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D1.1 – State of the Art and Failure Mode and Effects Analysis

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Abstract		

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V2	11/03/2022	Mohammad Ashadul Hoque	Added ceramic industry priority for highest ranked faults
V2	11/03/2022	Mohammad Ashadul Hoque	Added benefits of CO2 corrosion and H2 embrittlement resistant materials for energy-intensive industries as concluding remarks

* Dissemination level security:

PU – Public (e.g. on website, for publication etc.) / **PP** – Restricted to other programme participants (incl. Commission services) /

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Summary

The overall aim of the FORGE project is to create, for energy intensive industries, a knowledge-based machine learning (ML) model that will address degradation issues in current manufacturing processes as well as future damages envisaged in the implementation of carbon-saving technologies. The ML model will assist to create novel coating materials, defined as compositionally complex materials (CCMs), that will extend the lifetime of critically damaged components by addressing different performance targets or key performance indicators. This report will address the manufacturing processes and examine the areas of severe damages that occur in the four energy intensive industries in the FORGE project: cement, steel, ceramic and aluminium manufacturing (Section 2). Furthermore, this report will examine the state-of-the-art materials used to tackle emissions from these industries. To this aim, a failure mode and effects analysis (FMEA) has been conducted (Section 3) to identify the critical components of highest severity, occurrence and detection that will form the basis from which novel coating materials will be designed in later stages of the FORGE project.

Objectives Met

The deliverable contributed towards the work package objective:

- To map the typical failure points in energy intensive industries, for both current and future manufacturing processes, through Failure Modes and Effects Analysis (FMEA).
- To characterise the corrosion, erosion and wear behaviour of components in energy intensive industries such as steel, aluminium, cement and ceramic manufacturing industries which will be used to design criteria for compositionally complex alloys (CCA) and ceramics (CCC), materials & coating.

INTRODUCTION

Energy intensive industries in the EU are responsible for two-thirds of the industrial carbon dioxide (CO_2) emissions.[1] In a roadmap to milestones for 2050, the EU aims to reduce such emissions by 80% compared to levels recorded in 1990.[2] The bulk of CO_2 emissions occur from reactions in the manufacturing processes as well as from using fossil fuels and direct use of energy. Oberthür *et al.* notes that a global effort is required from many contributing countries, with guidelines such as ones from EU, to work together and aim to collaboratively meet such roadmaps to achieve a worldwide net zero emissions as early as possible.[3] Despite a reduction in energy consumption, energy efficiency remains a concern for the European industrial sector. Malinauskaite *et al.* highlights the trends and action plans of several EU members. The results show that although there have been many improvements in support of energy efficiency, the commercialisation of current available technologies to realise energy saving potentials and thus the reduction in environmental impacts and robust policy frameworks for long term transitions should be the way forward to maintain credibility and drive investment.[4] With the aim of reducing emissions in these industries, several approaches are possible:

a) Manufacturing process efficiency improvement, through extension of equipment lifetime,
b) Use of Hydrogen as fuel as opposed to fossil fuels,
c) Direct capture of CO2 emissions from the manufacturing process,
d) Capture and re-utilisation of waste heat from the manufacturing process.

Therefore, the objective of the FORGE project is to develop innovative compositionally complex alloy (CCA) and compositionally complex ceramic (CCC) coatings and materials that have the potential to drastically reduce or eradicate the frequent occurrences of failures of the components can therefore reduce the need for frequent maintenance and replacement of the components and subsequently reduce the cost of operation in the production plants. This report will focus on identifying where failure occurs in production plants and what technologies are in use or has the potentials to be used to minimise CO_2 emissions.

The structure of this report is as follows. Section 2 will cover the different industries that the FORGE project will be contributing to. This section will discuss how the respective industry processes work, where there are damages, what solutions are being used for such damages and the sources of carbon dioxide emissions and technologies being used to tackle such emissions. Section 3 will detail the failure mode and effects analysis (FMEA) of each of the respective industries. Finally, section 4 will conclude the findings of this report.

ENERGY INTENSIVE INDUSTRIES

The FORGE project will address current issues in the following four industries: Cement, Steel, Ceramic and Aluminium Industries. These industries are represented through our industry partners.

1.1 Cement industry

1.1.1 How the industry works

To make cement a typical processing plant usually has several stages, fig 1 shows a general schematic by J.F. Young.[5]

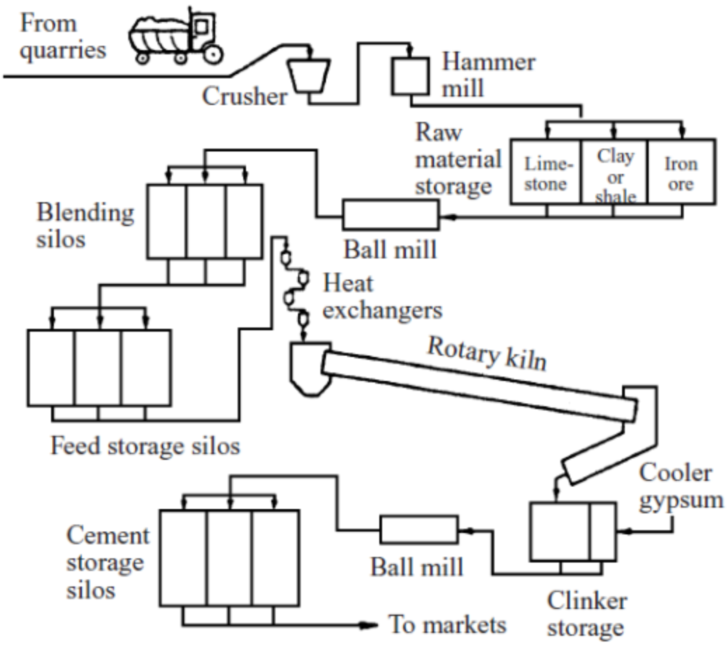

Figure 1: General schematic of a dry process cement plant.[5]

This is an example of a dry processing plant. Raw materials from the quarries are brought in and then separated to different components, then depending on the composition of the intended cement a mixture is blended/ground forming a clinker. The resulting clinker mixture is heated in a rotary kiln, then this is ground with the addition of gypsum in a ball mill to produce the final cement mixture.

1.1.2 Areas of significant damages

There are five components that faces significant damage cement industry. These include flue gas fan blades, which are affected by erosion caused by both high temperatures and abrasive dust contaminants in the gas; the mill separator blades are affected by erosion due to silica raw materials; erosion occurs on the roller table of the raw mill as well as in the inner body of the raw mill; and erosion occurs in the waste heat recycling system due to clicker dust and high temperatures.

1.1.3 Current solutions

Erosion in waste heat recycling (WHR) systems: Maintenance is performed once a year, mainly due to clinker dust and high temperatures. The recycling system is made with ST 37 steel and repair work is done by making a specific concrete covering. The replaced WHR system consists of 10,000 kg of both ST 37 steel and the same quantity of the concrete. The down time is 15 days.

Wear on the roller table of the raw mill: – This occurs more frequently and incurs problems once in every 3 months. The table is composed of NiHard IV alloy. The erosion is mainly caused by raw materials and physical pressure force effects. The technique of hard facing welding is also used here to repair the roller table; however, this must be fully changed every 3 years. The down time is 120 hours.

Erosion in the inner body of the raw mill: As with the roller table this incurs problems occurs every 3 months. The inner body is composed of ST 37 hard facing steel. Here the erosion is caused by silica based raw materials. For repairs similar welding techniques are used and ST 37 steel. The replacement for the inner body takes around about 5 days and around 3 tonnes of steel is used.

Erosion in the mill separator blades: – Similar to the roller table erosion in the separator blades are caused by silica raw materials. Annually corrosion incurs problems once a year.

Erosion in flue gas fan blades: The problem occurs twice a year and are due to dust contaminants and high temperatures of gases. The fan blades are comprised of H2/H3 boiler steel. Repair work is done by hard face welding onto the fans, though after 6 years the entire component must be replaced.

1.1.4 Major sources of Carbon Dioxide emissions

The combustion of fossil fuels and a process known as calcination of limestone in the raw mix are the greatest direct source of CO_2 in the cement industry. An indirect source of CO_2 is from electricity generation if that involved the use of fossil fuels. Worrell *et al.* notes that within the direct CO_2 emissions, 50 % is from the calcination of limestone and the remaining 50 % originates from the burning of fossil fuels.[6]

1.1.5 Technologies for limiting Carbon Dioxide emissions

Duda *et al.* describe several different methods to address greenhouse gas emissions (including CO_2) in the cement industry.[7] One method involves the use of waste fuels in place of natural fuels throughout the cement manufacturing process. This will reduce the overall emissions of gases such as CO_2 and reduce the quantities of fossil fuels required in the manufacturing process. This type of fuel substitution is easily manageable in a rotary kiln and thus is being highly considered as a method of reducing emissions. Although the use of alternative fuels has greatly reduced emissions from processes such as clinker sintering, the method of using oxy-fuel technologies has yet to be widely implemented. This involves the combustion of fuels in an oxygen rich enriched atmosphere, though due to factors such as costs this has yet to be fully utilised.[7]

A rapidly evolving method of CO_2 capture and utilisation in the cement industry is the use of WHR systems, especially to produce electricity. As the process uses thermal energy from areas like the rotary kiln, on average every kilowatt hour of electricity from this type of generation compared to conventional combustion generation of the same amount has much lower emissions.[7]

A study by Nidheesh and Kumar on the overview of the environmental sustainability in cement production also defines various methods in which CO_2 emissions can be reduced throughout the manufacturing processes. This includes the use of decarbonated raw materials such as steel slag, of fly ash in place of limestone.[8]

Barker *et al.* studied two methods of CO_2 capture and storage, new build cement plants with either post combustion CO_2 capture or oxy-combustion CO_2 capture. They note that use of CO_2 capture in the cement industry is a great opportunity towards avoiding contributing to anthropogenic climate change.[9]

Scrivener *et al.* found that several different groups were working towards applying alternative materials for cement clinker formation.[10] These include waste materials from other industry processes which can be rich in calcium oxides or other silicate materials such as in steel slag or calcinated clays. Additionally,

CO_2 mitigation through improving efficiency was also explored. The method stated was substituting clinker with reactive supplementary cementitious materials.

Karl Lindqvist *et al.* modelled possible multi-stage membranes that could be used in the post combustion CO_2 capture in cement industries.[11] They modelled 3 different membranes that could potentially be used for flue gas capture.

Griffin *et al.* conducted a study in which the cement sector of the UK was investigated in areas including greenhouse gas emissions and embodied energy (the total primary energy consumed, or carbon released, from indirect and direct processes).[12] This study highlighted several different methods that could be used to reduce CO_2 emissions such as for kilns, using alternative fuels including refuse derived fuels or specified recovered fuels. The rise of CO_2 capture and storage was another factor, the most promising methods were post combustion and oxy-fuel technologies. Both methods for capture and storage could provide new and existing cement plants approximately 85-95 % reduction in CO_2 emissions which was very promising.

Rissman *et al.* in 2020 described that to reach net zero greenhouse gas emission by 2050-2070 a global response would be required by all sectors.[13] The industrial sector as of 2014 had been responsible for at least 33 % greenhouse gas emissions. Within the industrial sector cement production was found to be one of the great areas from which emissions was and is still occurring. Over the years there have been many emerging methods and technologies to reduce emissions from the cement industry. There are three distinct subsections: process emissions, energy related emissions and carbon capture technology.

1.2 Steel Industry

1.2.1 How the industry works

There are two methods to producing steel. One method uses a blast furnace, and the other method uses direct reduced iron process. A schematic of the steel making process is shown in fig 2.

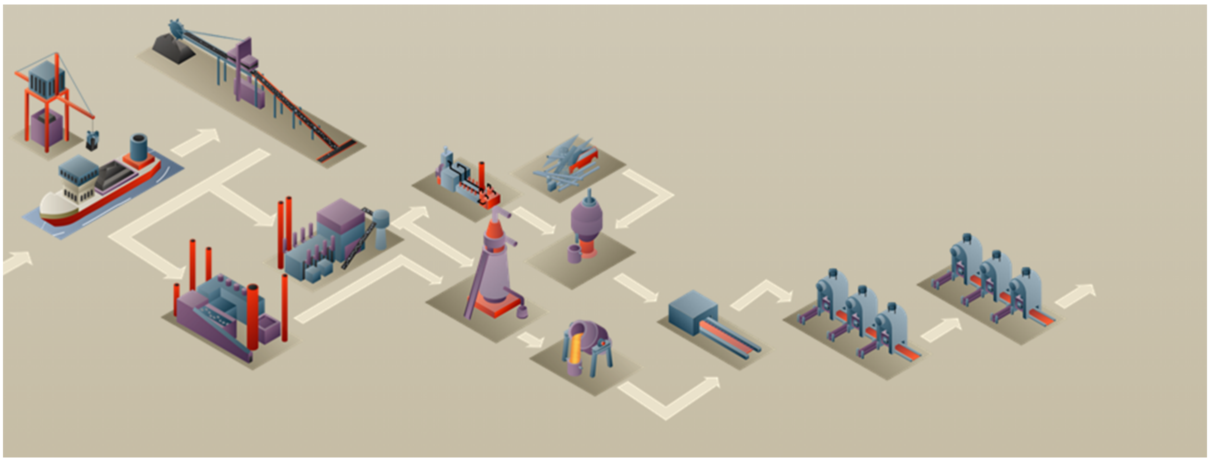

Figure 2: Schematic overview of steel making (source: www.arcelormittal.com)

There are four stages to steel making: raw materials, making iron & steel, casting & rolling, and finishing. Initially raw materials are stacked by grade and a machine known as stacker-reclaimer deposits the materials onto to a conveyer belt by using continually rotating buckets. The conveyer belt is used to arrange and deposit materials by grade ready for processing. The three main raw materials used for steel making include iron ore, coal, and scrap steel.

Coal is turned into coke in a blast furnace, in the absence of oxygen at 1250 °C, this removes any impurities, and the resulting gas (carbon monoxide) is reused to heat the coke furnaces or used to generate electricity. Other biproducts of this process, such as tar, sulphur or ammonia are captured and sold to the chemical industries.

Iron ore can sometimes be processed into sinter, this involves burning a mixture of iron ore, fluxes, and recycled substances for the steel plant. This sinter is then crushed, cooled ready for steel making.

Once the raw materials are processed and ready, there are two methods of forming liquid pig iron, which is required before steel can be made. One method uses a blast furnace in which hot air is injected into a continuous feed of sinter lime and coke to reduce or remove oxygen from the iron. The other method, known as direct reduced iron (DRI) process, uses natural gas to reduce iron ore pellets instead of sinter to produce liquid pig iron. The resulting liquid iron is then transported to a basic oxygen furnace (BOF).

Scrap steel is another key raw material as these can be infinitely recycled. Typically, these can be melted down in an electric arc oven or can also be added to the BOF liquid iron mixture (as a method to regulate temperature).

In the BOF the carbon content of the molten iron is reduced to 0.5 % (by blowing oxygen into the molten iron). Resulting steel is tapped into steel ladles and the slag is removed. Waste gases such as carbon monoxide from the BOF are captured and used for power generation.

At this point depending on the final required steel grading, further treatments can be applied. Though this process is individual and precise.

The molten steel is transferred into a continuous caster, in which the steel passes through a mould and a series of segments. Within these segments the vertical path from the ladle becomes horizontal as the steel cools. At the end when the steel emerges as a continuous slab it is solid but red hot. The block of steel is then cut into semi-finished products known as billets, slabs, or blooms.

These are reheated to 1200 °C and this makes it easier to form. During a process called flat hot rolling, steels can be reduced to thicknesses of 22-1.25 mm. then following hot rolling, cold rolling to even thinner thickness is possible if required. Various processes such as annealing, organic coating and galvanising can be applied to the products as per the requirements.

1.2.2 Areas of significant damages

In the steel making process wear occurs in almost every application through contact and friction and this is unavoidable. One component is a section within the pulverisation mill for coal. The finely ground pulverised coal and dust in the mill are very abrasive, especially particulates around 40 mm in size. Although wear and erosion occur through the entire mill a particular area where wear is most prominent is the classifier, a section of the mill that can separate the pulverised coal by size. Erosion occurs mostly on the different flaps in the classifier due to the particulates colliding on the edges of the flaps.

1.2.3 Current solutions

The pulverising mill/classifier operates under a nitrogen atmosphere and temperatures of 100-200 °C. Currently ceramic coatings of 8 mm are applied onto the low-strength structural steels to lessen the impact of abrasive particulates.

1.2.4 Major sources of Carbon Dioxide emissions

There are several areas in the steel making process where CO_2 emissions occur. In integrated steel plants, most CO_2 emissions (70%) arise from iron production in the blast furnace. Smaller but still significant CO_2 emissions come from rolling and finishing of products (12%), and ore preparation (12%). In scrap-based mills, the main emissions are from the electric arc furnace (45%), finishing and rolling (36%) and oxygen/power production (16%).[14]

1.2.5 Technologies for limiting Carbon Dioxide emissions

A study by Chisalita *et al.* showed that post combustion CO_2 capture technologies compared to a plant without such devices was successful in reducing CO_2 emissions. The two methods involved are conventional chemical absorption using mono-ethanol amine (MEA) and a innovative technique based on calcium looping (CaL).[15]

Whilst De Ras *et al.* considered different methods for reaching carbon neutral steel production.[16] Some potential methods included use of chemical adsorption and absorption as well as catalytic or enzymatic conversion of carbon dioxide and carbon monoxides into oxygenated hydrocarbons. Another concept is the use of hydrogen by-product from sections of the steel production such as coke oven gases or conversion of naphtha.

Conejo *et al.* described the ultra-low CO_2 steelmaking (ULCOS) program in the European Union, in which 48 companies in the EU would reduce CO_2 emissions by at least 50 %.[17] In this initiative several breakthrough technologies were proposed. This includes

- Top Gas Recycling Blast furnace,
- ULCORED: a direct reduction method,
- ULCOWIN: the production of iron at low temperatures using electrolysis,
- ULCOLYSIS: electrolysis-based method operating at liquid steel temperatures,
- HISARNA: a smelting methodology that resulted from a collaboration between Rio Tinto, Tata steel and ULCOS.

1.3 Ceramic Industry

1.3.1 How the industry works

There are multiple steps for manufacturing ceramic tiles, a typical method is shown in fig 3 below.

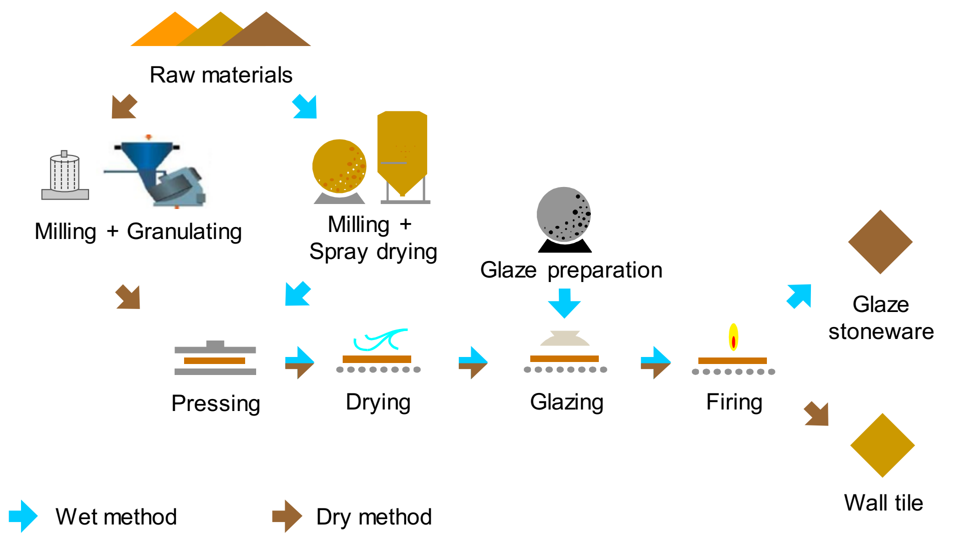

Figure 3: Schematic of a ceramics processing from raw materials to final products[18, 19]

Raw materials can be prepared by dry or by wet method. In both wet and dry methods there are six stages to ceramic tile production.

Dry raw materials are first milled in pendular mills and then in a granulator are turned into spherical particles. After granulation depending on the ceramic some water may be added to increase the humidity. In the wet route, a slurry is formed when raw materials are milled in ball mills with additives and water. The resulting slurry (containing approximately 35 % water) is transferred to a spray drier from which spray dried powder is attained.

Following either of these methods, the resulting granulates contain 6 % water. This is the desired level for the forming process. Hydraulic presses are used to form tiles, the granular powders from the previous step are placed into moulds and then are compressed using high pressure to be shaped. Once shaped the tiles are dried in continuous dryers (The drying temperatures ranges between 130-190 ºC in vertical dryers, and around 200-240 ºC in horizontal dryers). These dryers use natural gas burners as the heating source. There are temperature sensors located at various positions to monitor the drying cycle. Prior to decoration, the tiles are heated to 90 ºC.

The most common method of decorating involves an initial glaze and then ink jet printing of the pattern. The tiles are stored until firing in a kiln. The firing process takes place in a continuous roller kiln, which is achieved using natural gas. The tiles are rolled through and the firing process causes a transformation in the tiles which alter the physico-chemical properties that results in the final product. This can take up to 60 minutes and temperatures can reach in the range of 1100-1200 ºC. After reaching peak temperatures the tiles are cooled by ambient air in the latter stages of the kiln. The cooling gases are exhausted through a cooling stack, where some gases are recovered for combustion air in the former part of the kiln or alternatively for the dryers. Then the ceramic tiles are ready.

1.3.2 Areas of significant damages

A. In the dry method the **pendulum mills** suffer from wear due to continuous impact and friction from abrasive clay particulates. This can sometimes lead to metallic contamination in the tiles that alters and causes defects in the final ceramic tiles.
   In the wet route the ball mill is also subject to wear, also due to abrasive clay particulates. One area known as the diaphragm is made of steel and covered with a rubber coating. In this instance wear causes rubber contaminants in the tile that again results in defects. Also, in the mill another area known as the screw is subjected to wear, like pendulum mill. This can lead to metallic contaminants in the final ceramic tiles.
B. One other component in the wet method, the spray dryer is also exposed to wear, specifically the **spray nozzles**. This can result in uneven sized powders which in turn disrupt the final granular distribution in the tiles.
C. Within the **ink jet nozzles** an internal membrane that prevents the piezoelectric device from contacting with the ink, whilst also distributing the ink properly over the nozzles. These can break due to cumulative fatigue. High frequency sweeps and voltages, as well as high laydowns increase the risk of breaking.
D. Corrosion of the **refractory** in high temperatures due to acidic and alkaline elements. The corrosion effects and severity depend on the materials used as well as the condition of the kiln. The fire bricks that make up the refractory are comprised of mainly SiO_2 and Al_2O_3 and have density of about 900 kg/m^3. The corrosion occurs in the bricks when the acidic and alkaline elements penetrate the bricks and degrades the integrity.

1.3.3 Current solutions

A. Visual inspections of the **pendulum mill** are regularly carried out and elements of the mill are replaced when necessary. Similarly, for ball mill and screw, the elements are also replaced when damaged.
B. There are production controls in place when dealing with the spray dryers to monitor the degradation of the **spray nozzles**. Tungsten carbide is used for longevity but again after wear is detected these are replaced.
C. When the membrane in the **ink jet nozzles** break, ink starts to drip onto the tiles, a visual inspection is performed to ensure that the ink and patterns are applied correctly to the tiles. The whole membrane must be fully replaced when this occurs. To minimise the risk of breaking due to high frequency sweeps and voltages the speed of the line is reduced, and the firing temperatures are increased.
D. The entire **refractory** is usually replaced it breaks into pieces inside the kiln and defects are seen in final products. Replacements of these items usually take place every 5 to 7 years. The replacement of the refractory is a long process, which requires the shutdown of the kiln and only when temperatures reach ambient conditions is when the process can begin. Any damaged bricks must be fully replaced, and the lining is assembled using specific cements.

1.3.4 Major sources of Carbon Dioxide emissions

Fossil fuel combustion is a major source of CO_2 in the ceramic tiles industry. This provides thermal energy, which accounts for 90 % of total energy demand of the manufacturing process. The emissions produced by the decomposition of carbonates present in the raw materials during the firing process are responsible for the remaining 10 %.

The bulk of the consumptions occurs in three stages in the process, spray drying in the wet method, drying of tiles once pressed and the firing of tiles. The latter firing stage can consume up to 2556 kJ/Kg fired tile on average, the overall process is estimated on using 4608 kJ/kg fired tile.

1.3.5 Technologies for limiting Carbon Dioxide emissions

A case study of a ceramic tile industry in China by Peng *et al.* in 2012 highlighted that CO_2 emissions were a drastic factor to emissions from ceramic tile manufacturing processes.[20] They identified that most emissions occur in the firing and spray drying processes.

Caglayan *et al.* proposed in their evaluation of the ceramic industry that use of the spray dryer results in high energy consumption and CO_2 emissions.[21] They studied the energy costs to the industry to determine that the consumption of natural gas used for thermal energy production was the greatest in spray dryers.

The reduction of CO_2 emissions in the ceramic industry will only be possible with significant changes in the technology used: new fuels (biomethane, biogas, Hydrogen, for example), electric dryers and furnaces, carbon capture technologies, among others.[22]

1.4 Aluminium Industry

1.4.1 How the industry works

There are many methods for aluminium extrusion, fig 4 below shows a typical set of processes used to form aluminium extrusion products.

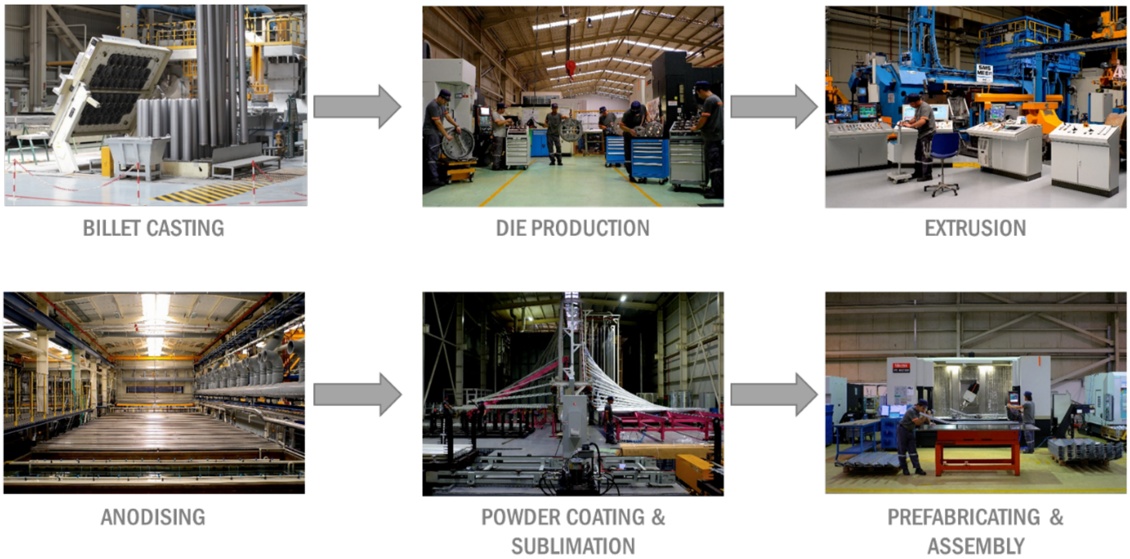

Figure 4: Processes of aluminium extrusion

There are six main stages to aluminium extrusion. The first step involves processing raw materials into billets. In this case the raw materials used are primary aluminium ingot-slabs, secondary aluminium ingot-slabs, scrap, and alloying elements. These are fed into a melting furnace to be smelted into a metallic load, the chemical composition is controlled by using an optical emission spectrometer. The billets are formed by using a direct chill casting method and these are then heat treaded to be ready for extrusion. The next step before extruding involves designing the extrusion dies, the die steels are processed with machining to produce the final die designs. This process is validated by QFORM extrusion simulation program. Then the extrusion of the billets takes place, once extruded the profiles are cut into 6 m lengths and then aged in ovens. Following aging, depending on the final product there can be several additional steps to reach the intended final profile properties, including but not limited to anodising, coating, cutting, and mechanical treatment (drilling or bending, etc).

1.4.2 Areas of significant damages

The main areas of damage are wear and erosion of steel dies used in the extruding processes such as the Solid Profile Dies (SPD) and Open Profile Dies (OPD). Various steels are used including but not limited to 2344, 2367, and DIEVAR hot working steels (HWS) of which 2367 is most common to produce the SPD. The steel used commonly for OPD are DIEVAR HWS.

Mechanical properties of the profiles must be optimized according to related standards. Mechanical properties can be neither low nor high. There are multiple processes which cause unsuitable mechanical properties. At the pre-heating billets in gas furnace step, if the billet temperature increases too much, mechanical properties of the final product varies. During log shearing, usage of two-part billet causes this problem by creating transverse weld zones and air inclusions. Another process related with this problem is billet heating at the induction furnace. Setting furnace temperature too high or too low result in mechanical properties to be sub-optimal. Extrusion speed is another damage mechanism related with mechanical problems. Cooling and aging temperature and time must be defined well to prevent this damage mechanism.

Wrong extrusion die design, die deformations, wrong bolster usage, pick-up defect on profile, wrong stretching ratio and wrong settlement during stacking of the profiles can yield geometrical problems like bending, unsuitable length, and roughness.

Air inclusions and blister on the profile, transverse weld, black lines on the profile, graphite marks on visible surface for below cavity, tear and scratch defects on visible surface are some surface problems of profiles. This problem can occur at different process steps.

1.4.3 Current solutions

The SPD are repaired using a nitriding process. On average the typical weight of a die is 77 kg. High silicon content is one factor that causes high wear on SPD and in turn creates high temperatures/deformation on the dies. Each SPD can be repaired in 4 hours and this can be repeated 3 times before the SPD has to be replaced.

The OPD cannot be repaired and hence replaced. On average the typical weight per die is 45 kg. The wear on OPD is due to the extruding products containing alloying elements that give the final products greater mechanical properties but results in greater wear deformations to the steel dies.

To deal with mechanical deformations on profiles, butt-end lengths are defined according to alloy and process parameters. After the trials, butt-end length ratios are introduced to PLC to increase controllability. Geometrical disorder caused by pick-up defects is limited with limiting the production with only 5 billets.

1.4.4 Major sources of Carbon Dioxide emissions

The main sources of carbon dioxide in the extrusion of aluminium are from the direct burning of natural gases in furnaces (for example in the extrusion press-billet burner, the aging furnace, the induction furnace, the melting-holding furnace, and homogenisation furnace) and diesel in electricity generation.

1.4.5 Technologies for limiting Carbon Dioxide emissions

A review of the aluminium industry by Brough and Jouhara in 2020 examined the emissions and technologies to reduce energy consumption.[23] In the Bayer process (a commonly used refinement method of aluminium) for everyone 1 kg of alumina refined 0.83 kg of CO_2 is produced and approximately 12.8 MJ/kg energy is required. The main technologies to reduce energy consumption in this study was waste heat recovery systems. Many sources of waste heat were identified, with the main sources listed as exhaust gases from kilns or furnaces. Although thermoelectric devices were invented in the 1820s, only recently these devices have gained increased research interest for applications as WHR systems. These thermoelectric devices were listed as potential WHR systems for use in capturing heat from exhaust gases from aluminium production processes.

FMEA ANALYSIS

1.5 Introduction

Several components within energy intensive industries such as exhaust gas extraction pipe in waste heat recovery subsystem of the cement industry, H_2 storage pressure vessel of the steel industry, refractory inner surfaces of the kiln in the ceramic industry and extrusion dies of the aluminium industry require protection and strengthening from the surrounding corrosive and aggressive environments during lifetime of these production plants. The form of protection varies depending on the nature and properties of the damages mainly CO_2 corrosion, H_2 embrittlement, erosion/wear and high temperature in the components. The occurrence of damages can result in decreased efficiency of the plant to detrimental failure of the components. Minimisation or eradication of these occurrences can therefore reduce the need for frequent maintenance and replacement of the components and subsequently reduce the cost of operation.

To find out the focus for protective solutions, the failure mode and effect analysis (FMEA) has been carried out. The rating of failure modes of the components generates ranking that reveals the most critical components in the plants. To determine this, four production plant operators were contacted and asked to rate the damages they experience with the components in their plants. The answers were then reviewed and combined to provide a general overview of potential failure modes and effects of production plant components. This report provides the combined FMEA results collated and reviewed by expert in this field. It describes the nature of FMEA and its effectiveness in categorising and prioritising failure modes for the components involved in four energy intensive industries. The results of the FMEA studies are intended to be used to support and further determine the applicability of using the novel technologies developed in this project to maintain the efficiency of the plant and to reduce the cost by improving component life, thereby reducing the need of maintenance.

An FMEA worksheet was constructed and sent to the operators of steel, cement, aluminium and ceramic industries to get their opinion on the severity, frequency and detectability of failures and their subsequent effect on their components. The answers were then combined, and the most critical cases were noted to get an overview of the most critical components of the plants and to develop the innovative coatings and materials (compositionally complex alloy/ceramic) for the betterment of the plants.

1.6 FMEA Method

Failure mode and effect analysis (FMEA) is a tool that is used to identify and prevent product and process failure before it occurs.[24] In this sense failure can either refer to how a process or component fails, or its capability reduces, as will be done in this report. Once identified, the failure modes can then be rated based on the severity (S) of each effect, the frequency of occurrence (O) and its detectability (D).

To perform a basic FMEA the failure mode, failure effect and failure cause must be clearly understood to be able to rate the severity, occurrence and detectability appropriately. It is therefore imperative that the individuals filling out the FMEA have a good understanding of the functionality and effects damage can cause to the system. Once this has been identified and rated the values for S, O and D can be multiplied together to produce a risk priority number (RPN). This number can then be used as a method for identifying critical areas in the system. While this can be represented by the RPN value, this number can be misleading as it is highly reliant on the values for S, O and D, and each of these has equal weight. To achieve more applicable results this number therefore must be used in conjunction with other values to provide results that are more tailored to desired scenario. Using the severity or occurrence value as extra criteria can provide such balance. Another method could be to use S*O as this removes the detectability factor and can therefore provide a more appropriate reference if the focus is on the severity of a failure mode and its frequency. This value is used to analyse results from FMEA and is commonly referred to as the criticality of the failure mode.[25] The FMEA can be used for a variety of industries as it is easily adapted to the environment through the specialized rating systems. This provides a basis to perform in-house analysis and comparison of systems but comparison between organizations is not possible unless the ranking scales being used are similar.

The overall methodology of this FMEA study is shown in Figure 5. A brief explanation of each step of this analysis is given below:

Objective definition and analysis strategy development

The main objective of this study is to understand the potential failure modes, causes, effects and possible actions to recover the potential harmful effects for the components involved within energy intensive industries. At the beginning of the study, TVS planned the following: extensive literature review, component listing, FMEA analysis template preparation, circulation of the template to the consortium members, compilation of feedback from the members and finalisation of the study.

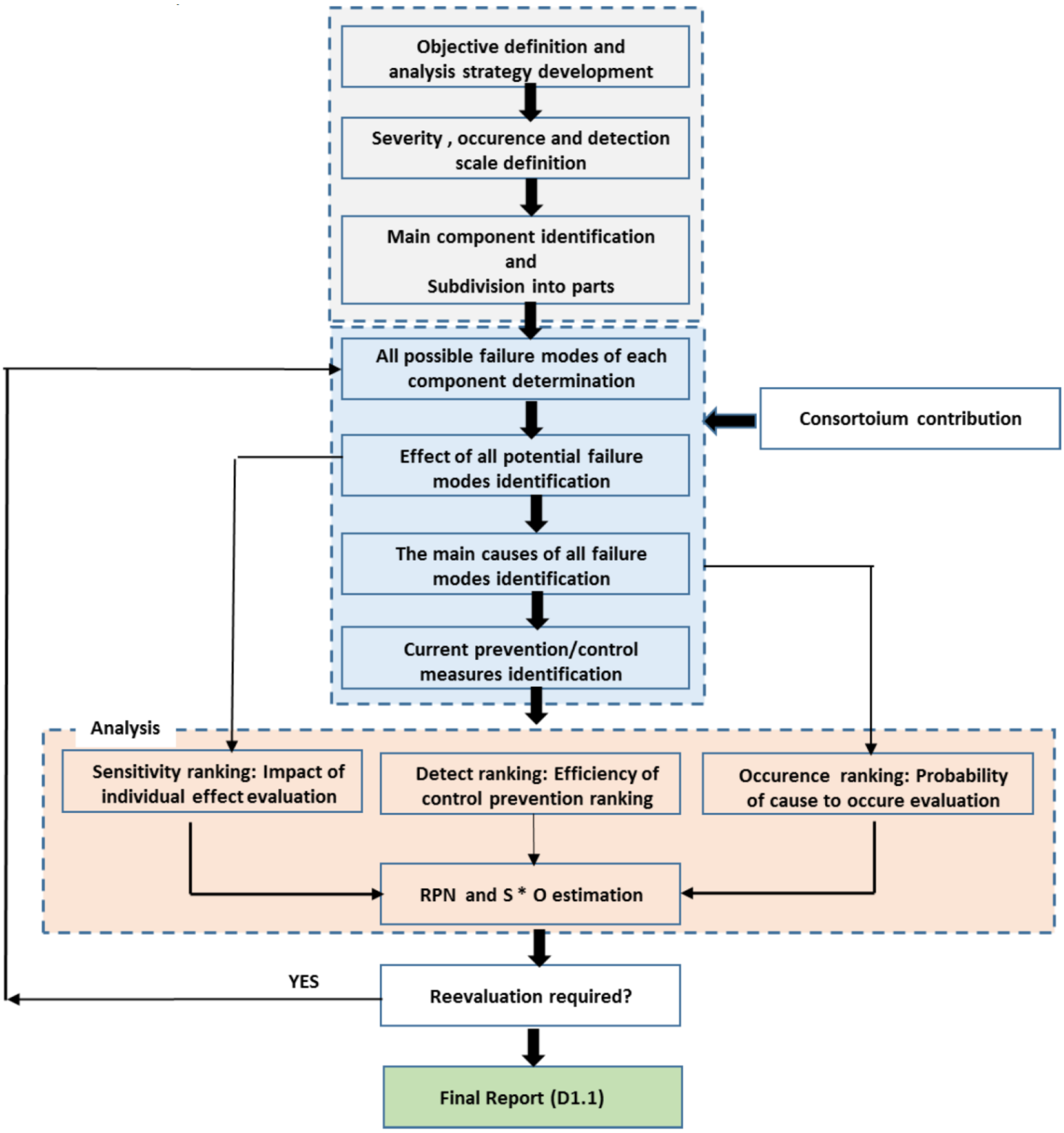

Figure 5: The main steps of the FMEA analysis for the FORGE project

Ratings of Severity (S), Occurrence (O) and Detectability (D)

The method by which severity (S), frequency of occurrence (O) and detectability (D) are defined can vary depending on the field the FMEA is being used for. Each indicator is split into a specific number of categories and the number pertaining to the category is used to rate each failure listed in the FMEA depending on its nature. The definition of the categories can therefore be highly specific to the area for which the FMEA is being used. Direct input from experienced consortium members also shaped the categorization.

Severity, occurrence and detectability were each split into 10 categories, ranked from 1 to 10. The categories are shown in Tables 1 to Table 3. The severity rating ranges between 1 and 10, with systematic increase in rank. Each category is given a short definition and a more in-depth description to make the categorization clearer. Occurrence is often based on probability of failure or number of failures per produced item. For this project, it was categorized based on likelihood of failure within a certain timeframe. The rating range does not follow a traditional mathematical curve. This does not have an adverse effect on the results, as S and D are not based on such formulae either. The highest rating for the occurrence is defined as the failure mode likely occurring within six months. The rating then decreases to "remote" which is defined as failure being unlikely to occur less than ten years. For detection the scale ranges from the lowest value of 1 where failure is easily detected through reliable detection control before it becomes problematic, to 10 where failure cannot be detected before it affects the system notably.

Table 1 – The severity ratings designed for the project.

Ranking	Definition	Description
10	Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur without warning
9	Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur with warning
8	Very High	Major disruption of service involving client interaction, resulting in either associated re-work or inconvenience to client
7	High	Minor disruption of service involving client interaction and resulting in either associated re-work or inconvenience to clients
6	Moderate	Major disruption of service not involving client interaction and resulting in either associated re-work or inconvenience to clients
5	Low	Minor disruption of service not involving client interaction and resulting in either associated re-work or inconvenience to clients
4	Very Low	Minor disruption of service involving client interaction that does not result in either associated re-work or inconvenience to clients
3	Minor	Minor disruption of service not involving client interaction and does not result in either associated re-work or inconvenience to clients
2	Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associated re-work or inconvenience to clients
1	None	No Effect

Table 2 - The occurrence ratings designed for the project.

Ranking	Definition	Description
10	Extremely high	Failure is likely to occur in 6 months
9	Very high	Failure is likely to occur in 9 months
8	High	Failure is likely to occur in a year
7	High	Failure is likely to occur in 2 years
6	Moderate	Failure is likely to occur in 3 years
5	Moderate	Failure is likely to occur in 4 years
4	Low	Failure is likely to occur in 6 years
3	Low	Failure is likely to occur in 8 years
2	Very low	Failure is likely to occur in 10 years
1	Remote	Failure is unlikely to occur under 10 years

Table 3 - The detectability ratings designed for the project.

Ranking	Definition	Description
10	Almost impossible	No known controls available to detect failure mode
9	Very Remote	Very remote likelihood current controls will detect failure mode
8	Remote	Remote likelihood current controls will detect failure mode
7	Very low	Very low likelihood current controls will detect failure mode
6	Low	Low likelihood current controls will detect failure mode
5	Moderate	Moderate likelihood current controls will detect failure mode
4	Moderately high	Moderately high likelihood current controls will detect failure mode
3	High	High likelihood current controls will detect failure mode
2	Very high	Very high likelihood current controls will detect failure mode
1	Almost certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.

Main component identification

The following components within the energy intensive industries have been considered for FMEA analysis:

- exhaust gas extraction pipe (WHR), inner wall, separator blades, flue gas fan blades & roller table of the raw mill in the cement industry,
- H_2 storage pressure vessel and line pipe and tubing for H_2 transport in the steel industry
- Refractory inner surface of the kiln in the ceramic industry
- Extrusion dies in the aluminium industry.

Failure mode, effect and causes determination

The FMEA template document had a sheet for each industry, to allow the consortium members more leeway to complete the FMEA as it best suited them. To assist them in filling out the FMEA, the exemplary components were provided with example entries (Appendix A). To avoid making the template unnecessarily complicated, predetermined failure modes were not suggested to the partners, who were invited to complete the FMEA is an unbiased manner. They were also asked about failure prevention, including maintenance and other actions for reducing the occurrence or improving detection of failure modes.

Analysis of results

The failure mode containing the highest RPN value was chosen to be the main outcome. Additionally, if another failure mode had a higher value for either S or O, this particular failure mode was also included in the combined FMEA to avoid losing this information. This can result in a similar failure mode and effect having two different rankings for the same component. Based on different ranking systems, this information can be used to determine the criticality of each failure mode.

1.7 Processing of results

The FMEA questionnaire focused on the damages caused by corrosion, hydrogen embrittlement, wear and erosion, and high temperature effects occurred in various components of cement, ceramic, steel and aluminium industries.

1.7.1 Cement industry

In cement industry, material corrosiveness, temperature effects and particle size are the main potential causes for damaging the exhaust gas extraction pipe, raw & coal mill roller table and plates and other components. Due to combination of these causes, the effectiveness of the components become degraded due to erosion. To combat this problem, the role of CCA coating on the low-alloyed steel are investigating in this project. Table 4 collates the information on the potential causes and effects of the damages occurred in various components and their current controls. The risk priority number (RPN) has been estimated based on the ratings of severity, occurrence and detectability, provided by the consortium partners, for each component affected and listed in Table 4.

Table 4 - The FMEA for various components in cement Industry on the high rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
What is the process step, change or feature under investigation?	**In what ways could the step, change or feature go wrong?**	**What is the impact on the operation if this failure is not prevented or corrected?**		**What causes the step, change or feature to go wrong? (how could it occur?)**		**What controls exist that either prevent or detect the failure?**			
Exhaust gas extraction pipe	**Erosion**	**Pipe bursts, false air inlet**	**9**	**Material corrosiveness, temperature, particle size**	**8**	**Sensors, regular inspections**	**3**	**216**	**72**
Inner wall of the raw and coal mill	Erosion	Mill stops, energy loss	8	Material corrosiveness, temperature, particle size	4	Sensors, regular inspections	3	96	32
Raw mill fan blades	Erosion	Mill stop, energy loss, balance problems, blades crack, fracture	8	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	120	40
Raw mill roller and table plates	**Erosion**	**Mill stop, energy loss, low production**	**9**	**Material corrosiveness, temperature, particle size**	**10**	**Sensors, regular inspections**	**3**	**270**	**90**
Coal mill fan blades	Erosion	Mill stop, energy loss, balance problems, blades crack, fracture	8	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	120	40
Coal mill roller and table plates	**Erosion**	**Mill stop, energy loss, low production**	**9**	**Material corrosiveness, temperature, particle size**	**10**	**Sensors, regular inspections**	**3**	**270**	**90**

ID Fan blades	Erosion	Kiln stops, energy loss, balance problems, blades crack, fracture	9	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	135	45
Separator blades	Erosion	Mill stop, energy loss, balance problems, blades crack, fracture	9	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	135	45
Electrofilter fan blades	Erosion	Kiln stops, energy loss, balance problems, blades crack, fracture	9	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	135	45
Bag filter fans	Erosion	Kiln stops, energy loss, balance problems, blades crack, fracture	8	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	120	40
Heat exchanger fan blades	Erosion	Kiln stops, energy loss, balance problems, blades crack, fracture	8	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	120	40
Raw material silos	Erosion	Mill stops	7	Material corrosiveness, temperature, particle size	6	Sensors, regular inspections	3	126	42
Heat exchanger pipes	Erosion	Kiln stops, energy loss, calorie loss	8	Material corrosiveness, temperature, particle size	2	Sensors, regular inspections	3	48	16
WHR gas pipes	Erosion	Energy loss	8	Material corrosiveness, temperature, particle size	5	Sensors, regular inspections	3	120	40
Cyclone walls	Erosion	Kiln stops, false air inlet, OHS accidents	8	Material corrosiveness, temperature, particle size	1	regular inspections	3	24	8
Meal pipes	Erosion	Kiln stops,false air inlet, OHS accidents	8	Material corrosiveness, temperature, particle size	1	regular inspections	3	24	8

It is seen from Table 4 that the highest RPN is 270 for raw and coal mills roller and table plates and the second highest RPN is 216 for exhaust gas extraction pipe.

1.7.2 Ceramic industry

In ceramic industry, the surface of the refractory bricks can experience corrosion damage and as a consequence surface cracks may appear on the surface. These damages of the refractory kilns are occurred mainly due to chemical attack from the combustion gases containing acid and alkaline elements to the firebrick surface, and depositions on the refractory surface (undesired condensation). These corrosive and alkaline elements in gaseous state penetrate the insulating firebricks through its porosity and degrade the performances of the refractory firebrick surfaces developing the cracks in the surface that can produce detachment of particles from the refractory bricks to the surface of the tiles that are being fired, causing a visual defect that causes its discard as low-quality material. Also, there is an increase of heat losses through the walls of the kiln, thereby increasing the energy consumption (natural gas). To address the problems, it is expected that the new coating materials (the role CCC materials) applied to the existing refractories could yield in a better insulating property of the whole system, so that the heat losses through the walls of the kilns will reduce, and hence the fuel consumption in the kiln will be lower. The new developed coating applied to the refractories is expected to increase the lifespan of the refractories (due to its better corrosion resistance), as now they need to be replaced after some years in service due to the corrosion caused by potassium and acid elements. A greater lifespan of the refractories means less maintenance costs, and less refractories to be produced, so that the fuel consumption and CO_2 emissions related to its manufacturing process will be reduced too. Table 5 collates the information on the potential causes and effects of the damages occurred in various components and their current controls. The risk priority number (RPN) has been estimated based on the ratings of severity, occurrence and detectability, provided by the consortium partner, for each component affected in the ceramic industry and listed in Table 5.

Table 5 - The FMEA for various components in ceramic Industry on the high rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
What is the process step, change or feature under investigation?	**In what ways could the step, change or feature go wrong?**	**What is the impact on the operation if this failure is not prevented or corrected?**		**What causes the step, change or feature to go wrong? (how could it occur?)**		**What controls exist that either prevent or detect the failure?**			
In the pendulum mill used in raw materials preparation by dry route, wear of the pendulums of the mill.	These parts of the mill, made of steel are also abraded by the clayey particles, which are highly abrasive	Metallic particles could be integrated in the ceramic composition and could provoke defects in the ceramic tiles	5	These phenomena are inherent to the process, every 3-4 years these parts have to be changed	5	Visual inspection of the mill	1	25	25
In the balls mill used in raw materials preparation by wet route, wear of the worm screw that feeds the mill	The screw is abraded by the raw materials entering the mill (specially clays)	Metallic particles could be integrated in the ceramic slurry and could provoke defects in the ceramic tiles	5	These phenomena are inherent to the process, every 3 months the screw must be changed	10	Visual inspection of the screw	1	50	50

In the balls mill used in raw materials preparation by wet route, wear of the diaphragm and mill liner	These parts of the mill, made of steel and with a protective coating of rubber, are also abraded by the clayey particles, which are highly abrasive	Rubber can cause defects in the ceramic tiles	5	These phenomena are inherent to the process, every 6-12 months these parts have to be changed	8	Visual inspection of the mill	1	40	40
Wear of the nozzles used for spraying the ceramic slurry in the spray dryers.	The nozzles suffer from wear during the pulverisation of the slurry into the spray dryer.	This wear in the nozzles causes sprayed droplets of bigger size, and hence a wrong final size granulates distribution.	8	The continuous contact within the nozzles and the (high solids content) ceramic slurry to be dried.	9	There are production controls to detect this failure, which are the determination of the granulates size distribution, and the measurement of the moisture content of the dried granulates, which increases when the droplets to be dried are of a bigger size.	2	144	72
Pressing stage: Wear of the blades used in the mould	The blades wear out during regular production periods, causing defects on the edges of the as-pressed ceramic tiles	The edges of the pressed pieces experience changes as the blades wear out with increasing working cycles, causing dimensional and/or aesthetic damage on the tiles.	5	Normal wear of the blades of the mould, caused by the unavoidable friction with the ceramic granulates used for forming the tiles	10	Visual inspection of the blades and of the edges of the as-pressed tiles	3	150	50

Printhead integrity used in the decoration inkjet printing	There is an internal membrane that distributes the ink properly over the nozzles as well as prevents the piezoelectric device from contacting with the ink. If it breaks, it is not possible to continue using this printhead, it is necessary therefore to remove and change it	When the membrane breaks, it is not possible to continue using this printhead, it is necessary to remove and change it. Hence, the production stops, causing a delay on the manufacturing process that influence the following stages.	10	Printheads are prone to suffer a membrane breakage because of the cumulative fatigue damage. High frequency sweeps and voltages, as well as high laydowns increase the risk.	8	When this problem appears, a dropping process begins. Consequently, a visual controlling procedure was made for ensuring a proper application of all colours and patterns on the tile surface.	10	800	80
Refractory integrity, located in the inner surfaces of the kiln	**The surface of the refractory bricks can experience corrosion, and consequently surface cracks may appear.**	**Surface breakdown, development of cracks in the surface that can produce detachment of particles from the refractory bricks to the surface of the tiles that are being fired, causing a visual defect that causes its discard as low-quality material. Increase of heat losses through the walls of the kiln, then increasing the energy consumption (natural gas).**	**7**	**Chemical attack from the combustion gases to the firebrick surface, and depositions on refractory surface (undesired condensations). Gases contain acid and alkaline elements.**	**4**	**Visual defects in final product, visual inspection of the refractory bricks during maintenance programmed production stops**	**3**	**84**	**28**

The printhead integrity used in the decoration inkjet printing system has been deteriorated due to membrane breakage and the RPN value is the highest and given 800. The second and third highest RPN values for wear of the blades used in the mould and wear of the nozzles used for spraying the ceramic slurry in the spray dryers and given 150 and 144, respectively. The refractory integrity located in the inner surfaces of the kiln has been degraded due to chemical attack from the combustion gases containing acid and alkaline elements to the firebrick surface and depositions on the refractory surface. The surface of the refractory bricks experiences corrosion damages and given the fourth highest RPN value of 84. Though three higher ranked faults exist in ceramic industry, refractory integrity was the only one that happens at high temperature and needs urgent solution. A visual controlling procedure was made for the highest ranked pinhead integrity fault to ensure proper application of all colours and patterns on the tile surface. Second and third ranked faults are easy to detect, hence are not an urgent need for the industry. Also, first, second and third ranked faults are not due to neither high temperature nor corrosion hence only refractor integrity fault meets FORGE call topic LC-SPIRE-08-2020 which addressed materials and components which are working in extreme conditions (high temperature or corrosive environments) to improve their durability and properties. For this reason, in the FORGE project, refactor integrity fault has been chosen as a development target with the application of compositionally complex material (CCC) which can protect the surface effectively.

1.7.3 Steel industry

In steel industry, low-alloyed carbon steel, medium carbon, nickel, chromium and molybdenum steels (e.g., ASTM-A517) as well as stainless steels (SA-705xM16) are used for hydrogen storage pressure vessels. The material which is affected due to hydrogen embrittlement (HE) is high strength steel, advanced high strength steels, etc. For strength levels of 700 MPa, the wall thickness needs to be at least 60 mm to withstand the pressure i.e., to be able to store a sufficiently large volume of H_2. To overcome the HE problem, FORGE project aims to investigating the role of CCA coatings on the low-alloyed steels (700 – 1000 MPa) with reduced wall thickness. Since CCA coating material offers remarkably high strength, it is recommended to use CCA coated carbon steel for H_2 pressure vessels and transportation pipes manufacturers. Table 6 collates the information on the potential causes and effects of the damages occurred in various components of steel industry and their current controls.

Table 6 - The FMEA for various components in steel Industry on the high rated answers

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	S*O
What is the process step, change or feature under investigation?	**In what ways could the step, change or feature go wrong?**	**What is the impact on the operation if this failure is not prevented or corrected?**		**What causes the step, change or feature to go wrong? (how could it occur?)**		**What controls exist that either prevent or detect the failure?**			
H_2 storage pressure vessel	Crack formation	Production loss	6	H_2 embrittlement	5	visual inspection or NDT before filling	2	60	30
		breakdown	10	H_2 embrittlement	1	limited lifetime allowance	2	20	10
	Vessel breakdown	Production loss	8	H_2 embrittlement	1	replacement at first crack detection	3	24	8
		Safety issues	10	H_2 embrittlement	1	replacement at first crack detection	3	30	10
Line pipe	**Crack formation**	**Production loss**	**6**	**H_2 embrittlement**	**5**	**visual inspection or NDT**	**3**	**90**	**30**
	Corrosion of the outer port	Production loss	2	H_2 embrittlement	2	visual inspection or NDT	2	8	4
		Breakdown	10	H_2 embrittlement	1	visual inspection or NDT	2	20	10
	Pipe breakdown	Production loss	8	H_2 embrittlement	1	repair at crack detection	4	32	8
		Safety issues	10	H_2 embrittlement	1	repair at crack detection	4	40	10

Piping	Crack formation	Production loss	6	H_2 embrittlement	2	visual inspection or NDT	1	12	12
		Breakdown	10	H_2 embrittlement	1	replacement at first crack detection	-	-	10
	Breakdown	Production loss	8	H_2 embrittlement	1	replacement at first crack detection	4	32	8
		Safety issues	10	H_2 embrittlement	1	replacement at first crack detection	4	40	10

1.7.4 Aluminium industry

In aluminium industry, extrusion profile production contains various steps. Main steps for profile production are direct chill casting of the billets, die production and extrusion. Main problem that are encountered mainly can be divided according to damage mechanism:

1- Problems related with mechanical properties of profiles: Mechanical properties of the profiles must be optimized according to related standards. Mechanical properties can be neither low nor high. There are multiple processes which cause unsuitable mechanical properties. At the pre-heating billets in gas furnace step, if the billet temperature increases too much, mechanical properties of the final product vary. During log shearing, usage of two-part billet causes this problem by creating transverse weld zones and air inclusions. Another process related with this problem is billet heating at the induction furnace. Setting furnace temperature too high or too low result in mechanical properties to be low or high. Keeping transportation time too high during loading of the billets into the extrusion press yields mechanical properties to get higher. Extrusion speed is another damage mechanism related with mechanical problems. Cooling and aging temperature and time must be defined well in order to prevent this damage mechanism.

2- Problems related with geometry of the profiles: Wrong extrusion die design, die deformations, wrong bolster usage, pick-up defect on profile, wrong stretching ratio and wrong settlement during stacking of the profiles can yield geometrical problems like bending, unsuitable length and roughness.

3- Problems related with surface quality of the profiles: Air inclusions and blister on the profile, transverse weld, black lines on the profile, graphite marks on visible surface for below cavity, tear and scratch defects on visible surface are some surface problems of profiles. This problem can occur at different process steps.

The damages occurred in solid and open profile of the extrusion dies are mainly erosion wear and fatigue and creep. Heat build-up and uneven pressure can cause the material degradation i.e., erosion damage. To protect the design profile of the extrusion dies, the CCA coating developed in this project can be applied. Table 7 collates the information on the potential causes and effects of the damages occurred in various components and their current controls. The risk priority number (RPN) has been estimated based on the ratings of severity, occurrence and detectability, provided by the consortium partner, for each component affected in the aluminium industry and listed in Table 7.

Table 7 - The FMEA for various components in aluminium Industry on the high rated answers

Process Step/Input **What is the process step, change or feature under investigation?**	**Potential Failure Mode** **In what ways could the step, change or feature go wrong?**	**Potential Failure Effects** **What is the impact on the operation if this failure is not prevented or corrected?**	**SEVERITY (1 - 10)**	**Potential Causes** **What causes the step, change or feature to go wrong? (how could it occur?)**	**OCCURENCE (1 - 10)**	**Current Controls** **What controls exist that either prevent or detect the failure?**	**DETECTION (1 - 10)**	**RPN**	**S*O**
Billet	Billet temperature is too high (overall billet zones)	Mechanical properties variations are too much. Customer complaint	10	Wrong parameters set (temperature too high)	4	Operator trainning Max. Limits are determined at process Hardness test according to control plan	2	80	40
Extrusion die	Wrong extrusion press selection	Extrusion die deformation	7	Lack of feasibility analysis	2	Control of designer's feasibility study	5	70	14
Extrusion die	High number of figures on die	Extrusion die deformation	7	Lack of feasibility analysis	2	Control of designer's feasibility study	5	70	14
Extrusion die	The mould template mismatch with target profiles tolerances	Wrong extrusion production	7	Faulty design	2	Control of designer's design study	5	70	14
Extrusion die	**Surface defects on the surface of the profile (scratches, tears, etc.)**	**Profile cannot be used by the client**	**8**	**Low wear resistance of used mold steels and wear during production;** **High silicon content of the alloy (above 3%)**	**10**	**100% control on the line**	**4**	**320**	**80**

				Wear of nitrided zone of the die before expected					
Extrusion die	**Wall thickness of the profile is out of tolerance**	**Profile cannot be used by the client**	**8**	**Broken mandrel** **High strength alloy extrusion**	**10**	**100% control on the line**	**4**	**320**	**80**
Extrusion die	**Linearity of the profile is out of tolerances**	**Profile cannot be used by the client**	**8**	**Strain or stretch of mandrel of the die**	**10**	**100% control on the line**	**4**	**320**	**80**

It is seen from Table 7 that the highest RPN is 320 for surface, wall thickness and linearity of the profile of extrusion cycle.

We have identified a number of critical components of the energy intensive manufacturing plants from our failure modes and effects analysis (FMEA). These components are particularly vulnerable to harsh operating environments and incur major costs associated with maintenance and replacement. To protect the critical components of energy intensive industries particularly from corrosion, erosion, hydrogen embrittlement and thermal breakdown damages, FORGE project has been designed to meet these challenges through developing high performance compositionally complex alloy (CCA) and compositionally complex ceramic (CCC) coating materials and materials technologies. The FORGE technology will be applied for different critical components in steel, aluminium, cement and ceramic manufacturing plants against four key performance indicators (KPIs) or performance targets (PTs), to extend the service life of these components from an average 3-6 years to 8-10 years, or, as the case of dies for Aluminium extrusion, to extend the production tonnage from 2 tons to 10 tons.

1.8 Summary

The FMEA carried out by the consortium provides a good overview of the different failure modes that are experienced in different components or subsystems of steel, aluminium, cement and ceramic industries. The FMEA analysis therefore give a strong basis on which a form of protection could be determined from the requirements (such as the most severe forms of failure, the most frequent, the hardest to detect or a combination of their criteria).

Tables 4 to **Table 7** show the ratings of the FMEA for different components or subsystems of cement, ceramic, steel and aluminium industries. **Table 8** collates this information and gives an overview of the highest rated faults for each of the energy intensive industries. Within the cement industry, raw and coal mill roller and table plates have the highest occurrence (10), whereas the exhaust gas extraction pipe has the second highest occurrence (8); the ratings of severity for each of these components is 9. The ratings of RPN values are 270, 270, and 216 for raw and coal mill roller and table plates and exhaust gas extraction pipe, respectively. Within the aluminium industry, surface, wall thickness and linearity of the profile have the highest occurrence (10) and the ratings of the severity for these components is 8. The rating of RPN value is 320 for each component in the extrusion cycle. For the ceramic industry, the FMEA ratings of refractory surface of kiln is included in Table 8 whose RPN, severity and occurrence ratings are 84, 7 and 4, respectively. For the ceramic industry, the FMEA ratings of refractory surface of kiln is included in Table 8 whose RPN, severity and occurrence ratings are 84, 7 and 4, respectively.

Table 8 – The highest rated components of cement, ceramic, steel and aluminium industries based on RPN

Industries	Components	Failure modes	Effects	RPN	S	O
Cement	Exhaust gas extraction pipe	Erosion	Pipe bursts, false air inlet	216	9	8
	Raw mill roller and table plates	Erosion	Mill stop, energy loss, low production	270	9	10
	Coal mill roller and table plates	Erosion	Mill stop, energy loss, low production	270	9	10
Ceramic	Refractory integrity, located in the inner surfaces of the kiln	The surface of the refractory bricks can experience corrosion, and consequently surface cracks may appear.	Surface breakdown, development of cracks in the surface that can produce detachment of particles from the refractory bricks to the surface of the tiles that are being fired, causing a visual defect that causes its discard as low-quality material. Increase of heat losses through the walls of the kiln, then increasing the energy consumption (natural gas).	84	7	4
Steel	Line pipe	Crack formation	Production loss	90	6	5
Aluminium	Extrusion die	Surface defects on the surface of the profile (scratches, tears, etc.)	Profile cannot be used by the client	320	8	10
	Extrusion die	Wall thickness of the profile is out of tolerance	Profile cannot be used by the client.	320	8	10
	Extrusion die	Linearity of the profile is out of tolerances	Profile cannot be used by the client	320	8	10

CONCLUSIONS

In conclusion this report has described the manufacturing processes of energy intensive industries represented in the FORGE project. This report has examined the areas of significant damages and current solutions used in industry to address such damages.

In addition to wear resistance and temperature stability of materials CO_2 emission reduction was identified as a crucial factor for energy intensive industries. Worldwide, steel sector accounted for 22% of industrial energy use and 8% of total final energy use in 2019. Energy typically makes up 10-25% of total production costs. Production of each tonne of crude steel results in 1.4 t of direct CO_2 emissions on average, or 2.0 t when including indirect emissions from imported electricity and heat generation [25]. The cement industries are the third-largest industrial energy consumer in the world, responsible for 7% of industrial energy use, and the second largest industrial emitter of carbon dioxide, with about 7% of global emissions [26]. Production of 1 tonne of cement creates emission of around 880 kg of CO_2. Carbon capture, utilisation and storage (CCUS) is one of the promising technologies in tackling CO_2 emission in energy-intensive industries due to the fact that integration of CCUS requires no large amendments to the system. From the experience in many industries, the presence of CO_2 tends to generate a corrosive environment for materials like carbon steels. The reaction of alloys in CO_2 environments is typically associated with oxide scaling kinetics and carburisation of metal beneath the oxide scale [27]. The CO_2 corrosion mechanism varies depending on combined factors, the most prevalent CO_2 environment. CO_2 corrosion resistance material hence is important for the industries.

Alternative fuel source will also support to decarbonise energy-intensive industries. H_2 is envisaged as a promising energy carrier for the transition to a clean energy system and can be an option to decarbonise sectors where few alternative mitigation solutions exist, because the H_2 functions as an energy storage medium to reserve energy until its conversion back to electricity through a fuel cell or engine or combines with CO_2 to produce synthetic natural gas for power plants or transportation applications. But H_2 storage and transportation is a challenging issue requiring stable materials without a strong interaction with H_2 or any other reactions, such as the physisorption of H_2 on materials. Thus, the development of H_2 storage and transportation methods is inevitably related to the phenomenon known as H_2 embrittlement which significantly decreases to both the fracture toughness and breaking strain as well as detrimental effect to toughness in higher-strength materials. The sustainable development in steel industry is driven primarily by deployment of innovative technologies and increased secondary production, thanks to H_2-based steelmaking. Electrolytic H_2-based direct reduction (natural gas-based direct reduced iron equipped with CCUS) is one of four key innovative technologies for ore-based production in the steel industry. Mineral Products Association published a roadmap for emission reduction concluding fuel switching to low carbon fuels like H_2 as one of three key technologies to decarbonising cement manufacture. If large quantity of H_2 can be implemented as low carbon methods via renewable electricity (electrification of kilns) or CCUS, it provides an option with great potential for cement manufacturing.

The FORGE project aims to create compositionally complex materials that will extend lifetime of severely damaged components and of energy intensive industries. Identifying the critical components will allow the FORGE project to develop novel coating materials that will address the most critical damage components that effect the industry partners. Additionally, this will build upon the knowledge-based machine learning model that will also address future challenges of sustainability and damages in other industrial sectors outside of those considered in this report and project.

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APPENDIX A

The FMEA templates

The following FMEA sheets were sent to four industry partners:

FORGE Consortium Project ID: 958457 - FMEA

Industry: Cement
Responsible: [redacted]
Prepared By:
FMEA Date (Orig.):
(Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Exhaust gas extraction pipe	erosion	e.g. pipe bursts	7	e.g. gas particulates	7	e.g. regular inspection	9				7	7	9	441
Inner wall of the raw mill														
separator blades of the raw mill														
Flue gas fan blades for the raw mill														
waste heat recycling system														

FORGE Consortium Project ID: 958457 - FMEA

Industry: Ceramic
Responsible: [redacted]
Prepared By:
FMEA Date (Orig.):
(Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Refractory inner surface	corrosion	e.g. surface breakdown	8	e.g. inner firebrick coating breakdown due to acidic or alkaline elements	5	e.g. visual defects in final product	6				8	5	6	240

FORGE Consortium Project ID: 958457 - FMEA

Industry: Steel
Responsible: [redacted]
Prepared By:
FMEA Date (Orig.): (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
H2 storage pressure vessel	H2 embrittlement	e.g. vessel breakdown, production loss	6	e.g. material dedradation due to h2 exposure	6	e.g. visual inspection every 6 month	7				6	6	7	252
Line Pipe														
Tube														

FORGE Consortium Project ID: 958457 - FMEA

Process/Product Name: Aluminium
Responsible: [redacted]
Prepared By:
FMEA Date (Orig.): (Rev.): 0

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	Action Recommended	Resp.	Actions Taken	SEVERITY (1 - 10)	OCCURRENCE (1 - 10)	DETECTION (1 - 10)	RPN
What is the process step, change or feature under investigation?	In what ways could the step, change or feature go wrong?	What is the impact on the operation if this failure is not prevented or corrected?		What causes the step, change or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?		What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure the actions are completed?	What actions were completed (and when) with respect to the RPN?				
Extrusion die	ersosion	e.g. breakdown of dies and production loss	6	e.g. material degradation due to erosion	10	e.g. fully replacing components or repairing using nitriding process	7				6	10	7	420
pipeline for hot water														
pipeline for steam														