Selective soldering nozzles: insights into wear mechanisms and future developments

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Selective soldering nozzles: insights into wear mechanisms and future developments

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Abstract
Selective soldering utilises wettable metal nozzles for controlled application of solder to components. The wetting of solder to the nozzles is part of a complex mechanism that causes wear of the nozzle due to chemical interaction between the solder and the nozzle. This study explores the fundamental interactions between flowing solder and the nozzle.

Nozzles can last for hundreds of hours with the correct maintenance, however dewetting and eventual wear results in a loss of productivity and therefore revenue. Performance improvements to selective soldering nozzles allows for operation in more demanding process environments, producing higher quality and more reliable products, whilst also reducing process downtime and producing fewer defects. Thus far, limited work has been produced analyzing the efficacy of alternative alloys to improve the lifespan and wettability of selective solder nozzles.

A joint research project between industry and academia[1] has been established to investigate the fundamental wear mechanisms of selective soldering nozzles and develop improved nozzles with increased wettability and lifetime. Alternative alloys are investigated for their operational viability.

Details of the methodologies employed will be given. Wear was quantified by proportional mass loss measured at regular time intervals throughout the nozzle's operational life. Wettability was quantified by measurement of the contact angle with solder in an inert atmosphere to mimic in-situ conditions.

Insights into field performance of these new nozzles will be presented with reports from key testing partners.

Introduction

The soldering nozzle has been present in the electronics industry since the early 1990s with the advent of the first selective soldering machines. This methodology was first utilized as it allowed for more control of individual solder joints than wave soldering enabling it to be applied to boards with high densities of components or those with complex geometry.

The adoption of lead-free solders has introduced numerous challenges such as the change in process parameters due to the higher melting point of the alloys, tin whisker formation and the altered mechanical properties compared to leaded solder [1–3]. Furthermore, the use of lead-free solders has highlighted the wear issue present with the use of wetted nozzles. As tin is the element most responsible for the wear of materials in contact with solder, the increase in tin content has increased the wear of nozzles as well as other components [4–6]. This can be observed in tin-iron phase diagrams wherein the increased tin content allows for more iron to be dissolved into the alloy [7–9]. Dewetting can occur in all nozzles; this issue is not new but by tackling the challenge of the nozzle wear, dewetting can also be addressed.

Current understanding of the wear of solder nozzles

The current soldering literature interchangeably utilizes the terms erosion and corrosion to describe the wear of nozzles and other parts exposed to solder. Though these terms are correct in a sense, they both describe long term wear processes wherein material is removed from the surface of a part, but the fundamentals of these wear mechanisms are different. Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices [10]. Tribology is otherwise known as, the study of friction, wear and lubrication. In relation to this study, we are focusing on the wear of selective solder nozzles and providing insight into its fundamental mechanisms.

In tribological terms, erosion is the removal of material due to the impingement of liquid or solid particles on a solid surface. Liquid damage is generally due to the formation of momentary stresses in the material that can lead to cracking [10,11]. Particulates such as sand can cause damage to valves, pumps and pipework [12]. A material's erosion rate is dependent on its

[1] Pillarhouse International Ltd. are the industrial partner and Coventry University are the academic partner.

relative brittleness/ductility in addition to the velocity and angularity of the erodent material [13]. Corrosion, however, occurs as the result of surface chemical interactions resulting in the removal of material. An example is the formation of an oxide layer on a material which can be subsequently removed and reformed [10,11]. Erosion and corrosion can act synergistically in a process called tribo-corrosion [14]. This will generally lead to an increased wear rate over any of the two processes alone [14].

Wettability

Wettability refers to the interaction of a liquid with a solid. This can refer to the spreading of a liquid over a surface, the penetration of a liquid into porous materials or the displacement of one liquid by another [15]. Understanding the solid/liquid interface is key in a number of fields such as catalysis, crystal growth, lubrication, electrochemistry and colloidal systems [15].

Surface energy is defined as the work required to build a unit of area of a given surface. Using the sessile drop technique (described below), the measured surface energy depends not only on the solid samples but also on the properties of the applied liquid and surrounding gas [15]. High surface energy materials include metals and inorganic compounds (e.g. oxides, silicates, nitrides and diamond).

Quantifying a liquid’s surface wetting characteristics is normally done by measuring the contact angle of a drop of liquid placed on the surface of an object. This is referred to as the sessile drop method and a goniometer is a piece of equipment used to measure this contact angle. Liquids are said to wet surfaces when the contact angle is less than 90° [15]. This methodology can be employed to measure the wettability of solder. However, it requires a goniometer capable of heating the solder to the operational temperatures of the soldering process and an inert chamber to ensure that no oxide film is present that could affect the surface tension of the solder.

Various methods exist for assessing solderability, these being the wetting balance technique (assessing the wetting force and time with a sensitive balance) [16], solder spread [17] and contact angle analysis [18].

Current nozzle technology

Current nozzle technology has only seen token advancements in the materials employed for wettable nozzles. The paradigm for wettable nozzle technology is a ferrous alloy with electroplated coatings. The electroplated coatings mainly serve to protect the nozzle from general corrosion while also providing some initial benefit to the wetting between the solder and the nozzle. The lifetime of thin coatings on nozzles will be discussed later in this paper.

In general, there are two types of nozzle: the wetted nozzle and the non-wetted nozzle. A wetted nozzle is shown in Figure 1, in which the solder flows all around the tip of the nozzle. For this nozzle, the contact angle would be less than 90°. This design allows for both dip and draw steps wherein the wetting of the solder around the nozzle, along with variations in the pump speed, facilitates control during the soldering process

Figure 1. An example of a wetted nozzle.

Figure 2 shows a nozzle that is not wetted by the solder. In this case, the solder forms a single lateral stream to a side of the nozzle, and controlled soldering processes would not be able to be performed as would be possible in with the nozzle in Figure 1.

Figure 2. An example of non-wetting nozzle.

Designed non-wetting is available for custom dip “nozzles” as shown in Figure 3.The shape of these nozzles are tailored to the layout of pins to be soldered and to direct the solder pooling within the cut-out. The nozzles would be raised to deposit solder to the pins on the underside of the printed circuit board.

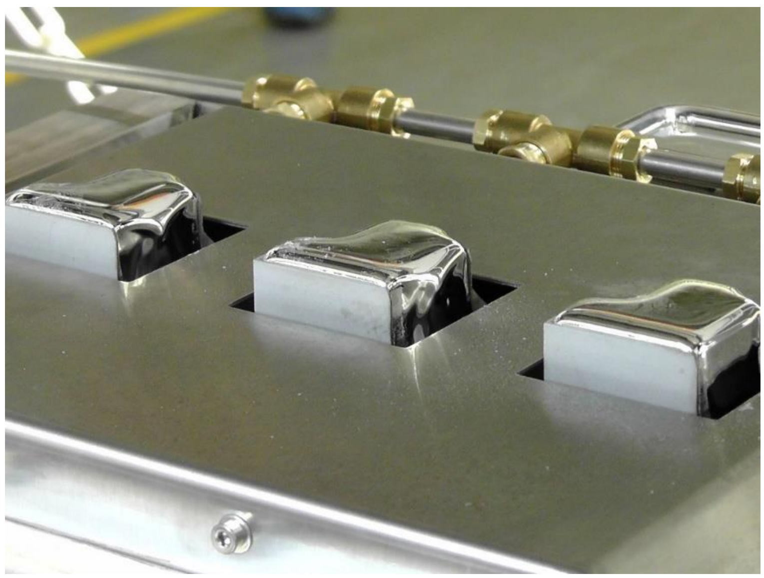

Figure 3. Dedicated multi-dip nozzle set up.

The innovations discussed within this paper will focus on the wetted nozzle, the establishment of a wear measurement methodology for the wetted nozzles and insights into the wear mechanism of nozzles determined from the results generated herein. The motivation for this work is to develop a new nozzle with improved soldering performance and increased lifetime. Revenue lost due to unplanned downtime and maintenance can be significant. An idea of the scale can be quantified with a model of an 8-hour shift with 1 hour given up to maintenance per day for a typical 5 day work week. In this model, we will assume 60 printed circuit boards are produced per hour with a cost of £100 per PCB. If the manufacturing process is run for 50 weeks a year, that would result in a revenue loss of £1,500,000. If the nozzle would no longer need to be rewetted during each of these shifts, £500,000 could be saved. This could be further increased with longer life nozzles that would not need to be replaced as often.

Figure 4 shows the steps and methodologies employed in this project that will be detailed in this paper.

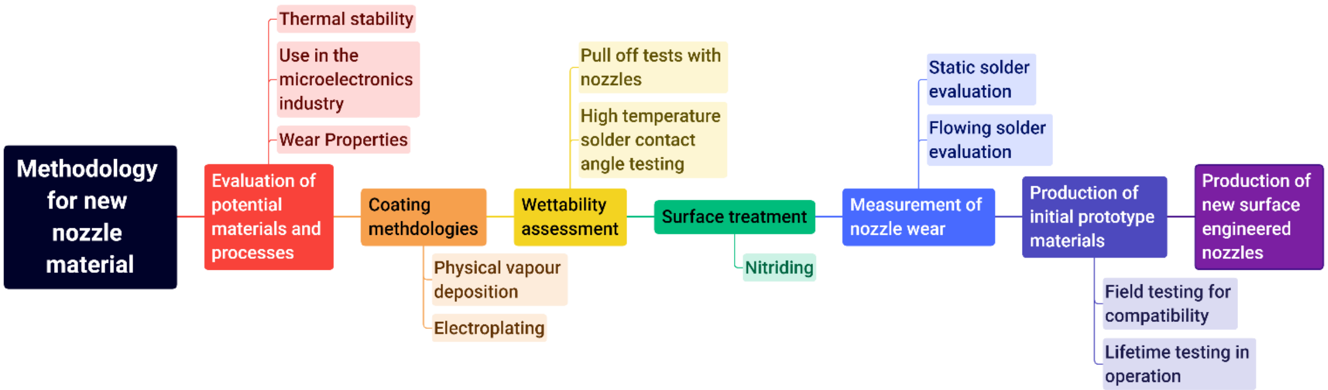

Figure 4. Map of the steps and methodologies used in the development of new selective solder nozzles.

Methods and Materials

Determining material compatibility

Before any lifetime tests can occur, any potential material should first be tested for compatibility with the solder and to ensure that a wetting reaction can occur. A quick method for determining whether a material can initially be wetted by solder is by dipping it a solder bath. The material should first be cleaned with a flux, in this instance a water-based flux was used. Following this, the nozzle is then dipped into molten solder and held for 10-15 seconds to allow the metal nozzle to heat up and for the wetting to initiate. If the material can wet, it will have a thin film of solder that will evenly coat the surface. For a non-wetting nozzle, it is common to observe dewetting patterns which generally appear as fractal or dendritic structures [19,20].

Preparation of coatings

Currently, most nozzles are electroplated with wettable metal coatings. These coatings provide numerous benefits, the first of which is facilitating the initial wetting of the solder to the nozzle. This forms a radial wave of solder at the tip of the nozzle.

Coatings were prepared on selective solder nozzles to test their effectiveness at extending the lifetime of the nozzles. Nickel and tin coatings were investigated primarily, however TiN was also coated in a multi-layer structure of Ti/TiN/Sn. Testing was performed with the aim of creating a wettable nozzle with a non-wearing base material. Coating with thin layers (to facilitate other applied coatings) and then coating with a material that has a longer lifetime on exposure to solder (such as precious metals [21]) was tried, as it was theorized that a nozzle could thus be created with a longer lifetime than current nozzles.

Physical vapor deposition (PVD)[2] was utilized to deposit coatings on titanium nozzles. As titanium is considered extremely difficult to electroplate, this coating methodology was used for its ability to coat a wide variety of materials. PVD coatings were prepared using a magnetron sputtering equipped deposition system.

For ferrous substrates, electroplating was used to deposit nickel onto the angled surface of the nozzles. A Woods strike and subsequent Watts bath [22] was used to deposit nickel onto the surface of the nozzles.

Precious metal coatings (for copper nozzles) were deposited by electroplating shops. The following structures were deposited for each of the coatings:

- Platinum: 5 μm of intermediate nickel, gold flash and 1 μm of platinum.
- Rhodium: 5 μm of intermediate nickel, gold flash and 1 μm of rhodium.
- Ruthenium: 5 μm of intermediate nickel, gold flash and 1 μm of ruthenium.
- Palladium: 2 μm of nickel and 2 μm of palladium.

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[2] PVD is an atomistic vaporization technique in which material is vaporized from a solid or liquid source through a vacuum or low pressure/plasma environment, after which it condenses on a substrate, thus forming a coating. Coating thickness varies however a few nanometers to several microns is common. A multitude of methods exist by which to apply PVD coatings including vacuum evaporation, sputter deposition and ion plating [44,45].

The thickness measurements stated are nominal and determined by the electroplaters. Copper nozzles were chosen as copper is known to readily dissolve into solder, therefore making it simple to determine the potential improvement of any precious metal coatings; any additional lifetime before the nozzle dissolves can be taken as an improvement attributed to the precious metal coatings.

A scanning electron microscope (Field Emission Scanning Electron Microscope) was used to inspect prepared cross sections to measure the coating thickness. Figure 5 shows a cross-section of a platinum electrodeposited coating on copper.

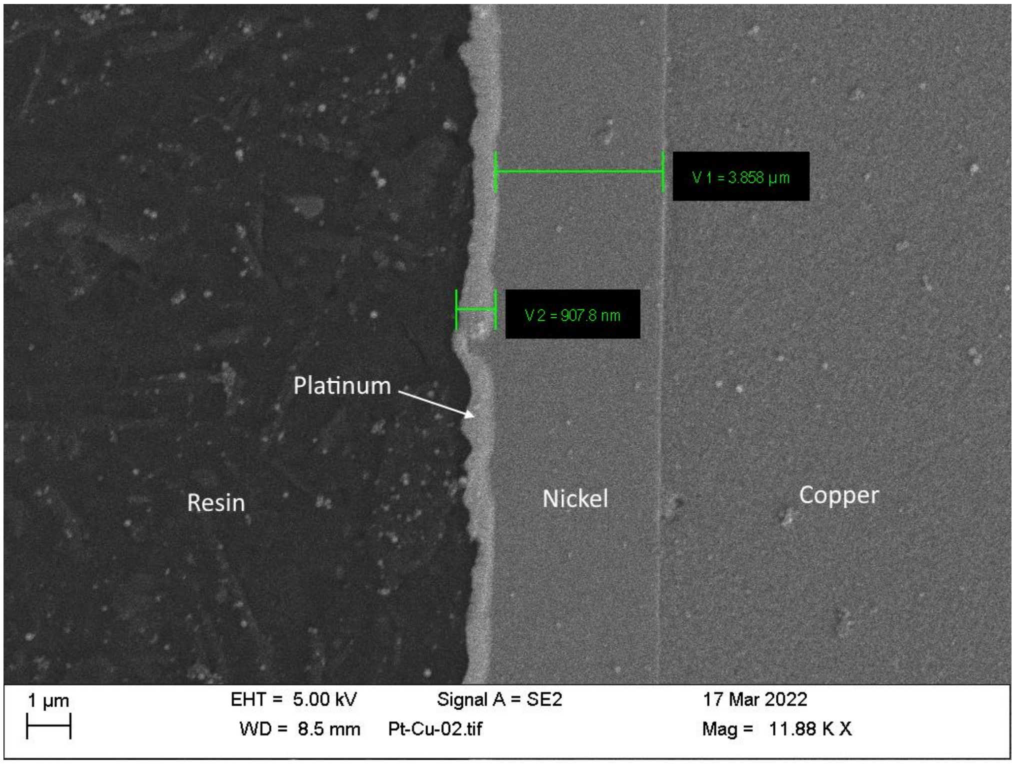

Figure 5. Scanning electron micrograph of cross-section of platinum electroplated coating on copper. The resin on the left of the image is used to set the metal for imaging with the electron microscope.

Measuring Nozzle Wear

Static nozzle testing was performed to investigate the wear of the nozzles without solder flow through the nozzles. Nozzles were suspended in a bath of SAC305. The solder temperature was 290°C, making it typical for a selective soldering process. In one case, the nozzle did not have flux applied to it, and in the other, flux was applied every 24 hours. The nozzle was weighed before being immersed in solder. At each weighing interval, the mass was measured and compared to the initial mass for a percentage change to normalize the results. This is to allow comparison between different nozzles.

For the case of flowing solder testing, the same measurement procedure was used (i.e. comparing the percentage difference in mass), but mass measurements were taken on a daily basis. Flux was applied to the nozzle when required to achieve wetting when reinstalling the nozzle into the machine. Dross was scraped from the surface of the bath once per day, at the same time as nozzle mass measurements. A more thorough bath clean was performed once per week to clean the impeller chamber. All nozzles were offset to 0% mass at the beginning to eliminate any inconsistencies due to early mass gain from solder adhesion.

The copper nozzles and precious metals were tested by time to failure instead of mass loss due to the shorter operational time. The nozzles were observed in their flowing state and tests were stopped once the nozzle had dissolved into the solder.

The results are an average of at least 3 nozzles tested in each case.

Surface Modification methodologies

In addition to the coating methods employed for the nozzles there are other surface engineering methods that can be used to modify the nozzles. Surface engineering is the application of both traditional and innovative surface technologies with the goal of producing a composite material with properties unattainable with bulk materials alone [10]. These changes can improve the appearance, protect from environmental damage and enhance the performance of the surface [23].

Nitriding is a ferritic thermochemical method of diffusing nascent nitrogen into the surface of steels and cast irons. The solubility of nitrogen in the various alloys controls the diffusion process. This process is not a new one, having been developed in the early 1900s and used in the manufacture of aircraft, bearings, automotive components, textile machinery and turbine generation systems [24,25]. Typically, a nitriding process would involve placing a part into a low pressure chamber in which the atmosphere is vented. The part is then heated to around 520°C and kept in a nitrogen containing atmosphere for 24-48 hours. Sályi et al. [26] showed that nitriding steels both extended the lifetime and improved the wettability.

High temperature contact angle analysis

High temperature contact angle analysis was performed using a modified contact angle goniometer. The equipment features an inertion chamber and ceramic needle dosing system. Plate samples are cleaned with a water-based flux before testing. Once the samples were heated to 290°C (to mimic selective soldering conditions) in the inert atmosphere, molten solder was applied to the surface. The water-based flux was then applied to the interface between the solder droplet and the plate to ensure that no oxides would be present so that solder could spread unimpeded.

Prototype testing

Before any new innovation is deployed industry wide, prototype testing is essential. Due to the many types of solders, fluxes and process conditions utilized within selective soldering, any change in the materials must be compatible. Multiple different types of selective soldering nozzles are routinely used depending upon their process requirements.

Companies performing testing were polled for their soldering process information and asked to report on the daily operation of the nozzles. Of particular interest is the amount of rewetting required and other cleaning methods used (i.e abrasive). Operators were briefed on the use of new nozzles and asked to compare them to the current nozzle technology.

Results

Material compatibility

It was presumed that a wettable coating could be deposited to achieve standard nozzle function with minimal wear rate. However, subsequent testing showed that the dissolution rate of wettable materials (especially thin coatings) is extremely fast. Grade 2 titanium was chosen as the base material. Nickel coatings on titanium had a thickness of approximately 1.2 µm (measured with a cross-section methodology as above). Under solder flow conditions, the coating had a lifetime of 150 seconds. This was determined from the start of solder flow to when the nozzle lost wettability due to the dissolution of the wetted coating. The titanium base material was non-wetting. The multilayer TiN coating also lost wettability within 120 seconds as the tin layer melted into the solder bath and the ceramic (TiN) layer was found to be completely non-wetting.

Static bath

Figure 6 shows the mass difference in nozzles suspended in a static bath. Fluxed and non-fluxed nozzles both showed mass gain due to adhesion (wetting) of the solder to the nozzle. The fluxed nozzle, however, showed a consistent increased mass gain in each measurement step over the non-fluxed nozzle. The largest difference is at 672 hours where the fluxed nozzle had a mass difference of approximately 8.2% versus 2.5% for the non-fluxed nozzle.

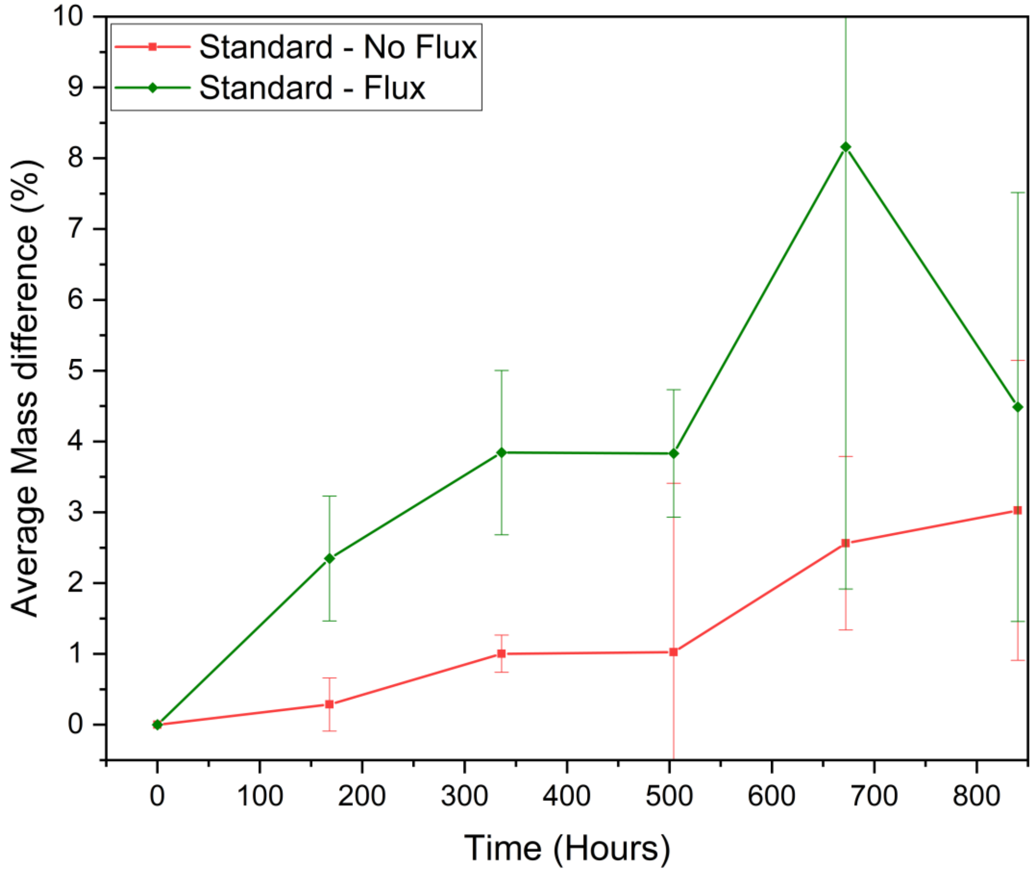

Figure 6. Normalized mass readings for nozzles suspended in a solder bath for static testing.

Standard nozzle wear results

Figure 7 shows the normalized mass loss results of the current standard nozzle under flowing solder conditions. Testing for long time periods can reduce errors due to excess solder adhering to the nozzle;. However, efforts were also taken to remove solder by mechanical cleaning (wiping off solder or tapping the nozzle against the side of the bath). Initially, measurements were taken at more regular intervals (8 hours). However, the testing found that once in a 24 hour period is sufficient to capture the mass loss without also measuring variations due to adhesion of the solder to the nozzle.

The line at -17% mass loss represents the loss of function of the nozzle due to geometric modifications in the wear process. This has been determined by long term testing of nozzles and checking their suitability for soldering.

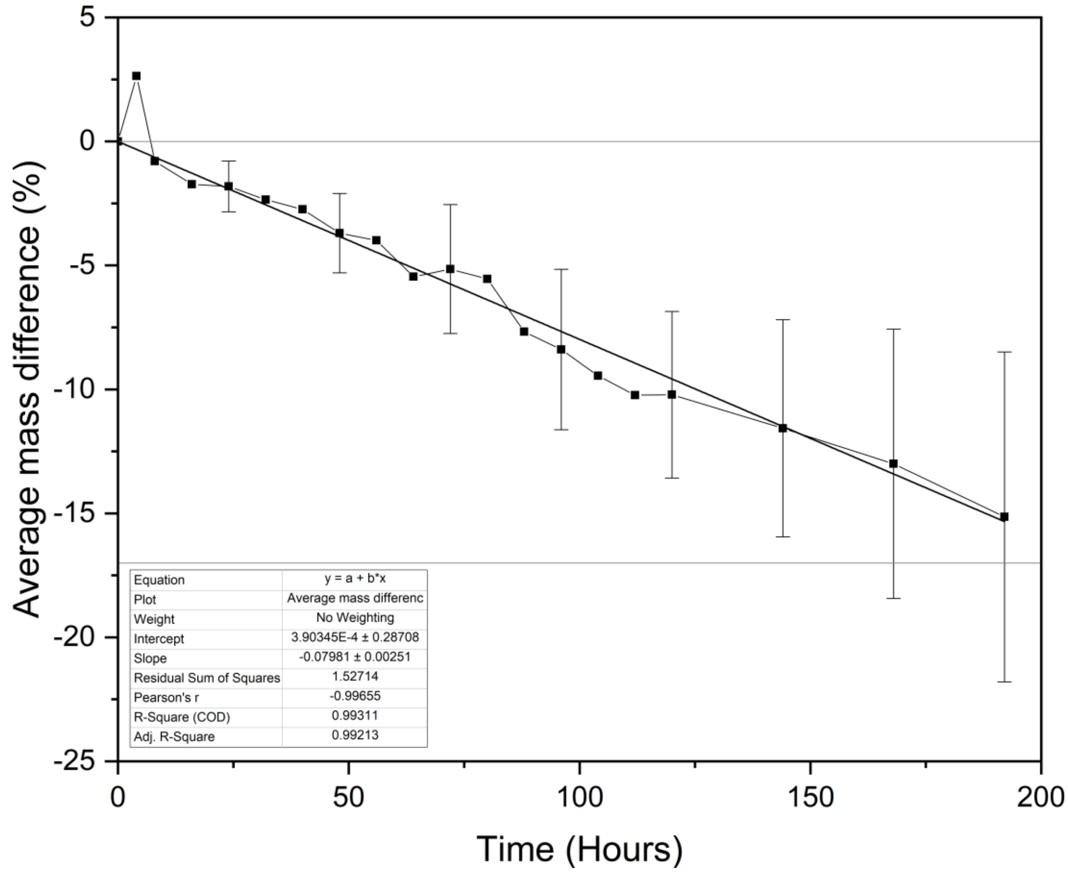

Figure 7. Normalized mass loss results for a standard pure iron nozzle. Results are averaged over 4 nozzles.

Figure 8 shows the result of a nozzle towards the end of its usable lifetime (nearing 17% of total mass loss). Nozzles will generally have a radius at their top edge. However, Figure 8 clearly shows a sharpening of the end radius due to the removal of material.

Figure 8. A worn nozzle after approximately 200 hours of testing.

Figure 9 shows the time to failure of copper nozzles and copper nozzles with electrodeposited coatings. The right-hand axis shows the percentage improvement compared to the copper nozzle alone. The higher percentage improvement was observed with platinum coatings with a time to failure of 217 ± 8 mins (38% improvement) compared to 157 ± 42 mins for copper.

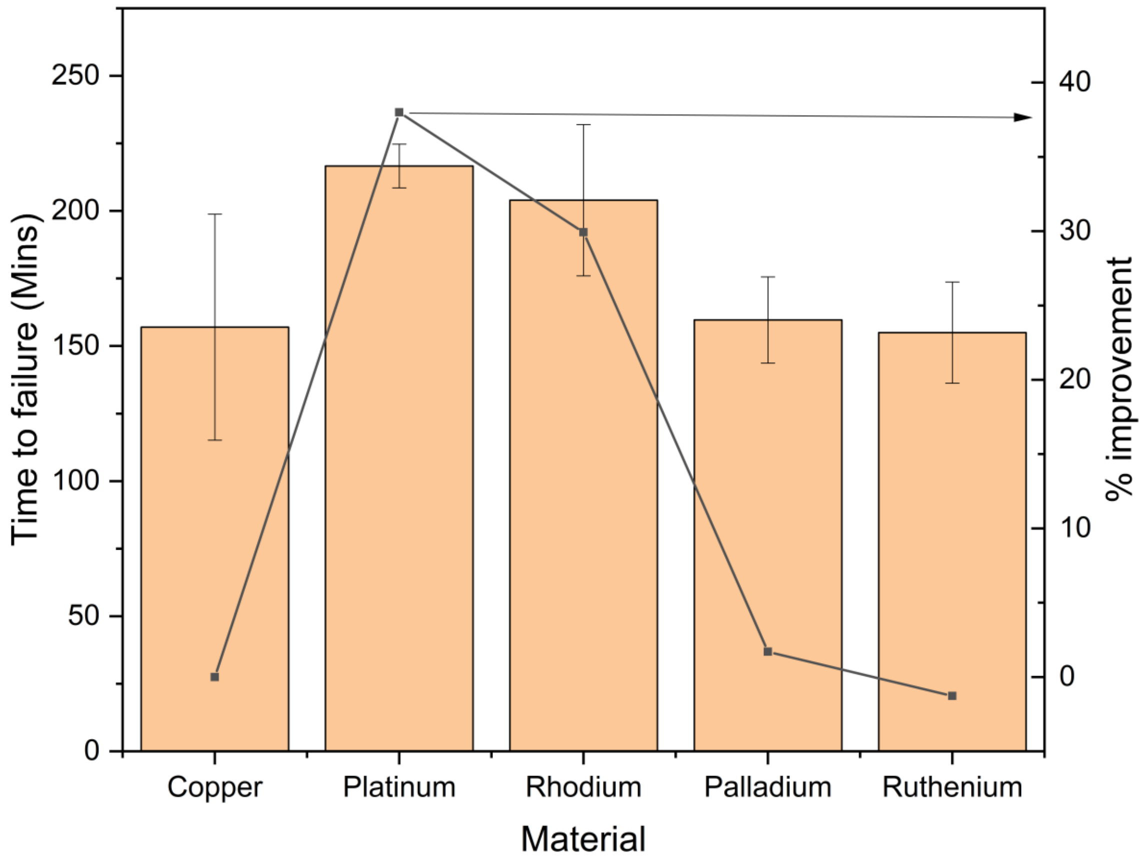

Figure 9. Time to failure results and percentage improvement of precious metal coatings on nozzles.

Potential lifetime improvement

Lab based testing has shown that the current standard selective soldering nozzle for this research has a lifetime of approximately 200 hours. This equates to 5 weeks of use for shifts of 8 hours per day for 5 days each week. This has been corroborated with data collected from customer surveys.

Figure 10 shows the effect of increasing the lifetime compared to the current nozzle. With each step in increasing the performance, the negative gradient becomes shallower, thereby increasing the time to reach the point of nozzle failure (-17% mass loss).

The percentage improvements shown in the figure are based on materials currently under assessment. As with Figure 7, the materials under consideration had their mass measured once every 24 hours.

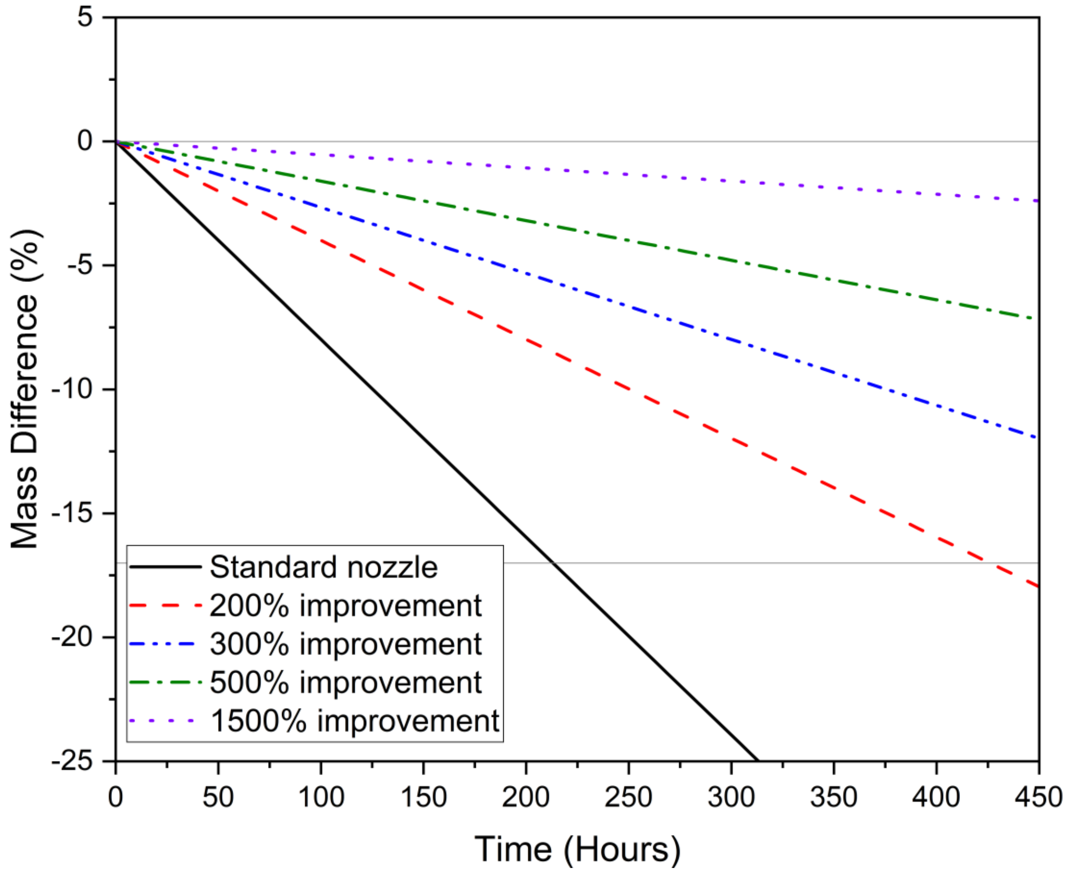

Figure 10. Graph of linear fitting of standard nozzles compared to projected increased lifetime of improved nozzles.

Table 1 shows the approximate lifetime of each of the results presented in Figure 10 (time to reach -17% mass loss).

Table 1. Approximate lifetimes of the current standard nozzle and materials with significantly improved lifetime. The equivalent lifetime for continuous running in days is shown in the right-hand column.

Material	Approximate lifetime (Hours)	Approximate lifetime (Days)
Standard nozzle	213	8.9
200% improved material	426	17.8
300% improved material	639	26.6
500% improved material	1065	44.4
1500% improved material	3195	133

High temperature wettability assessment

Figure 11 shows a comparison of the contact angles of the new nozzle base material (a) and the current base, i.e. pure iron (b). The new material displays a greater spreading and a lower contact angle of 32° on the left and 24.7° on the right.

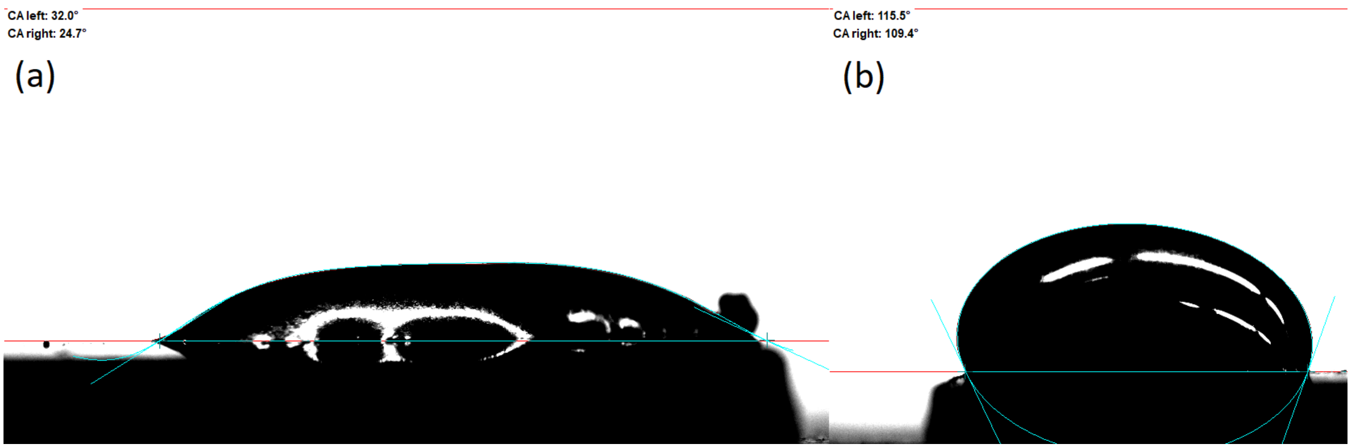

Figure 11. Comparison of the contact angles of (a) new nozzle base material and (b) the current pure iron base material.

Ideal alloy composition

Testing of numerous pure metals and alloys has allowed us to subsequently choose materials that have an optimal composition to balance the wetting of the solder and lifetime exposed to flowing solder.

Refractory metals such as tungsten will not wet to solder. Therefore alloys containing this element (such as M2 tool steel) display poor wetting characteristics. Titanium is well known to be solder resistant, but this may be primarily due to its thick oxide layer growth [27,28]. This oxide is supposed to function by inhibiting the interaction between the metal and the solder in addition to changing the surface energy. Furthermore, Morris et al. [7] reported that, at wave soldering temperatures (265°C), an extremely small amount of titanium will be dissolved into the bath but this increases with temperature according to the phase diagram of titanium and tin. In addition, chromium is detrimental to wetting (as found in stainless steel) as the chromium oxide layer will prevent interaction with the iron in the alloy.

Insights from Prototype testing

Prototype testing partners have delivered results showing that the chosen alloys perform well under full process conditions. It was theorized that the additional complications of changing the pump speed, movement of the bath and exposure to board cleaning fluxes may have a deleterious effect on nozzle lifetime. Overall, nozzles have been observed to last approximately as long under true process conditions as in idealized testing. Dewetting events were infrequent (approximately once per shift if at all) and wetting was quickly able to be regained with flux application. Operators found the new nozzles as easy to work with as the current nozzles.

Discussion

Nozzle wear testing

Previous works have focused on the use of static test set ups to measure the wear of the materials caused by exposure to solder [6,21,29]. These methods are based on exposing a section of material to solder in a static bath. This method will determine the basic interaction (dissolution) between solder and a material. However, it doesn't accurately represent the selective soldering process. Wetting in a dynamic nozzle scenario is not accounted for, nor is flow velocity of solder over the wetted material. Figure 6 supports this as only mass gain was observed for these nozzles. Wetting and adhesion were observed over the extended immersion time but with minimal wear.

Figure 7 shows that for a flowing solder system and the use of regular measurement intervals and a sensitive balance, the relative mass loss can be recorded, allowing for better comparison between different materials. For this work, it was determined that this method is more suitable as it closely mimics the conditions of the soldering process. There are some caveats in that the solder bath is static (unlike a true soldering process), no pins are being soldered and the nozzle is not exposed to any flux that is used to clean circuit boards. All these things may affect the lifetime of the nozzle. However, the benchmark results created in idealized laboratory conditions have been supported by surveys of current nozzle performance and in prototype testing reports of new nozzles.

Insights into the wear mechanism of selective solder nozzles

In most of the soldering literature, the wear mechanism is discussed in terms of erosion. This is the case for the IPC J-STD-002E [30] and for the BSI test method for wear (referred to as erosion) of wave soldering equipment [31–33]. Wave soldering apparatus does not need to be wetted by solder to continue functioning, although there will still be some wear present. This suggests that despite the lack of wetting interaction, there is still a mechanical component to wear caused by the moving solder.

Furthermore, materials known to have good wettability are also known to dissolve into solder. The precious metals shown in Figure 9 are known to have good wettability [16] but also dissolve into solder relatively quickly [21]. This provides evidence of the link between wetting and corrosion (chemical interaction with the liquid solder). Wetting for soldering systems is regarded as a reactive model wherein a new phase is formed during the process [34,35]. This wetting reaction is complicated, involving the interplay of fluid flow, heat and mass transport, capillary interactions, and phase formations [34,35]. Figure 11 shows that the wetting for the new materials is greater than for pure iron (lower contact angle). However, as Figure 10 shows, the wear rate is lower.

Intermetallic formation is sometimes regarded as detrimental to solder joints, but is, in fact, a fundamental part of their formation [36–39]. They are a part of the wetting process, making their formation on the nozzle surface. As they are brittle, however, they are more susceptible to cracking [36–39], but the diffusion of the various elements into each other can also cause Kirkendall voids that may exacerbate this issue [38,40].

As temperature is noted to be a contributing factor to the wear of wetted materials [5], this would suggest a substantial corrosive component as temperature controls chemical reactions. The wetting reaction requires a minimum temperature to create adhesion between the liquid and solid. Mechanical wear is also affected by temperature, but generally to a lesser degree within the temperatures considered in this work [41,42]. Furthermore, the impacts of particulates in erosion would generally cause a greater amount of wear than would be observed by removing the oxide layer as oxides are generally in the scale of nanometers [43]. This oxide layer providing protection also suggests a corrosive wear component as it will prevent reactions between a corrosive fluid and the surface[14]. The removal of this oxide layer (by either abrasive cleaning or flux) allows for wetting to occur, which, with the addition of flowing solder, leads to more severe wear. Figure 6 shows that without the flow of solder (Figure 7), we just measure wetting (adhesion) of the solder to a nozzle.

Due to the compositions of the new alloys under consideration (Figure 10 and Table 1), the surface interactions between the metal and solder may be different, thereby causing a reduced corrosive wear component. Additionally, all alloys under consideration have higher hardness, thereby making them more mechanically wear resistant [10,11].

Conclusions

In conclusion, this paper presents the methodologies used to test the compatibility of materials for selective soldering nozzles as well as quantitatively measuring their mass loss in an equivalent in-situ test mimicking real operating conditions. Ongoing prototype testing corroborates the lab data in terms of lifetime with few dewetting events noted. Evidence has been presented to link the wear of nozzles to the dewetting of materials and to show that the wear process is a complex synergistic corrosion-erosion process. s

Due to the commercial nature of the work and the patent currently pending, more details of the materials discussed herein cannot yet be revealed. The fundamental interactions between flowing solder, wettable materials and the wear process is currently being investigated by a PhD project linked to this project. Findings from this project will be published later to expand upon the initial work presented here.

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