4.1 Final publishable summary report

- Executive summary:

Much higher efficiencies of coal-fired power plants can be achieved by raising steam turbine temperatures and employing innovative combustion processes. Reducing both emissions and dependence on fossil fuels is an important area of energy research.

A novel coal-burning process that is the topic of global research could increase the likelihood of corrosion. Oxy-fuel coal combustion, in which coal is burned in an almost pure stream of oxygen, is a more efficient process that uses less fuel. In addition, it produces flue gases consisting mainly of water and carbon dioxide (CO_2). The concentrated CO_2 stream is easier to purify in carbon capture and sequestration schemes designed to reduce CO_2 release into the atmosphere.

The EU-funded project 'Production of coatings for new efficient and clean coal power plant materials' (POEMA) has developed 31 anti-corrosion coatings deposited by means of 8 different techniques (painting, dip- and spray-coating, pack cementation, thermal spray: APS, HVOF and pulsed plasma detonation, physical vapour deposition: EB-PVD and PDV-HIPIMS, plating: Electroplating and Electroless, and Nitriding) on metal alloy substrates mainly consisting of a ferritic steel (P92) and an austenitic (HR3C). They were tested in steam and fireside environments up to 650ºC and 700ºC. They were characterized by typical and more specialized techniques (SEM-EDS, XRD, TEM, Raman spectroscopy, etc.). From these original 31 coatings, 7 were chosen to be applied internally and/or externally on large components (tubes and blades) for the steam and fireside atmospheres.

On the other hand, their mechanical properties (creep strength, fatigue, wear resistance, etc.) have been evaluated according to ASME standards. In addition, models to predict corrosion scales growth, interdiffusion, phase stability, coating lifetime and also environmental point of view is considered through Life Cycle Assessment (LCA) have been performed over the coatings.

Finally, new electrochemical sensors able to do a continuously monitoring the corrosion produced in steam and fire-side atmospheres have been developed for laboratory and simulated industrial environments.

- A summary description of project context and objectives:

The overall objective of POEMA project is the development of new coatings for supercritical steam power plants for efficient and clean coal utilization. A significant reduction of emissions is expected by increasing efficiencies to values higher than 50%. Currently, efficiencies of 45% have been achieved in the last 30 years from subcritical 180 bar/540ºC to ultra-supercritical 300 bar/600-620ºC corresponding to a specific reduction of 20% of CO_2 emissions. Efficiencies of 50% and more can be achieved by further raising the temperature but conventional ferritic steels are not sufficiently oxidation resistant since the temperature designed for operation was 550ºC. From the mechanical properties perspective, ferritic steels can be used at temperatures up to 650ºC and for higher temperatures austenitic steels. One of the main objectives of this project is therefore to develop advanced coatings for steam environments which can resist the chemical attack of steam and fireside corrosion at temperatures higher than 620ºC employing materials with the required high temperature mechanical properties in particular creep strength. Ferritic–martensitic steels will be considered as substrate materials for up to 650ºC whereas austenitic steels are being explored up to 700ºC.

The introduction of carbon capture and sequestration (CCS) technologies also aiming to reduce emissions in power generation has increased the interest in developing new material solutions able to reduce the economic and environmental penalty associated to energy production systems due to CO_2 generation. For instance oxy-fuel combustion takes place in a N_2 free atmosphere so oxygen is burned in near stoichiometric conditions with the fuel (pulverized carbon) producing exhaust gases mainly composed of CO_2 and H_2O. CO_2 can be stored or used directly for example in enhanced oil recovery, without requiring expensive purification. Oxy-fuel combustion is currently under investigation for combined cycles and boiler applications as very little is known regarding the effect of the gas composition (higher concentrations of CO_2, H_2O and SO_2) in the corrosion behaviour of the materials commonly employed in boilers.

In this project, new coatings to protect materials both from steam oxidation and fire-side corrosion employing pulverized carbon as fuel are being studied in steam and oxy-fuel combustion atmospheres. Along the project different coating processes have been studied, comprising HVOF, PVD, application of slurries by dip-coating, thermal-spray, etc.

In order to achieve the impacts of the programme NMP2012.2.2-3, “an increase of at least 30% allowing operations at substantially higher temperatures” means an increase of steam turbine temperatures and the employment of more efficient combustion technologies, such as oxy-combustion the development of new coatings specifically studied in this technology is linked with lower emissions of CO_2, since this technology is linked with the CCS (CO_2 caption and sequestration).

There is also a need to increase reliability related to materials, incrementing safety of operation, and this can be achieved by in-plant high temperature corrosion monitoring. In this context, there is a significant interest on new monitoring systems that result in continuous measurement of the materials lifetime inside the boiler (steam side and fireside). Therefore, the second main objective of POEMA is to develop a new high temperature corrosion monitoring system to follow the oxidation rate in real time and the performances of new coating system to develop also in this project on the steam and fire-sides. This innovative system is necessary, since there is not available experience in CCS plants to follow possible failures of coated materials in real time.

- A description of the main S&T results/foregrounds (not exceeding 25 pages),

A literature and patents search on the technological area was performed every three months to up-date the state of the art from the date of the POEMA's DoW (e.g. Fig. 1). Those results related to the topic of this project were uploaded on “Myndsphere” database (private access for POEMA's partners). The patents and literature found with relation to POEMA were classified in two categories:

- Of scientific interest: patents with some scientific relation, but without impact on POEMA.
- Relevant: patents related to one or more coating processes used or designed in POEMA that could influence the patenting in the project.

So far no publication or patent were found that would have crucial impact on POEMA. However, relevant journals for future publications were found.

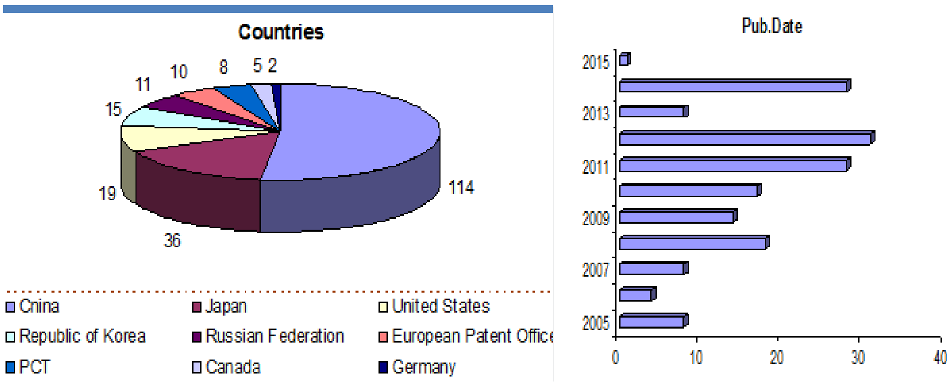

Fig. 1. Patent search with the key words “method and repair and coating and high and temperature”.

Consequently, two main substrates were selected base on the two temperature conditions studied in the project: P92 ferritic-martensitic steel for 650ºC and HR3C austenitic steel for 700ºC, but also deformable austempered ductile iron (DADI) and a nickel-iron-chromium alloy (IN-800HT) were evaluated.

During POEMA a total of 31 coatings were designed following different approaches concerning the deposition procedure as well as the coating composition. Several deposition techniques have been utilized: slurry and sol-gel were applied by painting, dip-coating and/or spray-coating, pack cementation, thermal spray: high velocity oxy-fuel (HVOF), air plasma spray (APS) and pulsed plasma detonation), physical vapour deposition (PVD): by electron beam (EB-PVD) and by high power impulse magnetron sputtering (PVD-HIPIMS), nitriding, electroless and electroplating. These coatings have different processing routes which manifest their microstructure and interaction with the substrate material. This might have a large influence on corrosion protection and working performance of the material system. All coatings developed in POEMA are shown in the Tables 1-5 below on which a short summary of the results is also included.

For instance, prototype coatings based on iron with boride eutectic suitable for coating by various methods (thermal spray, PVD and electrospark) were developed. In addition, the production of powders has been tested on industrial equipment and it has been observed that the size and shape of the (Ti,Cr)B2 crystals depend on cooling rate from the liquid state (see Fig. 2). On the basis of this system more complicated alloys, additionally doped with Ni and Al, were obtained.

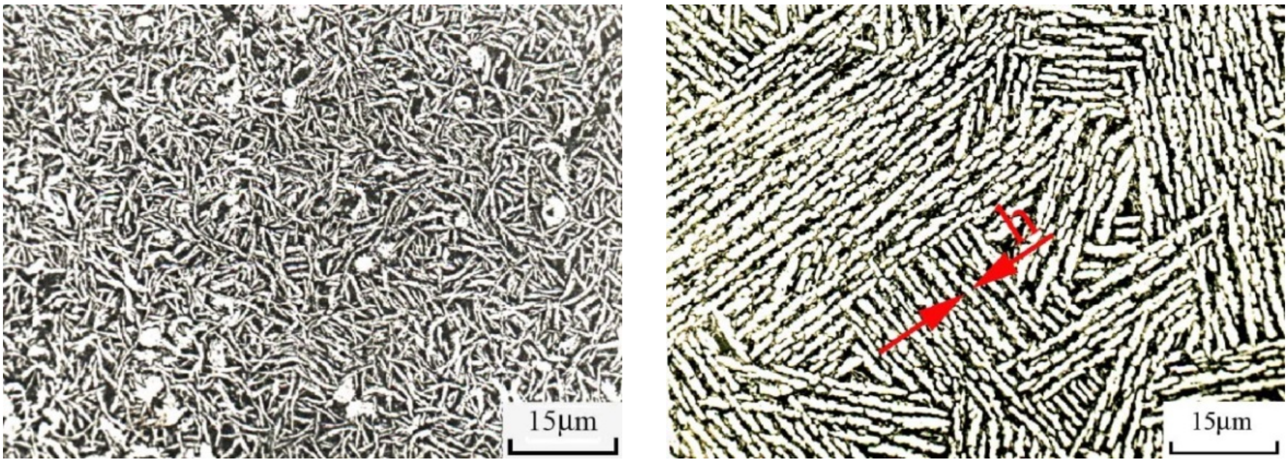

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Fig. 2. Prototype iron with boride eutectic at (a) 100 K/s and (b) 10 K/s cooling rate.

Table 1. Diffusion coatings designed, deposited and a short summary of the obtained results.

	Coating	Partner	Summary of results
	DIFFUSION COATINGS		
1	MinimAl (Al slurry) on P92 and HR3C	ICT	Slurry deposition as thin as possible and as thick as necessary. Forms FeAl after >500 h at 650°C at 1 and 300 bar in steam.
2	Slurry formulation	ICT	Formulation of transportable Al slurries with adjusted rheology for spraying sag-free slurry layers of up to 200 µm on vertical surfaces.
3	Al slurry on DADI	ULR.GTU	The aluminization improved the performance of DADI at 650°C and 750°C (air) at least by the factor of 15 and 30 respectively.
	Al slurry on IN-800HT	ULR	Passed all lab tests (steam, oxy-fuel and air) at 650°C and 1 bar.
	Al slurry on HR3C	ULR	Passed all lab tests (steam, oxy-fuel and air) at 700°C and 1, 30 and 300 bar.
	Al slurry on P92	ULR	Passed all lab tests (steam, oxy-fuel and air) at 650°C and 1, 30 and 300 bar. Applied on real components (tube) externally and internally.

4	Al/Si slurry on P92 and HR3C	ULR	Coatings OK but discarded to avoid having too many slurry coatings to long-term test.
5	Al slurry on HR3C	INTA	Passed all lab tests at 700ºC.
6	CrAl slurry on P92	INTA	Passed all test at 650ºC in steam high and low pressure and in oxy-fuel. A tube was coated internally and externally.
7	BAl slurry on P92	INTA	Results are no different from plain Al slurry.
8	Aluminizing (Pack cementation) on P92 and HR3C	TBCOAT	Passed all tests at 650°C and 700ºC at low and high pressure (300 bar). One tube was coated internally.

Table 2. Thermal spray coatings designed, deposited and a short summary of the obtained results.

	Coating	Partner	Summary of results
	THERMAL SPRAY COATINGS		
9	CoNiCrAlY (HVOF) on P92 and HR3C	TBCOAT	Passed all lab tests under oxy-fuel conditions. Applied externally in a tube for the field test.
10	Cr_3C_2-NiCr (HVOF) on P92	TBCOAT	Did not pass the first screening test under oxy-fuel condition due to spallation of the coating.
11	Al_2O_3*TiO_2 (APS) on P92	TBCOAT	Signs of corrosion detected onto the base material due to porosity levels.
12	CoNiCrAlY+ZrO_2 (HVOF+APS) on P92	TBCOAT	Passed the screening test but was discharged due to high brittleness and low thermal conductivity
13	FeCrNiAlTiB (HVOF) on P92	IMP.INTA	Passed all lab tests.
	FeCrNiAlTiB (pulsed plasma detonation) on P92	IMP	Passed successfully mechanical tests. Oxy-fuel tests not completed due to technical problems.

Table 3. Ceramic paints designed, deposited and a short summary of the obtained results.

	Coating	Partner	Summary of results
	CERAMIC PAINTS		
14	Boehmite sol-gel (dip- and spray-coating) on P92 and HR3C	BAM	Passed all oxy-fuel corrosion test. It was applied on the outside of a 1 m tube.
15	$AlPO_4$ (dip-coating) on P92	CISC	Passed lab tests at 650ºC and 1 bar, promising for flue-gas application.
16	K_2SiO_3 base (dip-coating) on low carbon steel	CISC	Passed lab tests including thermal cycling at 650ºC and 1 bar in air, promising for high-temperature coatings under insulation.
	K_2SiO_3 base (dip-coating) on P92 and HR3C	CISC	Coating failure under flue-gas conditions because of high-temperature silicate volatility in water atmosphere.
17	SiO_2 sol-gel (dip-coating) on P92	CISC	Did not pass screening test under oxy-fuel.

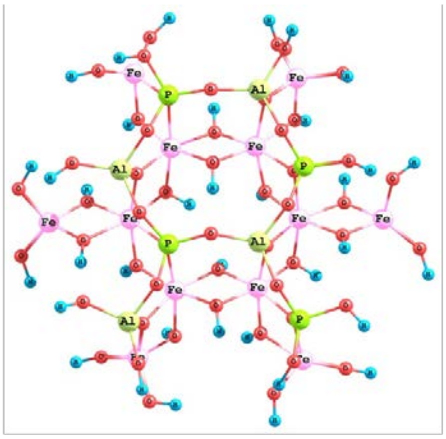
Table 4. PVD coatings designed, deposited and a short summary of the obtained results.

	Coating	Partner	Summary of results
	PVD COATINGS		
18	Fe-44Cr-4Al on P92 and DADI	GTU	Showed very protective behaviour. It has superior high temperatures resistant features when exposed at in air, steam and flue gas.
19	Fe-44Cr-4Al-La on P92 and DADI	GTU	Did not perform better than Fe-44Cr-4Al.
	Fe-44Cr-4Al on HR3C	GTU	Cracked when exposed at the HTs. Mismatch of the CTE with substrate.
20	CrN/NbN (Low Nb) on P92	SHU	Passed all mechanical and wear resistant tests including water droplet erosion. Deposited on a real turbine blade.
21	CrN/NbN (High Nb) on P92	SHU	Similar results as above but with reduced steam oxidation resistance.

Table 5. Hybridized coatings designed, deposited and a short summary of the obtained results.

	Coating	Partner	Summary of results
	HYBRIDIZED COATINGS		
22	NIEPAL-2: Electroplate Ni+Al Slurry on P92	ICT	Stoichiometric adjustment of the Ni- and Al-portions to form Ni-aluminides only. Heat treatment in air: oxide formation could not be avoided.
23	Double layer of Boehmite+$AlPO_4$ on P92	BAM.CISC	Passed lab tests at 650ºC, promising for flue-gas application.
24	Electroless Ni+Al slurry on P92	INTA	Too much porosity at the Ni-P92 interface. Coating failure.
25	Electroplate Ni+Al slurry on P92	INTA	Less porosity but still neds improvement.
26	Nitrided P92+Al slurry	INTA	Very good results but nitriding step needs improvement.
27	FeCr on P92+nitriding	INTA	Waiting to be tested for water droplet erosion resistance.
28	CrN/NbN+Al slurry	SHU.INTA	The aluminide did not form as CrN/NbN behaves as a diffusion barrier.
29	CrN/NbN+Al slurry	SHU.ULR	The aluminide did not form as CrN/NbN behaves as a diffusion barrier.
30	CoNiCrAlY+ZrO_2 + $AlPO_4$ on P92	TBCOAT	Passed the screening test but was discharged due to high brittleness and low thermal conductivity
31	Al_2O_3*TiO_2 + $AlPO_4$ on P92	TBCOAT	

On the other hand, thermodynamic simulations of systems designed were modelled for steam and oxy-fuel environments: uncoated substrate-atmosphere as a baseline, coating-substrate and coating-atmosphere interactions (e.g. Fig. 3).



$Fe_{12}(OH)_{36} + Al_4P_4H_{16}O_{24} \rightarrow Fe_{12}Al_4P_4H_{36}O_{52} + 8\ H_2O$

E_{tot} (Hartree): -2076.90577 -427.30631 -2367.34836 8×(-17.14419)

ΔE (kJ/mol) = -760.9 kJ/mol. Energy/bond formation = -760.9/8 = –95.1 kJ/mol.

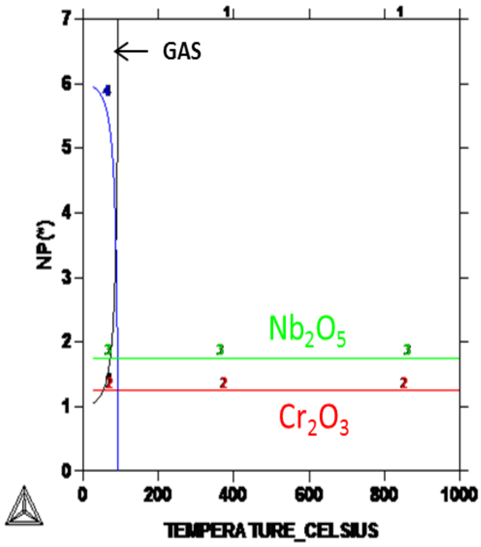


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Fig. 3.Thermodynamic simulations: (a) $AlPO_4$ coating-substrate (with native iron oxide film Fe_2O_3) and (b) CrN/NbN coating-steam.

Moreover, the effect of the cooling rate on the mechanism of crystallization and structure formation of the eutectic alloy CTN 23 was simulated by methods of physical experiment. It was shown that the alloy crystallizes by cooperative and independent mechanisms. The critical cooling rate, at which the mechanism of crystallization changes, was determined by analysing the structures of sprayed by a jet of inert gas powders. The powder particles cooling rate depends on their size with decreasing of powder particles diameter the cooling rate increases. With increasing of cooling rate the thickness of the borides crystals in the colonial structure decreases.

A study about the welding influence in 9-12% Cr steels was performed too. The microstructure of these steels is characterized by a high displacement density and martensite lath structure, which is stabilized by $M_{23}C_6$ and MX precipitates. So the heating rates for welding processes on these steels might cause phase transformations (ferrite to austenite), recrystallization temperature, solution temperature of carbides and nitrides and grain growth. In addition, P92 steel also shows susceptibility to stress corrosion cracking (SCC) after welding and subsequent cooling to ambient temperature. Therefore, the microstructure of the thin coatings investigated within POEMA project will be thermal influenced by the welding process. In worst case the coatings will be destroyed in the area of highest temperature and the area has to be recoated.

Repair processes were studied for slurries and FeCrNiAlTiB (HVOF) coatings. For latter, by means of another deposition technique will be local repaired, for example by electrospark deposition. For the one of the Al slurry, soft acid stripping and final grit blasting removes in a controlled manner either different layers of the additive zone or the full coating (additive and interdiffusion zones). For other slurries, blasting with steel grit was employed to remove the still existent coating as well as the corrosion products. Recoating with Al slurry is possible for both types of aluminides and oxidation resistance is comparable to that of new Al slurry coatings.

For those coatings exhibiting cracks or pores, sealant methods we developed. In particular a sealant for the CoNiCrAlY+ZrO_2 was performed. It was a well behaviour but the coating was disregarded for other reasons. In addition, mixtures H_3PO_4 and acetone sealed the thin and thick cracks on an aluminide coatings produced. These cracks remain sealed even after drastic thermal cyclic conditions. Also ethanolic-aluminophosphate formulations were designed with different Al/P ratios for sealing pores, natural defects and cracks in the as-synthesised and utilized coatings including on-site repairing.

The overall objective of the POEMA project was to demonstrate the benefit of coated steel components for harsh working conditions, which are the corrosion in oxy-fuel flue gas with and without influence of ash and steam oxidation.

For example (Fig. 4), the thicker coatings containing Al (FeCrAl, Al and AlCr slurries and its hybridizations) define their lifetime by the time to transform the total Al reservoir into Al_2O_3. The formed Al_2O_3 film on the surface may spall which shortens the total life time. The thin non-metallic coatings ($AlPO_4$, Boehmite, CrN/NbN, Al_2O_3*TiO_2) do not interact with the substrate but may fail by spallation. Plasma sprayed coatings typically suffer from corrosion of their adherent layer and the corrosion of the coating itself.

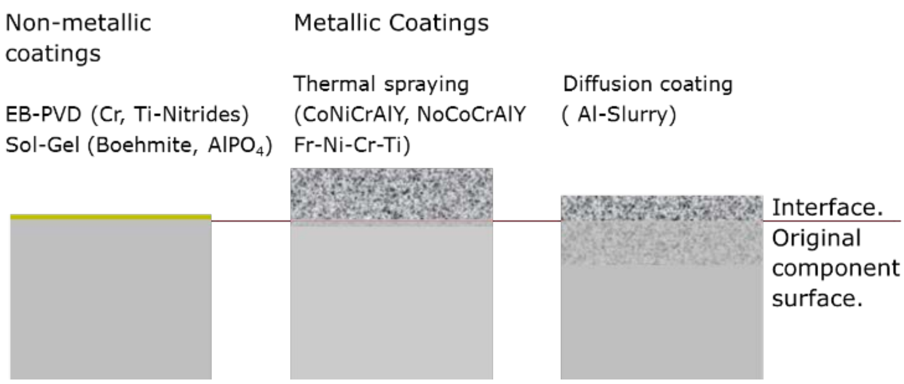


Fig. 4. Coating characteristic.

All coatings may interact with the substrate. For example, the “diffusion coatings” undergo the diffusion of Al into the steel microstructure to form the necessary adherence and protection. However, the thin non-metallic coating will not influence the microstructure. Based on the mass change during corrosion/oxidation test, the formation of protective oxides which are stable in the working environment and the diffusion of O and S into the coating were assessed. A second thermal cycling test was suggested to accelerate life time consumption. Table 6 presents an overview of the defined test conditions and the coated material. To pass the screening phase less than 1 mg/cm^2 mass change and no diffusion of S into the interface or oxide growth in the interphase was required.

Table 6: Test conditions on POEMA.

	Flue gas	Steam	Cyclic test
Flow$_{med}$ (vol.%)	60 CO_2-30 H_2O-2O_2-1SO_2-7N_2	De-ionized water. (< 1 ppm dissolved O_2)	Media gas or steam
Ash (fraction of tests)	BAM reference ash for oxy-fuel; Power plant ash	Not applicable	Not recommended, because ash reduces the heat flow.
Flow (m/s)	0.03	0.07	As gas or steam
Time	Screening test = 300 h Long-term test ≤ 2000 h	Screening test = 2000 h Long-term test ≤ 4000 h	Heat rate: 10 K/min Cooling rate: 15 K/min Hold time: T_{max}/T_{min}: 60/30 min
P_{tot} (bar)	1	1, 30 and 300	1
Temp.	650°C for coated P92, DADI and IN-800HT 700°C for coated HR3C or another austenite		300°C - annealing temperature

All coatings and their variations were subjected at different tests following the working flow chart (Fig. 5). Early in the screening period it became obvious that coatings could be combined. For example, $AlPO_4$ turned out to be a good sealant for thermal sprayed coatings and is able to enhance the performance of Boehmite coatings due to the support of forming a dense δ-Al_2O_3.

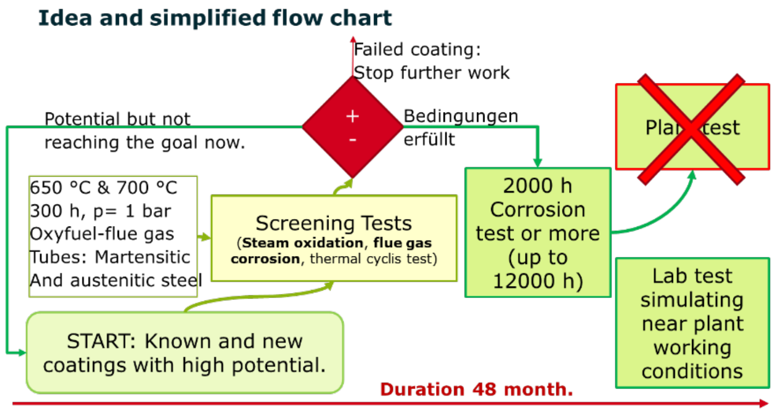


Fig. 5. Working flow chart.

Accelerated test conditions by just simply increase the temperature were applicable in our corrosion system, because these kinds of tests are only valid if the diffusive mass transport is without change in phase stability of the oxidation/corrosion scale or the steel. In P92 the Cr-Laves phase starts to be dissolved above 600°C and becomes instable at 700°C. Above 600°C Fe and Cr-sulfates are instable and sulfide formation starts. The only way to define a lifetime test for fast damage screening has been the cyclic tests in Table 6. This test combines chemical damage and thermal stresses due to different thermal expansion of different types of materials. Other mechanical tests like erosion or mechanical strength are tests to judge on the materials system behaviour.

A typical result is represented in Fig. 6. All samples had a lower mass change of 2 mg/cm^2 within 300 h and could pass the screening test. But there are obvious differences in its mass change development. All coatings protected the steel within the limit set for mass change. The green column symbolizes the mass change of unprotected P92 after 300 h. This result demonstrates the benefit of combined coatings. The combination of double layer of Boehmite+$AlPO_4$ is better than the single coating $AlPO_4$. The best coating here is the Al-Slurry coating, which in general showed excellent corrosion resistance. The sol-gel coating is relatively quickly in an equilibrium with Cr from the material and oxygen and shows in general a fast-initial mass change which decreases later.

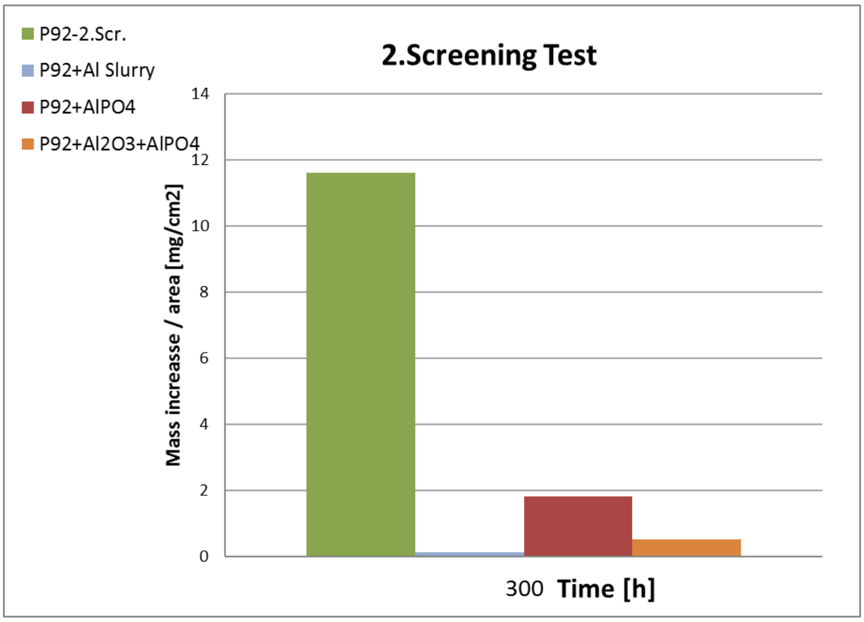


Fig. 6. Example of one result from screening coatings on P92.

The second example Fig. 7 from the second screening test package demonstrates the comparison between corrosion with ash and without ash layer. The ash layer was applied according draft of ISO 17224:2015. It is obvious in Fig. 7 that the corrosive mass change of uncoated P92 is lower than with coated P91 and if no ash melt is formed as frequently observations show. On the other side, in this scale the Al Slurry without ash is again the most protective material but with ash all material systems showed a material loss in the range of the material change of uncoated P92. To measure the mass loss the ash must be removed from the surface. Because of ash sintering this is damaging the steel interface also. Because of the faster corrosion rate in pure gas it is recommended to use pure gas as long as hot corrosion type I or II is not happen.

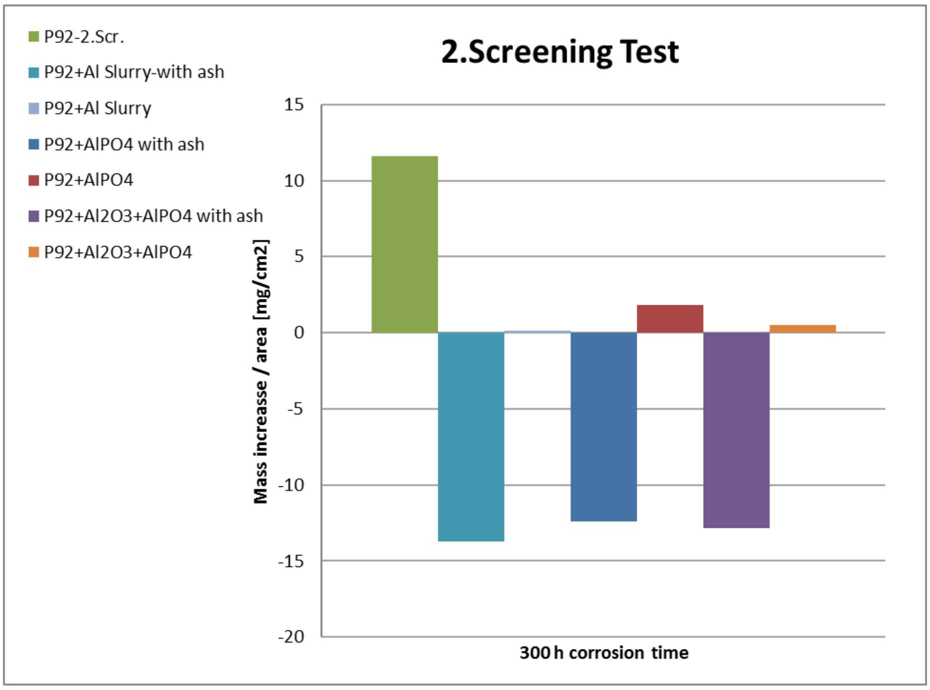


Fig. 7. Mass change of coated samples in contact with ash.

The good performance of Al_2O_3 forming materials were demonstrated in the planned 2000 h tests. In Fig. 8 the results demonstrates the performance of Al coatings on P92 in a 2000 h test at 650 °C in oxy-fuel. Al Al-based coatings perform even after 2000 h below the critical limit set to 2 mg/cm^2 for the 300 h screening test. It was no evaporation damage visible in the cross sections but an evaporation of Cr diffusion might be possible.

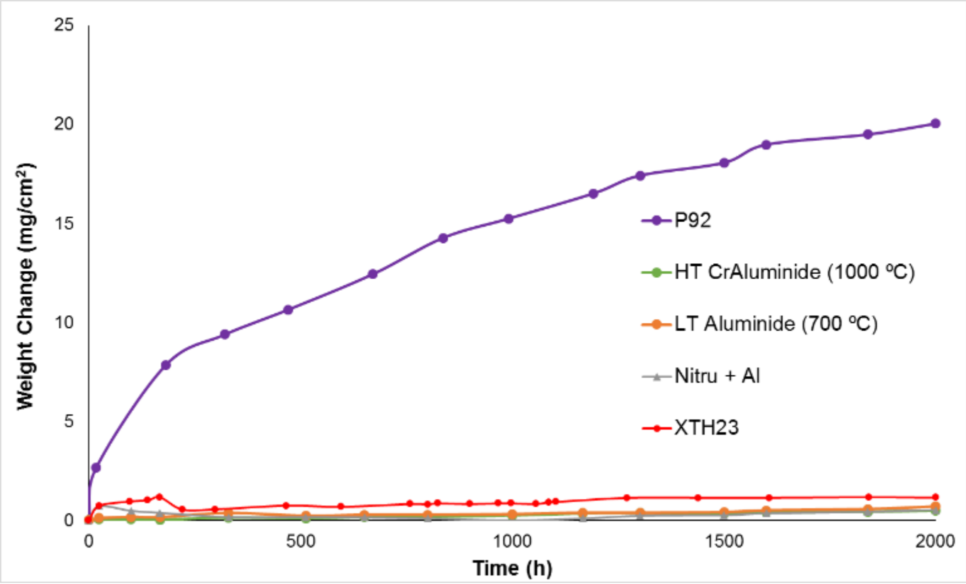


Fig. 8. Mass change of uncoated and coated P92 in Oxyfuel

Al Slurries past also cyclic oxidation tests and demonstrated maintenance potential. Cracks were forced to develop upon the Al slurry coating process to simulate harsh conditions. The cracks were sealed with 0.2M and with 0.5M mixtures H_3PO_4/acetone mixtures. Then, the not sealed and the 0.2M and 0.5M sealed coatings were subjected to thermal cycles at 650°C for 1 h and subsequent cooling in natural air for 5 min for more than 1000 cycles. The Fig. 9 shows that the coatings remained unaltered after the cyclic tests, i.e. the cracks did not develop further into the substrate and the oxide scales were like those of the not-sealed coatings.

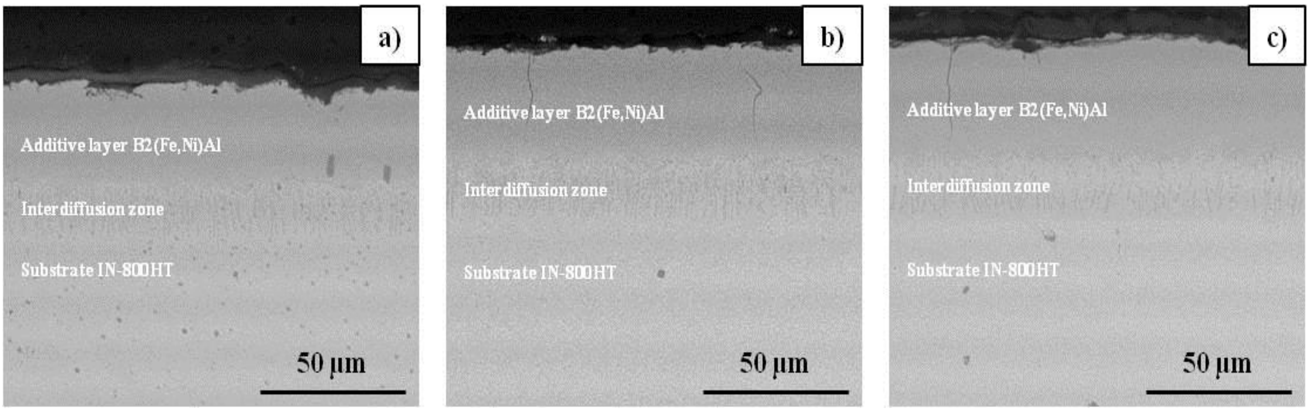


Fig. 9. SEM cross-sections of the Al slurry coatings (a) not-sealed and sealed (b) with 0.2M and (c) with 0.5M after 1000 cycles thermal cycles at 650°C-1h /room temperature-5 min in air.

The corrosion behaviour of austenitic steel was less critical. In several experiments the need for coatings under these test conditions did not became obvious.

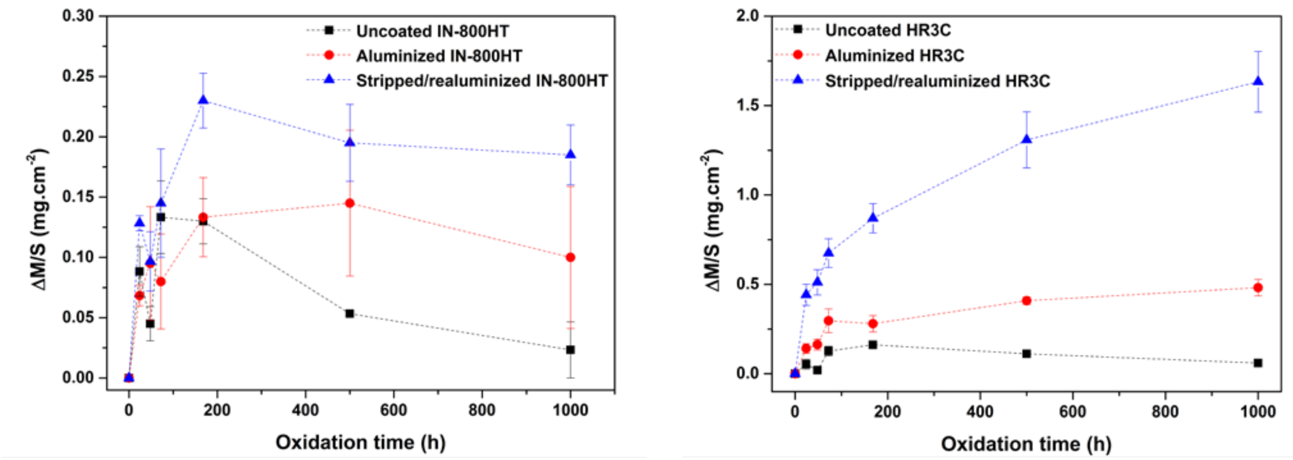


Fig. 10. Evolution of the specific mass gains with time of uncoated, Al and re-aluminized on (a) IN-800HT and (b) HR3C after 1000h of isothermal exposure in air (650°C IN-800HT; 700°C HR3C).

The steam corrosion experiments showed the excellent performance of Aluminide coatings. However, Boehmite coatings or $AlPO_4$ were not stable in steam. In the long term experiments the P92 showed constant mass change at 1 bar in steam. Compared to this behavior the Al_2O_3 formers exhibited a very good stability and protection. The Fig. 11 shows an example of gravimetric curve from long-term test in pure steam at atmospheric pressure; the color bars symbolize the stop times in order to control the weight of the samples.

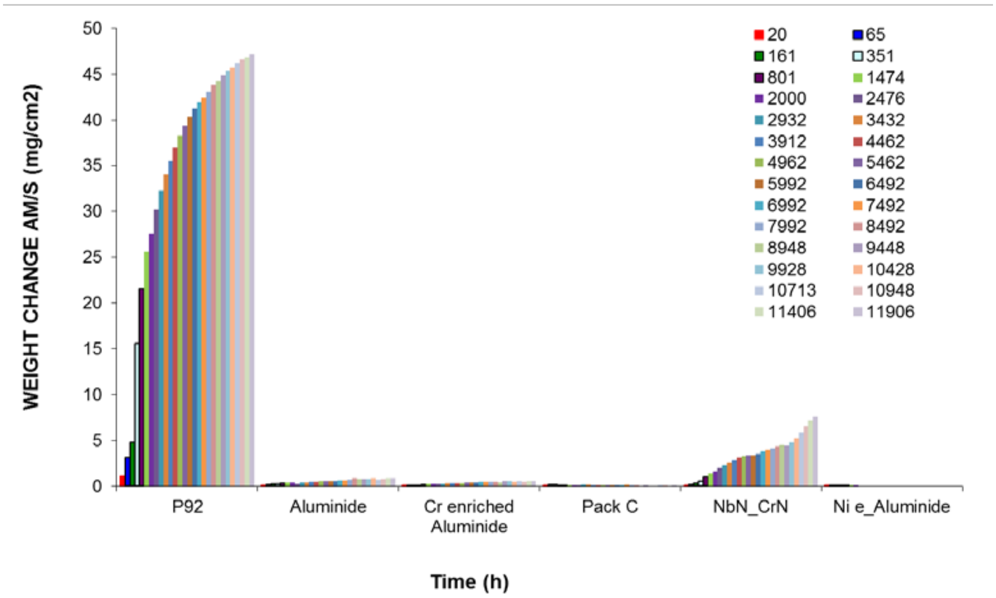


Fig. 11. Long term tests in steam at 1 bar.

To sum up, the difference in environment is mirrored in the differences between the coatings which can be used. In the oxy-fuel flue gas environment more coatings can be used such as Boehmite, $AlPO_4$ and combination were as good as Aluminide coatings to protect martensitic steel. The austenitic steel HR3C forms a naturally growing protective scale which was more effective under the test conditions of this project than the protective coatings. Under steam conditions the Aluminide coatings outperformed the coatings in the competition. The team worked out test conditions and presented a corrosion test methodology to compare coatings in a fast initial benchmark test program which allows concludes fast on the performance of coating materials and more general on the performance of the layer composite system.

Regarding the mechanical properties of developed coatings, creep tests, low cycle fatigue testes as well as hot tensile tests were carried out at 650°C with additional post-exposure metallographic analysis in order to reveal the coating integrity. The results of the mechanical testing show that there are partially remarkable differences between the resulting properties of the coated P92 samples whether it is creep, fatigue or tensile testing as shown in Fig. 12.

Especially the slurry coated samples do not show acceptable properties. The thermal treatment of the different coating procedures strongly influence the substrate properties leading to partially poor and partially good creep, fatigue and strain behaviour, depending on each coating procedure. Coating temperatures above the austenite transformation temperatures (Ac1, Ac3) lead to a normalization effect of the precipitation strengthened martensitic structure of P92. In addition, it is recommended to perform a subsequent quality heat treatment in case of high temperature coating to recover the microstructure of P92 in terms of reforming precipitates ($M_{23}C_6$, MX). Light optical post exposure investigations showed that the slurry coatings have an overall reasonable integrity even after plastic deformation. The other coatings showed few cracks and detachments after irreversible deformation. A reversible elastic deformation results in a good integrity of almost all tested coatings.

In addition, the resistance (adherence) of the coatings to the substrate by thermal cycling in air at 650°C (P92 steel) and 700°C (HR3C steel) for 1000 cycles (Fig. 13) was evaluated. The results allow anticipating the thermal fatigue behaviour of the coated components (cycling in the power plants).

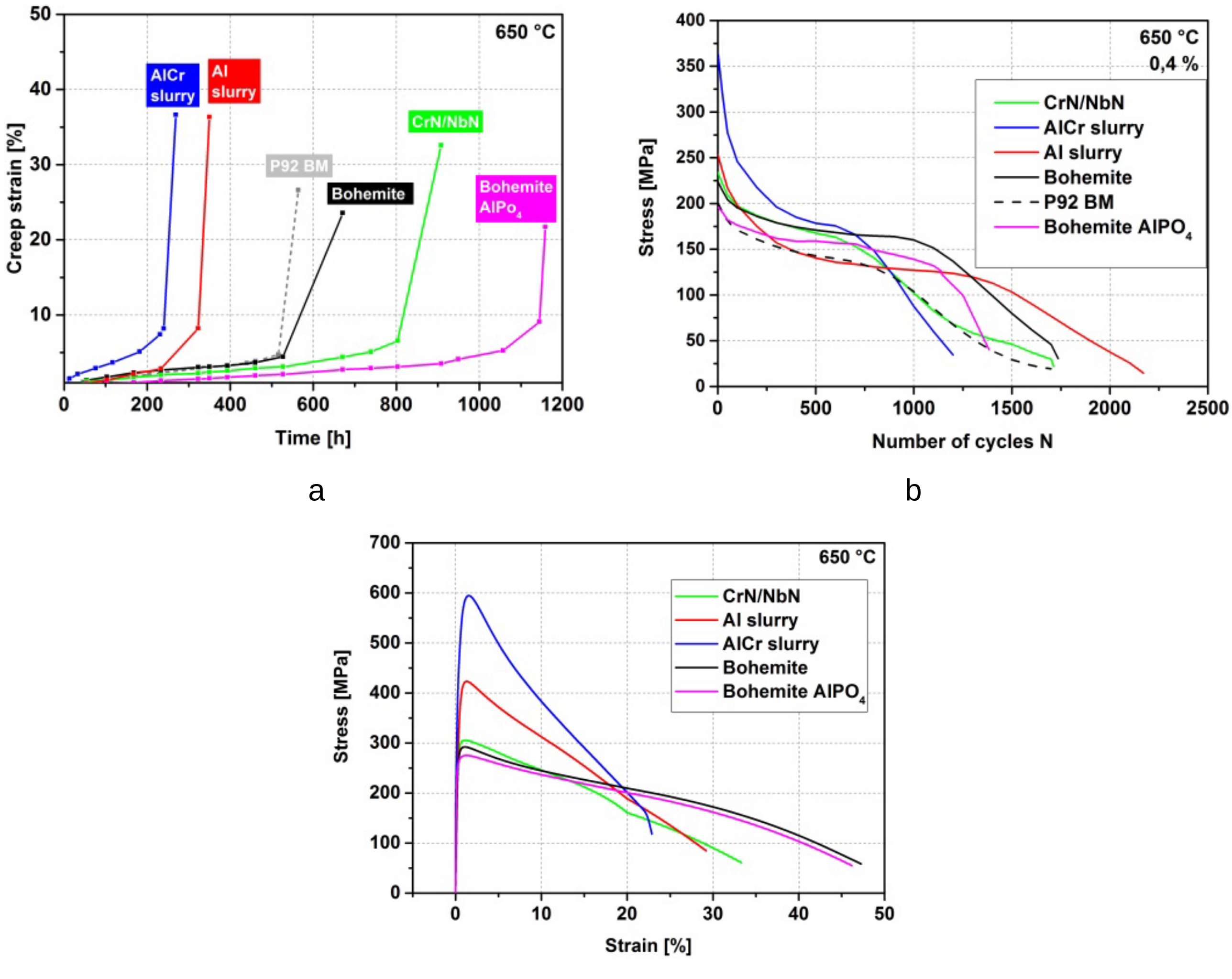


Fig. 12. Results about (a) creep, (b) low cycle fatigue and (c) hot tensile test properties of coated P92 steel at 650°C.

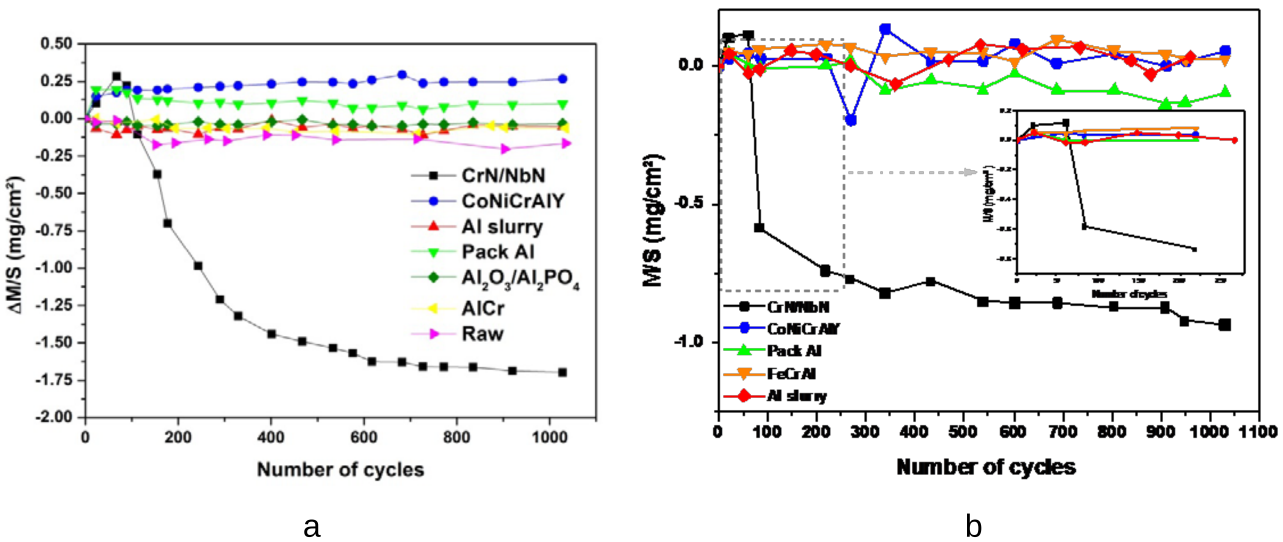
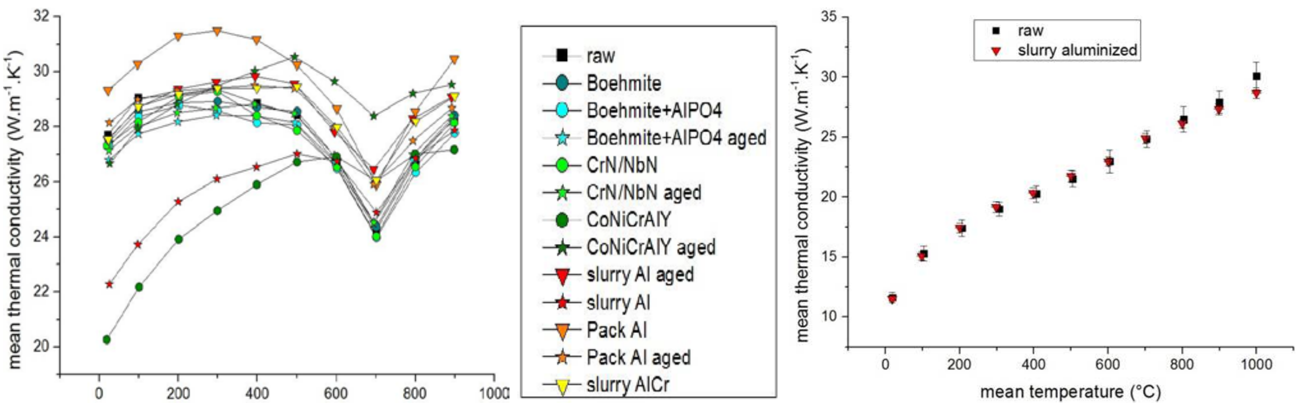


Fig. 13. Mass loss as a function of number of cycles for coated a) P92 and b) HR3C.

The potential changes in thermal conductivity of the substrates when coated were studied too. This was required to validate that there is adequate heat transfer from the external wall of the tube to heat the steam circulating inside the tube and that the fatigue and creep properties will not be affected by overheating or lower temperatures. The thermal conductivity (λ) were calculated as follows: $\lambda = \alpha \cdot C_p \cdot \rho$ where α, (C_p) and ρ are, respectively, the thermal diffusivity, the heat capacity and the density. Thus the latter parameters were measured and the evolution of λ with temperature is shown in Fig. 14. It was demonstrated that below 600°C, the Curie temperature of P92 steel marked heavily the λ. Also CoNiCrAlY and Al slurry coatings had a lower conductivity due to pores and defects in the as-deposited condition. In the aged condition, these defects disappeared and the values were similar to those of the other coatings. Above 700°C, all the coatings displayed similar values (<5% difference) in the as-coated and aged condition. In contrast, the slurry Al coated HR3C displays the same λ than the substrate due to the presence of less defects and of the absence of Curie temperature in austenitic stainless steels.



a b

Fig. 14. Thermal conductivity of coated steels versus temperature a) P92 and b) HR3C.

Comparative studies of relaxation processes and mechanical properties of P92 steel samples were conducted using the internal friction and shear modulus temperature- and amplitude dependence in different conditions: as-received, after electric current tempering at 700ºC under external mechanical tension, and after annealing at 950ºC/20min. The obtained results demonstrated the visible increase (more than ~40%) in strength characteristics at elevated temperatures (550-700ºC), achieved by the additional electric current tempering under mechanical tension. For instance, the results of $Q^{-1}(T)$ and $f^2(T)$ measurements derived from logarithmic decrement and vibration frequency of the P92 steel specimen in an as-received condition and after annealing at 950°C/20min inside a relaxometer, are shown in Fig. 15. The activation characteristics (given in Table 7) may play an important role in determination of alloying atom diffusion parameters for corrosion studies of the investigated ferritic steel in the temperature range 500-750°C.

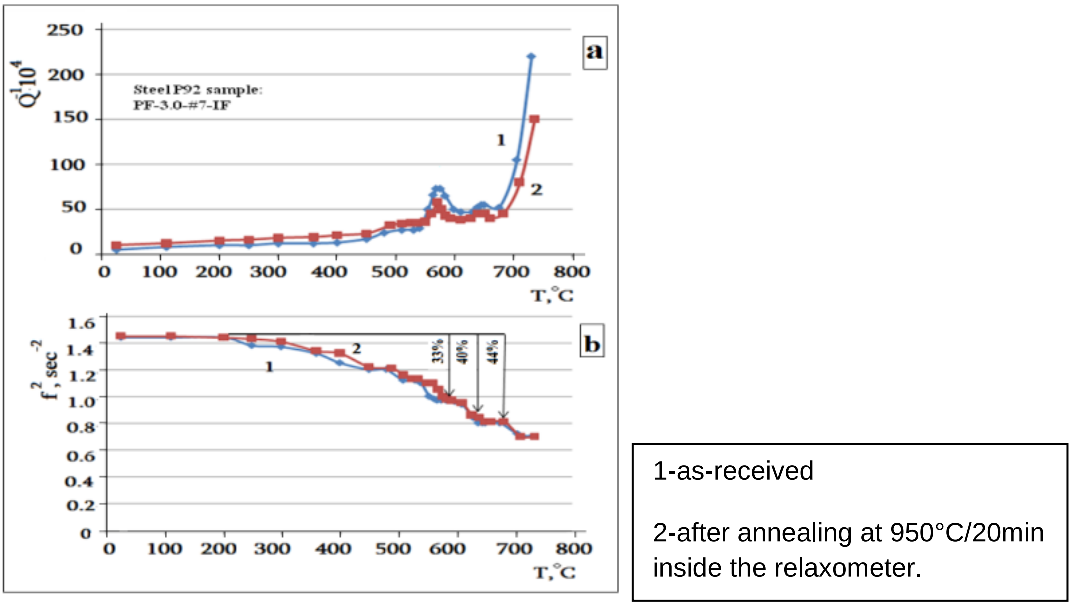


Fig. 15. The temperature spectra of (a) internal friction $Q^{-1}(T)$ and (b) the dynamic share modulus $G(T) \sim f^2(T)$ for P92 steel.

Table 7. Activation characteristics of the relaxation processes in P92 steel.

Condition P92 sample	T_{max} of IF peaks,°C	f_{max} of IF peaks, s^{-1}	Act. energy, *H*, cal/mol	Frequency factor, τ_0^{-1} ,s^{-1}
Initial "as-received"	520 570 645	1.6 0.98 0.89	47900 52700 56000	$6 \cdot 10^{13}$ $1 \cdot 10^{14}$ $8 \cdot 10^{13}$
Tempered by electric current under mechanical tension	520 570 640	1.4 1.36 1.22	48500 50500 56000	$8.7 \cdot 10^{13}$ $2 \cdot 10^{13}$ $1 \cdot 10^{14}$

On the other hand, the method of X-ray diffraction when heated in situ allows you to define the thermal expansion of the surface layer corresponding to the absorption of radiation. The method is effective for the study of thermal expansion of the coatings. Thermal expansion of most metallic coated steel P92, which have been studied, has a little difference from the thermal expansion of the substrate. According to this criterion coatings can be declared fit for use. Oxides, phosphates and other non-metallic coating steel due to the small thickness have little effect on the thermal expansion interface. Thus, the difference in thermal expansion of the coating and the substrate does not lead to the accommodation layers, though does not exclude the use of such coatings on steel.

During the course of the project the adhesion and the hardness of various coatings from the POEMA partners deposited on P92 and HR3C steels were characterised thoroughly. The adhesion property was measured by two methods namely Daimler- Benz Rockwell C Indentation Test and Scratch test. The hardness was measured by a high precision nanoindentation using CSM nanoindenter whereas microhardness was characterised by Mitutoyo Microhardness tester, HM221 (e.g. in Fig. 16).

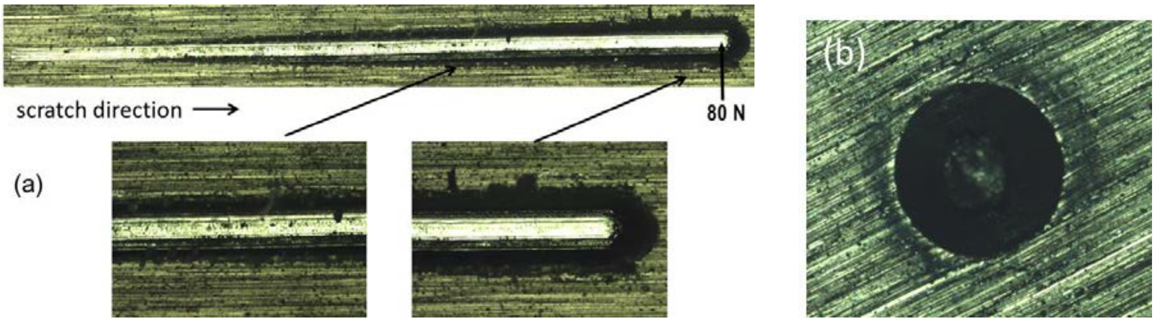


Fig. 16. Optical images of (a) scratch adhesion test and (b) Rockwell C, Daimler- Benz indentation.

All coatings and substrates were characterized (thickness, uniformity, morphology, composition and potential defects or irregularities) prior to exposure to harsh conditions (steam, oxy-fuel, air and mechanical strains) at high temperatures. Post exposure examination aimed at establishing the protection/degradation mechanisms, nature of the corrosion products and amount of metal loss, also observing and study the substrate materials, coating's and their combined system's structure and their peculiarities in order to be able to govern them according to the needs of the project and thus understanding the mechanisms of the processes going on inside, on the top and in the gas-oxide, oxide-coating, coating-substrate interfaces. The characterization means for the as-coated and post-exposure conditions included optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), Raman spectrometry (RS) and other specific methods. Round Robin Tests were performed among partners at the start of the project for comparative purposes in the EDS analyses. Exemplary, some representative results of the coatings developed and investigated within POEMA project are given below.

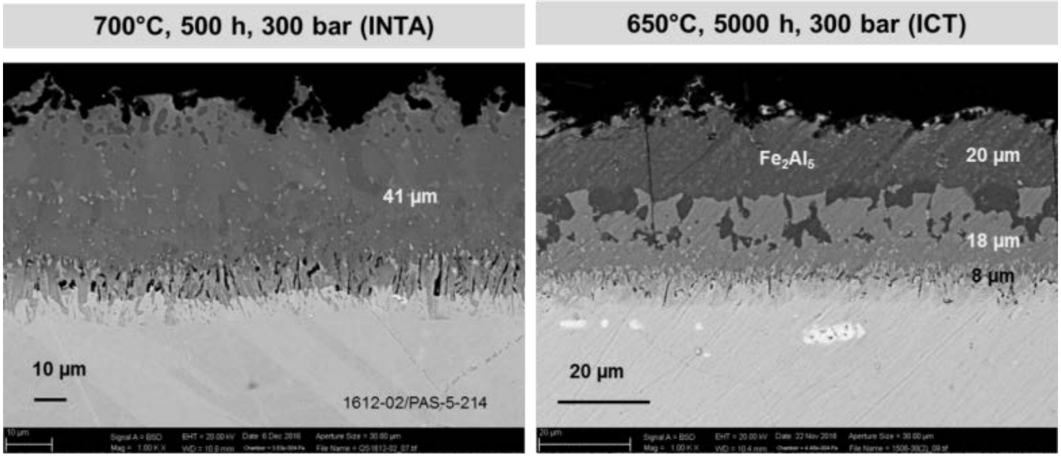
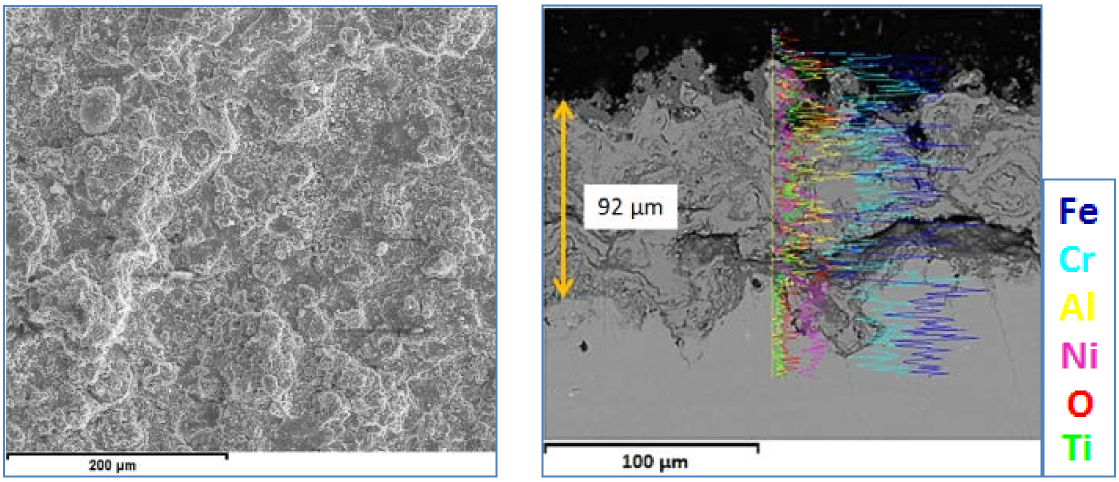


Fig. 17. MinimAl on HR3C in pressurized steam at 700°C after 500 h and at 650°C after 5000 h.

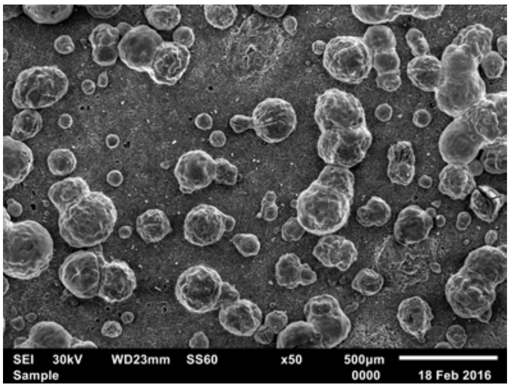
The MinimAl concept (Fig. 17) is made Al slurry coatings as thin as possible and as thick as necessary in order to provide minimum Al consumption and to facilitate the formation of less brittle Al phases with the exposure time. It can be concluded that depositing slurries with wet thicknesses from approximately 60 µm to 120 µm comparable thicknesses and structures of the diffusion coating are obtained, which remain stable up to the investigated 5000 h, both at 1 and 300 bar. This means that depositing a slurry coating on industrial level with a given wet thickness, a deviation of the wet slurry thickness in the same order of magnitude would not affect the coating performance significantly. A deviation tolerance for the wet slurry thickness can thus be defined for industrial coating processes.

Following more examples about the characterization of developed coatings:



a b

Fig. 18. SEM-EDX micrograph of FeNiCrTiB on P92 steel (a) surface morphology and (b) cross section after 2000 h in steam atmosphere at 650ºC and 1 bar.



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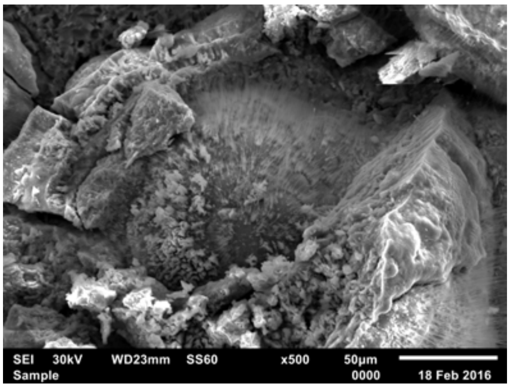

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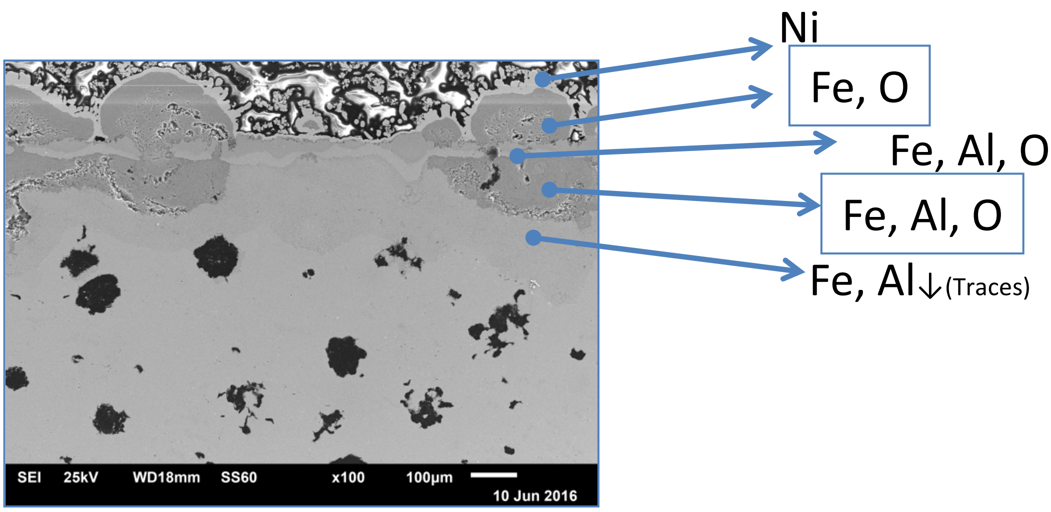
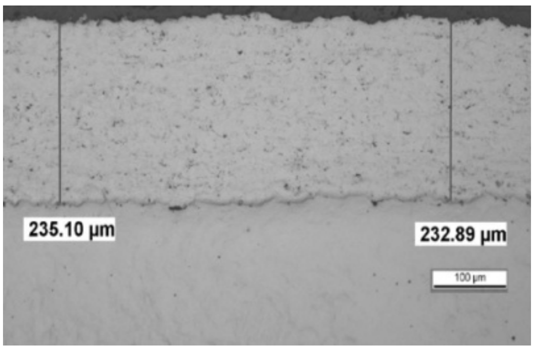


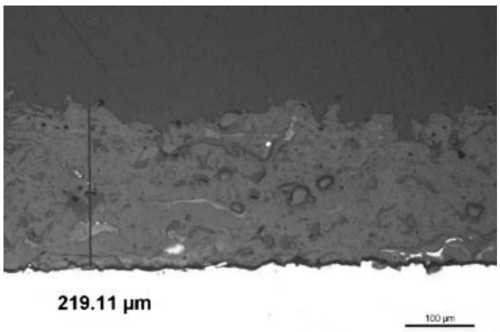
c

Fig. 19. SEM images of the thermally treated DADI after Al slurry deposition (15 mg/cm^2) and oxidation at 650ºC after 3000 h in air: (a) surface morphology, (b) the microstructure of iron rich nodules and (c) its cross section with the composition of sub-layers.

Therefore, constantly the microstructure and thickness of the developed and applied coatings was checked, for example by means of optical microscope.



a



b

Fig. 20. Thickness of (a) CoNiCrAlY by HVOF and (b) Al_2O_3*TiO_2 by APS.

Also during POEMA project, a new monitoring system has been developed for high temperature oxy-combustion and steam corrosion, that allows monitoring in an on-line and continuous mode the corrosion produced in oxy-combustion power plants both in the components exposed to steam and those exposed to oxy-fuel and ashes environment. The system is based in different electrochemical measurements that provide information about the corrosion mechanism that is occurring and its evolution and also the corrosion rate. The system is composed by sensors that incorporate the steel/material that the plant components are made of, special cables to transfer the measurements and a potentiostat where the measurements are acquired and treated in order to get useful information such as when the plant is in a critical situation that requires maintenance shutdown.

Other main purposes in frame of POEMA project were estimation of the coatings lifetime by the protective element diffusion modelling employing the computational and experimental approach. The essential advantage of this approach is the identification of unknown model parameters, which are assessed from the short-time experimental tests and then used for long-term prediction and lifetime estimation. It was applied for some POEMA coatings, in particular for Al slurries.

The computer model, considering components interdiffusion, phase transformation and oxidation, based on a numerical solving of the differential equations of diffusion was developed. The mathematical model is based on the Fick's first and second laws where a diffusion mass flux depends on the chemical potential gradient, which allowed considering phase transformations. The model was implemented as a separate computer program during the POEMA progress and has a number of advantages comparing to available software because it allows assigning concentration dependent diffusivities, phase concentration ranges and oxidation in a convenient manner due to made simplifications and assumptions.

For example, the model developed for Cr diffusion in Fe44Cr4Al coating on P92 showed that the Cr diffusivity appears to be rather low and it is expected that its distribution in coating and in the substrate will not significantly change with time. Using literature data led to high discrepancy between simulation and experimental results although different literature sources indicated different values which do not agree with each other whereas using Inverse problem solution method led to good fit with results of test in POEMA.

Other thermodynamic simulation about the stability of the phases that may appear upon the Al slurry process on the IN-800HT. Correlations between the experimental and the model results were established. The ternary diagrams simulated. The phases detected for the concentrations measured by EDS, predicts the formation of ß-(Fe Ni)Al for the high (1000 and 1100°C) temperatures. At lower temperatures (800 and 900°C) an additional ζ2 $(Fe,Ni)_3Al_{10}$ phase formed (see Fig. 21). Therefore, the thermodynamic model suggested that the aluminizing temperatures should be above 1000°C.

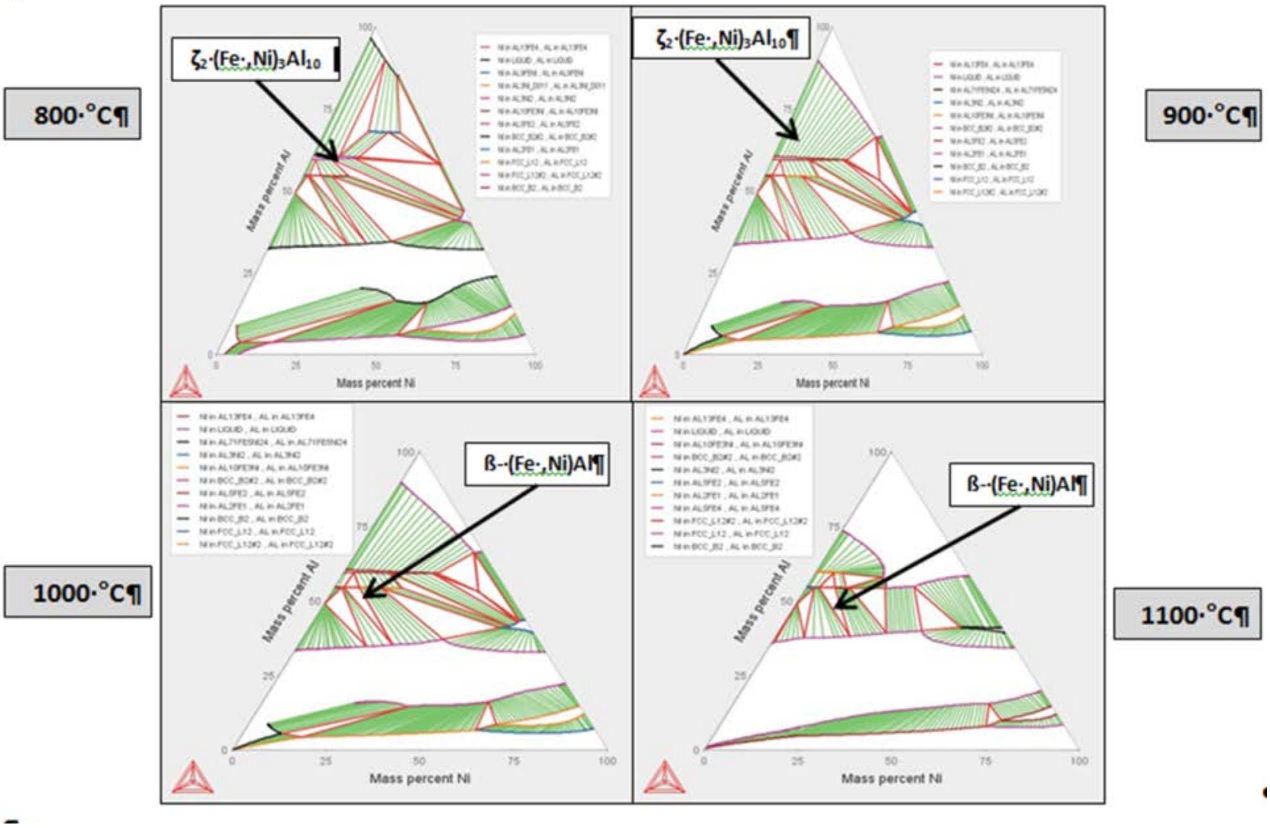
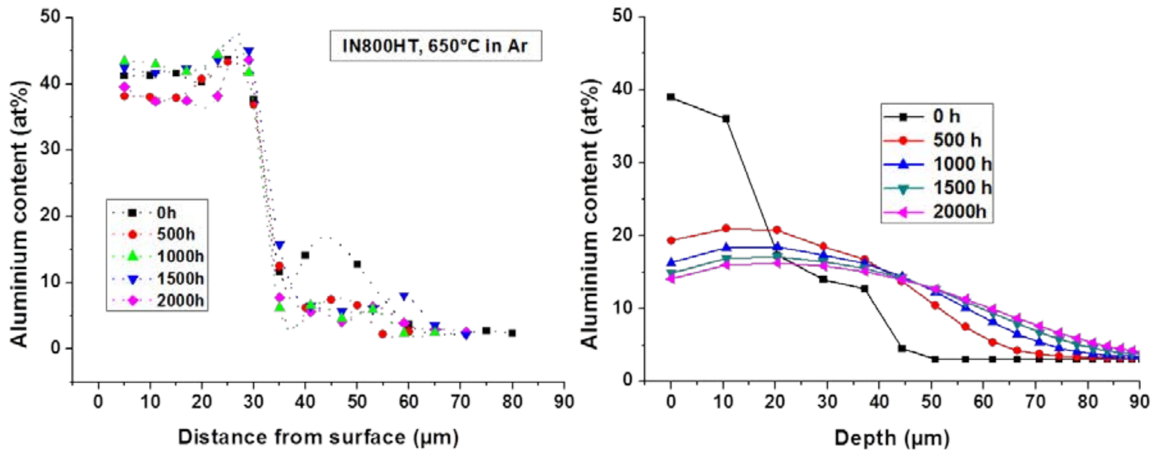


Fig. 21.Ternary diagrams (Al, Fe, Ni) and the phases expected to form upon Al slurry on IN-800HT at different coating temperatures.

Moreover, the interdiffusion mechanisms between Al and the major elements from the substrates were also established by simulation and from experimental results in view of determining the lifetime of the aluminide coatings on IN-800HT in different atmospheres (argon, steam and air) at 650°C for 2000 h. Strong deviations between the experimental and the modelled profiles appeared regardless of the atmosphere (air or Ar) and of the substrate. It was assumed that the absence of grain boundaries, of size of grains and the presence micro segregations render the theoretical model far away from the experiments (Fig. 22).



a b

Fig. 22. Evolution of the Al concentration with coating depth and increasing exposure time at 650°C in $Ar_{(g)}$: (a)experimental EDS results and (b) simulation results.

Other important simulation in POEMA project was to compare from an environmental point of view the uncoated austenitic steel tubes with the coated ferritic tubes developed in the project. Life cycle assessment (LCA) methodology was applied to evaluate the impact associated with the consumption of energy in the coating processes (ISO standards 14040-14044), and the structured framework breaks down the LCA procedure in four distinct phases: goal and scope definition, inventory analysis, impact assessment and Interpretation. The indicator used to compare the results was the cumulative energy demand (CED) which is evaluated by taking into account the total consumed energy for production of the resource materials (powder for coating e.g. aluminium/aluminium oxide), coating processes and substrates production (e.g. ferritic, austenitic). SimaPro software and Ecoinvent database was use to process the data into impact categories such as CED and CO_2 emissions. Following the results it can be observed that the pack cementation technique requires higher energy consumption when comparing to other coating techniques. In addition, it is observed that the energy required to produce one ferritic tube coated with the other coating systems developed in POEMA requires less energy when comparing to the production of one tube of austenitic steel (see Fig. 23).

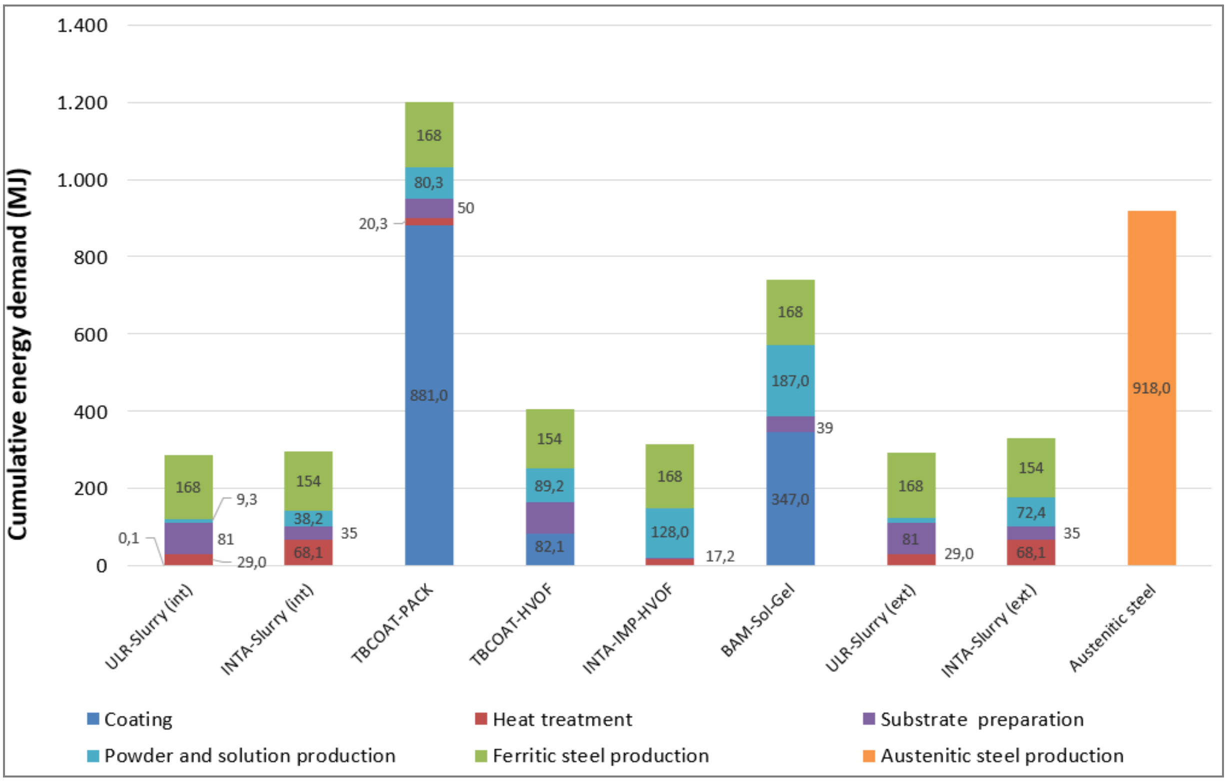


Fig. 23. Contribution of sub-process cumulative energy demand.

Additional activities were carried out to compare the costs of the coated tubes produced in the project, the results showed that the ferritic tubes coated with slurry (INTA) are much more expensive than the tubes coated with other techniques. Ferritic tubes coated with slurry (ULR), HVOF and sol-gel are cheaper than the austenitic steel tube (see Fig. 24).

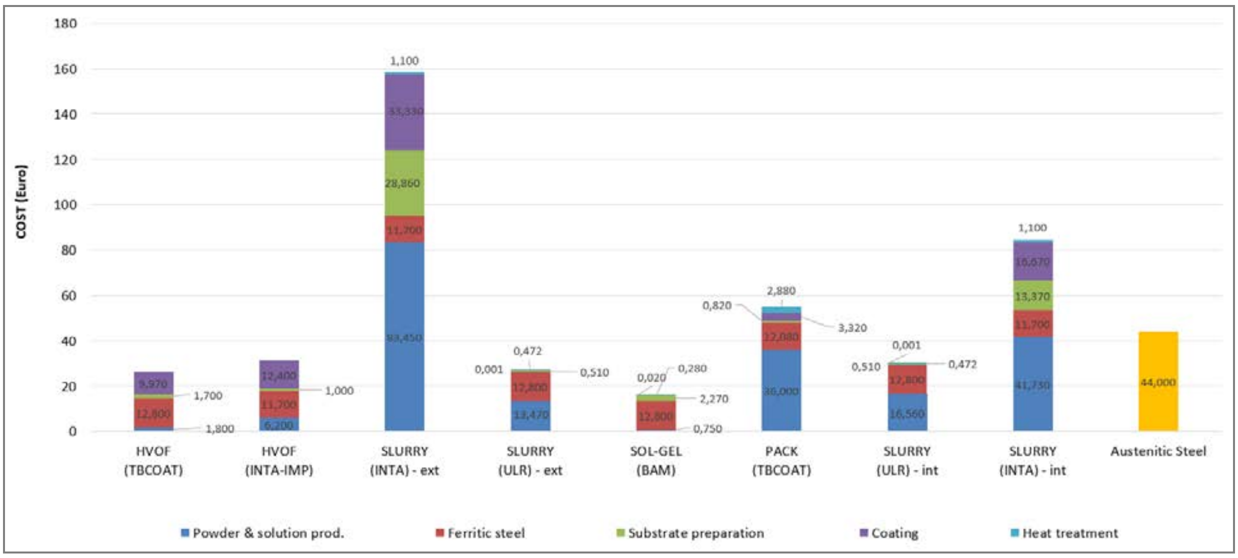


Fig. 24. Comparison of tubes regarding their costs.

According to the results showed in the previous figures, it is observed that from an environmental point of view the coated ferritic tubes are comparable with the austenitic steel. Most of the coatings are showing an environmental performance which is slightly better that the austenitic steel tube. In regards to the costs, one can observe the same pattern; most of the coated ferritic tubes developed in the projects appear to be cheaper when comparing with an austenitic tube (see Fig. 24).

An attempt to use industrial data was made in this study whenever possible. However, the level of uncertainty should be carefully considered when making judgements on results which are mostly coming from a laboratory scale process.

Numerous coating solutions to be applied over ferritic-martensitic (P92) and Austenitic (HR3C) components were investigated. The main purpose was the application of these coating under specific conditions for the steam power plants applications: ultra-supercritical steam production and oxy-fuel combustion technology.

Several thermal spray coatings were examined for the external surface of the steam power plant components (under oxy-fuel conditions) while aluminide coatings were investigated for the internal component surfaces. All these coating undergo an initial screening test under oxy-fuel and steam conditions for external and internal applications respectively. This test allowed to shortlist the investigated coating, detecting the best performing coating under such conditions.

HVOF sprayed CoNiCrAlY and Pack aluminide coating were selected as the best performing coatings after screening tests in oxy-fuel (300 h of test). These coating were successively tested for longer period of times giving promising results under their corresponding conditions. Both coatings were finally selected among all the applied coatings as one of the most promising solutions for the new generation of steam power plants components and for the final field test.

CoNiCrAlY was applied on an external surface of a 1 m long tube while pack aluminide coating was applied in the internal cavity of the same tube. The coating process was optimised in terms of surface cleaning and spraying parameters in order to obtain an homogeneous coating with high adhesion strength to the base material (see Fig. 25).

Fig. 25. P92 tube coated externally by CoNiCrAlY (HVOF).

After the first trials the main issue that had to be took into consideration was the cleaning process: some residuals from the sand blasting step had to be removed from the base material-coating interface as showed in Fig. 26.

An optimal cleaning process able to remove these residuals was developed, avoid detachment and spallation problems during the field test under severe conditions.

The final coating microstructure for CoNiCrAlY and Pack aluminizing are showed in Figure 27a-b, respectively.

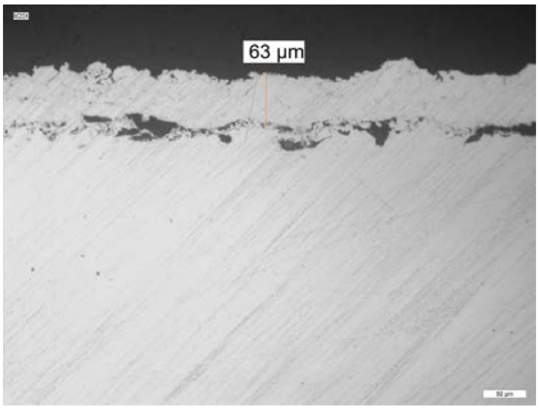
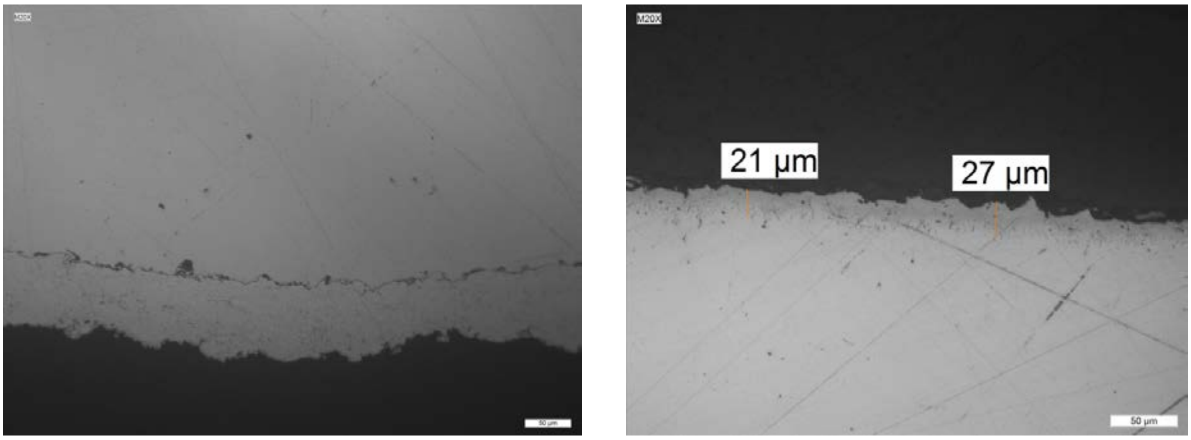


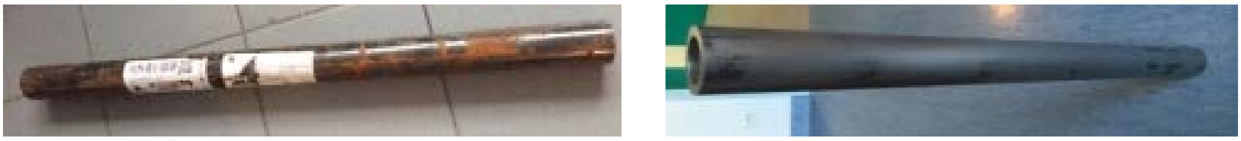
Fig. 26. Interface CoNiCrAlY (HVOF)- P92 tube.



a b

Fig. 27. Cross-sections of (a) CoNiCrAlY and (b) pack aluminizing optimized.

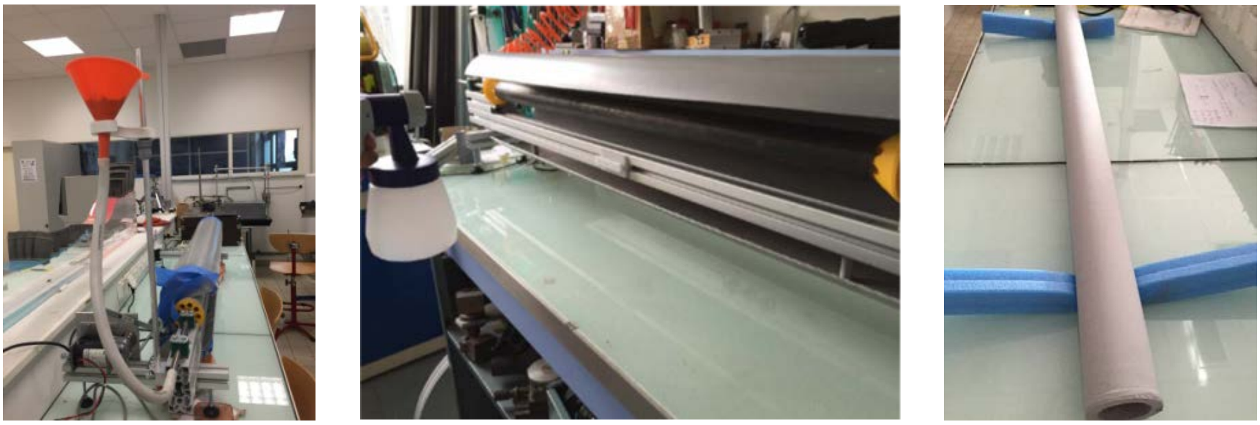
The elaboration of environmentally friendly Al slurry coatings on austenitic (IN-800HT and HR3C) and ferritic-martensitic (P92) steels were developed. It appeared that these coatings were easy to produce on flat and curved surfaces. Moreover, the coated materials were tested in steam and oxy-fuel atmospheres. The characterization revealed an excellent integrity of the coating/substrate systems after thousands hours of exposure to different aggressive hot atmospheres (steam, oxy-fuel, air). Thus, the Al slurry coatings deposited on ferritic-martensitic P92 steel was selected for extrapolation to larger (real) components. The external and internal surfaces of the P92 tube were severely oxidized (Fig. 28 a). The surfaces were thus pickled and then polished with emery paper till mat grey surface finish before application of the Al slurry (Fig. 28 b).



a b

Fig. 28. (a) P92 tube as-received and (b) and after pickling and polishing.

An experimental setup was designed and built to coat simultaneously the internal and the external surfaces of the tube (Fig. 29). During the rotation, the external face can be sprayed with an air gun. The internal surfaces are coated by dripping the slurry through a concentric tube pierced regularly along its axis. The slurry excess can be recovered for reuse. A full coverage of the surfaces can be achieved in less than 2 h of rotation. The slurry is dried and can coated part can be handled and transported. The Al slurry coated P92 tube is shown in Fig. 29c.



a b c

Fig. 29. Experimental set-up to coat 1 m long tubes: (a) the funnel through which the slurry is dripped into the internal surface of the tube; (b) the spray gun that moves along the external surface of the tube; (c) the P92 tube evenly coated with Al slurry.

After optimizing the surface cleaning and deposition methodology, a P92 tube of 1 m was coated both internally and externally with Cr aluminide coating (Fig. 30) to be tested simultaneously for fire-side and steam oxidation.

a

b

Fig. 30. P92 tube coated with CrAl slurry (a) externally and (b) internally.

CrN/NbN is a potential candidate for protection of turbine blades against the environmental attack in steam turbines as it possesses a package of properties required for this application. Excellent adhesion, high hardness and wear resistance, does not deteriorate mechanical properties of the substrate material such as high temperature, (650ºC) tensile strength, fatigue strength and creep properties. The coating shows high resistance against water droplet erosion, $2.4 \cdot 10^6$ impacts. In steam corrosion tests the coating shows localised corrosion however, the weight gain remains factor of 10 lower than that of the bare substrate after 12000 h exposure to pure steam at 650ºC. The coating has been successfully deposited on a real turbine blade (see Fig. 31).

Fig. 31. Turbine blade coated with CrN/NbN by PVD-HIPIMS.

- The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results:

Europe 2020: A strategy for smart, sustainable and inclusive growth (COM(2010)2020)44: POEMA proposal contributes specially to the targets established in the Europe 2020 Strategy, specially , to 'improve the conditions for R&D, in particular with the aim of raising combined public and private investment levels in this sector to 3% of GDP' and to achieve the Climate Change/ energy targets, reducing GHG emissions by 20% compared to 1990 levels to reduce greenhouse gas emissions by 20%, rising to 30% for industrialized countries by 2050, for the EU and other industrialized countries, the targets for cuts in emissions rise to 80 to 95%); an moving towards a 20% increase in energy efficiency.

European Strategic Energy Technology Plan (SET Plan) which follows to foster development, testing and deployment, testing and deployment of new energy-efficient technologies in order to reduce the costs and improve the performance of energy efficient technologies, generating new solutions and facilitating widespread market take-up.

European Economy Recovery Plan (2008): This European Economic Recovery Plan is the Commission's response to the current economic situation. The proposal is aligned with the targets and actions of the EERP, which enhances the *"investment in energy efficiency to create jobs and save energy, in clean technologies to boost sectors and investing in infrastructure and inter-connection to promote efficiency and innovation".*

A lead market initiative (LMI) for Europe (2007) is established in order "*to support developing an innovation driven economy that is crucial for competitiveness for EC compared to other regions"*. Different categories of innovative products and services face their own specific problems and require different kinds of concerted policy action. The LMI therefore firstly identifies promising emerging markets to be supported by such a concerted policy action based on in-depth analysis, intense consultations as well as feed-back mechanisms. Secondly, it designs a process to better streamline legal and regulatory environments and accelerate the growth of demand.

To be successful, the process needs to:

- Incorporate global market needs and customer preferences to maximize market potential.
- Facilitate the acceptance of EU standards and approaches by non-EU markets, notably in domains affected by global trends (e.g. environmental issues).

- Aim at reducing the cost of bringing new products or services into the market, by easing market access and measures to facilitate the aggregation of demand. Competition among different innovation designs must be ensured, thus encouraging constant adaptation to evolving market requirements.

POEMA proposal will support standardization, legislation more innovation-green friendly technologies. Furthermore, it will bring green technologies closer to the no-EU market.

The strategic energy technology plan (SET plan) presented by the Commission aims to help achieve European objectives and face up to the challenges of this sector:

- In the short term by increasing research to reduce costs and improve performance of existing technologies, and by encouraging the commercial implementation of these technologies. Activities at this level should in particular involve second-generation biofuels, capture, transport and storage of carbon, integration of renewable energy sources into the electricity network and energy efficiency in construction, transport and industry.
- In the longer term by supporting development of a new generation of low carbon technologies. The activities to be carried out should focus, among other things, on the competitiveness of new technologies relating to renewable energies, energy storage, sustainability of fission energy, fusion energy, and the development of Trans-European Energy networks.

Implementation of this SET plan will involve collective effort and activities in the private sector, the Member States and the EU, as well as internationally.

The SET plan first of all proposes a new governance method for energy technologies, based on joint strategic planning. With this in mind, a steering group, created by the Commission in 2008 and made up of representatives of the Member States, will improve coherence by developing joint actions, making resources available and evaluating progress. Also, a European summit on energy technologies is planned for 2009. Furthermore, the Commission will set up a European information system, comprising technology mapping and capacity mapping.

The SET plan also improves the effectiveness of the implementation of the jointly decided actions, so as to take full advantage of the possibilities offered by the European research area and the internal market.

The Commission will therefore gradually launch new European industrial initiatives, in wind energy, solar energy, bio-energy, capture, transport and storage of CO_2, the electricity network and nuclear fission, which will take the form of public-private partnerships or joint programmes between Member States. Furthermore, the Commission wants to create a European energy research alliance to better coordinate, in terms of programming, the efforts of research centres and universities. A prospective approach will also be adopted to prepare the future development of Trans-European energy networks and systems.

An increase in resources, both financial and human, is another major element of the SET plan. Investment in research and innovation must increase at Community level, through the research Framework programme of the "Intelligent Energy-Europe" programme and the European Investment Bank, as well as in the Member States, in order to double the overall effort made in the EU within three years. A communication from the Commission will be issued in 2008 on the subject of funding of low carbon technologies. In addition, the training of energy researchers will be promoted and new research and training opportunities will be created, to increase the number and quality of engineers and researchers.

Finally, the SET plan makes provision for intensified international cooperation, in order to promote the development, marketing, deployment and accessibility of low carbon technologies worldwide. The EU should speak more often with one voice on this matter. Cooperation with developed countries will involve public interest research and long-term exploratory research. As for developing countries and emergent economies, cooperation should allow their sustainable development while creating opportunities for European companies; cooperation could be involved, for example, in networking of research centres, large-scale demonstration projects and increased use of the mechanisms of the Kyoto Protocol.

Power plants suffer from oxidative, erosive, and other thermal impact on the internal surfaces that critically limit the performance, technical life and economical operability of the plants (Table 8). The project has developed advanced protection systems to allow an increase in the steam temperatures (650-700ºC) and thereby a significant higher reduction in emissions than what is currently possible. Thus, all the possibilities in microstructure engineering have been evaluated as a novelty with high technological impact.

Table 8. Targets for future power plants.

Plant/ Component	T_{max} (ºC)	Base materials	Protective/Systems
SH, RH	600-650	Austenitics	Shot peening*
	670-720	Ni-alloys	To be developed
Headers Piping	600-650	Ferritics	Coatings*
	670-720	Ni-alloys	To be developed
Turbines	600-650	Ferritics	Coatings*
	670-720	Ni-alloys	To be developed

* To be improved

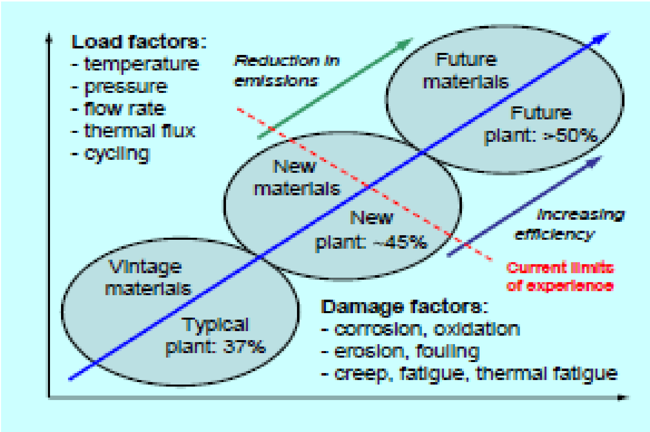


Fig. 32. Power plants: load factors vs Damage factors.

In plants that will operate at 600ºC, steam oxidation is important but not enough to justify protective coatings use on all surfaces. In this situation, oxide scales will detach and can cause important damage of down-stream components.

Therefore steam oxidation-erosion resistant coatings use is being considered for some key components. For example, studies carried out during COST Action 522 have indicated the formation and spallation of oxide scales in uncoated substrates after few hours when they are exposed to plant conditions (Komet results) at 640ºC, , but under laboratory conditions no spalling was seen up to 15000 h of exposure. Preliminary results from COST Action 536 indicate accelerated spalling by thermal cycles. However, it is necessary to determine the optimum cycle in order to better simulate plant conditions, if possible in an accelerated manner. Definition and validation of test parameters by the partnership may lead to a currently lacking standard for steam oxidation testing.

The design and validation of erosion testing facilities simulating this environment is also very important. Steam-side erosion conditions in steam turbines are very different than those observed in other situations (low particle velocity, low impact, corrosive atmosphere, etc.) and testing in the available facilities has not resulted in credible results. Definition and validation of test parameters by the partners may also lead to a standard for erosion testing. Finally, better steam oxidation and erosion resistant, lower cost coatings are still needed.

Moreover, the coating systems for oxycombustion atmospheres are in development at this time, since this combustion conditions with excess of water vapour, among other reactants, gives a very extreme high temperature conditions that would need the development of coating systems for this purpose.

On another hand, the monitoring system proposed, is another novelty, since the new temperatures and pressures in SCC will require a continuous monitoring of the oxidation performance. It will be the first attempt to do this in an EU project.

The next two scenarios are considered in this project

Steps during the project:

- Standardization strategy for lab testing recommendation, following the ISO-TC156-WG 13.
- Standardization strategy at “in situ” plant testing and “on line” monitoring testing recommendation.
- “Advisory group” for standardization establishment, involving research and industrial partners to give inputs to WG13 of ISO TC156.
- Reparability technical instructions.
- Observatory group as dissemination channel and impact accelerator establishment.

Steps after completion of the project:

- Project results integration in guidelines, regulations, and technical instructions for power plant operators, designing their maintenance strategy.
- Direct participation in the TC156-WG13 standardization group, bringing all the project experience after completion to give up more standards in this field.
- European network in this field promotion to keep enhance guidelines in the key point developed under this project.
- Actions promoting gender issues and young training schools to show the latest achievements to bring up the power efficiency in the plants.

The results obtained in POEMA were reported and will be presented to the scientific community in international congress and conferences as well as in international journals, according to the consortium agreement.

The main event concerning Young Students was conducted in Kiev on June 22^{nd} and 23^{rd}, 2016. The main goal of this event was to promote the knowledge transfer between young scientists involved in the project through workshops and training seminars. Also the gender aspects were encouraged, promoting the participation of women in dissemination activities.

At the end of the project two workshops were organized showing the non-confidential results and the main aspects. The participation of the industry was encouraged on the last one which was carried out in Madrid on December 15^{th}, 2016.

The Table 9 shows, the compromised dissemination activities at the end of the POEMA project have been accomplished take into account those compromised with EU.

Table 9. Summary of dissemination activities on POEMA and the agreement with EU.

		POEMA	*Agreement*
Type of contribution		*Number*	*Number*
Publications	***Published, accepted for publication, submitted for publication, in preparation***	*33*	*24-36*
Congress	***Orals***	*29*	*18-36*
	Posters	*20*	
Ph.D. Students		*5*	-
Ph.D. Thesis		*2*	-
Patents		*2*	-
Students or researchers exchanges between partner's institutions		*6*	*6*
Educational activities		*6*	-
Young Scientist School		*1*	*1*
Workshop		*2*	*1*

In the following sections, it is presented the exploitation plans of the results obtained during POEMA project:

- High temperature oxycombustion and steam corrosion monitoring system that allows monitoring in an on-line an continuous mode the corrosion produced in oxycombustion power plants both in the components exposed to steam and those exposed to oxy-fuel and ashes environment. The system is currently under PCT patenting process (Publication Nº: 2573178; Application Nº: 201500674; Application date: 18/09/2015)
- MinimAl coating with three possible slurry formulations to be transportable as ready-to-use slurry. The slurry is deposited by spraying and subsequent heat treatment to form the final aluminide diffusion coating as protection against high temperature oxidation and corrosion.
- Simple aluminide coating on steel by slurry which is environmentally friendly and cheap.
- Cr aluminide coating which maintains a very stable microstructure after long term exposure to both steam and oxy-fuel atmospheres at 650ºC.
- Thermally sprayed coatings by HVOF for fireside application.
- Pack aluminide coatings for steam side application.
- Process of preparation to obtain the optimal adhesion with the base material.
- The methodology for coating application and test conditions over the internal and external surfaces of large components.
- A multi-component eutectic alloy based on FeNiCrAlTiB system for production of protection coatings for steel parts against high temperatures (600-700ºC), oxidation, corrosion and wear. As a powder it is used for Plasma Spray Deposition, HVOF, and detonation deposition by MCDS. The coatings are deposited in air and do not require additional heat treatment.
- The electrodes for PVD-CAE (physical vapour deposition by cathode arc evaporation) or ESD (electro spark deposition) methods could be produced from the cast state without processing into powder. The coatings do not require the finish heat treatment.
- Water-borne multilayer silicate coatings can be applied to steel substrate from aqueous silicate composition. The formulation is deposited by brushing or dip-coating with subsequent heat treatment (curing) to form the final barrier coating as protection of steel against high temperature oxidation and corrosion.

- The address of the project public website, if applicable as well as relevant contact details.

  Public website: http://cordis.europa.eu/project/rcn/106505_en.html

  Relevant contact details:

Table 10. Contact details to partners of POEMA project.

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