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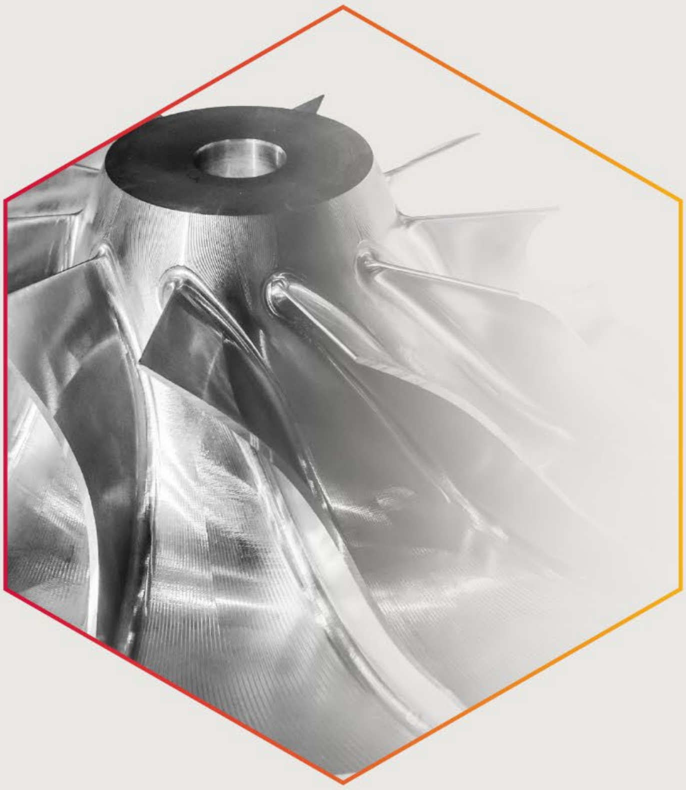

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D4.1 Roadmap on Green technologies for lightweight castings

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NetCastPL4.0 aims to enhance excellence and innovation capacity at AGH, putting AGH in a leading position to nuclei the Networking Pole for Castings Foundry Innovation and Sustainability to face the strategic challenges of Poland and EU foundries and of lightweight components end-user industry. It also aims to engage the country in pan-European collaborative efforts on this topic twinning with the Consiglio Nazionale delle Ricerche (Italy) and AALTO University (Finland). It will put AGH This will be achieved through realization of following specific objectives implemented via 7 WPs:

1. Improving the overall capacity and resources at AGH in advanced lightweight castings science & technology and in emerging Industrial Sustainability assessment and management practices and tools.
2. Conducting exploratory research on “High-tech cast iron and Al alloys for lightweighting castings for the medium and heavy-loaded conditions produced by green molding materials” demonstrating enhanced capacity in novel lightweight materials and components fabrication, modelling and characterisation.
3. Establishing an AGH European Networking Pole on Lightweight Castings Innovation and Sustainability. This will enhance the replication potential developed at AGH, creating strategic partnerships with Research organizations, Universities, Foundries, Industry, Public and Governmental Organizations, and Agencies in light-weighting casting components and Technologies for casting foundries 4.0 development.
4. Providing new results and experiences analysing 3 case-studies in production of light-weight castings components in medium and heavy loaded conditions and automotive for the preparation of a Guide Document on Best Available Practices in the Green Foundries Industry.
5. Leveraging the NetCastPL4.0 partnership at a European level and creating the enabling conditions for a long-lasting joint collaboration.
6. To arrange schools and training workshops in partner countries for scientists and for potential follower foundries and other relevant stakeholders.
7. Raising mobility (internal and external) of scientists and staff in green molding/casting science and technologies.
8. Improving the research management and administration skills at AGH, by creating the Department of European cooperation within AGH.
9. Fostering gender equality issues at AGH and in the castings foundry through implementation of the action plan for Equality, Inclusion, and Diversity.

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1. Scope of the deliverable

Metal casting is one of the most widely used manufacturing processes and involves pouring molten metal into single-use (expendable) or permanent molds to get desired shapes. It produces complex and large-size parts for various industrial applications of automotive, construction, metallurgical and medical industries. Regulations regarding pollution and energy efficiency requirements are triggering growth in the light metal casting industry.

To enable greener production of metal castings, two areas of development are be identified; molding materials in expendable molding processes and the metals cast into said molds. To get a proper outlook on the state of the industry in this area and future of the developments, investigations through surveys and research are done. The compiled data in this report consists of the following

- Analysis on the status of the foundry industry in Poland, current and future needs
- Analysis of the cast materials related to industrial lightweighting
- Analysis of 'Green molding technologies' and ongoing development actions
- NetCastPL4.0 actions on the above topics

The data is compiled into the following

- Identified cast material groups with wider industrial growth potential for future investigations
- Molding materials roadmap for wider utilization in expendable mold foundries

2. Materials for advanced lightweighting castings investigations

Background

The NetCastPL4.0 objectives include investigations into high-tech alloys for lightweighting castings produced by green moulding materials. The motivation for the investigations is the results of previous European projects, international cooperation, and finally the influence on potential economic growth and environmental protection. For example, the number of motor vehicles in use prompts the intensification of environmental protection activities. The European strategy toward reducing CO_2 emissions, is leading to a growing demand for lightweighting across industries. This requires the development of materials that have a higher strength-to-weight ratio than materials currently used. Future research and development should adhere to several of these points of view at the same time, market needs, material properties and sustainable properties. The work on this topic is based on the following sections:

- Market needs analysis on cast alloys
- Material use-case challenges
- Exploratory research actions on the identified cast alloys

NetCastPL4.0 'Analysis report for Foundry needs and major players by application'

In NetCastPL4.0 Work Package 6, the following surveys have been commissioned and analysed:

- Polish Foundry Chamber of Commerce: ***Production of thin-walled castings in Poland compared to Europe, including casting alloys: superalloys, aluminum alloys, ductile cast iron, and cast steel. Current status and perspectives.***

- Polish Foundrymen's Association: **Market and Market Needs Analysis in the Area of Lightweight Castings for Foundry 4.0 in Poland**

These findings were analysed and compiled into a NetCastPL4.0 Report **Market analysis and needs in the area of light-weighting castings for Foundry 4.0 in Poland**

The reports, available through the NetCastPL4.0 E-Library, compiled data from the following perspectives:

- status of thin-walled castings production

- the market and needs from the ferrous and non-ferrous foundries perspective

In the reports, the status of thin-walled castings in the foundry industry was elaborated. The definitions of thin wall in the scope of analysis is as follows: for aluminium alloys, thickness of less than 2 mm was considered, while for cast iron and steel castings, a wall thickness of up to 10 mm was still considered thin-walled.

Of the companies in Poland, non-ferrous foundries are the main producers of thin-walled castings. The customers for thin-walled aluminium alloy castings are primarily global automotive companies, which outsource production to Poland with product quality and lower production costs compared to Western Europe in mind.

Ductile iron, a cast iron type where graphite morphology is nodular, is another material gaining popularity in the production of thin-walled castings. From an economic perspective, thin-walled ductile iron castings can be less expensive than counterparts made from aluminium alloys. Additionally, they can exhibit superior mechanical properties. An analysis conducted by the Polish Foundry Chamber of Commerce showed that among foundries producing ductile iron products, a growing number of companies include thin-walled castings in their portfolios. This may already account for nearly 30% of the total production of ductile iron castings in Poland.

In the case of steel castings, the situation of thin-walling is quite stark compared to non-ferrous and cast iron alloys. Despite the developing technologies for the production of thin-walled structures, Polish steel foundries do not, for the most part, focus on the production of thin-walled castings. Some of the known challenges with regards to cast steels are the lesser fluidities and high pouring temperatures compared to cast irons.

One of the material groups traditionally used in thin-walled geometries are superalloys. They are classified as advanced materials that require precise manufacturing techniques. Superalloys are crucial in production of turbine blades and other components exposed to extreme conditions. Cast superalloys are also used in energy, chemical, and medical industries, where high corrosion and high-temperature resistance are required. The use cases of superalloys are in general highly specialised, and the production costs are high compared to many other material groups, which will limit the growth of production volumes.

Summarizing the research conducted by Polish Foundry Chamber of Commerce among Polish and European foundries, and an analysis of the needs of modern industries that purchase castings, it can be concluded that thin-walled castings offer very broad development prospects. The main industries interested in this solution are automotive, aviation, and electronics, where weight reduction is crucial. Although there are no official statistics on thin-walled casting production volumes, Polish Foundry Chamber of Commerce's research predicts that currently thin-walled castings are responsible for over 20% of total production in Poland. The demand for thin-walled castings is expected to show a growing trend, with increasing requirements for simultaneous lightness and strength in components. This higher-level analysis points at key growth potential especially in the following materials:

- cast irons, specifically high strength ductile irons, in the ferrous materials group

- aluminium alloys, in the non-ferrous materials group

In the survey aimed at the foundries in Poland, made in collaboration with the Polish Foundrymen's Association, the same type of general trend was seen. When the production of thin-walled castings in Poland is considered, the most common materials, are aluminium (52.670 tons) and ductile iron (48.422 tons). Thin-walled castings produced from other material groups are much less common. The most common molding process used by respondents was sand casting, while die casting in was also a common production process

Majority of respondents noted an increase in demand for lightweight castings over the past five years. This was primarily observed in automotive and machinery industries, while demand for thin-walled castings was observed also in aerospace and energy industries. The most important requirements for the castings were dimensional precision and mechanical strength. Light weight of the castings also appeared to be very important. The survey included questions about the perceived barriers in thin-walled casting utilization. According to respondents, the main barriers hindering development of production are primarily high production costs.

The outlined results from both the surveys can be summarized as follows:

- In the general industry trends and usage**, aluminium alloys and cast irons were the main interest in lightweight casting design.** Cast steels are widely utilized in many industries, but analysed from both reports, lightweight design is not a major consideration when these alloys are used. **Superalloys and thin-walled components are a natural combination, used in heavily stressed aerospace and energy industries.** However, **the cost of production will be a clear limiting factor** in wider usage of these alloys outside of these specific industries. In this scope, aluminium and cast-iron alloys are seen as a clear market development leaders with regards to thin-wall castings. Ultralight metals, like magnesium, are considered to be a part of lightweight designs, but has low production volumes compared to aluminium alloys.
- Although the potential in thin-walled and lightweight castings is quite universally seen throughout the foundry industry, one barrier in future utilization is seen. The main one being higher production costs. This links heavily sustainability goals, which is another major development area in foundries. It should be made sure that production costs won't be driving companies out of implementing various green technologies.

Literature background

Important key points and areas were identified from the surveys and reports dealing with the thin-walling and lightweighting aspects. Growth potential was seen especially in the use of aluminium alloys and ductile cast irons, while superalloys saw continued use in the energy and aerospace sectors. The main materials with regards to lightweighting are outlined further.

Cast irons

Although iron is not classified as a particularly low-density material, finding the need to reduce weight of castings does not mean abandoning iron-based materials. Cast irons are traditionally associated with bulky, heavy castings. This association relates to the usual practise of component design, as when designing such castings, the foundry properties are considered quite conservatively and therefore, for technological reasons, castings with a wall thickness of less than 3 mm are not designed as a standard practise. However, the excellent fluidity of cast irons does allow for very thin-walled designs when specific process parameters are considered.

Considering the potential high strength capabilities of cast irons, wall thicknesses can be minimized, if the proper requisites are met. Research on thin-wall castings made from ductile iron is being carried out at research centres around the world. The results of studies indicate that excellent property combinations (Tensile Strength > 1000MPa, Yield Strength > 700MPa, Elongation 10-25% and Impact strength up to 250 J) of thin-walled ductile iron variants have opened new horizons for high quality castings in many engineering applications with potential cost benefits. Thus, it is fairly accurate to say that modern grades of ductile iron should be considered as a potential material for lightweight castings with good mechanical and utility properties at relatively low cost.

From the point of view of economics and ecology, thin walling can be an avenue to reduce material use while simultaneously reducing costs due to the same reason. Thin-Walled Ductile Iron (TWDI) castings can compete in terms of mechanical properties with the castings made of aluminium alloys. This capacity comes from the higher strength-to-weight ratios combined with thin sections. From the viewpoint of material selection, ductile iron is cost-effective solution in many applications, including automotive, light and heavy trucks, construction and mining, equipment, railroad, agricultural, gears and crankshafts, and brackets, among others.

The highest known strengths of any cast iron type currently known is associated to Austempered Ductile Irons (ADI). These cast iron types are a heat-treated variation of ductile irons. It is possible to utilize the advantageous fluidity and castability properties of ductile irons to shape the castings, and then subsequently heat treat them to the desirable high-strength states. Therefore, Thin Walled Austempered Ductile Irons (TWADI) as a concept offer one of the best general property combinations available, as they combine manufacturability and mechanical properties for complex shapes.

If this topic is generalized, the following divisions can be made:

- **Thin-Walled Cast Irons** – General lightweighting applications
- **Thin-Walled Ductile Irons** – Mechanically stressed lightweighting applications
- **Thin-Walled Austempered Ductile Irons** – Heavily stressed lightweighting applications

Aluminum alloys

Aluminium-silicon alloys are the most widely used cast aluminium alloy types. Their main advantages are related to the shaping capabilities through high fluidity. High fluidity makes it possible to cast these alloys into very thin-walled structures without massive technological challenges. Hindering the push of this alloy-system to wider use in stressed thin-walled applications relate mostly to their achievable mechanical properties in standard foundry practise. While some variants of this alloys system can reach ultimate tensile strengths between 200-300 MPa, the highest strength cast aluminium alloys can reach considerably higher results.

High strength aluminium alloys, which are commonly used in the aerospace industry, can be adopted as a substitution to Al-Si alloys due to their excellent combinations of mechanical properties. Within the framework of thin-walling, some of the most promising alloy types are based on the Al-Cu group, with lower amounts of European point-of-view critical raw elements (Mg, Si) *(Study on the critical raw materials for the EU 2023 – Final report https://data.europa.eu/doi/10.2873/725585)*. If properly researched and implemented, the use of Al-Cu alloys can contribute to both material savings and lower consumption of critical raw elements, and therefore greater independence from fluctuations on global markets and geopolitical problems: in fact, 85% of the world production of Mg and 72% of Si comes from China.

Increasing recycling rates with higher scrap content is also a must for sustainability in the future, as the secondary aluminium production requires about 5% of the energy consumption when compared to primary aluminium production from ore. The effects of secondary elements like iron, also in trace amounts coming from scraps, can be detrimental for microstructure and mechanical properties. The possible corrective actions on these challenges need to be investigated to enable production of sound Al-Cu thin-walled castings. The Al-Cu alloys in general are characterized by very good mechanical properties. They are currently used for instance, aerospace components resistant to long-term fatigue. However, these alloys are technologically difficult especially in thin-walled casting designs, due to their high propensity to shrinkage cavities and hot cracking. Some of the challenges related to this area can be summarized as follows:

- Fluidity compared to Al-Si alloy system
- Hot cracking tendency of Al-Cu alloys
- Effect of trace elements on mechanical properties

NetCastPL4.0 investigations on lightweight cast materials

The NetCastPL4.0 consortium conducts research in the exploratory Work Package 4. Research work done and disseminated in scientific conferences and journals associated to the NetCastPL4.0-project are presented. Some of these works are submitted/under preparation, and do not include journal references.

The properties and utilization of cast iron alloys

Cast irons are a key topic of research activities, as several cast iron types offer good shaping capabilities in thin sections and excellent mechanical properties. However, certain aspects of production require additional research to realise the potential of thin walling. Some of the specific topics of interest to rectify some of the utilization challenges are:

- properties of cast irons in thin-walled sections – section sensitivity
- microstructural stability of thin-walled structures
- testing capabilities of thin-walled sections compared to traditional testing

Marosz, J., Górny, M., Kawalec, M., Chulist, R., Angella, G., Austempered Ductile Iron Castings Reinforced with TiC Particles Obtained by SHSB Reaction. 3rd Carl R. Loper Conference

Abstract The aim of the presented research was to produce a new cast composite material based on the widely known and used ADI (Austempered Ductile Iron). The transformation of classic ADI cast iron into a composite material was based on SHSB (Self-Propagating High-Temperature Synthesis in Bath) reaction. This was a “solid Ti” – “solid C”, which ensures that TiC particles are obtained in the microstructure of the alloy. The titanium carbides are thermodynamically stable as a result of their covalent bonding nature, so they do not undergo transformation during the heat treatment process. In the present work castings with different wall thicknesses ranging from thin-walled, i.e. 3 mm, up to 25 mm were attained. The study showed that it is possible to produce a ductile iron using the SHSB reaction with a titanium content of 2% mass, in which titanium carbides of up to 5μm in size are evenly distributed in metallic matrix. Heat treatment was carried out to attain upper and lower ausferrite, reinforced with titanium carbides. The characterization of an attractive engineering material in terms of mechanical and performance properties was carried out using XRD (synchrotron radiation), light microscopy, scanning microscopy and mechanical properties. Finally it was shown that ADI strengthened with TiC using SHSB synthesis makes it possible to obtain an attractive material that can be used in the areas such as defense, railroad or automotive.

Górny, M., Kawalec, M., Marosz, J., Bork, M., Angella, G., Insights into Carbides in Cast Iron. 75th World Foundry Congress.

Abstract This work focuses on carbides in high-alloyed, gray, vermicular, and spheroidal cast iron. The presence of complex carbides containing elements such as V, Ti, Mo, and Cr is crucial for strengthening cast iron and improving specific functional properties, including wear resistance, hardness, and increased thermal stability. In addition to the classic method of introducing carbide forming elements into cast iron, the high-temperature synthesis reaction in a metal bath of the SHSB (Self propagating High-temperature Synthesis in Bath) reaction was used to produce ceramic phases (carbide phases). The paper explores crystallization, structure formation, and the properties of cast iron with particular emphasis on the influence of carbides with different morphological characteristics and their distribution. The study also analyzes the impact of carbides on the formation of the primary structure, i.e., austenite dendrites, and their role in enhancing the thermal stability of cast iron. Metallographic examinations, including electron backscattering diffraction (EBSD), were conducted to reveal macro- and micro-structural features during the primary and eutectic solidification of cast iron. Furthermore, this work demonstrates that melt quality is closely linked to the resultant morphology and number of carbides, graphite, and matrix structure.

Górny, M., Kawalec, M., Marosz, J., Tokarski, T., Angella, G., Bork, M., Solidification and structure of thin-walled austenitic ductile iron castings. 18th European Congress and on Advanced Materials and Processes

Abstract Austenitic ductile iron, with a nickel content of 20% to 36%, is characterized by nodular graphite that is relatively uniformly distributed within a face-centered cubic matrix. This unique microstructure gives the material relatively high strength, ranging from 380 to 550 MPa, along with exceptional ductility, often achieving elongation exceeding 45%. In addition to its excellent mechanical properties, Ni-Resist ductile iron offers high resistance to creep, corrosion, and wear. It also boasts outstanding castability and machinability, making it a versatile material for various industrial applications. Capable of performing reliably across a broad temperature range from -200°C to 850°C, it is widely used in demanding environments. Typical applications include gas turbine housings, gas compressors, motor components, and other critical engineering parts that require both structural integrity and durability under harsh conditions.

This study presents research findings on the primary structure and graphite eutectic formation in castings with wall thicknesses characteristic of thin-walled components (≤5 mm), compared to thicker castings (25 mm). The investigation explored the use of Ti, Zr, Nb, and CeO_2 as potential grain refiners. Metallographic analyses, including electron backscatter diffraction (EBSD), were conducted to examine the macro- and microstructural characteristics during the primary and eutectic solidification of austenitic ductile iron. Additionally, novel quantitative assessments were performed to evaluate the morphology and distribution of graphite nodules. The results demonstrated that in thin-walled castings, the primary structure can be effectively refined using Ti

and CeO_2, promoting a transition from columnar to equiaxed grains. This transformation is strongly influenced by metallurgical process parameters and the cooling rate at the onset of solidification.

Górny, M., Angella, G., Jalava, K., Gondek, L., Marosz, J., Cygan, B., Thermal Stability and Section Sensitivity of Ni and Cu Alloyed Austempered Ductile Iron. Heat Treat 2025.

Abstract This study emphasizes the formation of microstructure and its impact on the thermal stability of high-quality cast iron, specifically austempered ductile iron (ADI). The role of the initial heat treatment stage, namely the austenitization process, in determining structural stability and homogeneity of the investigated ADI castings was examined. Additionally, the issue of the presence of unstable high-carbon austenite was addressed. Experiments were conducted on castings with varying wall thicknesses ranging from 3 to 12.5 mm under different austenitization temperatures between 800°C and 900°C. X-ray diffraction (XRD) analyses were performed on test castings over a temperature range from -260°C to 450°C to study structural parameters, including phase fractions, lattice parameters, stresses within the microstructure, and crystal lattice expansion. Additionally, mechanical properties under both static and dynamic conditions were analyzed. It was demonstrated that achieving a homogeneous structure, free of unstable austenite strongly depends on heat treatment parameters, especially the austenitization stage. Furthermore, thin-walled castings showed improved structural homogeneity and stability compared to reference castings. The present work also aims to develop strategies for enhancing structural stability in ADI castings to maintain microstructural homogeneity and high thermal stability.

Kawalec, M., Trela-Przybyło, A., Skurzak, M., Górny, M., Optimisation of the chemical composition of cast iron for high wear resistance. XXXI International Scientific Conference of Polish, Czech and Slovak Foundrymen

Abstract Cast iron is a structural material whose properties can be controlled as required: from ductile, through high strength grades, to high hardness and wear resistance grades. Iron alloys with increased hardness are the largest group of materials used for wear resistant structural components. The most commonly used are cast steels: mainly martensitic, austenitic manganese and chromium steels and, to a lesser extent, white martensitic and chromium cast irons. Wear-resistant plastics also include a group of composites reinforced with hard ceramic phases such as nitrides, carbides, borides or oxides.

This paper describes the influence of chromium, titanium and vanadium alloying additions on the properties of white cast iron. The chemical composition of the cast iron was designed to give the highest possible abrasive wear resistance at low production cost. Four grades of white cast iron were cast, thermally analysed and then heat treated. Initial and post-heat treated samples were examined for microstructural analysis (optical microscopy), chemical composition of crystallised phases (scanning electron microscopy), hardness and abrasive wear resistance. The study showed that

small additions of titanium, chromium and vanadium resulted in a significant increase in hardness and wear resistance. The alloying additions also cause stabilisation of both eutectic and primary carbides.

Marosz, J., Gorny, M., Kawalec, M., Olejnik, E., Angella, G., Chulist, R., The impact of heat treatment on the microstructure and mechanical properties of the Si-Mo cast iron. Heat Treat 2025

Abstract Si-Mo cast iron belongs to the group of high-quality alloyed cast irons, offering excellent properties at elevated temperatures. The operating environment of Si-Mo cast iron reaches approximately 750–800°C, and its applications include components such as exhaust manifolds and turbochargers. The primary carbides found in these materials include Fe_4MoC_3, $FeMo_2C$, M_6C, and M_7C_3. These phases are thermodynamically unstable due to the nature of their metallic bonding and, consequently, undergo morphological changes at elevated temperatures.

In this study, the SHSB (Self-propagating High-temperature Synthesis in Bath) reaction synthesis method was employed to produce thermodynamically stable carbides. This method enabled the transformation of Si-Mo cast iron into a composite material reinforced with particles such as TiC, WC, or NbC. It was demonstrated that the formation of a composite-like structure in Si-Mo cast iron using the SHSB method is possible regardless of the graphite morphology, thereby expanding its potential application range. The SHSB synthesis also enhanced the thermodynamic stability of Si-Mo cast iron while maintaining its mechanical integrity.

Fu, L., Xiao, H., Olofsson, J., Schiralli, M., Vedani, M., Gorny, M., Donnini, R., Ripamonti, D., Angella, G., Tensile properties of thin-walled Austempered Ductile Irons. SPCI XIII 2024

Abstract Austempered Ductile Irons (ADI) are advanced ductile irons with excellent physical and mechanical properties, and thin-walled castings made of ADIs fit perfectly into the modern trend of interest thanks to their favorable strength-to-density ratios. So ADIs are candidates to replace steel castings and forgings in many engineering applications with considerable cost and CO2 production benefits for lightweighting design of transport components, like in automotive, military, railroad and agricultural applications. ADIs microstructure comes into a biphasic metallic matrix called ausferrite that consists of bainitic ferrite and metastable austenite reach in C, where nodular graphite is embedded. During loading the metastable austenite may transform into martensite causing rupture, so the assessment of the stability of ausferrite during loading is important for service purposes by predicting the plastic behavior of ADIs in industrial thin-walled components. Thin-walled ADIs have been produced with 1.5 wt.% content of Ni and have been tensile tested with round and thin-walled flat specimens to investigate the effects of geometry on the tensile behavior of ADIs. Digital Image Correlation (DIC) techniques has been used on thin-walled flat geometry to investigate the local plastic behavior, and Finite Element Modeling (FEM) have been implemented to support the interpretation of the tensile behavior in thin-walled flat and round tensile specimens.

Microstructure characterization has been carried out through Scanning Electron Microscopy and XRD measurements have been for austenite volume fraction determinations. Some preliminary considerations of the tensile specimen geometry on the strain hardening behavior and final rupture were also drawn.

Angella, G., Cygan, B., Gondek, L., Marosz, J., Gorny, M., Ausferrite stability in thin sections. ECIG 2025

Abstract Because of excellent mechanical property, with Tensile Strength > 1000 MPa, Yield Strength >700 MPa, Elongation 10-25 % and Impact strength up to 250 J, and a density 10-12% lower than steels with similar mechanical properties, Thin-Walled Austempered Ductile Iron (TWADI) castings can be considered as potential materials for lightweight design with good utility properties at relatively low cost. From the point of view of economics and ecology, thin-walled ADI castings can compete in terms of mechanical properties with the "light" castings made of aluminium alloys, while from the viewpoint of material selection, ADI is a cost-effective solution in many applications, including automotive, light and heavy trucks, construction and mining, equipment, railroad, agricultural, gears and crankshafts, and brackets, among others. However, the structural homogeneity and thermal stability of ausferrite in ADIs is the main limitation to their use, since they affect the behaviour of ADIs when subjected to static and dynamic loads within a wide temperature range. So, thermal stability investigation of ADIs through XRD analysis is fundamental for characterize the different production routes of ADIs. Besides, also the mechanical loading stability investigation is important, and a simple and innovative method to analyse the mechanical stability of ADIs can be implemented, based not only on the engineering mechanical properties, but also on the tensile strain hardening analysis that is very sensitive to subtle microstructure features and changes, as it can happen in unstable ausferrite of ADIs.

Fu, L., Olofsson, J., Schiralli, M., Vedani, M., Gorny, M., Donnini, R., Angella, G., Effects of specimen geometry and tensile testing system on the ductility and stability of ausferrite. 18th European Congress and on Advanced Materials and Processes.

Abstract In ferrous-alloys, ausferrite is a metallic matrix consisting of Widmänstatten acicular microstructure of bainitic ferrite and metastable austenite reach in C. In ductile irons where graphite nodules are imbedded, it results from the two-step industrial heat treatment of austempering, coming into a first step of austenitization at high temperatures for having a high carbon austenite, followed by quenching in salt bath for an isothermal austempering transformation for producing proper ausferrite, and a final slow cooling to room temperature. The resulting Austempered Ductile Irons (ADIs) have outstanding physical and mechanical properties, with excellent strength-to-density ratio, and so ADIs are valid substitutes to steel castings and forgings in many weight-saving transportation applications with considerable cost and CO2 production benefits, like in heavy trucks, military, railroad and agricultural applications. However, the main

concern in the use of ADIs, is the stability of ausferrite, as during loading the metastable austenite may transform into martensite causing rupture. So, the assessment of the stability of ausferrite in industrial thin-walled ADI components is important, and, first of all, it is needed to assess the eventual sensitivity of ausferrite stability to the tensile specimen geometry and the tensile system configuration. So, different tensile specimen geometries (round and 2 mm flat with different gauge geometries) have been tested with different gripping systems to investigate the stability of ADIs. A procedure based on the tensile strain hardening analysis has been implemented to assess the stability of ausferrite, and microstructure investigations have been carried out through Scanning Electron Microscopy and XRD measurements, while Digital Image Correlation (DIC) technique and Finite Element Modeling (FEM) have been used to investigate the local plastic behavior with different specimen geometries and gripping systems.

Tokarski, T., Wojciak, K., Górny, M., Marosz, J., Graphite Crystallization in Austenitic Ductile Iron: Insights from TKD and TEM Diffraction. THERMEC'2025 International Conference on PROCESSING & MANUFACTURING OF ADVANCED MATERIALS Processing, Fabrication, Properties, Applications

Abstract Austenitic ductile iron (Ni-Resist) is a class of cast iron known for its exceptional mechanical properties, including high toughness, wear resistance, and corrosion resistance, making it highly suitable for demanding engineering applications. These superior properties are largely attributed to the presence of austenitic metallic matrix and graphite nodules, which play a crucial role in determining the material's strength, ductility, and fatigue resistance. The size, distribution, and morphology of these nodules significantly influence the alloy's overall performance.

Despite extensive research, the mechanisms governing graphite crystallization, particularly the role of various nucleation sites, are not yet fully understood. One contributing factor is the difficulty of crystallographic analysis of nodular graphite due to its softness and low atomic number. Conventional local crystallinity analysis using Electron Backscatter Diffraction (EBSD) is ineffective in such cases. To address this challenge, Focused Ion Beam (FIB) techniques will be employed for the precise preparation of thin lamellae, enabling high-spatial-resolution examination of the internal graphite microstructure. This study aims to investigate the local microstructure of graphite nodules and its relationship with nucleation sites using advanced characterization techniques, including Transmission Kikuchi Diffraction (TKD) and Transmission Electron Microscopy (TEM) with local diffraction analysis. Special focus will be given to local crystallinity variations, ranging from amorphous regions to turbostratic structures and fully crystalline graphite.

Tokarski, T., Bork, M., Gorny, M., Angella, G., Wojciak, K., Cygan, B., Tracking of particles distribution inhomogeneity: model and experimental verification in ductile iron.

Abstract This study presents a quantitative approach for assessing the distribution inhomogeneity of graphite nodules within ductile cast iron. Traditional classifications based on macroscopic mechanical properties overlook the intricate effects of particle/graphite distribution on properties such as thermal stability, fatigue resistance, and magnetizability. Presented examination relying on the light microscopy analysis, enables an efficient evaluation of distribution inhomogeneity of particles across sample microstructure. By mapping particle count and its area in sub-regions, modified coefficient of variation has been introduced as inhomogeneity parameter of particles distribution, which are dimensionless scalar quantities, ensuring broad applicability across various materials. The proposed model is fully independent of image magnification and microstructural scale, providing consistent results regardless of image resolution or resizing. This eliminates the need for size calibration and enhances the robustness and universality of the analysis. Digital twins (synthetic microstructures) were generated to validate the method, replicating different scenarios of particle distribution and particle size variability. Experimental analysis on ductile cast iron samples with varying cooling rates further confirmed the model's relevance; variations in graphite distribution were correlated with solidification parameters and microstructural features. Results demonstrate the model's ability to quantify inhomogeneity of spheroidal graphite distribution in the ductile cast iron. This approach offers a framework for enhancing numerical description of the microstructure in ductile cast iron.

Angella, G., Govahi, P., Schiralli, M., Gorny, M., Masaggia, S,, Zanardi, F., Section-Sensitivity Assessment of 4.2 Wt Pct Silicon Ductile Iron Based on New Material Integrity Index. Metallurgical And Materials Transactions A

Abstract *Defects and metallurgical discontinuities significantly affect the magnitude and the variability of the mechanical properties of materials; this can be very significant in castings because of their sensitivity to chemical compositions and section thicknesses. A new procedure for assessing the integrity of Ductile Irons (DIs) that is based on tensile-strain-hardening analysis has been proposed via the modelling of experimental tensile-flow curves with the constitutive equation of Voce. The goodness of this approach is based on the unexpected regular strain-hardening behaviour of defective materials that has been called "Defects-Driven Plasticity" (DDP), which gives rise to the definition of a new Material Integrity Index (MII). The tensile-flow behaviour and microstructural analysis of 4.2 wt pct Si DI that was produced in different geometries and Y-blocks were reported on in order to study the sensitivity of the microstructural and mechanical properties to section thickness in this innovative grade. The tensile mechanical properties seemed to indicate that the mechanical behaviour of the section with the slowest cooling rate was better than the thinner section (which was in contrast with the microstructural results). The new Material Integrity Index that was based on the strain-hardening analysis rationalised the mechanical behaviours of all of the sections with different*

cooling rates differently, thus resulting in integrity assessments that were consistent with the microstructural findings.

Fu, L., Schiralli, M., Vedani, M., Olofsson, J., Gorny, M., Govahi, P., Donnini, R., Losurdo, M., Angella, G., Effects of tensile specimen geometry and gripping system on the mechanical stability of ausferrite in Austempered Ductile Irons. MDPI Materials

Abstract Different combinations of round and flat tensile specimens for different gripping systems of Austempered Ductile Irons (ADIs) were produced from the same 25 mm Y-block castings to investigate the effect of the specimen geometry and gripping system on the tensile mechanical properties of ADIs. Particular attention was paid to the analysis of strain-hardening behavior of ADIs that can be related to the stability of ausferrite, when austenite transforms into martensite. Moreover, Digital Image Correlation (DIC) was carried out on the flat tensile specimens to analyze the strain distribution of the material in real time. To quantify the austenite stability with plastic deformation, X-ray Diffraction (XRD) analysis was performed on ADIs before and after straining. Finally, Finite Element Modeling (FEM) simulations were carried out to analyze the stress distribution along the tensile specimens in all the different tensile testing configurations (tensile specimen geometry + gripping system). The flat specimens showed lower ductility and higher strain-hardening rates; however, the flat tensile specimens with the wedge gripping system experienced the highest strain-hardening rate, suggesting a significant decrease in the ausferrite stability in this tensile testing configuration. FEM simulations showed that the specimen geometry and the gripping system influenced the tensile behavior of ADI by reducing the ductility because of stress intensification and triaxiality effects. Furthermore, the stress intensification and triaxiality factor caused a higher strain-hardening rate, which was associated with increased ausferrite instability.

Marosz, J., Górny, M., Gałek, R., Chulist, R., Morgiel, J., Kawalec, M., Angella, G., Zapała, R., Tupaj, M., Structure and Thermophysical Characteristic of Compacted Graphite Cast Iron Composite Castings.

Abstract This work deals with the development of new Compacted Graphite Cast Iron Composite Castings as an alternative to Si-Mo ductile iron. The new material is a silicon-molybdenum cast iron (Si-Mo), transformed into a cast composite using the Self-propagating High-temperature Synthesis in Bath (SHSB) method, which synthesizes ceramic carbide particles of metals such as Ti, W, Nb, Mo, Zr. SHSB is used to ensure the formation of thermodynamically stable ceramic phases, in this case, carbide phases. Among the listed metals, titanium was selected for the SHSB synthesis process due to the exceptionally favorable physicochemical properties of titanium carbide and its highly exothermic enthalpy of formation. The described process strengthens the matrix of the material, changing its characteristic operational properties. The resulting composite is designated as Si-Mo TiC. Conventional Si-Mo cast iron is widely applied in the automotive industry, where it is used, for instance, in the production of exhaust manifolds and turbocharger components, where high resistance to thermal shock and excellent heat resistance are required. Transforming this material into a composite material improves many physicochemical parameters. Additionally, titanium desferoidizing effect helps stabilize graphite in the compacted (vermicular) form. Castings of both conventional Si-Mo iron and the TiC-reinforced Si-Mo composite with compacted graphite were produced with varying wall thicknesses. The microstructural characteristics and thermophysical properties, such as thermal conductivity and thermal stability, of the classical and composite materials were compared. The new Si-Mo cast iron reinforced with thermally stable TiC particles has been demonstrated to exhibit excellent structural integrity and thermal stability.

Bork, M., Górny, M., Palumbo, G., Angella, G., Marosz, J., Microstructure, mechanical parameters, and corrosion resistance of austenitic ductile iron castings. Archives of Civil and Mechanical Engineering

Abstract Austenitic ductile iron, also known as Ni-resist cast iron, belongs to the cast iron group, which is characterized by a high-nickel content ranging from 18% to 36% by weight. Although this level of nickel content significantly increases the production costs, it imparts numerous beneficial properties that justify the price. One notable property is its ability to operate across a wide temperature range, with a minimum service temperature of − 200 °C, and a maximum, depending on the grade, reaching up to 1050 °C. This family of high-quality alloys demonstrates mechanical properties, where grades without carbide-forming elements achieve elongation exceeding 40%. On the other hand, by adding Cr, which is a carbide-forming element, the Ni-resist cast iron's plasticity decreases, while its corrosion resistance properties increase. However, a comprehensive investigation into the correlation between mechanical properties and corrosion resistance, particularly in relation to various nickel contents in the presence of Cr in high-nickel cast iron, is scarce. Therefore, the primary aim of this study was to elucidate the role of nickel content and chromium content in influencing the mechanical and corrosion resistance properties of austenitic ductile iron. The addition of 21, 25, 28, and 35 wt% of nickel with and without 2.5 wt% of chromium was investigated. Characterization of the materials was carried out using optical and scanning electron microscopy, static tensile tests, impact strength tests, and corrosion resistance assessments at room temperature in a 3.5 wt% NaCl solution. The investigation revealed a significant influence by changing the nickel and chromium content on the properties of high-nickel cast iron. In addition, it was proved that by controlling the content of these elements, the cast iron with establish properties can be achieved—depending on expected final properties, results show that it is possible to substitute part of the nickel content with smaller amount of chromium to get similar corrosion resistance properties and reduce the production costs, but it will influence to mechanical properties, which dependent on plasticity.

Kawalec, M., Górny, M., Kozana, J., Marosz., J., Structural, Mechanical and Functional Assessment of Thin-Walled CGI Castings.

Abstract This study investigates the impact of titanium (Ti) additions, up to 0.13 wt%, on the microstructure and mechanical properties of iron castings. To account for varying cooling rates, the research examined thin-walled castings with thicknesses of 3 mm and 5 mm, alongside a 13 mm thick reference casting.

Microstructural changes were quantitatively assessed using image analysis and qualitatively examined with a scanning electron microscope (SEM). The addition of 0.13% Ti was found to significantly influence graphite formation in thin-walled castings, reducing the graphite nodule fraction in 3 mm castings from 73% to 34%. In 5 mm castings, the nodule fraction was reduced to below 20%, meeting ASTM standards. The study also measured key mechanical and functional properties, including hardness, wear resistance, and machinability. While hardness showed no significant increase with Ti additions, the ultimate tensile strength of 5 mm castings with 0.10% Ti increased slightly before decreasing with higher Ti content.

Metallographic analysis revealed that the addition of titanium significantly influences graphite formation in thin-walled castings, to a much greater extent than in thicker sections. This is particularly crucial given the differing solidification kinetics in components of varying thicknesses. Furthermore, thin-walled castings with a high degree of inoculation that solidified under high cooling rates exhibited a homogeneous structure, free from chilling. This desirable microstructure, combined with favorable mechanical and functional properties, positions these castings for potential use as substitutes for aluminum alloy castings in diverse applications.

The properties and utilization of Al alloys

As outlined, aluminium cast alloys are an important part of the thin-walling industry. The challenges that the ongoing exploratory research activities aim to investigate are:

- How to mitigate effects of the more limited fluidity in Al-Cu alloys in thin-walled applications
- How to mitigate the tendency of Al-Cu alloys with regards to hot tearing

Górny, M., Marosz, J., Lelito, J., Kawalec, M., Gondek, L, Angella, G., Piątkowski, J., Synthesis of A201-TiC in-situ composites via SHSB technology for thin-walled castings.

Abstract The aim of the present research was to develop a cast metal matrix composite based on the Al–Cu system, reinforced with titanium carbide (TiC) particles. The A201 aluminium–copper alloy is known for its exceptionally high mechanical strength, particularly after T6 or T7 heat treatment. In this study, the A201 alloy was transformed into a composite material containing varying amounts of TiC (up to 5wt%) using the Self-Propagating High-Temperature Synthesis in Bath (SHSB) method. The research focused on thin-walled castings with wall thicknesses of 3mm and 5mm. Particular attention was given to the role of TiC particles in reducing the hot tearing susceptibility (HTS) of the A201 alloy. Microstructural evolution, including grain refinement induced by TiC addition, was analyzed using optical microscopy, SEM, EDX and EBSD. In addition, X-ray diffraction (XRD) analysis was carried out up to 300°C to monitor phase fractions, lattice parameter changes, and internal strain variations.

Shah, A., Numerical simulation and experimental verification of Al-Cu alloy in thin-walled sand castings. Aalto University - School of Engineering | Master's thesis

Abstract This thesis dives deeper into the casting behaviour of Al-Cu alloys in thin-walled castings and their comparison with more commonly used alloys, using a combination of numerical simulation and experimental validation. The primary objective is to assess the fluidity and casting limitations of Al-Cu alloys, or more specifically AlCu4Ti, and compare the results with AlSi10Mg. The study primarily focuses on wall thicknesses from 1 mm to 5 mm, with the aim of producing defect-free thin-walled sand castings.

Initial simulations using thin plates examined the general flow behavior and porosity formation across varying plate thicknesses. The study also explored gating designs, filter usage, and runner designs. With that fluidity, tests were simulated at variable thickness and temperatures. To validate the results from the simulations, experimental studies were also carried out using Archimedes spiral of different thicknesses. That comparison revealed a significant discrepancy between simulated flow lengths and experimental flow lengths. Which can be attributed to factors as differences in heat transfer coefficients and other less-known parameters. Despite the difference in actual flow lengths, the validation stayed true to other trends found in simulations.

Notably, AlSi10Mg demonstrated higher fluidity under all the testing conditions as compared to the AlCu4Ti alloy. As it was simulated at multiple temperatures and experimentally verified at 720 °C with multiple thickness plates. This pattern reinforced the literature claims that Al-Cu alloys exhibit poorer castability due to wider solidification ranges and increased shrinkage defects. Also, the literature claim of an increase in fluidity with the increase of temperature was well supported by both experiments and simulations.

This thesis concludes by stating that although numerical simulations present a powerful tool to evaluate different casting scenarios and designs, but their accuracy also depends on proper material data, boundary conditions, and mesh resolutions. The work emphasizes the critical role of experimental validation in combination of numerical simulations especially for limited fluidity alloys and complex geometries like thin walls.

Cast materials for future lightweighting investigations

The main groups of cast materials for lightweighting applications that are interesting from the European foundry industry point of view, at the time of making this report, can be summarized mainly to the following materials

- **Non-ferrous castings** – cast aluminium alloys
- **Ferrous castings** – cast iron alloys

These two material groups account a major portion of the current foundry market of lightweight castings, shown in the analysed reports related to the topic. Thus, near-term investigations on these material groups would pose the best avenues for growth in industrial utilization. Other material groups should naturally be considered as well, but their industrial market demand is currently not as high. Some of the key challenges and use-case potential are summarized below.

Challenges and future of high strength cast irons

Cast irons offer a large variety of properties, and most of the alloy types have excellent castability compared to other cast materials. The possible variation in microstructures offers optimizable strengths for differing use-cases. Heat treatability offers even more potential in properties.

Ausferritic ductile irons are the highest strength to weight types available in the market with regards to cast irons. With their generally great mechanical properties, utilization of such alloys has potential in making thin-walled iron castings more widespread in general. As previous research and the NetCastPL4.0 ongoing research activities have shown, these materials do have their own specific challenges. The structural homogeneity and thermal stability of ausferrite in ADIs is the main limitation to their use, since they affect the behaviour of ADIs when subjected to static and dynamic loads within a wide temperature range. It is, however, possible to affect the stability of microstructures through heat treatment optimization. Some of the challenges might not be as critical in thicker walled castings as they are in thin-walled designs, necessitating more knowledge on their behaviour.

Further studies on both thin-walled structures in general, and stability of microstructures are still needed in order to fully realise the potential in the highest strength alloys. However, the following classification in lightweight cast irons can be made:

- **Thin-Walled Cast Irons** – General lightweighting applications
- **Thin-Walled Ductile Irons** – Mechanically stressed lightweighting applications
- **Thin-Walled Austempered Ductile Irons** – Heavily stressed lightweighting applications

Challenges and future of cast aluminium alloys

A majority of the world foundry production in aluminum alloys comprises of alloy systems with favourable fluidity and other casting properties, mainly in the Al-Si system. Due to their good fluidity properties, thin-walled designs are possible in many casting processes, in both permanent and non-permanent (expendable mold) processes. Their limitations from the European point-of-view are:

- Required raw materials for alloying (Si, Mg) are produced primarily outside of EU, the availability can heavily fluctuate depending on the global market, especially in crisis-scenarios
- The achievable mechanical properties are not considered particularly high strength, ultimately limiting their use in increasingly more demanding applications

Aluminum-copper-system (Al-Cu) offers avenues for change, related to either the lower potential strengths offered by the Al-Si system, or from the raw material availability and carbon footprint points-of-view. One of the supporting factors for developing these alloys further is the already existing industrial capacity, and the fact that the alloys are relatively well-known in general. Some of the challenges also being addressed in the NetCastPL4.0 project are:

- Lower fluidity of Al-Cu alloys compared to Al-Si alloys hindering the casting of thin-walled components
- Mitigating the tendency of Al-Cu alloys to hot tearing
- Simulation capabilities in industry-standard software need to be further verified to enable confident use in industry, as thin-walled geometries are challenging both in production and numerical modelling points-of-view

If the Al-Cu system challenges in foundry production cannot be overcome, different experimental cast aluminium alloy systems can offer a possibility. One point that is a limiting factor near-term in these alloy types are that they aren’t widely known, and will face the usual challenges in adoption, starting from basic availability onwards.

3. Molding materials for green lightweight castings

Background

NetCastPL4.0 investigates ecological molding materials, such as inorganic molding sands with binders based on hydrated sodium silicate for the production of light-weighting castings. These processes are a part of European GREEN DEAL policy thematic, with the aims of making industries cleaner and 'greener'. In the made research, activities are aimed at investigating and developing also organic molding sands with reduced harmfulness to the environment. These different molding systems can undergo regeneration processes in which the grain matrix is recovered for reuse, having a positive effect on reducing the consumption of fresh raw material and reducing costs related to transport and storage. Inorganic binder systems are already widely used in non-ferrous foundries, as their technological properties are good in relation to the used metal pouring temperatures. The challenges in relation to ferrous cast materials mainly come from the secondary hardening effects near the higher pouring temperatures associated with cast irons and steels. This additional hardening phenomenon results in disadvantageous use-properties, like poor shakeout of molds and cores. If wider utilization of inorganic binder system is to be gained, these challenges need to be overcome.

This part of the report compiles data from synergistic research projects at EU-level and presents a roadmap on green molding materials for lightweight castings.

Literature background

Status of the green molding technologies in the European foundry industry and utilization aspects

The different green molding technologies have been under investigation in different EU-level research initiatives in increasing amounts, with evolution in market needs, environmental impacts and regulations related to health and emissions. With this in mind, the NetCastPL4.0 consortium did not aim to procure data by surveys in the similar manner that was elaborated in Section 2 – Market needs. Recent public data and results are available to compile the current state of the European foundry industry from green molding materials point of view.

One of the recently published data packages relates to 'Green Casting Life'-project (LIFE21-ENV-FI-101074439). Some of the key findings related to the project are summarized here.

Emissions from laboratory level testing and pilot foundry scale testing. High temperatures during casting processes causes thermal decomposition of organic components in molding sand, leading to the formation of harmful gaseous and volatile compounds (BTEX, PAH, phenol, CO, NOx, SO2) and several particulate substances. The data shows that emissions are significantly higher for molds and cores produced using organic binders, such as furan, phenolic urethane, and alkaline phenolic, compared to those made with inorganic binder systems.

LCA Analysis of main organic and inorganic binder systems available on the market. The main studied factors were: Acidification, Climate change, Ecotoxicity fresh water (5 categories), Particulate matter, Eutrophication (3 categories), Human toxicity (2 categories), Ionising radiation, Land use, Ozone depletion, Photochemical ozone formation, Resource use (2 categories), Water use.

The studies were conducted on the following commercial systems; organic binders (Phenolic Urethane, Phenolic Alkaline, Furan), inorganic binders (Sodium silicate, 2 types). These binder systems correspond to the industrially widely used no-bake hardening process. In the case of the inorganic binder systems reported in the study, the processes were binder+hardener processes, which means that they contain an organic component in the hardener, making them semi-organic in the scope of the NetCastPL4.0 report.

The key points from the report are:

• The use of an inorganic binder-hardener system achieves a reduction in all the analysed impact categories compared to traditional organic binder systems

• One commercial inorganic system showed decreases in 10 out of 12 categories. In the "ozone depletion" category, the use of silicic acid, a sodium salt in the binder is responsible for almost all of the contribution to this category. Additionally, in the "resource use, minerals and metals" category, the use of another compound causes higher values associated with this category.

• In inorganic systems, the most notable decreases in the assessed impact categories are seen in the five ecotoxicity freshwater impact categories with reductions exceeding 90%, the 'human toxicity cancer' with reductions surpassing 97%, and the 'photochemical ozone formation' with reductions exceeding 70%.

• Considering the “climate change” indicator, the use of inorganic systems as substitutes for current organic systems offer a favourable alternative, reducing equivalent CO_2 emissions by over 55%.

These results show that in the semi-inorganic processes, already a major reduction in environmental and health impacts can be seen. The impact reduction potential in ferrous and non-ferrous foundries is therefore high. Fully inorganic binder systems will have the smallest emissions, as outlined previously.

Ferrous foundry industry views on green molding materials. In the ‘Green casting life’- project, a report on *‘Inorganic binder experiences in Europe and analysis of the questionaries for the selection of pilot foundries’* has been published. The industrial point of view on different potential systems had been compiled through surveys to ferrous foundries, where organic systems are the majority of all used binders, and thus where the largest potential in impact reduction exists. The following key points have been identified:

Currently, inorganic binders are sparsely and sporadically implemented, with only 13% of respondents saying to have tried them, and only 2% working with them regularly. However, 73% express interest in trying them and evaluating their technical and economic viability. They are also considering the possibility of making necessary investments once various technical issues are resolved.

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was done in relation to the survey, broadly reflecting the current situation of inorganic binder systems. The inorganic binders have been identified as a significant opportunity for environmental improvement, affecting the most crucial environmental aspects of foundries: wastes and emissions. The current environmental performance is a strength due to high legal compliance and existing environmental awareness in the sector. However, weaknesses arise from their limited implementation in the industry, widespread unfamiliarity with these products, and potential technical issues. Mentioned weaknesses in the report are such as few previous experiences, limited information (costs, technical characteristics, use in the process), incompatibility with the current process, and potential quality issues. Finally, the most significant threat identified is the loss of near-term competitiveness resulting from increased costs, and potential quality problems.

The outlined results from the data on foundry market point of view can be summarized as follows:

- reduction potential in emissions related to both environment and health is high when inorganic binder systems is considered. Use of both semi-organic and fully inorganic systems will result in dramatic decrease in harmful emissions.
- reduction in environmental and health impacts is also high, when considered from Life Cycle Analysis (LCA) point of view
- in ferrous foundries, where the use of inorganic binder systems is traditionally low, interest to test and implement inorganic binders widely exists, if the technological challenges are overcome and the implementation does not result in drastic increase in production costs

These results point out some key elements in the potential implementation of green molding technologies:

- healthy amount of industrial interest exists in the inorganic binder systems
- a smooth transition is required, to limit effects of technological challenges
    - first actions could be to limit the impacts of currently utilized binder systems as a stop-gap solution, before transitioning towards greener technologies
- the economic side of transition needs to be well planned to limit risks

NetCastPL4.0 investigations on green molding materials

The NetCastPL4.0 consortium conducts research in the exploratory Work Package 4. Research work done and disseminated in scientific conferences and journals in NetCastPL4.0-project on the green molding materials topic are presented here. These research activities align well to the findings from the analyzed reports, and have been divided into two distinct areas:

- Optimization of organic binder systems use for lesser impact
- Investigations into the technological challenges in inorganic binder systems

Decreasing the effect of organic binders

Organic binder systems are the most widely used in the global foundry industry, with various excellent technological properties enabling their use. Feasibility of switching to inorganic binder systems in the near future depends a lot on the specific foundry capabilities to invest in new machinery and the technological capabilities of the inorganic systems, as also seen from the analysed reports. One avenue to lessen environmental impacts in the near-term is to seek ways to decrease the harmful effects of organic binders. The activities related to this area up to the writing of this report are:

Major-Gabryś, K. Environmentally friendly foundry molding sands as a part of Green Deal policy. XXXI International Scientific Conference of Polish, Czech and Slovak Foundrymen.

Abstract Thanks to strict environmental regulations, improvements in energy efficiency, and the trend in European industry to move away from harmful technologies over the past few decades, the negative impact of European industry on the environment has improved. In order for the European industry to become more environmentally friendly in the future, it is necessary to implement new innovative technologies.

The total production of castings in CAEF countries in 2023 amounted to over 14 million tons, and a significant part of these castings were produced using sand molds and cores. Thus, the development of environmentally friendly molding sand technologies is an important part of the Green Deal policy. The aim of the paper is to analyze modern solutions for molding sands, both with organic and inorganic binders. In molding sands with organic binders, the innovative approach of replacing part of the binder with biodegradable additives reduces the harmfulness of molding sand at the stage of casting production and contribute to solving the problem of hazardous post-regeneration dust utilization, which is crucial from waste management point of view. Another solution are molding sands with organic binders based on modified with furfuryl alcohol resins cured by hardeners with reduced sulfur content, which are less environmentally harmful and ensure production of high-quality ductile iron castings.

Molding technologies with alkyd resins hardened by catalyst based on isocyanates and alkaline phenolic resin hardened by esters are a less environmentally harmful alternative to molding sands with commonly used in foundry practice furfuryl resin. Molding sands with environmentally friendly inorganic binders based on sodium silicates and aluminosilicates were also analyzed. Molding sands with solid and hydrated sodium silicates with additives improving their knocking out properties can be used as well as new ester hardeners based on esters of carbonic acid and their mixtures with hardeners based on acetic acid used commonly in chemically hardened molding sands with hydrated sodium silicate. Finally, due to the harmfulness of respirable dust from silica sand for foundry workers, various sand matrixes, including advanced synthetic ones, were analyzed, also for 3D printing of sand molds and cores.

Major-Gabryś, K., Halejcio, D., Selection of chemically cured molding sands' with inorganic binders dedicated to 3D sand printing

Abstract Due to the high technological potential, 3D printing technologies in the foundry industry are developing very dynamically. Binder jetting technology is most commonly used for the production of sand molds and cores with 3D printing. The binding materials used in foundry practice are organic resins modified with furfuryl alcohol. These materials are characterized by excellent technological properties, but at the same time, they are harmful to the environment. Environmentally friendly inorganic binders are an alternative to the organic binders used for the production of molds and cores, and this is the subject of research carried out at various research centers.

This work determines the influence of molding sands' with different inorganic binders composition on their chosen properties. The molding sands with 3 commercial inorganic binders used in traditional mold and core production technologies were tested as well as the molding sands dedicated to 3D printing with binders based on them. Four types of hardeners were used for chemical curing. The technological (strength, permeability, abrasion) and thermophysical (thermal deformation) tests carried out on molding sands and the physicochemical tests on binders (viscosity, wettability of the quartz substrate) have shown that inorganic binders elaborated on the basis of commercial binders can be used in 3D printing technology. The selected sands' compositions were chosen for further research.

Major-Gabryś, K., Halejcio, D., Effect of binder type on properties of molding sands dedicated to 3D printing. ECIG 2025, Milan Italy.

Abstract The production of thin-walled iron casting with complex shape, characterized by high quality while maintaining the required properties, involves many steps in the production process. One of them is the appropriate selection of the technology of molding and core sands, taking into account strict environmental requirements.

3D printing technologies are classified as innovative additive production methods. In the production of foundry molds and cores, the binder jetting technology is used. It is a modern technology that enables the production of molds and cores with shapes and layout impossible to obtain using traditional molding methods. The method involves binding layers of sand grains (with or without hardener) together using binders and/or other agents. 3D sand printing technology mainly uses quartz sand with a grain size of 0.14-0.25 mm as a matrix. The binders used are resins, mainly furfuryl alcohol modified resins bonded in no-bake technology. Environmentally friendly inorganic binders are rarely used for molds and cores production using binder jetting technology.

This paper will present the influence of binder type on the properties of molding sands, including sands dedicated to 3D printing. Based on studies of commercial resins intended for molding and core production by traditional methods and in 3D printing technology, the authors will demonstrate the possibility of replacing environmentally harmful organic binders with inorganic binders. Various technologies for binding molding compounds will be presented, including chemical, thermal (also microwave) or combined binding. The effects of different binders on the strength, permeability, abrasion of the tested sands will be presented, as well as their influence on the kinetics of binding or thermal deformation.

Major-Gabryś, K., Halejcio, K., The influence of furfuryl resin type – classical and designed for sand 3D printing, on cast iron castings' microstructure and surface roughness.

Abstract Resin-based binders are one of the main materials used in foundry molding and core sands. Self-curing sands with furfuryl resin dominated the production of large-size castings. This work is part of the research on new molding sands for molds 3D printing. The work concerns the influence of furfuryl resin type (designed for 3D printing of sands molds) on cast iron castings properties. 3D printing technology in the production of sand casting molds and cores is finding increasing industrial application in the production of castings from non-ferrous metal alloys. The aim of the research presented in this paper was to determine the effect of the furfuryl resin based binding system modification on cast iron castings properties. The pouring parameters were elaborated on the basis of MAGMA software. The microscopic observations of castings, produced in classical and 3D printed molds, microstructure (SEM, EDS) were conducted as well as the standard tensile test.

Inorganic binder systems and additives

The smallest amount of harmful emissions is associated with the use of fully inorganic binder systems. In the case of industrial adoption, the different fully inorganic systems pose challenges, as seen from the previously outlined reports. The activities associated with the NetCastPL4.0 exploratory research can be divided into several approaches: use of both a semi-organic/inorganic systems (inorganic binder + organic hardener), and fully inorganic systems. The use of advanced molding processes like additive manufacturing of sand molds is also covered in the activities. Descriptions of activities on the topic are summarized below.

Halejcio, D., Major-Gabryś, K. Selection of chemically cured molding sands' with inorganic binders dedicated to 3D sand printing. XXXI International Scientific Conference of Polish, Czech and Slovak Foundrymen

Abstract Due to the high technological potential, also in thin-walled casting, 3D printing technologies in the foundry industry are developing very dynamically. Binder jetting technology is most commonly used for the production of sand molds and cores with 3D printing. The binding materials used in foundry practice are organic resins modified with furfuryl alcohol. These materials are characterized by excellent technological properties, but at the same time they are harmful to the environment. Environmentally friendly inorganic binders are an alternative to the organic binders used for the production of molds and cores, and this is the subject of research carried out at various research centers.

This work determines the influence of molding sands' with different inorganic binders composition on their chosen properties. The molding sands with 3 commercial inorganic binders used in traditional mold and core production technologies were tested as well as the molding sands dedicated to 3D printing with new binders based on them. Four types of hardeners were used for chemical curing. The molding sands' technological (strength properties, permeability, abrasion) and thermophysical (thermal deformation) tests and the physicochemical tests of binders (viscosity, wettability of the quartz substrate) have shown that inorganic binders elaborated on the basis of commercial binders can be used in 3D printing technology. The selected sands' compositions were chosen for further research.

Anwar, N., Major-Gabryś, K., Jalava, K., Orkas, J., Effect of Additives on Heat Hardened Inorganic Solid Foundry Binder. International Journal of Metalcasting.

Abstract Renewed interest in inorganic binders for sand molding has also intensified research on different forms of it. In this study, solid inorganic sodium silicate binder was tested with different additives to see how these affected the silica mold quality. The five additives used were: glucose, sucrose, boric acid, aluminum oxide and iron(III)oxide powders. The mold quality was assessed through tests like bending strength, tensile strength, hot distortion, wear resistance, gas evolution and collapsibility tests. In addition, SEM imaging was done on some select mold fracture samples. In the end, a casting trial was carried out followed by a surface roughness and defects analysis. A reduction in mold strength was noticed with glucose and boric acid, while collapsibility was improved by glucose, sucrose and boric acid additives. Casting trials have shown the best surface finish to be obtained with sucrose additive. All the casts in general showed some penetration; however, repeat casts have proven that altering some casting parameters could result in casts with excellent surface finish using solid silicates.

Research work on molding materials that hasn't yet been compiled to publications is underway in the NetCastPL4.0-project. A small preview on actions at the time of writing this report:

As part of the development of molding compounds for thin-walled castings within the project, self-hardening molding compounds with organic binders and compounds with inorganic binders are being tested. Tests were carried out on the tensile and bending strength, permeability, friability, and bench life of the compounds. Selected sands were tested for thermophysical properties (hot distortion parameter), gas generation, and thermal degradation. Molding sands with appropriate strength were selected for the designed mold for the production of thin-walled castings. Test castings were produced simultaneously in a similar mold made using 3D printing technology with no-bake molding sands.

The forementioned research builds upon a wealth of previous work on the subjects handled in this report. The following listing is given as a reference:

- *Puzio S., Kamińska J., Angrecki M., Major-Gabryś K., The influence of inorganic binder type on properties of self-hardening moulding sands intended for the ablation casting process, Journal of Applied Materials Engineering; ISSN 2658-0152. — 2020 vol. 60 iss. 4, 99–108.*
- Major-Gabryś K., Hosadyna-Kondracka M., Puzio S., Kamińska J., Angrecki M. The influence of the modified ablation casting on casts properties produced in microwave hardened moulds with hydrated sodium silicate binder, Archives of Metallurgy and Materials / Polish Academy of Sciences. Committee of Metallurgy. Institute of Metallurgy and Materials Science ; ISSN 1733-3490. — 2020 vol. 65 iss. 1, 497–502.

- *Kamińska J., Angrecki M., Puzio S., Hosadyna-Kondracka M., Major-Gabryś K., The use of Floster S technology in modified ablation casting of aluminum alloys, Archives of Foundry Engineering — 2019 vol. 19 iss. 4, 81–86.*
- *Puzio S., Kamińska J., Major-Gabryś K., Angrecki M., The use of phosphate binder for ablation casting of AlSi7Mg modified TiB alloy, Archives of Foundry Engineering — 2022 vol. 22 iss. 1, 62–68*
- *Puzio S., Kamińska J., Angrecki M., Hosadyna-Kondracka M., Major-Gabryś K., Microwave-hardened moulding sands with inorganic binders for ablation casting, Foundry Journal of the Polish Foundrymen's Association / Kraków; ISSN 0033-2275. — 2019 vol. 69 (5-6),114–120.*
- *Major-Gabryś K., Hosadyna-Kondracka M., Stachurek I., Determination of mass loss in samples of post-regeneration dust from moulding sands with and without PCL subjected to biodegradation processes in a water environment, Journal of Applied Materials Engineering; ISSN 2658-0152. — 2020 vol. 60 iss. 4,121–129.*
- *Major-Gabryś K., Hosadyna-Kondracka M., Polkowska A., Warmuzek M., Effect of the biodegradable component addition to the molding sand on the microstructure and properties of ductile iron castings, Materials, ISSN 1996-1944. — 2022 vol. 15 iss. 4 art. no. 1552, 1–14.*
- *Hosadyna-Kondracka M., Major-Gabryś K., Warmuzek M., Brůna M., Quality assessment of castings manufactured in the technology of moulding sand with furfuryl-resole resin modified with PCL additive, Archives of Metallurgy and Materials / Polish Academy of Sciences. Committee of Metallurgy. Institute of Metallurgy and Materials Science; ISSN 1733-3490. — 2022 vol. 67 iss. 2, 753–758.*
- *Hosadyna-Kondracka M., Major-Gabryś K., Brůna M., The influence of biodegradable additive in moulding sand on structure of ductile iron casting, W: Współpraca 2020: XXVI International Scientific Conference of Polish, Czech and Slovak Foundrymen: 7-9.09.2020 r., Baranów Sandomierski*
- *Major-Gabryś K., Stachurek I., Hosadyna-Kondracka M., The influence of biomaterial in a binder composition on biodegradation of waste from furan moulding sands / // Archives of Foundry Engineering, ISSN 2299-2944. — 2022 vol. 22 no. 2, 17-24.*
- *Major-Gabryś K., Hosadyna-Kondracka M., Skrzyński M., Stachurek I., The influence of biomaterial in the binder composition on the quality of reclaim from furan no-bake sands, Archives of Civil Engineering, ISSN 1230-2945. — 2022 vol. 68 iss. 4, 163–177.*
- *Major-Gabryś K., Stachurek I., Hosadyna-Kondracka M., Homa M., The influence of polycaprolactone on structural changes of dusts from molding sands with resin-based binder before and after the biodegradation process, Polymers, ISSN 2073-4360. — 2022 vol. 14 iss. 13 art. no. 2605, 1-16.*
- *Major-Gabryś K., Hosadyna-Kondracka M., Skrzyński M., Pastirčák R., The quality of reclaim from moulding sand with furfuryl resin and PCL additive / // W: Współpraca 2020: XXVI International Scientific Conference of Polish, Czech and Slovak Foundrymen: 7-9.09.2020 r., Baranów Sandomierski.*

Molding materials roadmap basis

The key findings of the associated literature and exploratory research activities can be summarized:

- Emissions and other environmental impacts from inorganic binder systems are dramatically lower when compared to organic ones, as seen from laboratory and foundry level testing
- Strategies to limit the harmfulness of organic systems can be implemented, including the types of binders and use, such as additive manufacturing
- Use of mold systems with both organic and inorganic binder elements can be a mid-point solution, while further development of the inorganic binder systems is done
- Fully inorganic binders for both ferrous and non-ferrous cast material foundries would have the biggest reductions in environmental and health impacts
- Technological development needs on inorganic binder systems include mold processing/hardening time, collapsibility after casting and other production process related factors

These point towards the following potential avenues of implementation

- **Near-term:**
    - Mitigation of impacts through optimization of organic binder chemistry and use
    - Use of a combination of inorganic molds and organic cores can be mid-point solution to cover technological challenges while collapsibility properties of inorganic molding sands are further developed
    - Emissions monitoring of processes for validation

- **Medium-term:**
    - Wide use of binder + hardener variations (semi-organic) of inorganic systems
    - Wide use of fully inorganic systems in both ferrous and non-ferrous foundries
    - Utilization of fast heat hardening systems, like microwaves, with fully inorganic binder systems

- **Long-term:**
    - Research and development of brand-new chemical bases for foundry binder systems

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ICMATE

Green Molding Processes

Greener Future Tech

Near-term

Optimization of organic binder use through additive manufacturing and associated advanced processes

Medium-term

Use of inorganic binder + organic hardener system and variations

Long-term

Fully organic binder systems
New binder chemistries

Medium-term

Wide use of inorganic molds and cores in ferrous foundries

Near-term

Use of inorganic molds and organic cores in mitigating collapsibility challenges