

Industrial acidic environments and metal corrosion: Comparative behaviour of Cu, Al, and stainless steel

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Abstract

Metallic components used across the chemical, petrochemical, fertiliser, food-processing, and metal-finishing industries are routinely exposed to acidic process streams, cleaning solutions, and effluents. Copper, aluminium, and stainless steel are the three structural and functional metals most widely specified for such duty, yet they respond to acidic attack through fundamentally different mechanisms and at markedly different rates. This article reviews and compares the corrosion behaviour of copper, aluminium, and stainless steel in industrially relevant acidic environments, drawing on electrochemical, gravimetric, and surface-analytical studies reported in the corrosion-science literature. Copper corrodes chiefly through simple electrochemical dissolution that accelerates with oxidising acids, dissolved oxygen, and temperature, and lacks a self-healing passive layer once attacked. Aluminium relies on a thin, amphoteric oxide film that offers excellent resistance in mildly acidic and neutral media but breaks down rapidly once pH falls below about four or halide ions are present, producing severe localised pitting. Stainless steel possesses the most robust passive chromium-oxide film of the three, but this film is itself vulnerable to breakdown under chloride contamination, low pH, elevated temperature, and crevice geometries, sometimes yielding catastrophic localised failure despite a low overall corrosion rate. The comparative analysis shows that no single metal is universally superior; material selection in acidic industrial service must instead be matched to the specific acid, its concentration and temperature, the presence of chloride or other aggressive anions, and the geometry of the component. The article concludes with a discussion of practical mitigation strategies, including inhibitor use, cathodic protection, alloying, and protective coatings.

Keywords: Industrial corrosion, acidic environments, copper, aluminium, stainless steel, passivation, pitting corrosion, comparative corrosion behaviour

Introduction

Corrosion is one of the most persistent and economically significant challenges faced by process industries. The NACE International IMPACT study estimated the global cost of corrosion at approximately 2.5 trillion US dollars annually, equivalent to roughly 3.4 percent of global gross domestic product, with a substantial share of this loss attributable to metal degradation in acidic process environments (Koch *et al.*, 2016) [7]. Acidic conditions arise routinely in industrial practice: sulphuric and hydrochloric acid pickling baths in metal finishing, nitric acid in fertiliser manufacture, acetic acid in food processing and petrochemical distillation units, and sulphurous or carbonic acid formed by flue-gas condensation in power and process plants. Equipment exposed to these environments, including reactors, storage tanks, piping, heat exchangers, and valves, is fabricated predominantly from copper, aluminium, and stainless steel because of their combined mechanical, thermal, and economic advantages.

Although these three metals are often treated as broadly "corrosion resistant," their resistance mechanisms differ fundamentally, and their comparative performance in a given acid depends on acid type, concentration, temperature, aeration, and the presence of aggressive species such as chloride ions. A plant engineer selecting copper piping for an acetic acid line, or stainless steel vessels for a hydrochloric acid duty, is making a materials decision with direct consequences for service life, maintenance cost, and safety. This article synthesises recent experimental and review literature to compare the corrosion behaviour of

copper, aluminium, and stainless steel under representative industrial acidic conditions, with the aim of clarifying the mechanistic basis for their differing performance and offering practical guidance for material selection.

Industrial Acidic Environments: Sources and Characteristics

Industrial acidic exposure is rarely limited to a single, pure acid at constant concentration. Mineral acids such as sulphuric acid (H₂SO₄), hydrochloric acid (HCl), and nitric acid (HNO₃) are used directly in pickling, etching, and cleaning operations, while organic acids such as acetic and formic acid occur both as process reagents and as corrosive by-products of thermal degradation in petrochemical and food-processing streams (Goni, Bano, & Mazumder, 2019) [4]. Acetic acid in particular is a recurring corrodent in distillation columns, vinegar and ester production, and petroleum refining, where it forms through the breakdown of naphthenic and other organic compounds at elevated temperature. Unlike strong mineral acids, organic acids are only partially dissociated in solution, so their corrosivity depends on both the solution pH and the total acid concentration, since undissociated acid molecules can continue to dissociate at the metal surface and sustain the corrosion reaction even as hydrogen ions are consumed (Goni, Bano, & Mazumder, 2019) [4].

A second defining feature of industrial acidic service is the frequent co-presence of chloride or other halide ions, whether from process feedstocks, cooling water, or contamination. Chloride ions are particularly aggressive

because they adsorb preferentially onto passive oxide films, displace protective oxygen species, and initiate localised breakdown long before uniform dissolution would otherwise occur (Li *et al.*, 2018). Temperature compounds these effects: reaction kinetics roughly double for every ten-degree Celsius rise, while elevated temperature also lowers the solubility of protective corrosion products and can shift a stable passive film into an unstable regime, as demonstrated for stainless steel exposed to acidic chloride solutions at temperatures up to 423 K (Sun-type high-temperature passivity studies; Li *et al.*, 2018) ^[8]. Dissolved oxygen adds a further variable, since it can either stabilise a protective film, as in stainless steel, or accelerate dissolution, as in copper, depending on the metal system (Kaiser & Kaiser, 2019; Hu, Lin, & Tan, 1996) ^[5, 6].

Corrosion Fundamentals in Acidic Media

Metallic corrosion in acidic solution is fundamentally an electrochemical process combining an anodic metal-dissolution reaction with a cathodic reduction reaction, most commonly hydrogen evolution or oxygen reduction. The overall corrosion rate is governed by the kinetics of both half-reactions and by whether the metal surface can develop a protective barrier layer. Metals are broadly divided into two behavioural classes in acidic media: active metals, which dissolve continuously according to the applied potential and solution chemistry, and passive metals, which form a thin, adherent, and electronically insulating oxide film that dramatically reduces the dissolution rate below what thermodynamics alone would predict.

Copper behaves largely as an active-to-quasi-passive metal: it does not form a strongly protective oxide in most acids and instead corrodes through direct electrochemical dissolution, with the rate strongly dependent on the oxidising power of the acid and the availability of dissolved oxygen (Kaiser & Kaiser, 2019) ^[6]. Aluminium and stainless steel, by contrast, owe their practical corrosion resistance almost entirely to thin passive films, an amorphous or nanocrystalline aluminium oxide layer in the case of aluminium, and a chromium-enriched oxide layer, typically a few nanometres thick, in the case of stainless steel (Li *et al.*, 2018). The critical difference between the two passive systems is the pH and chloride window within which the respective film remains stable; aluminium oxide is amphoteric and dissolves readily outside a comparatively narrow near-neutral pH range, whereas the chromium oxide film on stainless steel is stable across a much wider pH range but is vulnerable to localised chloride-induced breakdown even when the bulk solution is only mildly acidic (Abbas, Adesina, & Suleiman, 2017) ^[1].

Corrosion Behaviour of Copper in Acidic Environments

Copper is prized in industrial construction for its thermal and electrical conductivity, ductility, and moderate resistance to atmospheric and mild aqueous corrosion. In acidic environments, however, copper's performance is markedly dependent on the oxidising character of the acid. In non-oxidising acids such as dilute hydrochloric or sulphuric acid, copper is thermodynamically resistant to hydrogen-evolution corrosion because its standard electrode potential lies above the hydrogen electrode; corrosion therefore requires an alternative cathodic reaction, typically oxygen reduction, and rates remain comparatively low in deaerated conditions (Al-Zubaidy & Hummza, 2014) ^[3].

Once oxidising species are introduced, whether dissolved oxygen, nitric acid, or oxidising contaminants, copper dissolution accelerates sharply, since the oxidant can support cathodic reduction directly on the copper surface without requiring hydrogen evolution.

Comparative gravimetric studies of copper and carbon steel in one-molar hydrochloric and sulphuric acid found that the sulphuric acid environment was the more aggressive of the two toward both metals because of its stronger oxidising character, and that metal dissolution increased steadily with exposure time and temperature over the range 283 to 333 K (Al-Zubaidy & Hummza, 2014) ^[3]. Comparative work on copper and copper alloys such as brass and bronze similarly found that corrosion rates in 0.5 M sulphuric acid substantially exceeded those measured in alkaline or saline media of comparable concentration, an effect attributed to the ready disruption of the thin, poorly protective oxide and hydroxide layer that forms on copper surfaces, in contrast to the more stable films that develop under alkaline or neutral saline conditions (Kaiser & Kaiser, 2019) ^[6]. The same study reported the formation of surface pores and visible colour change after prolonged acidic exposure, together with a measurable increase in thermal conductivity attributable to the very thin oxide-hydroxide film that does form, indicating that copper's corrosion product offers negligible long-term protection compared with the passive films characteristic of aluminium or stainless steel (Kaiser & Kaiser, 2020).

In organic acid media, copper shows a distinctive sensitivity to process variables relevant to petrochemical plant design. Electrochemical impedance and polarisation studies of phosphorus-deoxidised copper in acetic acid solutions found that increasing temperature, acid concentration, and dissolved-oxygen content all accelerated copper corrosion, in clear contrast to a companion stainless steel specimen tested under the same conditions, for which these same variables had little or even a stabilising effect (Hu, Lin, & Tan, 1996) ^[5]. This asymmetry is of direct practical significance for petrochemical acetic acid duty: process changes intended to improve stainless steel performance, such as maintaining aerated conditions, can simultaneously worsen the corrosion of adjacent copper-alloy components, so material compatibility must be assessed for the specific combined environment rather than for each metal in isolation.

Corrosion Behaviour of Aluminium in Acidic Environments

Aluminium's widespread industrial use rests on its low density, favourable strength-to-weight ratio, and the naturally forming aluminium oxide film that provides good corrosion resistance in near-neutral aqueous and atmospheric conditions. This oxide film, however, is amphoteric: it is thermodynamically stable only within an intermediate pH range, and dissolves through the formation of soluble aluminate or aluminium-ion species at high and low pH respectively. Consequently, aluminium's corrosion resistance falls away sharply once the surrounding medium becomes strongly acidic, and the metal is generally regarded as unsuitable for concentrated mineral acid service without alloying or coating protection.

Electrochemical polarisation and potentiometric studies comparing three aluminium alloys, AA8011, AA4017, and AA1200, in nitric and acetic acid solutions found that all

three alloys were susceptible to pitting in both acids, with nitric acid producing the more severe attack overall despite forming comparatively more stable passive films over time than acetic acid did (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2]. Alloy AA1200, a commercially pure aluminium grade with minimal alloying additions, exhibited the lowest corrosion rates in both acid media, whereas alloys containing higher levels of alloying elements such as copper and silicon were markedly more susceptible to pitting, reflecting the role of intermetallic particles as sites for localised passive-film breakdown (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2]. Scanning electron microscopy of the corroded surfaces confirmed pit formation across all tested alloys and acid conditions, underscoring that even nominally passive aluminium surfaces fail locally rather than uniformly once immersed in aggressive acidic media.

The sensitivity of aluminium alloys to alloying content is corroborated by immersion studies in hydrochloric and sulphuric acid, which found that increasing copper content in aluminium-copper alloys increased weight loss, while increasing nickel content at a fixed copper level reduced weight loss, and that corrosion rates in hydrochloric acid consistently exceeded those in sulphuric acid at equivalent concentration, an effect attributed to the more aggressive chloride ion attacking the passive oxide film relative to the sulphate ion. Related work on aluminium bronze alloys similarly found that chloride-bearing acidic media, particularly hydrochloric acid, produced markedly more severe and selective phase attack than sulphate-based acids or neutral saline conditions, to the extent that individual grains could be dislodged from the alloy surface under prolonged chloride exposure. Taken together, these findings establish a consistent pattern for aluminium: alloy purity and the specific anion present, rather than acid strength alone, are the dominant variables governing service life in acidic environments.

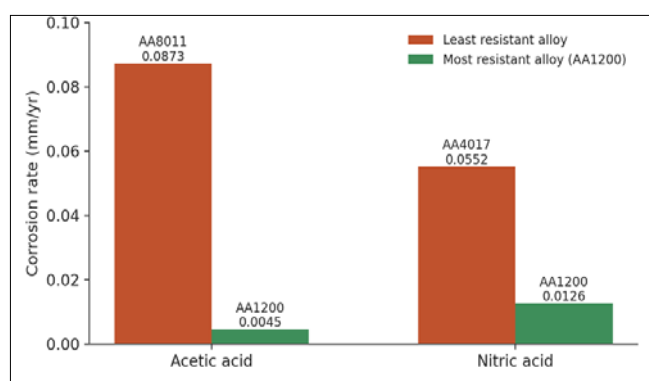


Fig 1: Reported corrosion rates of the least- and most-resistant aluminium alloys in acetic and nitric acid. Data from Adams, Akinwamide, Obadele, & Olubambi (2017).

Corrosion Behaviour of Stainless Steel in Acidic Environments

Stainless steel owes its name and its industrial dominance to the chromium-enriched passive oxide film that forms spontaneously on its surface, typically comprising an inner chromium-rich layer and an outer iron-rich layer only a few nanometres thick, yet capable of reducing corrosion rates by several orders of magnitude relative to unprotected carbon steel (Abbas, Adesina, & Suleiman, 2017 ^[1]; Li *et al.*, 2018). This film remains remarkably stable across a wide pH range

and in many organic and dilute mineral acid environments, which is why stainless steel is the default material of choice for pharmaceutical, food-processing, and much petrochemical acetic-acid duty. However, the same passive film is susceptible to two forms of highly localised attack, pitting and crevice corrosion that can produce component failure at overall corrosion rates that appear negligible when measured by weight loss alone.

Chloride ions are the principal agent of passive-film breakdown on stainless steel. Studies of 13Cr martensitic stainless steel exposed to chloride concentrations between 30 and 150 grams per litre under carbon dioxide found that both the passive breakdown potential and the repassivation potential decreased steadily as chloride concentration increased, with cation and oxygen vacancies accumulating at the metal-film interface until local film detachment and pit initiation occurred (Li *et al.*, 2018). Comparative immersion testing of mild steel and stainless steel in hydrochloric and nitric acid over a five-day exposure period found that nitric acid was the more aggressive medium of the two because of its additional oxidising character, but that stainless steel consistently outperformed mild steel under all tested conditions owing to the presence of the stable passive oxide layer, with mild steel undergoing substantially greater mass loss throughout the exposure period. A critical review of organic acid effects on stainless steel likewise concluded that acid concentration, temperature, and halide impurity levels are the dominant variables controlling pitting susceptibility, and that the behaviour of stainless steel differs considerably between static immersion testing and dynamic electrochemical polarisation testing, complicating direct comparison across studies (Abbas, Adesina, & Suleiman, 2017) ^[1].

Direct comparison between copper and stainless steel under identical acetic acid conditions further illustrates the contrast in corrosion mechanism between the two metal classes. Electrochemical impedance studies of coalesced copper and a chromium-bearing stainless steel type in acetic acid found that rising temperature, acid concentration, and dissolved oxygen consistently accelerated copper corrosion, whereas the stainless steel specimen showed no comparable sensitivity to these variables, and in some respects benefited from the presence of water and dissolved oxygen in stabilising its passive state (Hu, Lin, & Tan, 1996) ^[5]. This asymmetry is the empirical basis for the near-universal specification of stainless steel over copper alloys for acetic-acid distillation and storage equipment in the petrochemical and food industries, notwithstanding the vulnerability of stainless steel to chloride contamination in the same service.

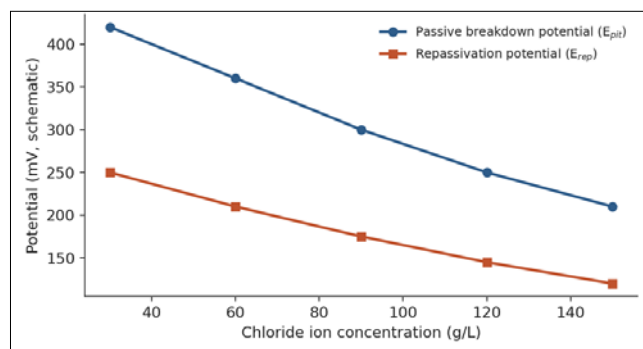


Fig 2: Schematic trend of passive-film breakdown and repassivation potential of 13Cr stainless steel with increasing chloride concentration. Direction of trend based on Li *et al.* (2018); plotted values are illustrative, not reproduced raw data.

Comparative Analysis of Cu, Al, and Stainless Steel

Bringing together the evidence reviewed above, three distinct corrosion profiles emerge. Copper corrodes through relatively uniform electrochemical dissolution without meaningful passive protection, making its corrosion behaviour comparatively predictable and strongly dependent on the oxidising character, temperature, and aeration of the acid rather than on chloride content specifically; it performs adequately in deaerated, non-oxidising, mildly acidic conditions but degrades rapidly once oxidising species or elevated temperature are introduced (Al-Zubaidy & Hummza, 2014; Kaiser & Kaiser, 2019) ^[3, 6].

Aluminium offers excellent resistance in near-neutral and mildly acidic conditions through its native oxide film, but this resistance collapses outside a comparatively narrow pH window, and the metal is highly susceptible to localised pitting once immersed in strong mineral or organic acids, particularly in the presence of chloride ions or when alloyed with elements such as copper that introduce sites for local passive-film breakdown (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2]. Aluminium is therefore best suited to mildly acidic, chloride-free duty, or to applications where a very high strength-to-weight ratio outweighs the need for aggressive acid resistance.

Stainless steel exhibits the most robust passive film of the three metals and the widest range of acid tolerance under chloride-free or low-chloride conditions, making it the preferred material for much acetic acid, dilute mineral acid, and general process duty in the petrochemical, pharmaceutical, and food industries. Its principal vulnerability is not uniform dissolution but localised pitting and crevice attack triggered by chloride ions, elevated temperature, and stagnant or crevice-forming geometries, a failure mode that can produce unpredictable, through-wall perforation despite an outwardly low general corrosion rate (Li *et al.*, 2018; Abbas, Adesina, & Suleiman, 2017) ^[1]. In chloride-rich acidic environments, therefore, standard austenitic stainless steel grades may in fact underperform relative to their apparent bulk corrosion resistance, and upgrading to molybdenum-bearing or duplex grades, or reconsidering the material altogether, becomes necessary.

A useful way to summarise the comparison is in terms of failure mode rather than corrosion rate alone. Copper fails by progressive, roughly predictable general thinning; aluminium fails by early, often severe pitting once its narrow passivity window is exceeded; and stainless steel fails, when it fails, almost exclusively by localised pitting or crevice attack under chloride contamination rather than by uniform dissolution. This distinction matters for inspection and maintenance planning as much as for initial material selection, since general corrosion rate measurements that appear reassuring for aluminium or stainless steel can nonetheless mask a high risk of sudden, localised, and difficult-to-detect failure.

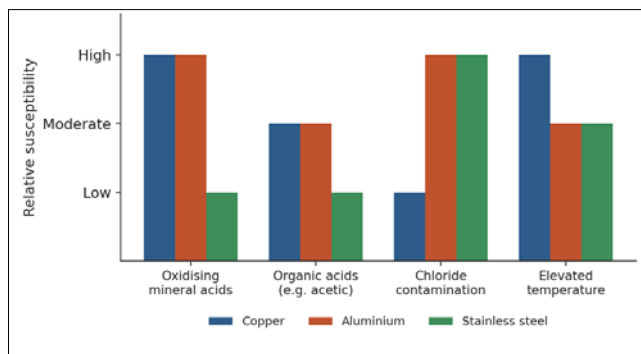


Fig 3: Illustrative synthesis of the relative corrosion susceptibility of copper, aluminium, and stainless steel across four common industrial stress factors, based on the literature reviewed in this article.

Factors Influencing Comparative Corrosion Performance

Several process variables consistently emerge across the literature as governing the comparative performance of these three metals, and each interacts differently with the three corrosion mechanisms described above.

Acid type and oxidising character: oxidising acids such as nitric acid accelerate copper dissolution directly but can, over time, promote more stable passive-film formation on aluminium and stainless steel, so the same acid can be simultaneously more aggressive toward one metal and less aggressive toward another (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2].

Chloride and halide content: chloride ions are the dominant driver of localised passive-film breakdown on both aluminium and stainless steel, while their effect on copper, which lacks a strongly protective film to begin with, is comparatively secondary to the acid's oxidising strength (Li *et al.*, 2018).

Temperature: elevated temperature accelerates reaction kinetics across all three metals, but its effect on protective films is metal-specific; it can destabilise the passive film on stainless steel at high chloride concentration while simultaneously promoting more protective film formation on aluminium in certain acid systems (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2]; Li *et al.*, 2018).

Dissolved oxygen and aeration: aeration accelerates copper corrosion by supporting cathodic oxygen reduction, yet can help stabilise the passive film on stainless steel, illustrating that process control measures cannot be optimised for one metal in a mixed-metal system without considering the others (Hu, Lin, & Tan, 1996; Kaiser & Kaiser, 2019) ^[5, 6].

Alloy composition and microstructure: intermetallic particles and second-phase precipitates provide preferential sites for pit initiation in both aluminium alloys and stainless steels, so nominally similar grades can show substantially different acid resistance depending on minor compositional differences (Adams, Akinwamide, Obadele, & Olubambi, 2019) ^[2]; Abbas, Adesina, & Suleiman, 2017) ^[1].

Industrial Implications and Mitigation Strategies

The comparative behaviour described above has direct implications for material selection, inspection strategy, and corrosion mitigation in industrial plant design. Where mildly acidic, chloride-free, and non-oxidising conditions

prevail, all three metals can perform adequately, and selection may be driven by cost, weight, or thermal considerations rather than corrosion resistance alone. As acidity, oxidising strength, chloride content, or temperature increase, however, the three metals diverge sharply in suitability, and blanket assumptions about "stainless steel resistance" or "aluminium's protective oxide" can lead to premature and sometimes catastrophic failure if the specific acid chemistry is not accounted for.

Several mitigation strategies are commonly applied across these metal systems. Corrosion inhibitors, including organic compounds that adsorb onto the metal surface to block active dissolution sites, have been shown to reduce copper corrosion rates substantially in acidic media and remain an active area of applied research (Goni, Bano, & Mazumder, 2025). Alloying strategies, such as increasing molybdenum content in stainless steel or minimising copper content in high-purity aluminium, directly improve resistance to pitting by stabilising the respective passive films or removing preferential pit-initiation sites (Adams, Akinwamide, Obadele, & Olubambi, 2019 ^[2]; Abbas, Adesina, & Suleiman, 2017) ^[1]. Protective coatings and linings, cathodic protection, and control of process chemistry, particularly limiting chloride ingress and controlling dissolved oxygen where appropriate, remain the primary engineering controls for extending component life once a base metal has been selected. Finally, regular non-destructive inspection focused specifically on localised attack, rather than average wall-thickness loss alone, is essential for aluminium and stainless steel components in chloride-bearing acidic service, given the demonstrated tendency of both metals to fail through pitting rather than uniform corrosion.

Conclusion

Copper, aluminium, and stainless steel each bring distinct corrosion mechanisms to industrial acidic service: copper through direct electrochemical dissolution accelerated by oxidising conditions, aluminium through a narrow-window passive oxide film highly vulnerable to acidic and chloride attack, and stainless steel through a comparatively robust but locally fragile chromium-oxide passive film. The comparative evidence reviewed here demonstrates that corrosion resistance in acidic environments cannot be ranked in the abstract; it depends on the specific acid, its oxidising character and concentration, temperature, chloride content, and alloy composition. Effective material selection and corrosion management in industrial acidic environments therefore require matching the metal's known failure mode, general dissolution for copper, early pitting for aluminium, and localised chloride-driven pitting for stainless steel, to the actual process conditions, supported by appropriate inhibition, alloying, and inspection strategies.

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