

An Analysis of Protective Coatings for Automobile Exhausts

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1 Introduction

The exhaust system of a vehicle has four primary functions, to control noise, to direct exhaust fumes away from passengers, to improve the performance of the engine and to improve fuel consumption. As a result of this some parts of the exhaust system are exposed and others hidden within the vehicle. The exhaust system as a whole receives physical attacks from the road, attacks from pollutants in the road and in the fuel, exposure to high temperature, thermal shock and environmental exposure. Physical attacks and pollutants in the roads are heavily dependent on where and when you drive. These factors all increase the rate at which components within the system will degrade and eventually fail. A coating helps to resolve and protect against a number of these issues. Coating the exposed sections of an exhaust system is necessary as it allows the system to perform its function for longer duration, decreasing the necessary maintenance required to operate the vehicle and the cost of said maintenance. Therefore, for consumers, a coating on an exhaust system must protect against the aforementioned environmental and physical attacks as well as being a more economical option than using the components until failure. There are additional characteristics which would be desirable in a coating considering the consumer automobile industry, those being the aesthetics of the applied coating and the weight of the coating. If a coating is not aesthetically pleasing it is unlikely to be purchased, especially for motorcycles and other vehicles where the exhaust system is a prominent feature. The weight of a coating must be considered as it affects the efficiency and design of vehicle, being that a heavy vehicle consumes more fuel and a heavier component requires more support to attach it to the vehicle lest there be stress concentrations which may lead to failure. The effect the coatings have on the performance of the system must also be considered, a coating which insulates the system will decrease the external temperature reducing damage to other components and allowing components with lower melting points to be in closer proximity to the system. The environmental factors in corrosion mean that dryer areas are likely to experience less corrosion, meaning the coatings may not be as necessary. Inversely this holds true for coastal areas or areas with winters cold enough to require the roads be gritted, which have an increased requirement for coatings due to the salt in the air or on the road increasing the rate of oxidation. Additionally, when people drive is a factor as many motorcyclists do not ride in the rain or during the winter period, reducing the vehicles exposure to as many pollutants, reducing the need for coatings to impede corrosion or oxidation.

Overall for an exhaust system both manufacturer and consumer would desire a coating which internally protects the system against pollutants in fuel causing internal corrosion and provide insulation against temperature leaking from the system. An external coating must resist the environmental factors it may be exposed to, which can lead to corrosion and oxidation, with any exposed parts of the system being protected against physical attack as well. The coatings must be economically preferable to replacing components and should ideally be aesthetically pleasing.

2 Coatings From Materials

Outside of motosports the most common materials for exhaust pipes to be made of are mild carbon steels and stainless steel [1], it is valuable to discuss the inherent properties of the materials as these materials do intrinsically form their own protective coating through the process of corrosion.

When mild carbon steel rusts it forms an iron-oxide coating protecting it, to a certain degree, from atmospheric corrosion. Due to its lower density the layer of iron-oxide is quite permeable and readily flakes and rubs off. This low durability can easily lead to further corrosion simple from debris on the road hitting the layer, stripping it down and allowing for further corrosion to penetrate into the substrate [3]. In addition to this, this layer offers very poor protection when interacting with road salt and other pollutants. This iron oxide coating has poor durability, provides little to no protection against pollutants and the components will rapidly begin to fail, this tendency of steel to rust has led to the necessity of other coatings and alloys of steel.

Stainless Steel is an iron alloy that contains a minimum of 11% Chromium [3], the iron-oxide discussed above is not given the chance to form due to the chromium forming a near-invisible chromium-oxide layer when it reacts with oxygen. This gives it the "stainless" effect. Stainless steels are a very large family of alloys which have differing

resistances to corrosion, fatigue, creep and stress. The description following is extremely general and does not describe a particular best stainless steel for this role given that this analysis would be beyond the scope of this paper. Given enough time or exposure to moisture, heat and chemicals stainless steel can tarnish and lose its lustre. The chromium-oxide coating the substrate provides a tough protective layer which resists corrosion, leading to its extensive use from everyday cutlery to rockets. Stainless steel however suffers from pitting corrosion, a localised corrosion which attacks in the form of pits in the metal due to the coating acting as a cathode and the substrate as an anode, allowing oxidation to occur even without a source of oxygen when exposed to chlorides such as those in salt in gaps in the coating. This type of corrosion is extremely insidious as whilst it appears to remove very little material at the surface it penetrates deep into the substrate causing deep damage. As this is a natural rust of the material there is no need to prepare the surface to achieve the protective capabilities however it is often polished to achieve the shine stainless steel is known for.

The coatings created by these materials are not entirely sufficient to cover the requirements discussed as road salt is unavoidable during the winter season for exposed parts and the salt content in the air around coastal locations cannot be avoided for the whole system. It is possible to regularly clean the materials, reducing the rate at which the substrate will corrode however this can also have an inverse effect of removing the protective oxide layer. It is worth noting that some people find the shiny stainless steel effect, when not tarnished, to be desirable and so may choose not to coat the outside of their exhaust systems at the cost of more maintenance. In order to achieve less maintenance, economic value and longevity of the components a different coating must be applied to the material.

3 Coatings

During World War Two the possibility of material shortages for alloys and so in order to alleviate this issue they turned to ceramic coatings for high-temperature protection of steel. This work, begun in 1942, required the coating to be thin, to reduce weight and chance of cracking, to protect against oxidation when operating at high temperatures and to have high resistance to thermal-shock and temperature gradients [4]. They eventually decided on an alumina coating based ceramic coating due to its corrosion resistance, low weight and capability to operate at high temperature. All these properties, as discussed earlier are desirable to protect the exhaust system, and it was specifically used on exhaust manifolds. In order to coat these components the metal must first be prepared by removing all grease and cleaning the component in a 3 percent solution of nickel-ammonium sulfate heated to 160 degrees Fahrenheit or 71 degrees Celsius for 15 minutes. These ceramic coatings could be applied externally via spraying however internal application required the component be dipped. The component must then be fired in order to cure the coating. Since this period ceramic paints have been further developed to provide stronger protection, higher durability and increased performance boosts compared to early developments allowing manufacturers to improve the quality of parts with relative ease. Spraying is not the only method to apply these coatings with different methods providing their own benefits. Such as plasma transferred wire arc coating [5], this method can provide a coating which protects against thermal fatigue and corrosion and lower heat loss[6] however it is expensive and leaves a rough texture some wouldn't find aesthetically pleasing.

Ceramic paint technologies have further been developed to where a consumer can go into any automotive store and purchase either a can or spray can of high-temperature exhaust paint [7], in a variety of colours to apply this protection wherein the coating can self-cure with no need for an industrial oven. The metal surface must still be prepared and cleaned prior to application so as to not trap pollutants beneath the protective layer. This paint is often of a lower durability and has lesser effects on the performance of a part.

Another method of coating, done mostly for aesthetic purposes is the chroming of exhaust pipes. Much like stainless steel this chromium layer generates chromium-oxide when it reacts with oxygen in the atmosphere creating a similar protective coating to stainless steel. In order to chrome plate an component it must be submerged in a bath where electrolysis is performed to apply the chromium coating to the surface of the material. Prior to this the material must be sufficiently cleaned so as to not trap contaminants beneath the coating. Hard chroming is a more expensive option which differs from chroming in that it uses a thicker layer of chromium electroplated to the component. This thicker coating provides a much greater wear resistance and corrosion resistance to the pipe [11], however chrome plating comes with its own series of downsides [12]. If the component is not sufficiently cleaned, when the exhaust system is operating at high temperature blistering can occur. This occurs due to gasses trapped between the coating and substrate expanding under heat, eventually forcing the coating and substrate apart and creating a blister on the surface. The high temperature of the exhaust system can cause bluing of the chrome, especially in turns in the pipes where heat builds, this effect is mostly cosmetic. If sufficient damage is sustained to the coating to reveal the substrate layer, much like with stainless steel, pitting can occur quickly and with little sign of it occurring until it has caused major damage.

4 Coating Effectiveness

A coatings effectiveness must be measured by its capability to protect the component from corrosion and oxidation, its ability to resist high temperatures and thermal shock, its durability and its cost.

The field of corrosion testing is large with many different standards for different materials [8], in general to perform a corrosion a component can be submerged in a solution which can accelerate the corrosion process, such as ASTM G48 which is used on stainless steel by putting it in a chloride rich environment. This any substrate to oxidise and can be used to determine the temperature required to initiate pitting. Another test which can be performed is salt spray testing such as ASTM B117 which utilises a 5% salt solution at neutral pH to spray a component for an extended period of time. Parts can be tested in the orientation they will be used in and the spray can be directed at locations most likely to become in contact with pollutants. Finally there are high humidity tests such as ASTM D2247 which places components in a condensing humidity where condensation gathers on the component and corrodes it.

In order to test the suitability for a coatings use in high temperature there are many standards which can be used, I will be describing the method used by ASTM standard D2485-18 [9] which describes two tests, one for interior surfaces and one for exterior surfaces. The interior surfaces test requires at least two panels to be heated up in a muffle furnace for 24hrs at a desired temperature, one component is then plunged into water to rapidly cool it and the other cooled slowly. These panels are then subjected to a bend test to see how the coating has performed. This allows us to see the effect of the material and coating when they undergo rapid changes in temperature, additionally we can observe the effect of continuous exposure to high temperatures on the part. The exterior test requires at least two panels to undergo exposure to temperatures increasing from 205 to 425 degrees Celsius. One panel is then salt sprayed as described above for 24 hours and the other is left outdoors for 12 months. The panels are then examined for degradation of the coating and development of corrosion. Given the accelerating effect temperature has on corrosion it is important to be able to see what effect this increased temperature has on the part.

The durability of a coating can be tested through analysing their chipping resistance such as described by ASTM standard D3170/D3170M-14 [10] where road gravel is projected at the coated component through the means of a controlled air burst. This allows the tester to simulate gravel kicking up at the coating from the road at speeds the vehicle is most likely to experience. Tape is then applied to the area which has been in contact with the gravel and is then removed in order to remove any loose coating chips and the degree of chipping is determined. As described above a salt spray test can also be used as a measure of durability as it allows us to see any degradation of the coating over time.

As discussed previously coatings can be necessary to protect from necessary to protect corrosion and oxidation induced by its environment however it is worth noting that in dry climates there is little need to protect against something which, due to lack of water in the air, is unlikely to occur. In places like these it is still wise to internally coat an exhaust system to protect about against contaminants in the combustion products however either of the bare metals discussed previously would be suitable, with stainless steel being a better choice to the toughness the chromium-oxide layer provides over the mild carbon-steel. On the reverse coatings become ever more important in more humid, wet environments where water is better able to come into contact with the materials at hand. This becomes especially important for coastal areas where the salt in the air provides the chlorides necessary to anodise the substrate, causing the oxidation of the substrate even without oxygen.

5 Analysis of a failed exhaust system

In order to analyse the value of coatings I will be using an the old exhaust system from a 2019 Honda MSX125 which has fractured, likely due to temperature, corrosion and fatigue. The exhaust system was in use on the motorcycle for three and a half years and the motorcycle has been used in all weather conditions, mostly away from coastal areas, in a temperate environment and both on and off-road. The exhaust system has been externally coated with a high temperature ceramic paint. The exhaust system is attached to the motorcycle via three bolts, two connecting to the engine housing and one on the muffler connecting to the frame of the bike. Figure 1 shows the exhaust system as a whole piece.



Figure 1: 2019 MSX 125 exhaust system

Due to temperature, corrosion and fatigue a crack developed in the exhaust header, just before the catalytic converter which eventually led to catastrophic failure of the exhaust system, detaching the catalytic convert and muffler from the header.

Figure 2 shows how the protective coating has clearly been compromised on both the header pipe and the catalytic converter. The corrosion near the sharp turns in the components and on the header pipe itself are likely to have occurred due to extreme heat build up in these areas compared to other sections, however it could also be because these are the most exposed sections. Additionally rust is also prevalent around the welds in the catalytic converter, this is likely due to imperfections in the metal causing the coating to no apply as well to these areas. By cleaning off the red rust and whats left of the coating we can also see signs of pitting occurring in these areas, as shown in Figure 3.



Figure 2: Catalytic converter and broken header pipe.



Figure 3: Cleaned steel with pits of dark rust embedded

Figure 4 shows the cross section of the pipe and the internal coating of the pipe. We can see from this that corrosion penetrated fully through the walls of the pipe in this section, compromising the integrity of pipe such that, under normal operating procedure it could no longer sustain the weight of the catalytic convert and fractured. In order to inspect the condition of the internal coating the interior has been cleaned however there is still a large build up of soot deep in the pipe. No signs of corrosion has been found in the interior of the header pipe suggesting that the internal coating as outperformed the exterior coating. This is to be expected as the internal coating is not attacked as often physically or has as much exposure to oxidation. The internal layer of soot may also serve to protect the interior from contaminants in the fuel. It is however possible that the crack was formed purely due to fatigue in the metal and it later rusted prior to the failure.



Figure 4: Cross section of the header pipe

This particular exhaust shows that even with ceramic coatings if the exhaust system experiences an environment that can cause damage to the coating and substrate it is important to perform the rudimentary maintenance of cleaning exposed areas and reapplying the coating so as to prolong the lifetime of the part. From an economic standpoint a new stock exhaust system costs over £350 [11] which, compared to the cost of cleaning the motorcycle regularly and applying a coat of high-temperature exhaust paint annually, is significantly more expensive.

Under similar circumstances of exposure to oxidising contaminants it is unlikely another method of coating would have protected the component for as long, given that the paint does not itself participate in the oxidising reaction. However it does serve to demonstrate that the needs of a coating is highly dependent on how and where a vehicle is used.

6 Conclusion

From this analysis it is clear that it is necessary that the substrate and coating of the exhaust system of a vehicle cannot only be resistant to the high operating temperatures causing fatigue but are indispensable for prolonged use of a component. The coating chosen must factor the external environment of the vehicle into the decision of what coating to choose, with different coatings providing trade-offs in exchange for different protections. From my findings a ceramic coating is likely the best choice from a corrosion resistance and performance standpoint, additionally it comes in many colours and allows choices between matte and glossy finishes. However it can be prone to chipping should it be attacked. A higher quality ceramic is more expensive and can resolve this issue but it is much cheaper to simply reapply the coating with a store-bought can of high-temperature paint. Aesthetically speaking there are many who prefer chromed exhausts, which if hard chroming is used, can be a tough, corrosion-resistant option, however it provides little performance enhancement and under high-temperature operation can become blued.

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