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# Developments in Erosion-Corrosion Over the Past 10 Years

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**Abstract** Erosion-corrosion is attracting increasing attention as a research area, as the increased publication rate attests to. A decade has passed since the last general reviews of the field by one of the authors [1, 2], thus this review is designed to serve as an update to broader reviews published previously. In the past decade, computational fluid dynamics (CFD), semi-empirical and analytical models have been explored, the erosion-corrosion of stainless steels have been thoroughly investigated through testing and the performance of corrosion inhibitors and coatings have been evaluated. Thus, the research that has been conducted can broadly be described as focusing on one of three areas: modelling, testing of material response and protection against material loss due to erosion-corrosion. Although the research conducted in the past 10 years is both meaningful and relevant, it is hoped that greater attention will be given to the advancement of a more fundamental and general theory of erosion-corrosion.

**Keywords** erosion-corrosion · review · mapping · modelling · stainless steel

## 1 Introduction

Erosion-corrosion is a complex phenomenon that affects many different industries. Since attracting the attention of researchers, significant investigation of erosion-corrosion has been conducted in a wide variety of sectors: Marine, Oil and Gas, Nuclear, High Temperature, Power Generation, Mining, Manufacturing and Process Industry. Investigations into erosion-corrosion have also occurred in the Dental, Food and Aero sectors [3]. In the past decade, much of the research has been driven by the Marine and Oil and Gas sectors. However, additional sectors have also contributed to the body of knowledge. For example the automotive industry, where the erosion-corrosion of the engine cooling system (due the presence of particles in the coolant) has been investigated [4]. Since 1950, there have been 1901 papers published on the topic of erosion-corrosion, leading to a total of 13,423 citations over the years [3]. The topic enjoys a strong h-index, which was 46 as of July 2016 [3]. Figure 1 and Figure 2 show the trends in the number of papers published and total number of citations each year for erosion-corrosion. Please note that this data was accessed during the month of July in 2016, hence why there is a significant decrease in both measures for this year. The rapid increase in both of these metrics over the past 20 years supports the view that erosion-corrosion is increasingly coming to the fore as significant design consideration for engineers. Additionally, the inception (and now existence) of this very journal, adds further weight to the argument that erosion-corrosion is receiving increased interest and attention.

Despite significant research activity regarding erosion-corrosion over the past decade, the complexities of this material removal process have meant a general theory remains elusive. Previous reviews by one of the authors [1, 2], describing the mechanisms involved, are still current and recommended to those seeking to gain a general orientation in this area. A more recent review by Prozhega et al. (2014) [5] is also recommended. This

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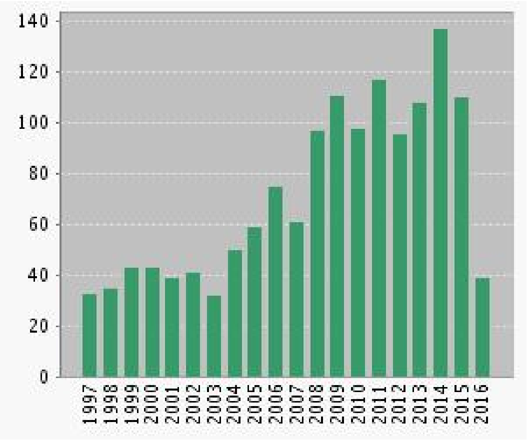

**Fig. 1** Number of publications per year on erosion-corrosion [3]

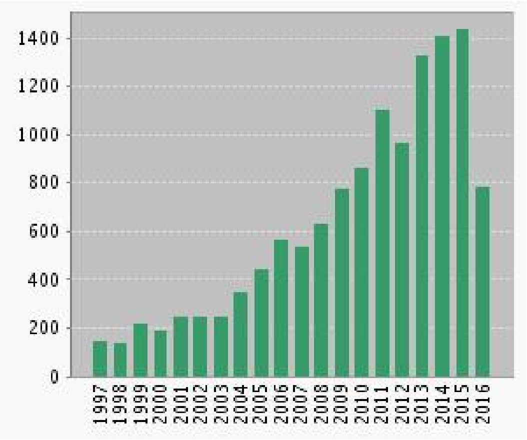

**Fig. 2** Number of citations per year of publications on erosion-corrosion [3]

review will seek to summarise the work that has taken place over the past decade, with the intention of offering an update to the two reviews (by one of the authors) mentioned previously. However, due to the volume of research that has been generated internationally on the subject (in excess of 600 publications in the last 5 years [3]), this review will focus on the activities of the founding members of the Tribo-Corrosion Network (TrICorrNET) in the past 10 years. It is hoped the general trends observed will still be broadly true for the field as whole, despite the steps taken to enable the scope of this review to be more manageable. The research that has taken place in these research groups can be generally categorised into one of three areas: advances in modelling, advances in understanding of erosion-corrosion and advances in protection against erosion-corrosion.

The synergism of erosion and corrosion has been known for a number of years [6]. The synergistic effect can be calculated by use of the following relationship:

$$S = T - (E + C)$$

where S is the synergistic wear rate, T is the total wear rate, E is the erosive wear rate and C is the corrosive wear rate. Some authors have extended the description of ‘erosion-corrosion’ to situations involving flow corrosion only [7]. This review considers erosion-corrosion to encompass situations were either solid particle erosion, liquid droplet erosion, cavitation erosion or a mixture of these is accompanied by corrosion. Therefore, flow corrosion is not considered as part of this review.

## 2 Current State of the Art

Despite the high level of research activity over the past decade, our fundamental understanding of the mechanisms involved in erosion-corrosion has not undergone significant change. Should the reader require a detailed explanation of the phenomenon of erosion-corrosion (particularly in the context of Oil and Gas or Marine applications) then they are encouraged to examine the 2006 review [1] by one of the authors. This review attempted to collate general trends across published literature using actual process conditions e.g. flow velocity, temperature etc. Readers may find Table 1 in this review particularly useful for understanding mechanisms, for example the description of the exposed area/repassivation approach. One very important conclusion of this review, that is as true now as it was then, is:

> (This review)... highlights the importance of understanding local mass transport phenomena and double layer stability and how mechanical erosion processes may influence these to alter charge transfer kinetics. For example, these mechanical-electrochemical interactions may influence repassivation kinetics and passive film composition which directly effect surface recovery times and corrosion rates of the affected areas under erosion.

For those seeking a broader scope, examining the full field of tribocorrosion, the 2007 review [2] by one of the authors may be more appropriate. This later review includes topics such as the conductive coatings on alloys, the influence of galvanic coupling as damage proceeds and the factors that determine the performance of a coating (e.g. ability to repassivate, microstructure, quality, density and adherence). Both reviews indicate the need for further electrochemical modelling of situations and the current lack of any mechano-electro chemical model hinders progress in understanding the fundamental mechanisms in erosion-corrosion [2].

With regards to experimental test methods, Prozhega et al. (2014) [5] concluded that an analysis of the data presented in the literature has shown that, from the methodological viewpoint, studies of erosion-corrosion wear in abrasive free media are the most clear. The standards of the American Society for Testing and Materials (ASTM) are widely employed as the method for studying erosion-corrosion wear [8]. However, at present, the use of abrasive particles in the tests presents a substantial methodological difficulty. Prozhega et al. highlighted the issue of ensuring a constant concentration of abrasive particles in a fluid, as well as their sedimentation and renewal, the development of a device for their dosing, and measuring their real concentration in a jet remains unsolved. Currently, there is no unified approach to ensure the reproducibility of results in tests with abrasives.

**Table 1** Approaches to modelling erosion-corrosion over past decade

| **Reference** | **Modelling Strategy** | **System Modelled** |
|---|---|---|
| Rajahram et al. (2009) [9] | Semi-empirical | UNS 31603 in 0.3 M HCl |
| Stack et al. (2010) [10] | CFD and erosion-corrosion mapping | Fe, Ni, Al & Cu single-elbow pipe (corrosive conditions on inner surface) |
| Stack and Abdulrahman (2011) [11] | CFD and erosion-corrosion mapping | Fe pipe with 90° bend (corrosive conditions on inner surface) |
| Telfer et al. (2012) [12] | Erosion-corrosion mapping | Fe, Ni, Al & Cu (in corrosive conditions) |
| Crawley et al. (2013) [13] | Erosion-corrosion mapping | Stainless steel (in corrosive conditions) |

## 3 Advances in Modelling

Over the past decade, an approach described as 'erosion-corrosion' mapping (either by itself or coupled with CFD) has been overwhelming employed in the modelling of erosion-corrosion. This is shown in Table 1 (a summary of the different modelling strategies employed) where only one study did not use this approach. Erosion-corrosion mapping involves the use of existing models to predict the various effects of erosion-corrosion. The output of this work is then presented in the form of maps of erosion-corrosion (hence the description). Section 4 discusses the contribution made to the understanding of erosion-corrosion by representing data in this form. In this section, the predictions and limitations of the modelling approaches used in the past decade (listed in Table 1) will be explored.

Rajahram et al. (2009) [9] proposed a semi-empirical model of erosion-corrosion for a passive system. This was developed from an existing semi-empirical model for an actively corroding system [14]. UNS 31603 in 0.3 M HCl at 40°C was used to represent a typical passive system. The slurry pot erosion tester used in the previous work [14] was employed for this passive system. It was found that all the components of erosion-corrosion (erosion, flow corrosion, erosion-corrosion and synergy) increase with increasing velocity and sand concentration. However, the relative proportion of the different components causing material removal varied. As the velocity of the slurry increased, the material removal characteristic was to move from a corrosion-erosion regime to an erosion-corrosion regime, indicating an increasing dominance of mechanical erosion. Similarly for increasing sand concentration, as the pure erosion rate increases, the other components causing material loss did not increase proportionally. Rajahram et al. proposed that the effectiveness of material removal at higher impact energies and depassivation-repassivation kinetics of corrosion were the cause of this. The semi-empirical model was employed with a good amount of success, with the model correlating well for high and very high synergy values. The synergy factors were observed to be dependent on velocity and sand concentration. However, it was noted that is was not clear how the corrosion mechanism contributed to the overall synergy.

Stack et al. (2010) [10] developed a numerical modelling approach in order to map the various regimes of erosion-corrosion occurring on a 3D geometry. A CFD package was employed (FLUENT) to run a Lagrangian-Eulerian simulation of the multi-phase flow and the 3D geometry inputed was a single-elbow pipe. Discrete phase modelling (DPM) was used to track the particles in suspension, the information from which was then used to calculate the erosion occurring at the surface. A number of different models for calculating the erosion rate were compared and the relationship proposed by Sundararajan (1991) [15] was selected to model the material removal. A number of assumptions were made in order to estimate the mass of passive film that would be removed for each impact. Thus, the expression derived is only valid for ring shaped erosion footprints. However, perhaps the greatest limitation of the modelling approach proposed by Stack and Abdulrahman was that it assumes no synergy or antagonism between the processes of erosion and corrosion. In a subsequent piece of research, Stack and Abdulrahman (2011) [11] employed the same numerical model in order to predict the various regimes of erosion-corrosion occurring on a 90° pipe bend. Like their previous work [10], the erosion rates predicted by the model compared favourably with previous experimental study of the same 3D geometries [16]. However, the authors acknowledge that the neglecting of synergy and antagonism between erosion and corrosion is a simplistic one and something that will be the subject of further work.

Telfer et al. (2012) [12] used modelling to produce material wastage maps (identifying regions where the material loss was either low, medium or high) for materials undergoing erosion-corrosion. The four materials modelled were iron, nickel, aluminium and copper. In addition, maps identifying the different regimes of interaction were also produced, with different particle concentrations, particle sizes or materials compared. The modelling conducted was based on the work of Stack et al. (1997) [17] and required the simplification of the phenomenon of erosion-corrosion by making a number of assumptions. Perhaps the more significant assumptions included: the entirety of the kinetic energy of the impacting particle is converted into plastic work, the material will always have time to repassivate before the next impact and the erosion-corrosion relationship is purely additive. Although the results of the modelling (and conclusions that follow) do not appear unreasonable, no comparison with experimental work was made. Crawley et al. (2013) [13] extended this modelling approach to the consideration of an alloy, namely stainless steel. In order to model erosion-corrosion process for multiple elements within the same material additional assumptions were made. These included considering stainless steel to be comprised solely of iron, nickel and chromium (existing purely as elements) and, once the passivation potential for one of the elements had been reached, the whole material would be instantaneously covered by an oxide film of that element. Again, the results of the modelling do not appear unreasonable. However, no comparison with experimental work were made and, given the complexities of passivation process of stainless steel, some questions may be raised regarding the accuracy of the results presented.

## 4 Advances in Understanding of Erosion-Corrosion

The majority of testing on bulk materials over the past decade has focused stainless and carbon steels, with the majority of testing taking place on stainless steels. Table 2 details the erosion-corrosion testing that has occurred on stainless steels during this period. The focus on stainless steel has not been entirely driven by application. The passivation characteristics of stainless steel are generally well understood and so stainless steels are a sensible material choice should a more general investigation of repassivation characteristics be one of the objectives of the research. The work on carbon steels is much more likely to be driven by application however, given their proliferation of use within the Oil and Gas sector. Table 3 details the erosion-corrosion testing that has occurred on carbon steels over the past decade. Finally, Table 4 details the erosion-corrosion testing that has occurred on materials other than steels over the past decade. However, the only other bulk material than steel tested in the past 10 years (by the founding members of TrICorr-NET under erosion-corrosion conditions) is nickel-aluminium bronze. This research has been stimulated by interest from the marine sector in the erosion-corrosion of ship propellers, where the erosion is caused by cavitation.

The individual investigations all add to the body of knowledge surrounding erosion-corrosion. However, researchers have struggled to advance the science of erosion-corrosion beyond material specific conclusions. Stainless steels may have been selected in order to represent a well-understood passive system, with the intention of extending those conclusions to other well understood passive systems. Yet, this critical step in on the journey to a more general theory of erosion-corrosion has proved to be difficult to materialise. For example, Rajahram et al. (2011) [21] experimentally tested the erosion-corrosion of UNS S31603, with a focus on the initial stages of material removal. A model describing the microstructural changes was proposed, describing the formation of three distinct layers in the UNS S31603. On the surface, lips and craters are formed due to the cutting and ploughing resulting from the impact of solid particles. Beneath this, a layer of nanocrystalline grains increases in thickness as a result of the repeated impact (a very thin layer exists initially due to the action of polishing the surface), increasing between 300 and 700 nm and then stabilising. The third layer in the sub-surface are micro-grains and twins, formed as a result of repeated impact. Finally, beneath this are the bulk grains, however these too are deformed after a threshold period. Again, this is all good science but is limited to just one material.

The complexities of erosion-corrosion mean that it is important to consider how best to communicate the characteristics of a system. Erosion-corrosion maps have increasingly been used as a mechanism of data presentation. The axes selected have varied, depending on the data collected; velocity vs. impact angle [26], velocity vs. momentum [27] or particle velocity vs. ap-

**Table 2** Erosion-corrosion testing of stainless steels over past decade

| Reference | Purpose | Steel Grade(s) | Corrosive Medium | Temp. | Speed | Measurement of Corrosion |
|---|---|---|---|---|---|---|
| Meng et al. (2007) [18] | Performance comparison of duplex/austenitic | UNS S32760, UNS S31603 | 3.5% NaCl | 20°C, 50°C | 7 m/s, 20 m/s | Potentiodynamic scans |
| Rajahram et al. (2009) [19] | Evaluate the repeatability of experiments and investigate the role of different parameters | UNS S31603 | 0.3M HCl, 0.1M NaOH | 40°C | 3 m/s, 5 m/s, 7 m/s, 9 m/s, 10 m/s, 12 m/s | None |
| Rajahram et al. (2009) [9] | Validate semi-empirical model for a passive system | UNS S31603 | 0.3 M HCl | 40°C | 5 m/s, 7 m/s, 9 m/s | None |
| Rajahram et al. (2010) [20] | Investigation into interaction between main parameters | UNS S31603 | 0.3M HCl | 40°C, 60°C | 5 m/s, 7 m/s, 9 m/s | None |
| Rajahram et al. (2011) [21] | Microstructural development during initial stages | UNS S31603 | 3.5% NaCl | 40°C | 7 m/s | None |
| Rajahram et al. (2011) [22] | Perform in-situ electrochemical measurements to investigate the effects of different parameters | UNS S31603 | 3.5% NaCl | 40°C | 5 m/s, 7 m/s, 9 m/s | Electrochemical noise |
| Aribo et al. (2013) [23] | Performance comparison of lean duplex/austenitic/duplex | UNS S32304, UNS S32101, UNS S30403, UNS S32205 | 3.5% NaCl | 20°C, 50°C | 15 m/s | Potentiodynamic scans |
| Wood et al. (2013) [24] | Develop previous work, which had demonstrated a clear dependence on microstructure | UNS S31603 | 3.5% NaCl | 40°C | 7 m/s | None |

**Table 3** Erosion-corrosion testing of carbon steels over past decade

| Reference | Purpose | Steel Grade(s) | Corrosive Medium | Temp. | Speed | Measurement of Corrosion |
|---|---|---|---|---|---|---|
| Rajahram et al. (2009) [19] | Evaluate the repeatability of experiments and investigate the role of different parameters | UNSG10200 | 3.5% NaCl, 0.1M NaOH | 40°C | 3 m/s, 5 m/s, 7 m/s, 9 m/s, 10 m/s, 12 m/s | None |
| Hu and Neville (2009) [25] | Systematic study of pipeline steel | API X65 | NaCl soln. sparged with $CO_2$ | 20°C, 40°C, 60°C, 70°C | 7 m/s, 14 m/s, 20 m/s | Potentiodynamic scans |
| Stack and Abdulrahman (2010) [26] | Identification of regimes in oil-water solutions | X52 | Oil-water (reservoir) | Not specified | 2.5 m/s, 3.5 m/s, 4.5 m/s | Potentiodynamic scans |
| Stack and Abdulrahman (2012) [27] | Identification of regimes in oil-water solutions | Not specified | Oil-water (reservoir) | Not specified | 2.5 m/s, 3.5 m/s, 4.5 m/s | Potentiodynamic scans |

**Table 4** Erosion-corrosion testing of materials other than steels over past decade

| Reference | Purpose | Material | Corrosive Medium | Temp. | Speed | Measurement of Corrosion |
|---|---|---|---|---|---|---|
| Barik et. al (2009) [28] | Explore mechanisms causing synergistic, additive and antagonistic effects | Nickel-Aluminium Bronze | 3.5% NaCl | Not specified | 3.1-6.0 m/s | Potentiodynamic scans |
| Rajahram et al. (2009) [19] | Evaluate the repeatability of experiments and investigate the role of different parameters | Nickel-Aluminium Bronze | 3.5% NaCl, 0.1M NaOH | 40°C | 5 m/s,<br>7 m/s,<br>9 m/s | None |

plied potential [12, 13] have been employed. However, the maps are all consistent in the identification of key regimes. For example, when examining wastage, the regions of low, medium and high material loss will be identified. Alternatively, when identifying the dominant erosion-corrosion mechanism, the regions that will be distinguished are: erosion dominated, erosion-corrosion dominated, corrosion-erosion dominated and corrosion dominated. These maps allow for quick and easy identification of the regimes for two parameters and perhaps most importantly, where the transition between them will occur. As discussed in Section 3, modelling of the erosion-corrosion process to produce theoretical wear maps has been performed [12, 13]. Crawley et al. (2013) [13] outlined how these could be used in industry for service management, taking the example of a tidal energy system. They demonstrated how the maps could first be used to understand what the dominant regime of erosion-corrosion would be for the chosen material. Then the material wastage estimated for that material in the expected environment. Thus, component life could be estimated, maintenance scheduled accordingly and a cost-benefit analysis conducted for systems to extend the component life, such as cathodic protection. The ability to conduct this work, before in-service failure occurs, is of great value to those in industry.

## 5 Advances in Protection Against Erosion-Corrosion

One of the questions that has been posed to researchers working in the field, is whether a carbon steel, used in conjunction with a corrosion inhibitor, is less expensive that using stainless steel for applications where both erosion and corrosion occur [29]. This has prompted a number of studies over the past decade to examine the performance of corrosion inhibitors in erosion-corrosion environments [29–32]. Neville and Wang (2009) [29] observed that for two different corrosion inhibitors an optimum concentration of inhibitor existed for erosion-corrosion tests conducted using a submerged impingement rig. The temperature was controlled at 50°C, the exit velocity from the nozzle at 20 m/s and the aqueous solution used (saturated with $CO_2$) was employed to simulate the water present in a gas condensate system (where the majority of dissolved salt is NaCl). It was found that resulting mass loss of the carbon steel, where each inhibitor was acting optimally, was very close to the mass loss of the stainless steel (UNS S31603) in the same environment. The same authors published an additional paper that year, where they compared the use of inhibitor with a number of different materials: Weldable 13 Cr martensitic stainless steel (UNS S41000), 25% Cr superduplex stainless steel (UNS S32760) and X65 pipeline steel (API-5L-X65) [30]. The same rig was employed for testing, with an exit velocity of either 10 or 20 m/s. However, Forties brine at 50°C (with various sand concentrations) was used as the fluid. It was found that the inhibitor can reduce the mass loss by nearly half for both the carbon steel and martensitic stainless steel. However, the use of inhibitor had no positive effect on the mass loss for superduplex stainless steel.

Although the use of corrosion inhibitors may appear to be an effective and convenient method to reduce the material loss due to erosion-corrosion, the optimal laboratory conditions for their operation can be quite different from actual service conditions. Hu et al. (2011) [31] conducted a forensic investigation into the reasons why a piece of ex-service carbon steel pipework had experienced such high material loss during service. CFD, metallurgical analysis and submerged impingement tests were performed in order to understand why the corrosion inhibitor had offered little protection to certain areas of the pipework. They concluded that flow-velocity distribution should have a greater influence in corrosion inhibitor selection, as in-service components present complex geometries that can experience very high levels of material loss. For more accurate future work they suggested laboratory tests need to go further in representing the more dynamic nature of in-service conditions, where the resulting fluid dynamics and solid particle impacts cause non-uniform material loss. Barker at al. (2015) [32] conducted an investigation into the performance of three corrosion inhibitors, with a particular focus on understanding the underlying mechanisms. The submerged impingement rig was set provide an nozzle exit velocity of 14 m/s, at a temperature of 45°C. The fluid used was $CO_2$-saturated Brine, with a sand loading of 500 mg/l. A number of different techniques were employed to investigate the mechanisms occurring including electrochemical impedance spectroscopy (EIS) and fourier transform infrared spectroscopy (FTIR). It was concluded that gravimetric measurements and the application of in-situ electrochemistry can potentially provide misleading results when determining the performance of inhibitors.

Another form of protection against erosion-corrosion is the use of coatings to create a functional surface upon a substrate that may exhibit quite poor resistance (comparatively) to material removal/damage. As was the case for inhibitors, the potential of coatings for protection against erosion-corrosion has stimulated a number of investigations over the past decade [33–37]. The majority of coatings that are the subject of investigation have been applied by Plasma Transferred Arc (PTA) [35–37] and all are tungsten carbide (WC) based. Flores et al. (2009) [35] found the addition of WC particles (to a NiCrBSi matrix), to form a metal-matrix composite (MMC), reduced the mass loss by almost 70% at 20°C in comparison to the matrix-only hardfacing. Tests were also conducted at 65°C, which led to effects of corrosion becoming more pronounced and the WC grains becoming more vulnerable, due to increased degradation of the matrix phase. The same authors investigated the erosion-corrosion behaviour of a FeCrC matrix, again with and without WC reinforcing phase [36]. Again, the addition of the WC grains significantly reduced the total mass loss. Similarly, the improvement was less pronounced at the higher temperature of 65°C, due to the increased effect of corrosion. The same test conditions were employed in both of these studies: a submerged impinging jet rig with a fixed nozzle exit velocity of 14 m/s, two different temperatures (20°C and 65°C) and two sand concentrations. The two sand concentrations used were only slightly different, 10 and 50 g/l [36] and 1 and 5 wt.% [35]. The same authors published again, this time in 2011, to report on another investigation into a PTA coatings [37]. Nickel and iron base non-reinforced matrix (NRM) were compared with a nickel and iron MMCs, with WC particles used as the reinforcement. Test conditions were the same as used previously [35, 36], with 10 and 50 g/l as the two sand concentrations. However, three different velocities were used (5, 10 or 14 m/s). Both MMCs presented reduced total mass loss compared with their NRM counterparts. The nickel base MMC was the most EC resistant in the majority of test conditions. The same pattern as observed previously occurred at higher temperatures, with MMCs more significantly affected than NRMs by the more favourable conditions for corrosion.

In addition to PTA, high velocity oxygen fuel (HVOF) has also been employed to produce erosion-corrosion resistant coatings. Stack and Abd El Badia (2006) [33] used HVOF to apply a WC/CoCr coating on a mild steel substrate. Impingement jet erosion apparatus was used with three different nozzle exit velocities: 2, 3 and 4 m/s. Synthetic seawater (prepared according to ASTM D 1141-98) was used as the fluid, with the sand concentration maintained at 6% by mass. No information is given regarding the temperature of the fluid. The mass loss of the coated substrate was far less than uncoated substrate under all test conditions. Souza and Neville (2007) [34] compared the performance of WC-Co-Cr coatings applied by HVOF and Super D-Gun under different erosion-corrosion conditions. However, due to industrial agreement, the process details and parameters for each coating are not revealed. The submerged impinging jet rig was set to deliver a nozzle exit velocity of 17 m/s. 3.5% NaCl solution was used as the fluid, with the temperature kept constant at 20°C. It was observed the overall mass loss was higher for the Super D-Gun than for HVOF in all three sand concentrations used (200, 500 and 1000 mg/l). The synergy behaviour of the coatings was found to be dependent on the environment and composition/microstructure of the coating.

## 6 Conclusion

The research into erosion-corrosion over the past decade has been dominated by application specific studies. Often, researchers are encouraged to compare two or more materials or protective measures, report the performance differential between them and suggest reasons why this is the case. However, further research towards a more general theory of erosion-corrosion is needed, one which extends beyond material specific domains. Yet, there are reasons to be hopeful for the future. The developments in erosion-corrosion mapping, employing CFD analysis and less invasive electrochemical techniques are all positive steps in the right direction. Also, investigations, such as the work by Barker et al. (2015) [32], that explore the underlying mechanisms at work give hope that a more fundamental theory of erosion-corrosion may emerge in the future.

The erosion-corrosion research community faces both challenging and interesting times ahead. Given the environmental and economic pressures on industry, that are only set to increase in the future, it is debatable whether we are currently ready for the future industry needs of: hotter, faster, lighter, longer, greener and cheaper. The increased use of coatings makes the phenomenon of erosion-corrosion even more challenging to model and understand. Also, the research conducted over the past decade has almost exclusively involved solid particle erosion; very few studies have involved cavitation erosion-corrosion and none have looked at liquid droplet erosion-corrosion.

Traditionally, many researchers have adopted a design of experiments approach to understanding the significance of various parameters in erosion-corrosion. However, when laboratory conditions can be very different from in-service conditions, we should consider how much practical understanding can be obtained by this approach. Perhaps a better strategy for future work would be to connect more extensively with the CFD and electrochemical research communities, in order to make laboratory testing more representative of in-service conditions. Also, it is increasingly apparent that the dynamic response of materials needs to be incorporated into our modelling. The time history and transient behaviour of materials can not be ignored and so our models need a temporal dimension if they are to be successful. This is in addition to the spatial dimension, where the effect of microstructure is required if we are to truly understand the mechanisms at work.

This review is not a complete one, however it is believed that the highlighted articles broadly illustrate the progress made in the field of erosion-corrosion in the past decade. It is hoped it will serve as a good starting point for further investigations in the field.

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## 7 Declarations

No new data were created in this study. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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