industrial Friction Stir Welding (FSW) machine was installed at SINTEF Manufacturing in Raufoss. The equipment is part of the infrastructure found in the Manufacturing Technology Norwegian Catapult Centre (MTNC). The equipment offers a new range of opportunities in terms of weldable geometries (flat profiles, round pipes and corners), weldable thicknesses (up to 20 mm tested currently) and process parameters. The equipment also allows for



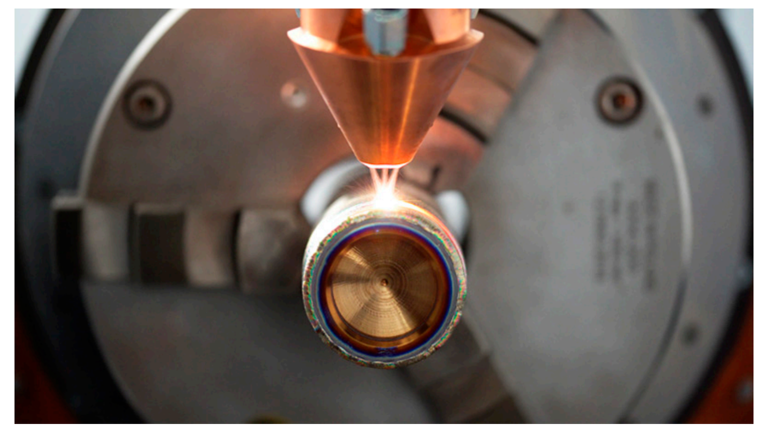


Figure 1. MSc student Henrik Elton characterizing AlMgZnZr welds in light optical microscopy [Photo: Geir Kvam-Langelandsvik]. Laser Metal Deposition (LMD) performed at Nordic Additive Manufacturing, Raufoss [Photo: SINTEF/FlexiMan]

Figure 2. The participants on the workshop organized at SINTEF Manufacturing (left) and tour/demonstration of FSW (right)

welding using a stationary shoulder, which will contribute to keeping the heat input at absolute minimum. The equipment will strongly contribute to advancing the studies on solid-state welding of dissimilar metals going forward in SFI PhysMet in 2025.

In August 2024, a workshop on solid state welding was organized at SINTEF Manufacturing in Raufoss in cooperation with the green platform project AluGreen, see figure 2. The purpose was to share knowledge about solid state welding with the industry partners and to discuss possible use cases in the industry. The workshop was also used to demonstrate the use and possibilities with the new FSW machine owned by MTNC at Raufoss.

Task 4.3 Laser-arc hybrid welding of thick steel and aluminium alloys

Results on hybrid laser-arc welding of thick steels

Deep penetration laser-arc hybrid welding (LAHW) may offer a significant increase of productivity. It provides low heat input which lowers distortions and residual stresses compared to traditional arc welding. However, LAHW might be challenging to optimize due to significant amount of process parameters and complex multi-physical processes. Due to high depth-to-width ratio, there are both a significant risk of welding defects as well as brittle phases being present in weld metal and heat affected zone (HAZ). Economic benefits of LAHW have been compared with traditional arc welding and showed enormous potential for efficiency and savings providing similar mechanical performance. This might be implemented in applications for joining thick steel sections for various heavy industries, e.g. offshore wind structures and bridges. See Figure 3

During 2023 and 2024, the highest priority for the research was hybrid welding of a 45 mm thick S355ML structural steel to achieve full penetration welds using double-sided welding technique. Optimized welding parameters for slow welding speed reduced hot cracking in the root area compared to fast welding speeds used for higher strength steels. Further reduction of cracking

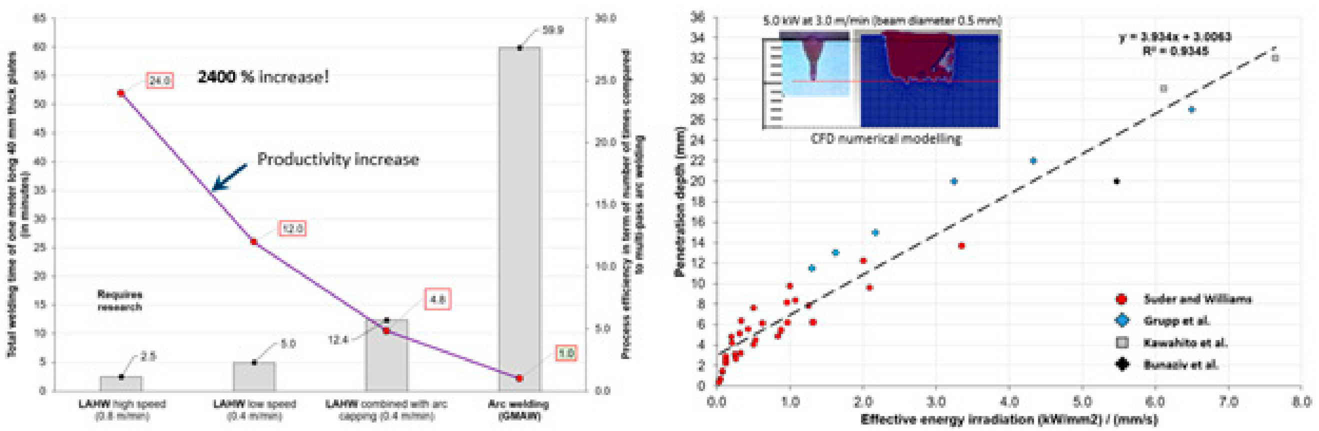


Figure 3. Joining efficiency comparison of different welding methods and prediction of penetration depth modelling using CFD and mathematical methods.

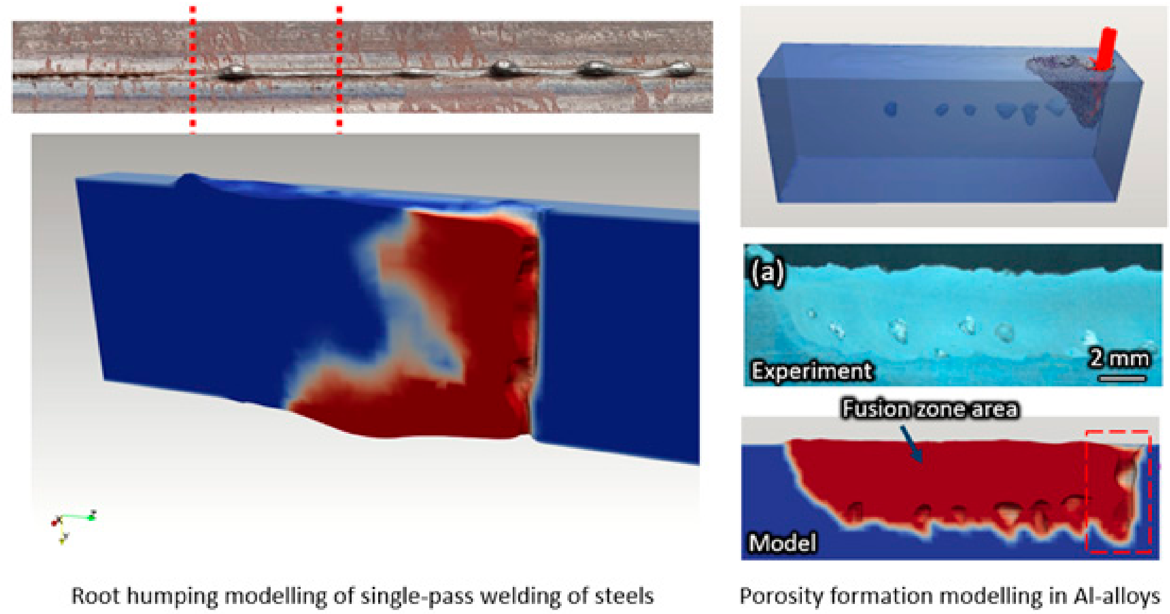


Figure 4. Numerical modelling of root humping in low carbon steels (on the left) and laser wobbling for Al-alloys (on the right)

occurrence was achieved by preplacing 316L stainless steel plates into weld gap prior to welding. In 2025, further research on hot cracking will be conducted using low transformation temperature filler materials (LTT) as well as deep welding made in vacuum. The main outcome in 2023 and 2024 was a publication related to efficiency of different welding processes. Studies showed that the use of hybrid welding may significantly reduce consumption of welding consumables, and increase welding speed and productivity compared to traditional arc welding. Optimized welding parameters for hybrid welding provided equivalent weld quality to the welds in conventional arc welding, displaying a high potential for the laser-based processes.

In single-pass laser beam welding of 15 mm thick plates, a high-speed imaging camera was used to record root formation at high resolution. Humping formation was recorded and will be studied further up to through 2025. High fidelity numerical modelling using computational fluid dynamics will be used to study and analyse different root formation modes and in-depth physics.

In 2024, numerical modelling using CFD was heavily introduced to the work task, cf. Figure 4. In 2024, such model was successfully applied to model humping phenomena in single-pass welding of steels. The method was also employed to study the effect of wobbling in laser welding of aluminium alloys. Further development of the CFD tool will be done in 2025. Furthermore, in 2025 a new ultra high-fidelity modelling will be tested where complex phase change modelling is involved allowing to have multiple phases with evaporation physics. This will open more possibilities to predict different defects during welding.

Novel experiments with deposited microparticles on welding edges and preplaced in a hole for spot welds were made to induce acicular ferrite formation in laser welding of steel. The experiments and results were performed in collaboration with Msc student Rajetha Sutha.

Preliminary results were not conclusive and showed very limited difference from autogenous laser beam welding. However, some promising results were spotted for using TiO2 nanoparticles with effect of grain refinement. Therefore, further experiments with different microparticles will be conducted in 2025.

Task 4.4 Laser cladding and surface treatment

In 2024, we have achieved an important milestone in this task, i.e., a test coupon was installed for field test for at least two years in a highly demanding environment with metal dusting deterioration. The coupon has Inconel substrate that is coated by nickel silicide using the powder bed fusion (PBF) method, see Figure 5. Silicides have

Figure 5. The coupons for the field testing (Photo: SINTEF/Kai Zhang).

excellent corrosion and wear resistance, and the field test will be used to demonstrate its potential in real service conditions. Moreover, this case study is also a great showcase for collaboration between centre partners. Elkem has delivered the powder, SINTEF performed AM and coating using PBF, and finally the coupon was installed in Equinor's process plant for testing. We also performed topography measurements as reference, and same characterization will also be performed for samples that are subjected for field testing after two years.

Task 4.5 AM by direct energy deposition (DED)
In 2024, PhD student Trond Arne Hassel successfully defended his PhD. Dr. Hassel has systematically investigated the effect of chemical compositions and AM process parameters on microstructure evolution in additive manufacturing (AM) of duplex stainless steel (Figure 6). His work contributed significantly to more successful use of duplex stainless steel in harsh service conditions through AM as well as using AM-based method for repair of duplex steel components.

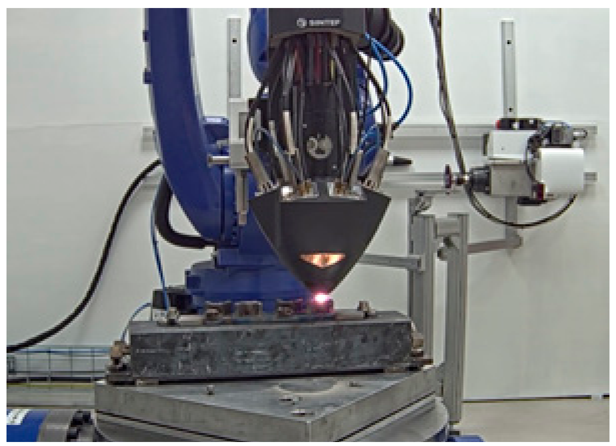


Figure 6. Experiment setup for Dr. Hassel's PhD work, i.e., laser DED of duplex steel.)

Seminars and workshops
A webinar was organised on 18th April in collaboration with FME Northwind, with the topic on Aluminium in Offshore Wind – possibilities and challenges. Here Geir Kvam-Langelandsvik presented "The challenges and opportunities with fusion welding." Here the focus was on how to consider and improve the heat affected zone (HAZ) in aluminium welding , especially on precipitated hardened alloys (cf. Figure 7).

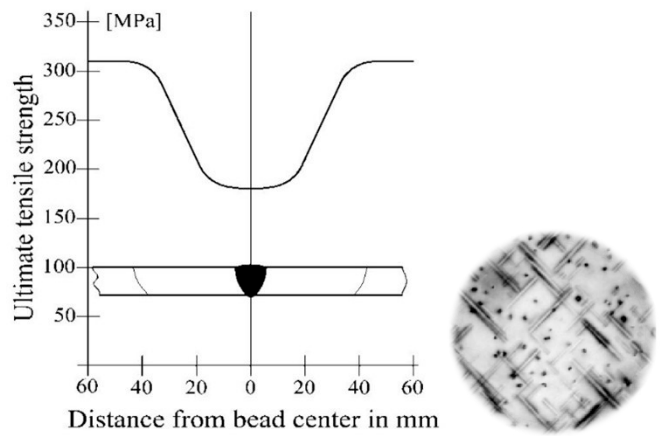


Figure 7. HAZ weakening in heat-treatable alloys after welding [aluminium-guide.com]

RESEARCH AREA 5.
DATA, SHARING AND DIGITAL PLATFORMS

RESEARCH AREA LEADER:
JESPER FRIIS
SINTEF

CONTRIBUTIONS TO CENTRE OBJECTIVES
- Make research results (data and modelling tools) accessible and easy to combine and reuse.
- Enabling both industry and research partners to make efficiently use of the project results promoting rapid innovation.

MAIN CHALLENGES TO BE MET
- How to share models and data produced within the centre.
  Strategy: create a web portal for physical metallurgy where the models and data can be shared.
- How to represent scientific results and knowledge within physical metallurgy such that they become FAIR (findable, accessible, interoperable and reusable) as well as traceable and actionable (allow action based on insight).
  Strategy: build a knowledge base for physical metallurgy using common standards and physics-based ontologies to describe the knowledge.
- A key challenge is to at one hand include enough details about the data to address the above points while at the other hand making the documentation process practical and simple enough that it will be realized.
  Strategy: develop new schemes for data documentation with a web interface to supporting tools.
- How to exploit the platform for increased quality and productivity in research and industrial innovation?
  Strategy: involvement of stakeholders and early demonstrations.

To tackle these main challenges, the work in this Research Area is organised into three research tasks: platform design, platform implementation and platform exploitation.

The effort is strengthened by close collaboration with key international players within the network surrounding the European Materials Modelling Council and reuse of experience and state-of-art technology developed in collaborative European projects.

Task 5.1: Platform design
This task focuses on the design of a digital platform for the centre that will allow to document and seamlessly connect results from advanced characterisation, experimental testing, data processing and modelling from electronic to continuum scale. Surrounding projects and other target users will also be invited, to ensure that the platform will extend after the end of the SFI and serve as a national digital hub for innovation and collaboration within physical metallurgy. An important part of this task is to

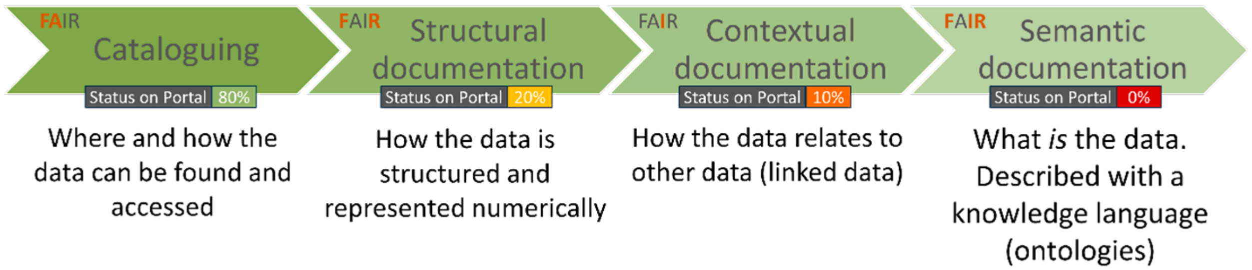


Figure 1. Steps for documenting scientific knowledge resources. In practice, these steps do not need to be documentation in sequence. A main objective for 2025 is to increase the indicated implementation status for all the steps.

create a domain ontology for metals and alloys, focusing on the needs from RA1-RA4.

Task 5.2: Platform implementation
The implementation of the platform is using core technology from various EU projects and tailored to the user needs expressed in task 5.1. It combines existing and new components: i) database management and associated search and visualization tools, ii) interoperability modules to apply seamlessly various numerical models, iii) secured and user-friendly web interface.

Task 5.3: Platform exploitation
This task focused on exploiting both the data and available models to produce new analysis and support innovation. This task will involve workflow demonstrators, development of application specific interfaces for data analysis, as well as training and frequent user meetings to encourage the active use of the platform in all RAs.

ACTIVITIES AND RESULTS IN 2024
Here we will only highlight a few key activities. Other important activities in 2024 include finalisation of a use case with Raufoss Technology on digitalisation and exchange of test results, further development of the microstructure ontology and a demonstration of how to use ontologies to provide a common representation of solidification results from Thermo-Calc and Alstruc such that the results can be compared.

Methodology for data documentation
Based on lessons learned in the EU projects OntoTrans and OpenModel, a new methodology was developed for documenting scientific data resources with a two-fold emphasis: (i) to formalise how data resources and knowledge can be represented in a knowledge base and (ii) to make the process of data documentation as practical and easy as possible. A data resource can be a data-set, a model, a sample, an instrument, etc… Information is acquired when meaning is given to data such that it

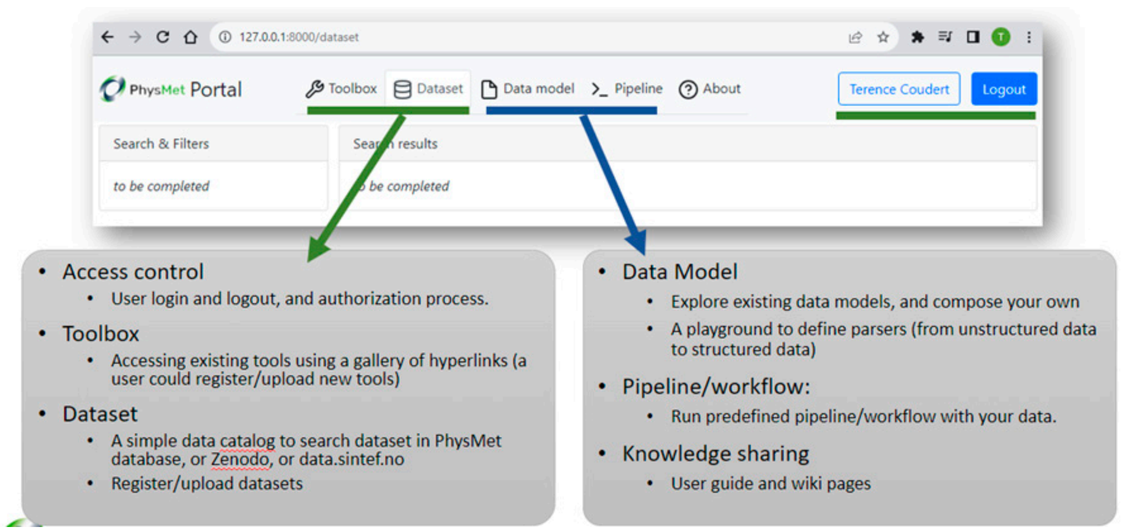


Figure 2. Features of the new web portal.

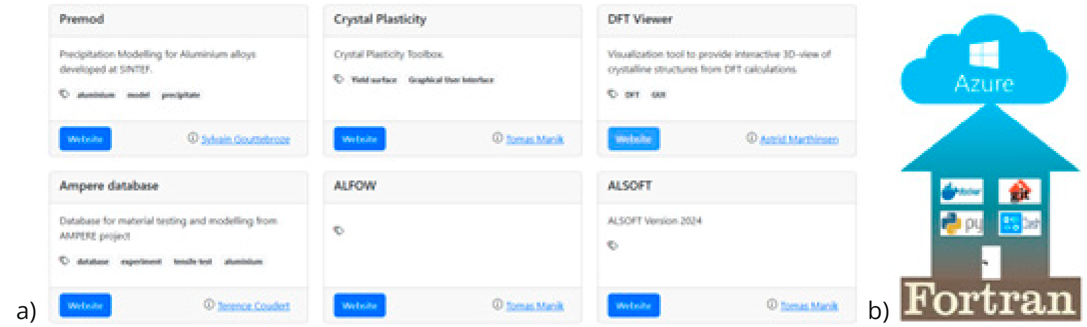


Figure 3. a) PhysMet toolbox of various web applications and b) schematics of how microstructure models were turned into a web application by combining existing technologies.

become useful. Knowledge is gained when pieces of information are connected to each other and wisdom is gained when the knowledge is combined with insight making it possible to act on it, e.g. for decision-making systems. Figure 1 shows four steps of address the abovementioned levels of data documentation.

The PhysMet digital platform and Web portal
The updated design of the PhysMet platform that was initialised in 2023 was further elaborated and deployed in 2024. An overview of the features provided by the web portal is shown in Figure 2. It serves as a gateway or starting point to the PhysMet digital platform that provides users access to various digital resources, services, and information.

The toolbox is one of the main features. It provides access to a gallery of tools, as shown in Figure 3a. A process for turning the microstructure models ALFLOW, ALSOFT and Crystal Plasticity Toolbox into the respective web applications is schematically illustrated in Figure 3b.

Furthermore, the platform will contain a catalogue of datasets from experiments and modelling results that are available to project partners. The structure of the datasets are formally described by data models who's semantic meaning is defined by ontologies. A demonstration of how TEM images can be semantically documented using data models and mapping to ontologies has also been developed and was presented at the consortium meeting in May.

New web applications: In 2024, the ALSOFT model was added to the already existing suite of physics-based microstructure models available as web applications, making the set of models more complete. Figure 4

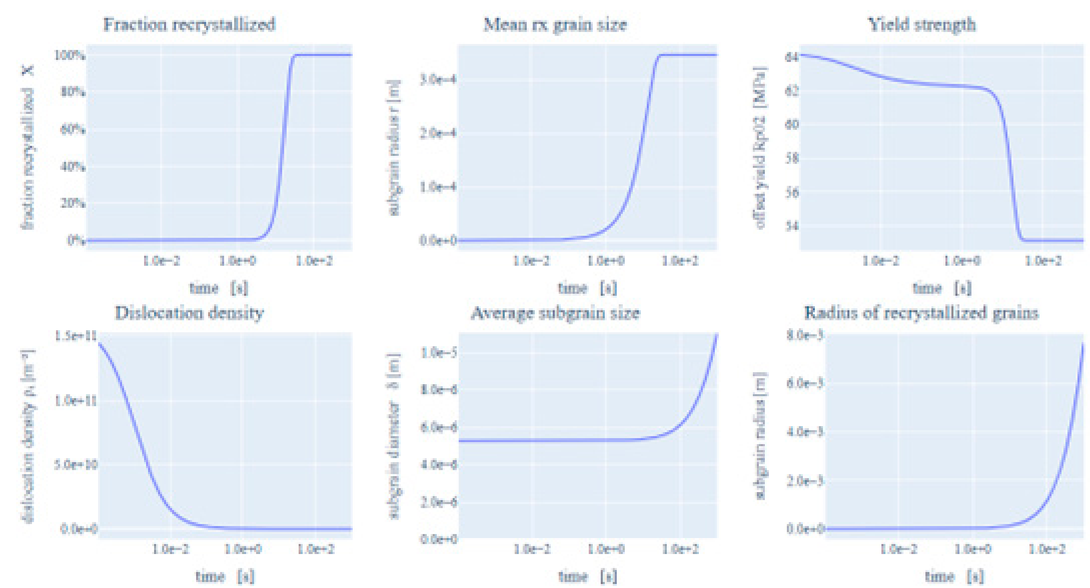


Figure 4. Screenshot from the ALSOFT web app showing the predicted softening upon back-annealing.

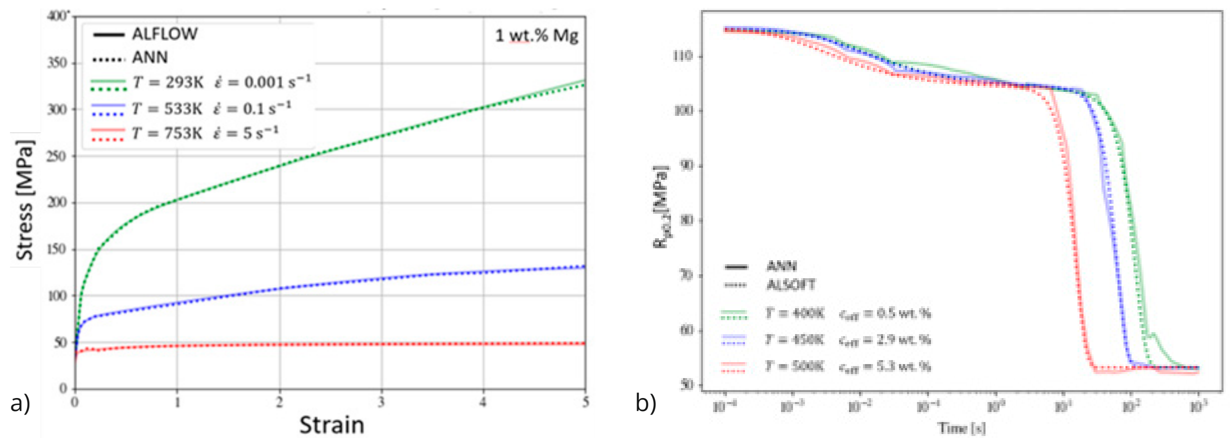


Figure 5. Comparison of yield strength predictions by ALFLOW (a) and ALSOFT (b) to their respective ANN based surrogate models. The ANN applied was a dense feed-forward neural network with three hidden layers of 40, 30 and 20 nodes.

shows an example output from the ALSOFT web App. The present models can now be used to address key issues in microstructural evolution, including precipitation phenomena (PREMOD), dynamic recovery, dislocation- and solute-based work hardening (ALFLOW), static recovery and recrystallization (ALSOFT), and texture and plastic anisotropy development due to plastic deformation (Crystal Plasticity Toolbox). Following the framework outlined in Figure 3b, this deployment step enables a comprehensive analysis of how these processes influence the yield strength evolution in aluminum alloys as a function of time, temperature, solute concentration, particle content, and loading direction.

ML-versions of ALSOFT and ALFLOW physics-based models

Increasing computational efficiency of classical physics-based models could open new industrial applications for these models, such as their integration into multiscale modeling strategies or real-time digital twin applications for e.g. forming processes. However, achieving this requires significant improvements of computational speed from the millisecond range to the microsecond range. Such advancements may not be feasible while relying solely on numerical solutions of the coupled differential equations in physics-based models. Instead, an alternative approach is to develop high-fidelity surrogate models using artificial neural networks (ANNs).

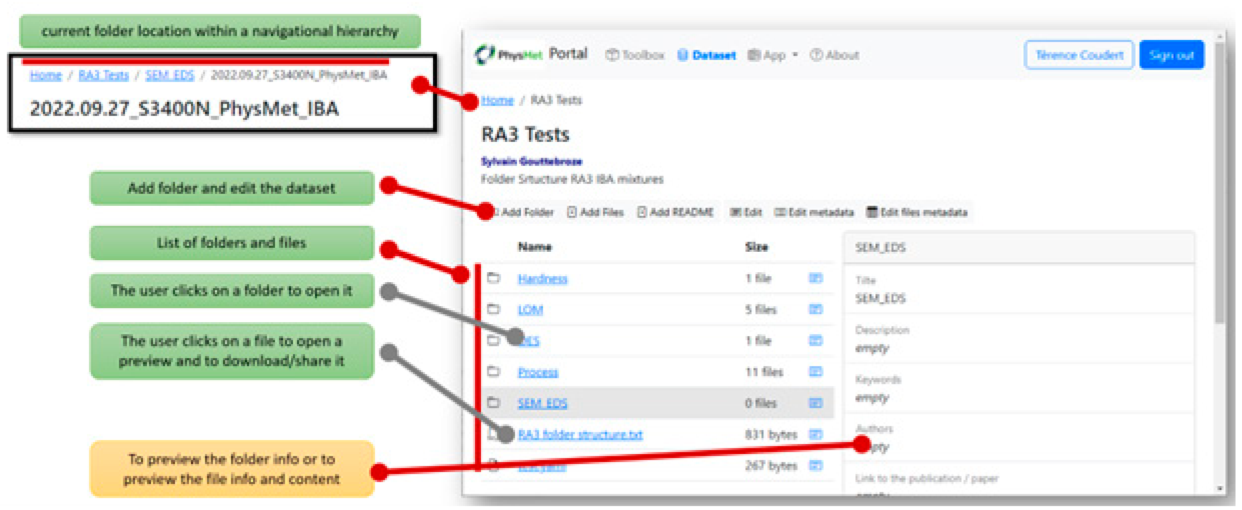


Figure 6. Storage and documentation of experimental results from RA3.

This was the core idea in the MSc project for a student Daniel Aaron Preminger. The goal was to develop surrogate models based on a feed-forward dense neural network architecture to replace the physics-based models ALSOFT and ALFLOW shown in Figure 5. Various ANN architectures were tested, mapping selected input variables—such as time, strain, strain rate, temperature, and solute content, to one output variable – the yield strength. His work studied both the accuracy and the potential computational efficiency gains achieved by replacing the physics-based models with trained neural networks. This promising approach highlights the feasibility of using machine learning to accelerate microstructure-based yield strength predictions, making real-time industrial applications more attainable.

Collaboration with RA3 on data documentation for IBA

The work started in 2023 was revised and integrated into the new platform design. This use case provides examples of dataset to identify the relevant metadata to be available for documenting files and folders. As illustrated in Figure 6, the interface provides a navigation panel to explore the datasets and a side frame to display preview or metadata information. The metadata facilitates the search based on category and free text information.

Collaboration with RA2 on data documentation for microstructure simulations

A series of simulations have been conducted in RA2 to build a surrogate microstructure model for additive manufacturing of duplex stainless steel. The input files and some of the output files have been stored on the platform. Some metadata were added directly to the dataset description. In addition, a separate file was created to store information about the simulations as illustrated on the right-hand side of Figure 7. This table groups essential information about the simulations (like the temperature or cooling rate) that enables post-processing of the results. Such information could later be included in the context/metadata of the simulations. This table was manually built, but could also be generated automatically using a parser for Micress files created at SINTEF.

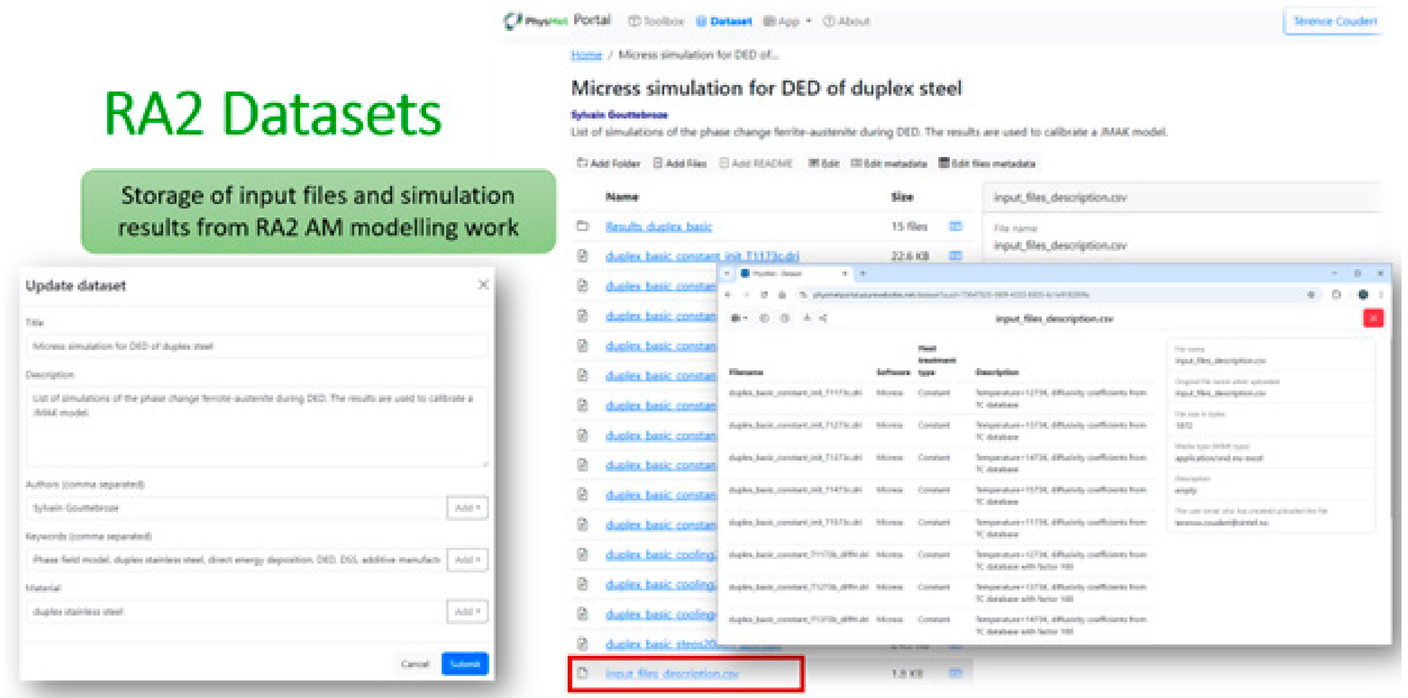


Figure 7. Storage and documentation of simulation results from RA2

FROM INNOVATION ADVISORY COMMITTEE

The overall objective for SFI PhysMet is to contribute to a greener, more sustainable and cost-efficient Norwegian metal-based industry. This should be realized through the development of cutting-edge physical metallurgy expertise, contributing to national competence building within five main areas: (i) New and recycle-friendly materials and alloys, (ii) New methods for recycling and processing of materials, incl. solid-state recycling and mechanical alloying, with the prospect of new alloys and composites with improved properties; (iii) New and improved processing methods (e.g. via rapid solidification, additive manufacturing), (iv) New and improved welding and joining methods and (v) Digital tools and models. The research activities combine advanced characterization of structure and properties at all length-scales with development of numerical models adapted to industrial processing conditions that the industry can use in their own R&D and innovation activities.

1. Which expectations have the user-partners to «Innovation and value-creation» in SFI PhysMet?

The industry partners in SFI PhysMet have high expectations for innovations and value creation that comes out of R&D projects. Physical metallurgy is today core competence for several of the industry partners in the SFI centre and will continue to be of vital importance also in the coming years in the tough competition of offering cost-efficient and recycling friendly products for more and more demanding customers. The expectations from the SFI-activities should lead to:

- Development of new alloys and improved production processes reducing cost and improved performance for future sustainable product applications.
- Maintain and further develop the world class competence in aluminium, ferro alloys, silicon and steel physical metallurgy at NTNU and SINTEF. This includes competence among scientists as well utilization of state-of-the-art equipments/facilities/softwares. Long term competence building secures Norwegian metal-industry to be competitive in the future.
- Shortened time for implementation of new R&D-results to the user partners.
- Increased number of talented engineers and scientists (MSc, Phd and postdocs) within physical metallurgy including downstream processes such as welding/joining and additive manufacturing. This is essential for the user partners in the recruitment of highly qualified workforce in the years to come.
- Closer collaboration between several industrial partners and academic partners provide an additional value compared to binary collaboration. Experiences from the area of additive manufacturing with a broader collaboration have been very good with increased innovation potential.

2. How do the user-partners facilitate "Innovation and value-cration" internally in own company? How are new generated R&D-results implemented in the companies?

- In order to take advantage of the R&D-results obtained in SFI PhysMet, it is a pre-requisite that the R&D activity is linked to concrete industrial cases for the user partner. When the selected R&D-cases focus on critical needs for the industry partner, the user will be active!
- Combination of short term and long term goals: Activities in SFI PhysMet generate results that are implemented continuously by the industry partners for incremental improvement of processes and product qualities. Other activities have a more long- term focus developing generic, basic competence that the user partners can implement in their technology development programs in the years to come.
- Close collaboration between NTNU, SINTEF and industry partners: Technical expertise from the industry partners secures that the activities in the centre are related to industrial needs and challenges. Industry partners offer access to pilot and production facilities in order to implement new R&D-results as fast as possible into industrial operational use.

3. How do SFI Physmet succeed? Where can SFI PhysMet improve (do better/ do more of for more innovation and value creation)?

The Innovation Committee in SFI PhysMet, led by industry partners, has the task to define, map and follow up innovations in the centre. The committee is facilitating knowledge transfer from the research partner to the user partners as well as innovation activities between the different industry partners.

A tool has been developed for monitoring innovation potential in the centre's activities. The Innovation Committee uses this to identify possible innovations and assess which activities can be lifted to a higher TRL level. A first set of results/activities with innovation potential (3-4 per RA) has been prepared based on this tool.

SFI PhysMet has established a strong network with close interactions between industry technical and R&D-experts, NTNU-professors and students and SINTEF scientist. The centre has united the different resources within physical metallurgy in one common **physical** centre. Earlier the resources in physical metallurgy were spread in different projects/locations/departments. The physical centre that was established in the start-up-phase of SFI PhysMet has been very positive for the networking and interactions between the various participants in the centre. This has also given opportunities for other relevant projects at NTNU and SINTEF taking advantage of this high-level competence centre.

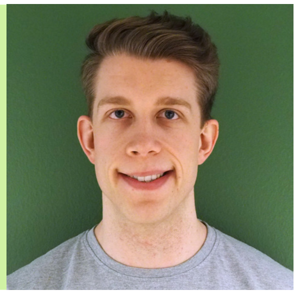
Mobility of staff between the centre and user partners could have been improved. Industry experts should be encouraged to visit the center more often. This is stimulating for both students and academic staff and can lead to a more dynamic centre in terms of creative discussions and idea generation. Also academic staff (professors and students) and scientists at SINTEF should be stimulated to visit industry partners in the centre both for shorter stays or longer sabbatical stays. This will give more industrial insight for scientists and academia personnel which is highly relevant for solving industrial challenges.

OUR PHD CANDIDATES

During the eight years Centre period we will recruit and educate numerous PhD candidates, Postdoctors and master students. We are looking for competent and motivated candidates in all of the Centre's research areas.

Seven talented PhD candidates have been recruited to SFI PhysMet, and three more started in 2024. We are looking forward to following their scientific progress in the years to come! Here is a short presentation of our PhD candidates.

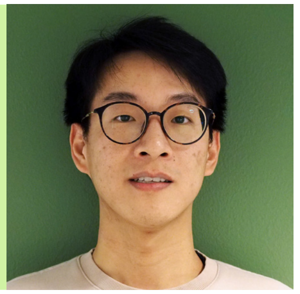
PHD CANDIDATE
ANDREAS VOLL BUGTEN (2021-2025)



Research topic: The effect of trace elements on the microstructure development and mechanical properties of cast irons.

Supervisor: Prof. Marisa Di Sabatino

PHD CANDIDATE
XUEZHOU WANG (2021-2025)



Research topic: Develop precipitation model with improved nucleation concepts, addressing the influence of impurity elements, vacancy and atom clustering kinetics.

Supervisor: Prof. Yanjun Li

PHD CANDIDATE
INGVILD RUNNINGEN (2021-2025)

Research topic: Development of nanoparticle-containing aluminum filler wires

Supervisor: Prof. Ida Westermann

PHD CANDIDATE
MAGNUS REIERSEN (2021-2025)

Research topic: Material development and microstructure control for powder based additive manufacturing processes

Supervisor: Assoc. Prof. Tomas Manik

Funded by SINTEF

PHD CANDIDATE
HÅKON LONGVA KORSVOLD (2023-2026)

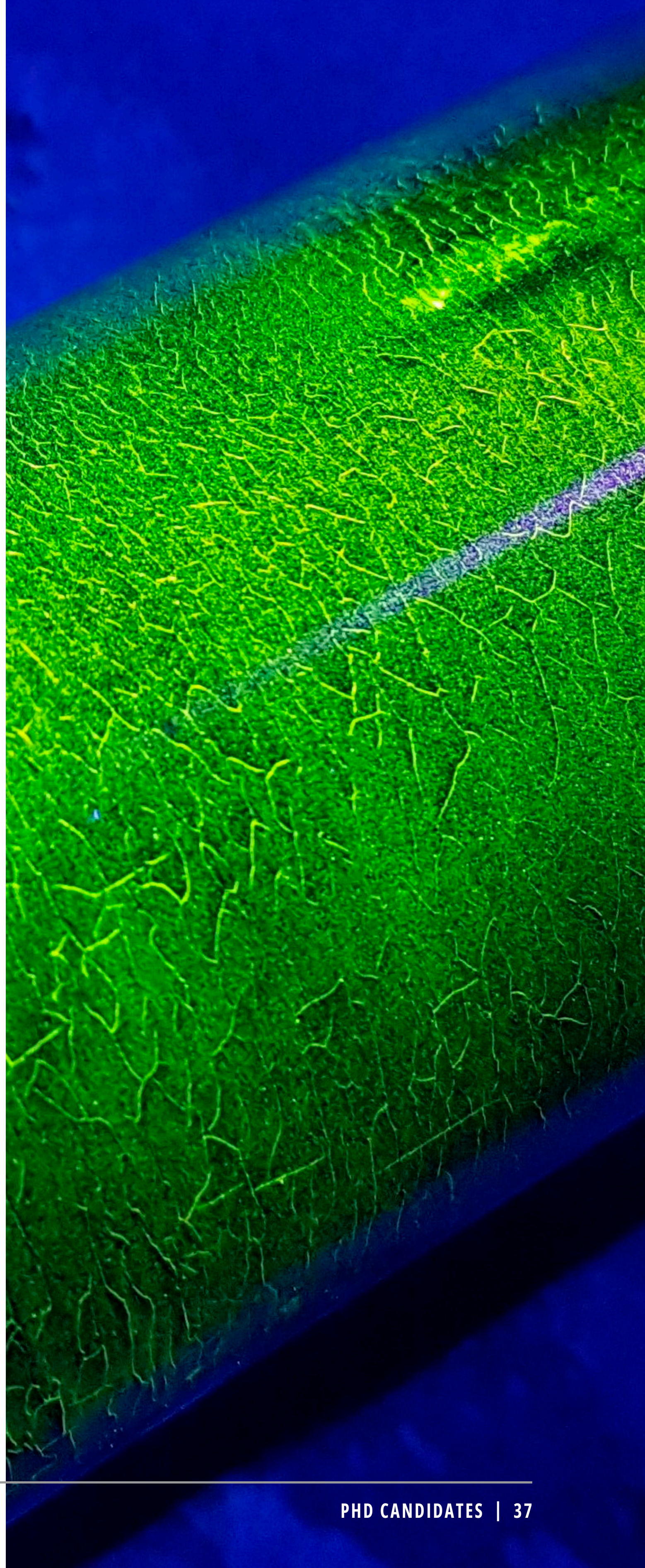
Research topic: Advanced nanoscale characterization of grain boundary segregation in metals.

Supervisor: Prof. Yanjun Li

PHD CANDIDATE
SUPREET KAUR (2023-2026)

Research topic: The effect of trace elements on recycled Al Alloys

Supervisor: Prof. Marisa Di Sabatino



NEW PHD AND POSTDOC CANDIDATES IN 2024

Three new PhD candidates started in 2024, and more will start in 2025. We have asked the new PhD candidates to give a short description of their projects and the expected impact for industry.

PHD CANDIDATE
JAN KONKEL (2024-*2027*)

Topic: Development of Low Transformation Temperature (LTT) Steel Alloys for Welding and Additive Manufacturing Applications

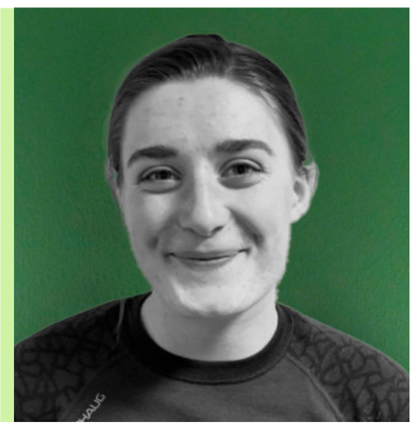
Supervisor Tomas Manik

Background Master's degree in Materials Science and Engineering from NTNU. Topic: Effect of Conventional and Screw Extrusion on the Properties of AA1370 Aluminum Process Scrap and End-of-Life Scrap Material.

The PhD project Utilization of the low martensite start temperature for LTT alloys and the occurring volume expansion during the austenite-martensite transformation to remove residual tensile stresses in the heat-affected zone and optimize the crack formation resistance in the weld area.

Methods Fabrication of welded components using LTT filler wires and subsequent microstructural characterization including light optical microscopy, SEM, EBSD analysis, residual stress assessment and mechanical properties measurements, e.g. dilatometry, hardness and tensile testing.

Expected impact for industry LTT filler wires can be used to increase the fatigue resistance in welded constructions. This leads to an enhanced lifetime, improved structural integrity and reduced manufacturing costs due to the avoidance of post-weld treatment of the components.



PHD CANDIDATE
INGA DAHLEN KONOW *(2024-2027)*

Topic: The effect of deformation on 6xxx Al-alloys

Supervisor: Randi Holmestad

Background: Master's degree in applied physics from NTNU. Topic: Characterization of gas atomized Si and NiSiV powders.

The PhD project: Nano-structure characterization of microstructure evolution in extruded 6xxx Al-alloys during deformation by cold rolling.

Methods: The main focus of the project will be on transmission electron microscopy (TEM) using techniques such as bright field, dark field, high-resolution TEM and high-angle annular dark field scanning TEM (HAADF-STEM) to characterize different alloys and process routes.

Expected impact for industry: Combining plastic deformation with thermal ageing for extruded 6xxx Al-alloys has shown an improvement in mechanical properties, including mechanical strength and strength-ductility balance. Understanding and implementing new thermo-mechanical routes gives a significant potential for growth for both standard and recycling-friendly 6xxx alloys.

POSTDOC
JIANBIN XU (2024-*2026*)

Topic: Laser-based welding of steel and aluminium alloys

Supervisor Knut Marthinsen, Magnus Eriksson

Background Phd's degree in physical metallurgy from NTNU. Topic: Deformation behavior of Aluminum alloys – Work Hardening and Portevin-Le Chatelier (PLC) effect.

The Postdoc project Laser-based welding of aluminium alloys. This project aims to enhance the reliability and efficiency of laser-based welding in industrial applications by reducing defects, minimizing rework, and improving weld quality through advanced process control, monitoring technologies, and numerical modeling.

Methods Mechanical characterization of the samples will be performed to evaluate the welding process. Numerical finite element modelling will be conducted to understand the deformation performance of the welded joints.

Expected impact for industry This project will contribute to improved weld quality, reduced production costs, and enhanced process efficiency, facilitating the wider adoption of laser welding in industrial manufacturing.

PHD CANDIDATE
HITESH KUMAR (2024-*2027*)

Topic: The Corrosion protection of floating structures using laser welding technology

Supervisor: Nima Razavi

Background: Master's degree in Materials Engineering from NIT Karnataka, Surathakal, India. Topic: Autogenous Diode Laser Welding of Fe-Ni based superalloy materials of A-286 & INCOLOY-800.

The PhD project: To optimizing laser cladding process with corrosion resistance alloy on bridge structure which can provide corrosion protection and meet the expected 100-year life.

Methods: Laser cladding of corrosion resistance alloy on S420ML, Parameter optimization, microstructure characterization: optical microscopy and SEM, mechanical testing, followed by corrosion analysis.

Expected impact for industry: This project is important for bridge and offshore structures for enhancing their corrosion life without need for regular maintenance, repair and inspection.

PHDS EDUCATED IN THE SFI PHYSMET ENVIROMENT IN 2024

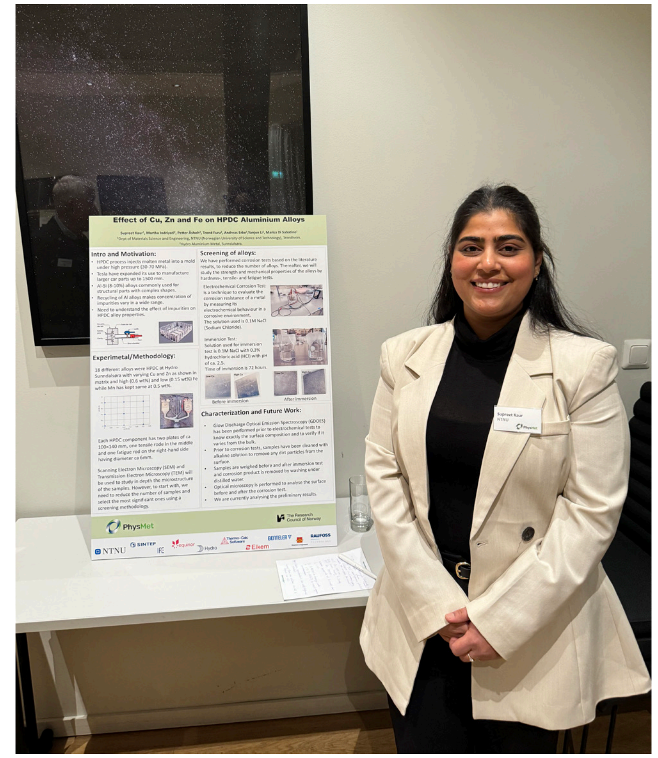
Dr. Trond Arne Hassel, as the first candidate to complete his PhD within SFI PhysMet consortium, 28. November 2024, successfully defended his PhD thesis "Additive manufacturing of duplex stainless steels with coaxial laser directed energy deposition". The main goal of this doctoral study has been to investigate and develop knowledge for the use of additive manufacturing (AM) in repair of large metal components. The work has been funded by the Research Council of Norway through the funding scheme "PhD scholarship in the Institute Sector" (Grant No 323332). The PhD work has also been supported by SFI PhysMet, where it has been a part of the research activities in Research Area RA4, Innovative processing and joining, and where he has worked closely with Dr. Siri Marthe Arbo, as one of his co-supervisors.

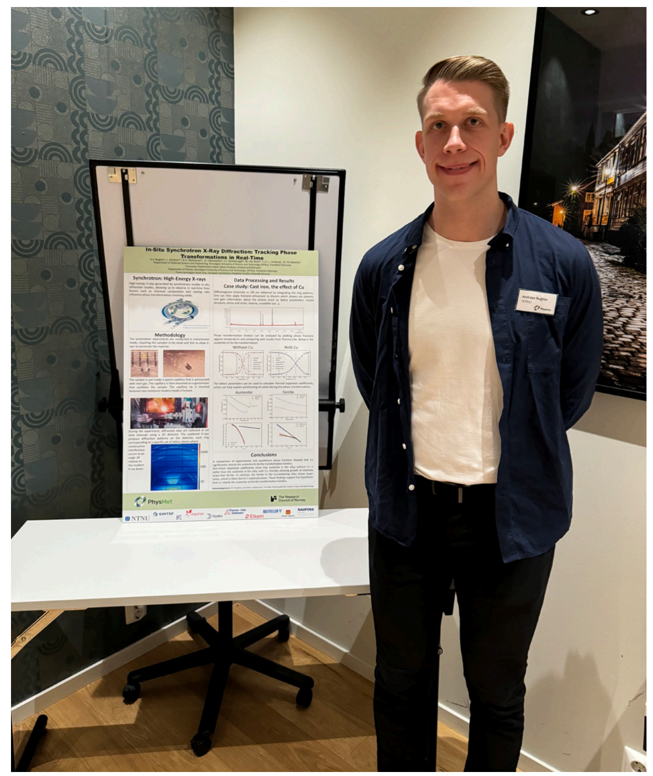
Dr. Håkon Wiik Ånes defended his thesis, "Effects of second-phase particles on texture during softening of an Al-Mn alloy investigated by correlative microscopy", 25th January 2024. Håkon has done his PhD work in the physical metallurgy group at Department of Materials Science and Engineering. The PhD project was funded by NTNU through the NTNU Aluminium Product Innovation Center (NAPIC) and also with support from SFI PhysMet. Professor Knut Marthinsen has been the candidate's supervisor and Professor Antonius Theodorus Johannes van Helvoort, Department of Physics, has been the candidate's co-supervisor.

PhD Endre Hennum successfully defended his PhD thesis on the 21st of May 2024. The title of his thesis was: "Effect of microstructure on precipitation of β-Mg2Si during cooling of Al-Mg-Si alloys", The doctoral work has been carried out at the Department of Materials Science and Engineering and Hydro R&D Center Sunndalsøra, where Professor Knut Marthinsen has been the candidate's main supervisor and Dr.techn. Oddvin Reiso and PhD Ulf Håkon Tundal, Norsk Hydro, have been the candidate's co-supervisors. The PhD work was co-funded by Norsk Hydro and the Research Council of Norway (RCN) through the funding scheme Industrial PhD scheme – Doctoral projects in industry.

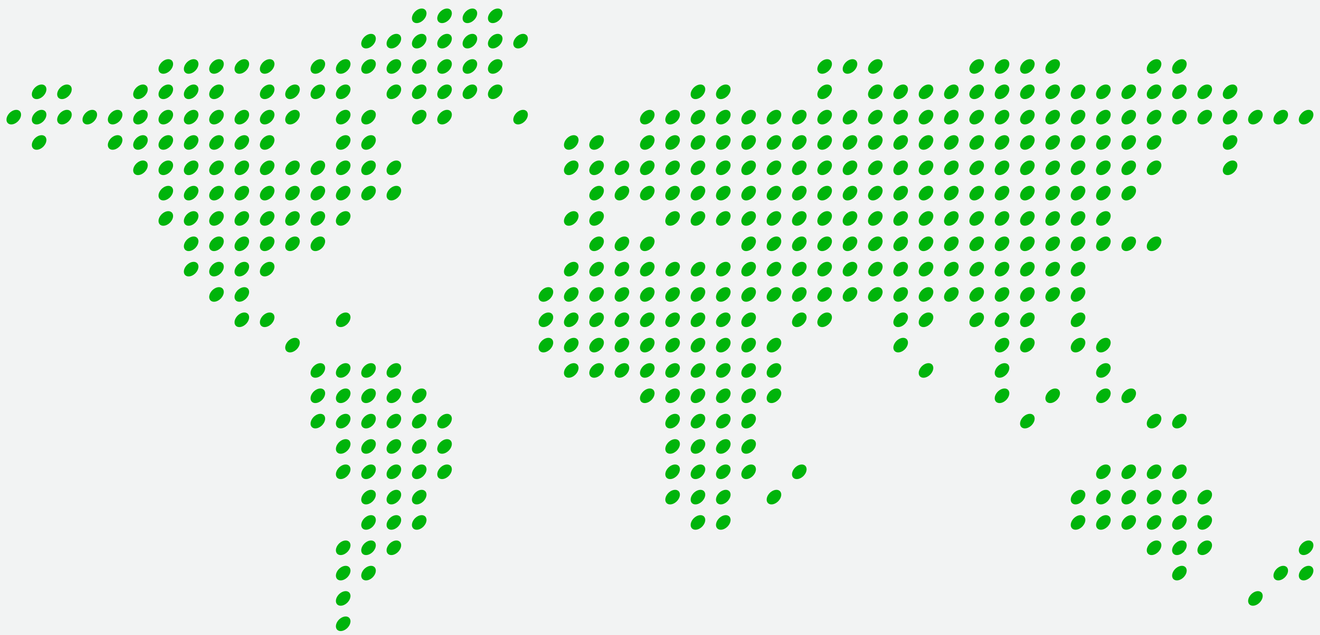
Dr. Trond Arne Hassel. Photo: Geir Kvam-Langelandsvik

PhD Arash Imani Aria defended his PhD thesis on the 12th of September 2024. The title of his PhD thesis was: "Crystal plasticity modelling and simulation of yield surfaces of aluminium alloys". The doctoral work has been carried out at the Department of Materials Science and Engineering, where Professor Knut Marthinsen has been the candidate's main supervisor and Professor Bjørn Holmedal and Associate Professor Tomas Manik, Department of Materials Science and Engineering, have been the candidate's co-supervisors. The PhD work has been funded by the NTNU Digitalization Transformation initiative through the project 'AllDesign'.





INTERNATIONAL COLLABORATION



SFI PhysMet has an extensive international network, and several of our academic communities are highly recognized internationally in their fields. The research partners in SFI PhysMet cooperate with several leading universities and research environments in Europe, Japan, China, and the USA in ongoing and adjacent projects, as well as in strategic education and research collaboration through several INTPART projects. The collaboration is documented through joint publications with international partners as well as through invitations to give keynote and invited lectures at international conferences and seminars. The international reputation and visibility are further emphasized by the fact that several of the SFI PhysMet researchers are regularly invited to serve on evaluation committees for project proposals, promotions and PhD committees in Europe and overseas.

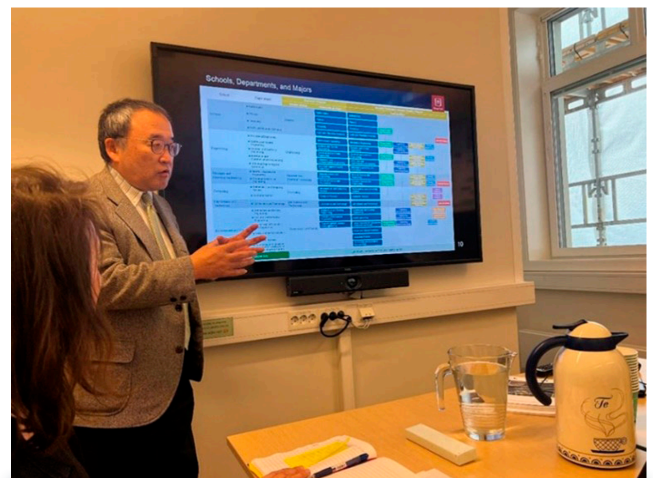
In March 2024, Professor Equo Kobayashi from Department of Material Science, Science Tokyo (formerly Tokyo Tech) visited NTNU, Department of Physics and Department of Material Science and Engineering. The main purpose of the visit was primarily to sign an AGREEMENT ON STUDENT EXCHANGE PROGRAM between School of Materials and Chemical Technology, Science Tokyo and The Faculty of Natural Sciences, Norwegian University of Science and Technology (NTNU). The agreement should also make a basis for the UTFORSK project, presented below, that was granted later in 2024.

Prof. Randi Holmestad, NTNU, presenting at ICAA19

In the fall 2024, Dept. of Physics and Dept. of Materials Science and Engineering were granted a joint 'UTFORSK' project: *Norwegian-Japanese collaboration on Sustainability and Recycling in Aluminium alloy development* (SuReAl) from the Norwegian Directorate for Higher Education and Skills (HKDir), with Professor Randi Holmestad as the project leader.

The project emphasizes sustainability, recycling, and life-cycle analyses in the aluminium value chain. It aims to create international networks, establish educational collaboration, promote cultural understanding, and enhance students' global competence. The main target groups are students from the university partners - NTNU, Science Tokyo, Kyushu University, University of Toyama, and Nagoya Institute of Technology. The industry partners are Hydro, Speira, YKK, Kobe Steels, UACJ and Toyo aluminium. SINTEF is also a project partner. The project will amongst other activities involve exchange of MSc and PhD students, industry internships (both ways), joint summer schools and workshops and 3-4 online webinars as are expected to have a positive impact on students, providing them with technical skills, cultural exposure, and networking opportunities. The project will sponsor travel and registration for ten Japanese participant to the International Aluminium Summer school in Trondheim summer 2025.

In August 2024, Professor Yves Brechet visited the SFI-PhysMet in connection with the National Conference on Materials Science (28-29/8/2024). Prof. Brechet gave a talk on *An example of a heavy industry for mass application: Building thermal management, thermal efficiency, electrification, decarbonation.* During his visit, he took time for discussions with some of the PhD students and key research scientists in SFI PhysMet. Professor Brechet is the Scientific Director at St. Gobain as well as adjunct Professor at Monash University, Australia. Prof. Yves is an internationally highly renowned expert in materials



Prof. Kobayashi giving his guest lecture as part of the SFI PhysMet webinar series.

Prof. Yves Brechet visited the SFI-PhysMet on August 30th, 2024.

science. His activities have spanned the fields of physical metallurgy, thermodynamics, microstructures, phase transformations, plasticity, fracture micromechanics, material selection, structural materials design, bio-interfaces, structural biomimetics.

A major challenge addressed by SFI PhysMet is ensuring that the research data and modelling software are findable, accessible, interoperable, and reusable (FAIR). RA5 (Data Sharing and Digital Platform) has focused on developing methodologies and a digital platform to document and make advanced characterization and modelling datasets and software tools available to partners. Collaborating closely with several EU projects, we have developed and tested methodologies for data documentation with industry partners in SFI PhysMet. The international collaboration has been invaluable for competence building, dissemination, and receiving feedback on the developed methodologies and tools. Researchers from RA5 have contributed to the European Materials Modelling Council (EMMC) roadmaps for Materials Modelling and Digitalization of Materials Sciences (2020) and Digital Transformation of Materials Science (2023). They have also participated in organizing EMMC international workshops in Vienna and served on the scientific committee for Materials Week in Cyprus 2024. Additionally, SFI PhysMet RA5 has led the collaborative development of microstructure ontology and contributed to several other ontologies, including the top-level EMMO ontology, the characterization ontology CHAMEO, the crystallography ontology, and the domain ontology for additive manufacturing (DOAM).

PhD candidate Andreas Bugten visited Michigan Technological University (MTU) (Host Prof. Paul Sanders) for four weeks in March 2024. At Michigan MTU he investigated cast iron contaminated with the chemical element boron. Samples were quenched at various temperatures (experimental setup in the photo below) to study the morphology of the graphite particles embedded in the iron, and experiments were conducted to examine the effect of cooling rate on the material. Furthermore, casting experiments were also carried out with the intention of binding boron in particles. A manuscript with the results from this work is going to be submitted to an international journal during Spring 2025.

The image shows the setup of the quenching experiments carried out by A. Bugten at MTU. Cooling cups with integrated thermocouples are filled with cast iron. The cups are then released into the water-filled container at appropriate temperatures.

In 2024, through Dr. Leander Michels and Håkon Trygve Mause of Elkem, we established collaboration with a Brasilian University, Universidade Federal do Rio Grande do Sul, UFRGS, Porto Alegre. Two Ph.D studens, Osvaldo S. Neto, and Marcos Paulo Ribeiro visited SFI Physmet in May and October 2024, carrying out collaborative research. The hosting professor at NTNU is Yanjun Li. Their research topics are about Grain refinment of High Cr Wear Resistant Cast Irons, and Grain refinement of High Mn wear resistant cast steels, respectively. In the projects, the innovative grain refiner produced by Elkem, EGR, has been used and promising results are achieved.

Visit to Elkem. From left: Osvaldo S. Neto, Elkem representative, Yanjun Li, Håkon Trygve Mauset, Andreas Narmo, Marcos Paulo Ribeiro, Leander Michels.

DISSEMINATION AND COMMUNICATION

Our aim is that results from SFI PhysMet shall be visible and implemented. Scientific publications and conference presentations are our main and most important arena to make our research visible in the national and international research communities. However, an important aim is also to facilitate and ensure implementations of new results in the industry sector. Scientists also have a responsibility to build bridges between science and society and explain complex science and its potential impact of to the general public.

An important arena to reach out to the public and make information from the Centre easily available is our website **ntnu.edu/phymet**

WEBINARS

Since 2021 we have invited all partners to attend monthly webinars with scientific presentations on topics relevant to SFI PhysMet members. The webinars are easily available for all researchers and industry partners, as they are presented online. The presentations have been a success, with many participants.

Date	Who	Title
25. January	Prof. Nathalie Bozzolo, Mines-ParisTech-CEMEF, Sophia Antipolis, France	Tentative: Recrystallization phenomena in nickel based superalloys
25. January	Dr. Carol Tragor-Cowan, Univ. of Strathclyde, Glasgow, UK	Pushing the limits of diffraction imaging in the scanning electron microscope for the structural characterisation of nitride semiconductor thin films and microstructures.
14. March	Prof. Equo Kobayashi	Alloy designing of biomedical >Ti-Zr based alloys - Phase stability, microstructure and properties
15. May	Dr. Tomas Flint, Univ. Of Manchester*	Computational Metallurgy in the Solid, Liquid, Vapour and Plasma States
12. June	Sen. Eng. Elvia Panduro, IMA	RECX National Infrastructre
21. August	Professor Laure Bourgeois, Monash Univ. Australia	From one structure to another: determining solid-state transformation mechanisms at the atomic scale in light alloys
30. August	Prof. Yves Brechet, Saint Gobain, France	Non classical aspects of nucleation of precipitation
13. Sept.	Dr. Matti Lindroos, VTT, Finland	Application of ICME to address process-structure and structure-property problems in engineering design/materials
6. November	Stig Tjøtta, Hydro	Decarbonizing Aluminium in a 2050 Perspective
5. December	Marie-Noëlle Avettand-Fènoël, Univ. of Lille	Wire Arc Additive Manufacturing of a martensitic stainless steel: How do the successive thermal cycles affect the microstructure of a freshly solidified layer during wall building?

CONSORTIUM MEETINGS

We organize bi-annual SFI meetings with participants from all partners. These meetings are good arenas for exchange of ideas and dissemination of the latest scientific findings from the five research areas.

The SFI PhysMet consortium spring meeting was held in Kristiansand 24 -25 April. Day 1 was mainly dedicated to presentation of recent progress and scientific highlights within the different research areas of the SFI, including presentation from the PhD candidates.

Day 2 included, among other things discussions focusing on ongoing research activities and plans, including feedback and input from the industry partners. After lunch our colleagues at Elkem had organized a guided tour at the Elkem Fiskaa plant. Impressive program and logistics, and a lot of interesting things to see and learn.

The SFI PhysMet consortium fall meeting was organized in Trondheim 13.-14. November.
Day 1 was mainly dedicated to presentations of recent progress and scientific highlights within each of the SFI Research Areas, as well as key elements of the work plans for 2025. The first day was rounded off with a poster session with all together 17 posters, illustrating the breadth and variety of the research activities, including several student specialization projects.

Day 2 started with three very interesting presentations related to microstructure and property modelling, including both a bit of history, via current status and instructive examples, to current and future trends related to the new possibilities of AI and machine learning approaches, which for sure will be an important part of future work in this connection.

Group photo from the consortium meeting in November.

NATIONAL CONFERENCE ON MATERIALS TECHNOLOGY

28-29 August 2024, SFI PhysMet co-organized together with Norsk Materialteknisk Selskap – Division Trøndelag, National Conference on Materials Technology, 2024, on the topic Materials for the Green Shift: Challenges and Opportunities. SFI PhysMet co-director Prof. Marisa Di Sabatino was the conference chair. The conference opened with a keynote presentation from Professor Yves Brechet, scientific Director at St. Gobain as well as adjunct Professor at Monash University, Australia. Prof. Brechet is an internationally highly renowned expert in materials science. SFI PhysMet was well represented and promoted at the conference with plenary lectures from two of our industrial partners, Equinor and Hydro, as well as with presentations from several of the PhD candidates as well from NTNU and SINTEF researchers.

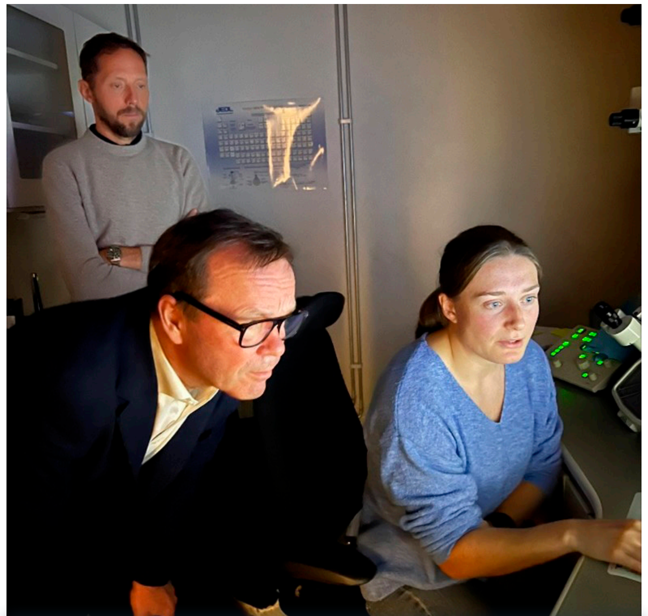
STUDENTS SEMINAR

The Physical Metallurgy students seminar was held at IMA/NTNU on November 28th.
All 17 students presented their results from the Fall semester and 9 of these theses are directly linked to the SFI-PhysMet. We concluded the seminar with a pizza lunch for everyone!

VISIT FROM HYDRO

On 30 October, NTNU and SINTEF received a visit from Hydro by CEO Eivind Kallevik, technology director Trude Sundset, VP, Company Specialist Christian Rosenkilde and Research Manager Trond Furu.

It is a long tradition that the top management of Hydro once a year comes to Trondheim to meet with NTNU and SINTEF leaders and key research personnel involved in the Hydro/NTNU/SINTEF research collaboration. The day started with a gathering in the premises of SFI PhysMet at Gløshaugen. During the day, visits were made to a number of NTNU/SINTEF laboratories, which are extensively used in Hydro/NTNU/SINTEF collaborative projects and activities, including the transmission electron microscopy laboratories in Chemistry building 1 (NORTEM facilities), where Professor Randi Holmestad and colleagues showed around, and the laboratories in Perleporten with laser welding, with Business developer Magnus Eriksson, SINTEF Industry as the host. Research Director, Nina Dahl, SINTEF, and SFI PhysMet Board Chairperson, guided the guests to the different laboratories at NTNU and SINTEF during the day. It was the first time the new CEO in Hydro visited NTNU and SINTEF and he was impressed by the extent of the collaboration between Hydro and NTNU/SINTEF and all the enthusiastic researchers the Hydro delegation met during their visit.



PhD candidate Inga Konow in front of the transmission electron microscope (TEM) together with the Hydro CEO Svein Kallevik. In the background, Chr. Rosenkilde. (Photo Randi Holmestad)

Magnus Eriksson is showing Eivind Kallevik the laser welding machine in Perleporten. (Photo: Silje Grytli Tveten)

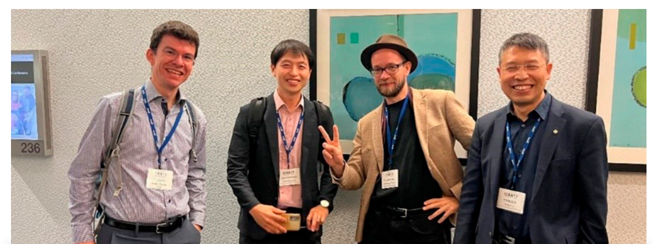
INTERNATIONAL CONFERENCES AND MEETINGS

During 2024 SFI PhysMet researchers have attended and presented their results at a number of international scientific conferences and meetings, as exemplified below.

Professor Knut Marthinsen participated on 5-6 February at a two-day scientific discussion meeting on Sustainable metals and systems in London UK. The meeting was organised by Professor Julian M Allwood FREng, Materials Science and Engineering, University of Cambridge and Professor Dierk Raabe, Max-Planck Institute for Iron Research, and gathered more than 80 experts from around the world, with physical presence or online. The meeting was hosted by the Royal Society, London, and took place in venerable and historic locations in central London, with big paintings of Sir Isac Newton, Ernest Rutherford and Stephen Hawkings on the wall.

May 26-31, 2024, Senior researcher Qiang Du from SINTEF, presented results from SFI PhysMet at the 51st International Conference on Computer Coupling of Phase Diagrams and Thermochemistry at Dorint Kongresshotel Mannheim, Germany. The International CALPHAD Conference was first held in 1973. Since then, it provides to scientists and students with an interest in thermodynamics of materials an opportunity to meet, present and discuss their work in a friendly atmosphere.

SFI PhysMet was well represented at the 19th International Conference on Aluminum Alloy (ICAA19). The International Conference on Aluminum Alloys (ICAA) is the world's leading conference series relating to science and technology of aluminum alloys. It was founded in 1986 and has been organized every second year since then, alternating between Europe, Asia and the American continent. Prof. K. Marthinsen is a long-time member of the International Committee for the ICAA conferences. This year conference, ICAA19 was organized in Atlanta, Georgia, US, 23-27 June, with Georgia Institute of Technology and Novelis as the organizers. While ICAA19 comprised the usual exciting mix of technical symposia, ranging from the latest techniques and capabilities, to advances in alloy design and modelling, and emerging markets and applications, the over-arching focus was the critical role that aluminium will play in enabling the low carbon and circular societies and economies of the future, including a special symposium dedicated to sustainability in design and recycling. Professor Randi Holmestad and Professor Yanjun Li, Research manager PhD Ruben Bjørge and Professor Knut Marthinsen all gave talks at the conference. Profs. Yanjun Li and Knut Marthinsen participated and gave presentations at the 44th Risø International Symposium at DTU Risø Campus (Roskilde) in Denmark. The topic of this years' Risø Symposium was Metal Microstructures and Additive Manufacturing. The conference weas organized by Department of Civil and Mechanical Engineering Technical University of Denmark, and with Prof. Dorte Juul Jensen (member of the SFI PhysMet Scientific Advisory Committee) as the chair. The conference gathered experts from all around the world to present and discuss the recent advances related to the formation and characterization of microstructures in Additive Manufacturing of metallic materials (incl. Aluminum, steel, titanium, +++).



An important part of attending conferences in person, is to meet with and discuss with both old and new friends and colleagues. Group photo above: From left: PhD Ruben Bjørge, SINTEF, Dr. JaeHwang Kim (former visiting researcher at NTNU), Dr. Flemming Ehlers, Nanjing Tech. University, (former postdoc at NTNU), Prof. Yanjun Li, NTNU.

There is a close collaboration between the research- and industry partners. Many of our industry partners have also an active role in the co-supervision of our master students. One of the outcomes of this good and fruitful collaboration in 2024 was the participation in the 17th Silicon for the Chemical and Solar industry conference in Trondheim, 11-13 September. Here, Dr Alberto Olivo from Elkem presented the work "Ageing of micro and nano silicon surface", which is the result of the collaboration with master student Martin Høyen and prof. Marisa Di Sabatino at NTNU. The work was also published in the conference proceedings.

Silicon for the chemical and solar industry XVII
Edited by M.Tangstad, H.Rong, A.Valderhaug, B.Andresen and I.G.Page
Trondheim, 10-13 September 2024

Ageing of micro and nano silicon surface

A. Olivo[1], L. Michels[1,2], M.M. Høyen[3], K. Friestad[1], and M. Di Sabatino[3]

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[2]Norwegian University of Science and Technology (NTNU), Dept. of Physics, Norway
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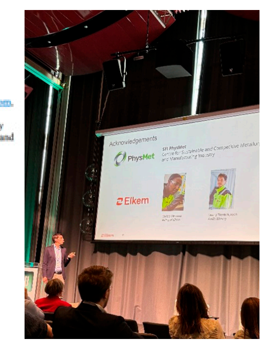
Keywords: silicon, surface, etching, ageing, oxidation, model

Abstract - Silicon (Si) can potentially become the raw material of the future due to its applicability into strategic technologies for net-zero transition, but the applicability of silicon in those fields strongly relies on a precise tailoring both of bulk and surface features. Micro and nano Si are also characterised by larger specific surface area (SSA) and the higher surface to volume ratio triggers Si reactivity towards water and oxygen, thus affecting the properties of Si native oxide layer (SiO_x). The present work was designed to unravel the most relevant features of SiO_x formation by characterising surface properties of several Si materials. All samples were stored for more than 18 months prior to analyses at atmospheric conditions, then etched to remove SiO_x layer, and finally re-oxidised by thermal treatment in controlled conditions.
The results indicated the effect of natural environmental oxidation on SiO_x surface consists in the hydrolysis of Si-H to Si-OH. This causes the agglomeration of Si, as observed by the increase of intra-particle porosity. Moreover, experimental data confirmed that oxidation was more severe in samples with smaller particle size distribution. Finally, through thermal treatment, it was possible to simulate SiO_x formation on etched samples and simulate the natural process of ageing.



PERSONELL SFI PHYSMET

CENTRE ADMINISTRATION

Knut Marthinsen	NTNU	Centre Director
Marisa Di Sabatino	NTNU	Deputy Centre Director
Torleif Nordskog	NTNU	Adminsitrative Coordinator
Magnus Eriksson	SINTEF Industry	Scientific Coordinator

KEY RESEARCHERS

RESEARCH AREA 1. MULTI-SCALE MATERIAL ANALYSES

Randi Holmestad	NTNU	Multi-scale material analyses
Sigurd Wenner	SINTEF Industry	Nano-/microstructure characterization (TEM and APT)
Marisa Di Sabatino	NTNU	Material-processing and characterization (GDMS and GDOES)
Calin D. Mariora	SINTEF Industry	Nano-/microstructure characterization (TEM)
Yanjun Li	NTNU	Scale and process bridging methodologies
Siri Marthe Aarbo	SINTEF Manufacturing	Materials, processing and properties
Ruben Bjørge	SINTEF Industry	Nano-/microstructure characterization (TEM and APT)
Tina Bergh	NTNU	Nano-/microstructure characterization (TEM, FIB, SEM)
Geir Kvam-Langelandvsik	SINTEF Industry	Aluminium welding
Tor S. Haugland	SINTEF Industry	Machine Learning

RESEARCH AREA 2. SCALE AND PROCESS BRIDGING METHODOLOGIES

Yanjun Li	NTNU	Scale and process bridging methodologies
Bjørn Holmedal	NTNU	Crystal Plasticity, microstructure- and property modelling
Knut Marthinsen	NTNU	Microstructure-, texture and property modelling
Tomas Manik	NTNU	Crystal plasticity modelling
Emre Cinkilic	NTNU	Microstructure modeling
Xuezhou Wang	NTNU	Atomic and microstructural modelling of clustering and precipitation kinetics
Sylvain Gouttebroze	SINTEF Industry	Materials modelling
Qiang Du	SINTEF Industry	Thermodynamical and microstructure modeling
Ole Martin Løvvik	SINTEF Industry	Atomic scale modelling
Yijang Xu	SINTEF Industry	Materials modelling
Tor Strømsem Haugland	SINTEF Industry	Atomic scale modelling
Xiaobo Ren	SINTEF Industry	Microstructure modelling, Welding process
Victor Fachinotti	SINTEF Industry	Thermodynamic and microstructure modelling
Kai Zhang	SINTEF Industry	Cystal plasticity modelling
Daniel Machand	SINTEF Industry	Atomic and microstructure modeling

RESEARCH AREA 3. SUSTAINABLE AND HIGH-PERFORMANCE MATERIAL DEVELOPMENT

Astrid Marthinsen	SINTEF Industry	Sustainable and high-performance material development
Kjerstin Ellingsen	SINTEF Industry	Sustainable and high-performance material development
Marisa Di Sabatino	NTNU	Material-processing, properties and characterization
David Wragg	IFE	Powder synthesis and characterization
Qiang Du	SINTEF Industry	Thermomechanical processing
Kai Zhang	SINTEF Industry	Sustainable and high-performance material development

RESEARCH AREA 4. INNOVATIVE PROCESSING AND JOINING METHODS

Magnus Eriksson	SINTEF Industry	Thermo-mechanical processing and welding
Geir Kvam-Langelandsvik	SINTEF Industry	Aluminium alloy process developments and characterisation for welding and AM
Ivan Bunaziv	SINTEF Industry	Laser materials processing; process study and stability, microstructure and properties
Xiaobo Ren	SINTEF Industry	Materials, processing and properties
Ida Westermann	NTNU	Thermo-mechanical processing, microstructure and mechanical properties
Jens Christofer Werenskiold	NTNU	Thermo-mechanical processing, microstructure and mechanical properties
Tomáš Mánik	NTNU	Materials, processing and properties, Material modelling
Nima Razavi	NTNU	Fatigue and fracture of metallic materials and structures. Properties of additive manufactured materials
Siri Marthe Aarbo	SINTEF Manufacturing	Materials, processing and properties
Jon Holmestad	SINTEF Manufacturing	Materials, processing and properties
Vegard Brøtan	SINTEF Manufacturing	Additive Manufacturing Materials, processing and properties
Jørgen Sørhaug	SINTEF Manufacturing	Materials, processing and properties
Luigi Viespoli	SINTEF Industry	Materials, processing and properties
Bård Nyhus	SINTEF Industry	Materials, processing and properties
Calin Marioara	SINTEF Industry	Nano-/microstructure characterization (TEM and APT)
Ragnhild Aune	SINTEF Industry	Welding, processing and properties
Morten Høgseth Danielsen	SINTEF Industry	Welding, Laser Arc Hybrid Welding, Processes
Nikolai Marhaug	SINTEF Industry	Welding, Arc Welding, Processes
Sigurd Wenner	SINTEF Industry	Nano-/microstructure characterization (TEM and APT)
Ruben Bjørge	SINTEF Industry	Nano-/microstructure characterization (TEM and APT), material physics
Kjerstin Ellingsen	SINTEF Industry	Materials, processing and properties

RESEARCH AREA 5. DATA, SHARING AND DIGITAL PLATFORMS

Jesper Friis	SINTEF Industry	Data, sharing and digital platforms
Sylvain Gouttebroze	SINTEF Industry	Materials modelling and digital platform
Tomas Manik	NTNU	Crystal plasticity modelling and digital platform
Terence Coudert	SINTEF Industry	Data, sharing and digital platforms
Stephane Dumoulin	SINTEF Industry	Materials modelling, digital platform
Astrid Marthinsen	SINTEF Industry	Data sharing and digital platforms
Johan Andreas Stendal	SINTEF Manufacturing	Data sharing and digital platforms
Tor S. Haugland	SINTEF Industry	Data sharing and digital platforms
Thawin Hart-Rawung	SINTEF Manufacturing	Data sharing and digital platforms

VISITING RESEARCHERS

Osvaldo S. Neto	Engenharia de Produto e Processo, USIPE, Brazil	Grain refinment of High Cr Wear Resistant Cast Iron
Marcos Paulo Ribeiro	Engenharia de Produto e Processo, USIPE, Brazil	Grain refinement of High Mn wear resistant cast steel

PHD STUDENTS WITH FINANCIAL SUPPORT FROM THE CENTRE BUDGET

Ingvild Runningen	2021 - 2025	New wires for welding of aluminium alloys
Andreas Voll Bugten	2021 - 2025	The effect of trace elements on the microstructure development and mechanical properties of cast irons.
Xuezhou Wang	2021 - 2025	Develop precipitation model with improved nucleation concepts
Supreet Kaur	2023 - 2026	Effect of trace elements on recycled Al alloys
Håkon Longva Korsvold	2023 - 2026	Materials Physics and Transmission Electron Microscopy
Jan Konkel	2024 - 2027	Development of Low Transformation Temperature (LTT) Steel Alloys for Welding and Additive Manufacturing Applications
Jianbin Xu (Postdoc)	2024 - 2026	Laser-based welding of steel and aluminium alloys
Inga Dahlen Konow	2024 - 2027	The effect of deformation on 6xxx Al-alloys

PHD STUDENTS WORKING ON PROJECTS IN THE CENTRE WITH FINANCIAL SUPPORT FROM OTHER SOURCES

Håkon Wiik Ånes	NAPIC/NTNU internal	Recrystallization and textures in Al-alloys. SEM/EBSD methodologies and experimental characterization (Disputation 25 January)
Endre Aasheim	Nærings PhD - Hydro	Nucleation, growth and dissolution of ß-Mg2Si particles in Al-Mg-Si (Disputation 21 mai)
Imani Aria Arash	NTNU Digital Transformation	Multiscale materials modelling; Crystal Plasticity (Disputation 12 September)
Gabriela Kazimiera Warden	FME Susoltec	Quartz crucibles for PV silicon solidification
Chunan Li	NFR KPN SumAl	Clustering and precipiation in Al-alloys
Håkon Linga	SFI Manufacturing	3D-printing
Hassan Moradi Asadkhandi	NFR FriNatek	Crystal Plasticity
Magnus Reiersen	Institutt-PhD SINTEF	Modelling and experimental framework for accelerated development of materials for Laser Powder Bed Fusion technology with application to Al alloys.
Trond Arne Hassel	SINTEF Manufacturing	Additive manufacturing (Disputation 28 November)
Hitesh Kumar		The Corrosion protection of floating structures using laser welding technology

POSTDOCTORAL RESERACHERS WORKING ON PROJECTS IN THE CENTRE WITH FINANCIAL SUPPORT FROM OTHER SOURCES

Rania Hendawi	FME Susoltec	Structure loss in CZ-silicon (untill August 2024)
Baptiste Reyne	Metplast, NFR	The next generation metal continuum plasticity theory (Untill April)
Yaping Wang	IPN-Dare2C2	Aluminium reinforced concrete (until May 2024)

MASTER STUDENTS

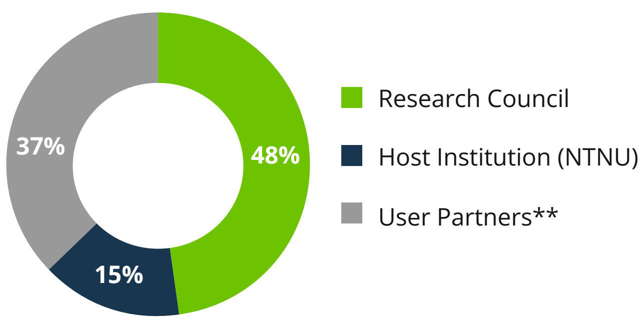
Jan Konkel	Comparison of conventional extrusion and Screw Extrusion of a 1xxx Aluminium alloy
Trine Homme Misund	Effect of Cu and Natural Ageing on Automotive Aluminium Alloys
Martin Myrstad Høyen	Characterization of silicon powders from different processes
Elias Breiland Hetland	Effect of Trace Elements and Impurities in Recycled Aluminium Alloys
Daniel Aron Preminger	Enabling microstructure models as a cloud-based solution
Inga Dahlen Konow	Silicon Powder and okside layers in TEM
Espen Gregory	The double-peak in Cu containing 6082 Alloys, TEM studies
Sindre Vie Jørgensen	Steels and Ce additions, TEM studies
Anne E Strømsnes	Development of high strength aluminium welding wires
Sigbjørn Lerum	Addition of microceramical particles in aluminium casting

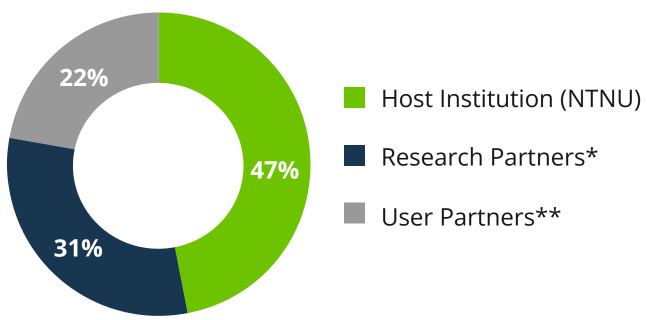
ANNUAL ACCOUNTS 2024

The total budget for the eight year SFI PhysMet centre period is 208 mill NOK. The financing of SFI PhysMet is based on contribution from The Research Council of Norway and cash and in-kind contribution from the user partners and NTNU. Results for 2024:

Funding (1000 NOK)	Amount
Research Council	13 248
Host Institution (NTNU)	4 064
Research Partners*	0
User Partners**	10 033
Total	**27 345**

Costs (1000 NOK)	Amount
Host Institution (NTNU)	12 921
Research Partners*	8 496
User Partners**	5 928
Equipment	0
Total	**27 345**





* *SINTEF AS, SINTEF Manufacturing and IFE.*
** *Hydro Aluminium AS, Elkem AS, Equinor, Benteler, Raufoss Technology, Thermo-Calc Software, The Norwegian Public Roads Administration.*

PUBLICATIONS AND CONFERENCE PRESENTATIONS 2024

PUBLICATIONS DIRECTLY FUNDED BY SFI PHYSMET:

- **Del Nostro, Pierluigi; Friis, Jesper; Ghedini, Emanuele; Goldbeck, Gerhard; Toti, Daniele; Zaccarini, Francesco Antonio**. *Top level ontologies: desirable characteristics in the context of materials science.* CEUR Workshop Proceedings 2024
- **Du, Qiang; Hamdi, Mohammed; Reiersen, Magnus; Hovig, Even Wilberg; Zhang, Kai.** *A fully kinetic phase diagram-coupled multicomponent columnar-to-equiaxed grain transition model with an application to additive manufacturing.* Calphad 2024
- **Han, F.; Luo, X.; Liu, Q.; Hou, Z.; Marthinsen, Knut; Wu, G.L.; Hatzoglou, Constantinos; Kontis, Paraskevas; Huang, X..** *The effect of grain size and rolling reduction on microstructure evolution and annealing hardening response of a Mg-3Gd alloy.* Journal of Magnesium and Alloys 2024
- **Han, Fang; Luo, Xuan; Marthinsen, Knut; Wu, Guilin; Hou, Ziyong; Huang, Xiaoxu.** *Effect of initial grain size on the recrystallization behavior and recrystallization texture of a Mg–3Gd alloy.* Journal of Materials Science & Technology 2024
- **Hassel, Trond Arne; Kulbotten, Inge Morten; Arbo, Siri Marthe; Rørvik, Gisle; Brøtan, Vegard; Sørby, Knut.** *Corrosion, Impact Toughness and Tensile Properties of Duplex Stainless Steels Manufactured by Directed Energy Deposition.* Metallurgical and Materials Transactions A 2024
- **Hassel, Trond Arne; Marken, Lene Anita; Arbo, Siri Marthe; Rørvik, Gisle; Du, Qiang; Brøtan, Vegard; Sørby, Knut.** *Microstructure Development in Duplex Stainless Steels from Additive Manufacturing with Coaxial Directed Energy Deposition and Heat Treatment.* Metallurgical and Materials Transactions A 2024
- **Hennum, Endre Asheim; Marthinsen, Knut; Tundal, Ulf Håkon.** *Effect of Microstructure on the Precipitation of -Mg2Si during Cooling after Homogenisation of Al-Mg-Si Alloys.* Metals 2024
- **Imani Aria, Arash; Holmedal, Bjørn; Manik, Tomas; Marthinsen, Knut.** *A Full-Field Crystal Plasticity Study on the Bauschinger Effect Caused by Non-Shearable Particles and Voids in Aluminium Single Crystals.* Metals 2024
- **Imani Aria, Arash; Holmedal, Bjørn; Manik, Tomas; Marthinsen, Knut.** *Crystal-plasticity modelling of the yield surfaces and anelasticity in the elastoplastic transition of metals.* European Journal of Mechanics. A, Solids 2024
- **Langelandsvik, Geir; Skorpen, Kristian Grøtta; Werenskiold, Jens Christofer; Roven, Hans Jørgen.** *Review of Metal Screw Extrusion: State of the Art and Beyond.* Metals 2024
- **Li, Chunan; Marioara, Calin Daniel; hatzoglou, constantinos; Andersen, Sigmund Jarle; Holmestad, Randi; Li, Yanjun.** *Accelerating precipitation hardening by natural aging in a 6082 Al-Mg-Si alloy.* Acta Materialia 2024
- **Ma, C; Zhao, Qinglong; Liu, Xiao; Li, Yanjun; Jiang, Qichuan.** *Introducing high-density growth twins in aluminum alloys by laser surface remelting via templated nucleation of grains.* Journal of Materials Science & Technology 2024
- **Wang, Yaping; Fagermo, Moa; Furu, Trond; Justnes, Harald; Marthinsen, Knut.** *Compatibility of Different Aluminium with a New Environmental-Friendly Concrete.* Advances in Science and Technology 2024
- **Wu, Zixuan; Jiang, Xiaosong; Sun, Hongliang; Li, Yanjun; Skaret, Pål Christian; Yang, Liu.** *Hybrid graphene nanoplatelets/multi-walled carbon nanotubes reinforced Cu/Ti3SiC2/C nanocomposites with high*

efficiency dispersal and strengthening through high-pressure torsionhigh-pressure torsion. Surfaces and Interfaces 2024

- **Xu, Yijiang; Tranell, Maria Gabriella; Li, Yanjun.** *Understanding heterogeneous nucleation and predicting grain size in wire and arc additive manufacturing of steels with inoculation.* IOP Conference Series: Materials Science and Engineering 2024
- **Zhang, Kai; Wenner, Sigurd; Marioara, Calin Daniel; Hovig, Even Wilberg; Du, Qiang; Onsøien, Morten Ingar; Marthinsen, Knut.** *Additive Manufacturing of 7xxx Aluminium Alloys by Laser Powder Bed Fusion.* IOP Conference Series: Materials Science and Engineering 2024

PUBLICATIONS FROM COLLABORATING PROJECTS

- **Bartawi, Emad H.; Marioara, Calin Daniel; Shaban, Ghada; Rahimi, Ehsan; Mishin, Oleg V.; Sunde, Jonas Kristoffer; Gonzales-Garcia, Yaiza; Holmestad, Randi; Ambat, Rajan.** *Effects of grain boundary chemistry and precipitate structure on intergranular corrosion in Al-Mg-Si alloys doped with Cu and Zn.* Corrosion Science 2024
- **Chrominski, W.; Christiansen, Emil; Choinska, E.; Holmestad, Randi; Lewandowska, M..** *Enhancing homogenous precipitation and strengthening effectiveness in AlCuMg alloy.* Journal of Materials Research and Technology (JMR&T) 2024
- **Gawel, Bartłomiej Adam; Busam, Jochen; Marthinsen, Astrid; Warden, Gabriela Kazimiera; Hallem, Benny; Di Sabatino, Marisa.** *Influence of aluminium doping on high purity quartz glass properties.* RSC Advances 2024
- **Gazizov, Marat; Mironov, S.Yu.; Holmestad, Randi; Gazizova, M.Yu.; Kaibyshev, R.O..** *Effect of ECAP and aging on microstructure of an Al-Cu-Mg-Si alloy.* Materials Characterization 2024
- **Gazizov, Marat; Zuiko, I.S.; Holmestad, Randi; Gazizova, M.Yu.; Kaibyshev, R.O..** *Particle morphology characterization in an over-aged Al-Cu-Mg-Si alloy using TEM.* Materials Characterization 2024
- **Gopal, Akash; Shah, Sohail; Holmedal, Bjørn.** *On the influence of crystallographic texture on cyclic hardening of an AlMgSi alloy.* Scripta Materialia 2024
- **Hell, Christoph Martin; Frafjord, Jonas; Bjørge, Ruben; Friis, Jesper; Holmestad, Randi.** *On the visibility of GP-zones in 6xxx Al alloys in atomic LAADF-STEM.* Materials Characterization 2024
- **Hendawi, Rania; Arnberg, Lars Erik; Di Sabatino, Marisa.** *Crucibles and coatings for silicon melting and crystallization: An in-depth review of key considerations.* Progress in Materials Science 2024
- **Hendawi, Rania; Di Sabatino, Marisa.** *Analyzing structure loss in Czochralski silicon growth: Root causes investigation through surface examination.* Journal of Crystal Growt 2024
- **Hendawi, Rania; Stokkan, Gaute; Øvrelid, Eivind Johannes; Di Sabatino, Marisa.** *Surface Examination of Structure Loss in N-Type Czochralski Silicon Ingots.* SiliconPV Conference Proceedings 2024
- **Holmedal, Bjørn; Kula, Anna; Niewczas, Marek.** *Plasticity of solid solution Al-Mn and Al-Mn-Si alloys.* Journal of Materials Science and Engineering: A 2024
- **Ling, Zihan; Chen, Mingyang; Wang, Liqing; Ma, Kai; Zhang, DongDong; Li, Yunlong; Zhang, Zhen; Zhao, Zhanyong; Bai, Peikang; Li, Yanjun.** *Microstructure evolution and mechanical property of Mg-Gd-Y-Zn-Zr alloy wires prepared by hot drawing.* Journal of Materials Research and Technology (JMR&T) 2024
- **Ma, Ning; Yu, Xuehao; Liu, Enzuo; Zhao, Dongdong; Sha, Junwei; He, Chunnian; Li, Yanjun; Zhao, Naiqin.** *First-principles interpretation toward the effects of Cu, Mg co-segregation on the strength of Al Σ5 (210) grain boundary.* Journal of Materials Science 2024
- **Manik, Tomas.** *Independent parameters of orthotropic linear transformation-based yield functions.* Mechanics of materials (Print) 2024
- **Marioara, Calin Daniel; Andersen, Sigmund Jarle; Hell, Christoph Martin; Frafjord, Jonas; Friis, Jesper; Bjørge, Ruben; Ringdalen, Inga Gudem; Engler, Olaf; Holmestad, Randi.** *Atomic structure of clusters and GP-zones in an Al-Mg-Si alloy.* Acta Materialia 2024
- **Mi, Xiaoxi; Dai, Lili; Jing, Xuerui; She, Jia; Holmedal, Bjørn; Tang, Aitao; Pan, Fusheng.** *Accelerated design of high-performance Mg-Mn-based magnesium alloys based on novel bayesian optimization.* Journal of Magnesium and Alloys 2024
- **Rhee, Yujin; Thronsen, Elisabeth; Ryggetangen, Oskar; Marioara, Calin Daniel; Holmestad, Randi; Kobayashi, Equo.** *Effect of Pre-Deformation on Precipitation in Al–Zn–Mg–Cu Alloy.* Metals and Materials International 2024
- **Di Sabatino, Marisa; Hendawi, Rania.** *Crystallization processes for photovoltaic silicon ingots: Status and perspectives.* Journal of Crystal Growth 2024
- **Di Sabatino, Marisa; Hendawi, Rania Tayseer Atieh; Garcia, Alfredo Sanchez.** *Silicon Solar Cells: Trends, Manufacturing Challenges, and AI Perspectives.* Crystals 2024
- **Warden, Gabriela Kazimeira; Ebbinghaus, Petra; Rabe, Maritn; Juel Mari; Gawel, Bartiomiej; Erbe, Andreas; Di Sabatino, Marisa.** *Investigation of uniformity in fused quarts crucibles for Czochralski silicon ingots.* Journal of Crystal Growth 2024
- **Zang, Ruojin; Wan, Bin; Ding, Lipeng; Ehlers, Flemming J H; Jia, Zhihong; Cao, Lingfei; Li, Yanjun.** *The combined effect of pre-aging and Mg/Si ratio on the natural aging and bake hardening in Al-Mg-Si-0.7Cu alloys.* Materials Characterization 2024
- **Zhu, Mengyi; Safarian, Jafar; Mochamad Ilham, Al Fariesy Irvansyah; Di Sabatino, Marisa.** *Effect of Mg alloying and cooling rate on the microstructure of silicon.* Frontiers in Photonics. 2024

CONFERENCE PRESENTATIONS

- **Bugten, Andreas Voll; Di Sabatino, Marisa; Michels Brito Miranda, Leander Edward; Arnberg, Lars Erik; Li, Yanjun.** *In-Situ Synchrotron X-Ray Diffraction: Tracking Phase Transformations in Real-Time.* SFI PhysMet Consortium meeting; 2024-11-13 - 2024-11- 14
- **Bugten, Andreas Voll; Di Sabatino, Marisa; Michels Brito Miranda, Leander Edward; Arnberg, Lars Erik; Li, Yanjun.** *Recycling of B-added Steel Scrap Into Spheroidal Graphite Cast Iron.* Nasjonal konferanse for materialteknologi; 2024-08-28 - 2024-08-29
- **Friis, Jesper; Bleken, Francesca Lønstad; Manik, Tomas.** *Data sharing for cross-disciplinary green solutions.* National conference for materials technology 2024; 2024-08-28 - 2024-08-29
- **Friis, Jesper; Ghedini, Emanuele; Zaccarini, Francesco Antonio; Goldbeck, Gerhard; Bleken, Francesca Lønstad; Gouttebroze, Sylvain; Haugland, Tor S..** *Ontologies for FAIR Data Documentation: Enabling Data Accessibility.* COSY 2024 Final Event; 2024-11-20
- **Friis, Jesper; Gouttebroze, Sylvain; Marthinsen, Astrid; Bleken, Francesca Lønstad; Manik, Tomas.** *Domain ontology for sharing data related to sustainable metallurgical and manufacturing industry.* Materials Week; 2024-06-17 - 2024-06-20
- **Hennum, Endre Asheim; Marthinsen, Knut; Tundal, Ulf Håkon.** *Controlling precipitation of Mg2Si particles during thermo-mechanical processing of AlMgSi-alloys.* The 8th International Symposium on Advanced Structural Materials; 2024-11-09 - 2024-11-10
- **Holmestad, Randi.** *Aluminium microstructure and alloy development by TEM – ongoing projects etc.* Seminar Hydro Extrusions Finspång; 2024-10-16 - 2024-10-16
- **Holmestad, Randi; Bergh, Tina; Sørhaug, Jørgen Andre; Hell, Christoph Martin; Thronsen, Elisabeth; Bjørge, Ruben; Marioara, Calin Daniel.** *Advanced electron microscopy – SPED and HAADF-STEM – of age hardenable aluminium alloys.* ELMINA24; 2024-09-09 - 2024-09-13
- **Holmestad, Randi; Bergh, Tina; Sørhaug, Jørgen Andre; Hell, Christoph Martin; Thronsen, Elisabeth; Bjørge, Ruben; Marioara, Calin Daniel.** *Advanced TEM studies of precipitation in aluminium alloys.* Ranshofener Leichtmetalltage 2024; 2024-09-26 - 2024-09-27
- **Kaur, Supreet; Indriyati, Martha; Åsholt, Petter; Trond Furu; Sharma, Ashok; Li, Yanjun; Di Sabatino, Marisa.** *Effects of Impurities on HPDC Aluminium Alloys.* National Conference for Material Technology; 2024-08-28 – 2024-08-29
- **Li, Yanjun; Xu, Yijiang; Mathiesen, Ragnvald.** *Understanding heterogeneous nucleation and predicting grain size in wire and arc additive manufacturing of steels with inoculation.* 44th Risø International Symposium on Materials Science; 2024-09-02 - 2024-09-06
- **Li, Yanjun; Xu, Yijiang; Mathiesen, Ragnvald.** *Understanding the grain structure development during normal solidification and additive manufacturing.* 19th International Conference on Aluminium Alloys, ICAA19; 2024-06-23 - 2024-06-27
- **Marthinsen, Knut.** *SFI PhysMet - Centre for Sustainable and Competitive Metallurgical and Manufacturing Industry.* Sustainable metals and systems; 2024-02-05 - 2024-02-06
- **Marthinsen, Knut.** *SFI PhysMet – Status and recent research highlights.* Nasjonal konferanse for Materialteknologi 2024; 2024-08-28 - 2024-08-29
- **Marthinsen, Knut; Hennum, Endre Asheim; Tundal, Ulf Håkon.** *Effect of microstructure on precipitation of -Mg2Si during cooling of Al-Mg-Si alloys.* 10th Forum of Center for Advanced Materials Research and International Collaboration(CAMRIC Forum10); 2024-11-14 - 2024-11-15
- **Marthinsen, Knut; Ånes, Håkon W.; Van Helvoort, Antonius.** *Phase and particle analysis in aluminium alloys using SEM EBSD and Dictionary Indexing.* ICAA19 - 19th International Conference on Aluminium Alloys; 2024-06-23 - 2024-06-27
- **Reiersen, Magnus; Zhang, Kai.** *Screening of nano-particles as grain-refiners for Additive Manufacturing of AA6061.* SFI PhysMet RA3 Technical Meeting; 2024-10-16 - 2024-10- 16
- **Runningen, Ingvild; Langelandsvik, Geir; Westermann, Ida.** *Flux-Assisted Sessile Drop Method on the Stability and Wettability of Al on TiC.* International Conference on Aluminum Alloys-ICAA19; 2024-06- 23 - 2024-06-28
- **Wang, Xuezhou; Li, Chunan; Xu, Yijiang; Li, Yanjun.** *Revisiting the vacancy diffusion behavior under the influence of solute trapping in dilute alloys.* The 11th International Conference on Multiscale Materials Modeling; 2024-09-22 - 2024-09-27
- **Wang, Xuezhou; Li, Chunan; Xu, Yijiang; Zhao, Dongdong; Li, Yanjun.** *Modelling the atom clustering kinetics under the influence of excess vacancies during natural ageing in 6xxx alloys.* ICAA 19; 2024-06-23 - 2024- 06-27
- **Wang, Xuezhou; Zhao, Dongdong; Xu, Yijiang; Li, Yanjun.** *Modelling the spatial evolution of vacancies across grains in multicomponent aluminium alloys.* TMS 2024 Annual Meeting & Exhibition; 2024-03- 03 - 2024-03-07

- **Zhang, Kai; Wenner, Sigurd; Marioara, Calin Daniel; Hovig, Even Wilberg; Du, Qiang; Onsøien, Morten Ingar; Marthinsen, Knut.** *Additive Manufacturing of 7xxx Aluminium Alloys by Laser Powder Bed Fusion.* 44 Risø International Symposium Metal Microstructures and Additive Manufacturing; 2024-09-02 - 2024-09-06

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