T he coincidence between hard surface treatments and failure by fatigue is well known, particularly in critically loaded components such as aircraft undercarriage components, high strength steel ropes and high pressure gas compression systems. In such applications, where failure can have disastrous consequences, the use of chromium plating as a surface treatment should be considered only with extreme caution.

Similar problems can arise with hot dip galvanised coatings, where a hard inter-metallic layer can be formed at the coating-substrate interface.

**Case 1: Failure of a hard chrome plated aircraft component**

This case concerned the nose wheel assembly on a commercial airliner, which unfortunately failed during low speed taxiing, resulting in one of the two nose gear wheels, together with its axle and bearings, becoming detached. The failure was observed by ground personnel and the aircraft returned to the ramp without further damage.

When examined, the failure was clearly initiated by a fatigue crack with multiple initiation points, (Figures 1 and 2). When examined metallographically, cracking in the chrome-plated layer was clearly visible (Figure 3) and in several locations, this cracking had propagated into the substrate. The substrate was, not surprisingly given the application, a very high strength alloy steel material with a tensile strength of about 2 100 MPa. This material has very little tolerance for notches of any kind, and sharp pointed cracks of the form observed are extremely problematic.

It was noted that while every crack in the substrate was associated with a crack in the plated layer, the converse did not apply and many cracks in the plated layer had not propagated into the substrate.

Hard chromium plating is applied to give a hard, wear resistant surface and is generally thicker – between 2.5 μm and 500 μm – than decorative chromium plating, which is usually around 1.5 μm thick. Hard chromium plating is also often used to restore a worn surface back to the dimensional tolerances during return to service operations. It is, however, known that the application of chromium plating to high strength materials can reduce the material’s fatigue life by up to 40% [1].

The consequences of failure of an aircraft undercarriage leg or axle, which will most probably occur during landing when the loadings are greatest, will almost certainly result in severe and expensive damage to the aircraft hull.
and a high probability of injury or loss of life. In addition, the probability that the aircraft will block the runway is high, which would result in a loss of airport handling capacity until the aircraft is recovered and the runway cleared. The combined consequences involve significant costs, time and manpower. Similar problems can be expected with the failure of, for example, a high-pressure gas compressor if the piston rod fails, particularly if the gas being compressed is toxic or flammable.

As deposited, thick layers of chromium are under tensile loading, resulting in the plated layer cracking to relieve these stresses. These cracks end at the plate/substrate interface, resulting in the formation of a severe stress concentration at that interface. Hard chromium plating, applied for wear and corrosion resistance, is applied directly to the material surface and does not employ any intermediate layer of copper or nickel, as is the case with the much thinner ‘decorative’ chromium plate. Such a soft inter-layer would have the effect of acting as a crack inhibitor, deflecting the propagating crack along the interface, but would effectively negate the anti-wear properties of the layer by allowing the chromium layer to deflect under load, resulting in spalling.

Two further problems may arise, these being hydrogen embrittlement and grinding abuse of the substrate beneath the plated layer. Electroplating of chromium is associated with a high hydrogen over-voltage, meaning that hydrogen embrittlement is a very real probability and de-embrittlement by heat treatment can be very difficult for ultra high strength materials, where the temperature needed for adequate de-embrittlement can exceed the tempering temperature of the material. De-embrittlement is also difficult when the chromium layer is thick, because of the layer’s tendency to obstruct the passage of hydrogen to the surface. Under these circumstances, effective de-embrittlement may not be possible and limitations on the number of times a component may be re-plated for repairs may be imposed.

The plated surface will almost certainly be ground to attain the required dimensions and it is possible for over-temperature exposure to the substrate during grinding to occur. The conventional method of inspecting for grinding abuse is by Nital etching [2] but this cannot be carried out with the plated layer present. It is possible to detect grinding abuse under chromium plating by using the Barkhausen Noise technique, but this requires both highly specialised equipment and highly trained personnel to interpret the results. It is thus essentially a laboratory technique that is yet to be developed into a practical technology for production use.

While grinding abuse was not detected in this case, at least one grinding abuse failure is known to the author, in which the aircraft was effectively destroyed and the pilot only escaped serious injury by using his ejection seat.

Case 2: Failure of a mine winding rope

Mine winding ropes, employed in the deep level gold mining industry for hoisting ore to the surface and for conveying both men and materials to underground workfaces, are subject to highly corrosive conditions through exposure to water that, with an acidic pH of between 4 and 5 or worse, can be very aggressive. To reduce corrosion and thus extend the life of the rope, it is often manufactured from wire that has been rendered more resistant to corrosion by hot-dip galvanising prior to the final draw pass and laying up of the rope.

The rope in this case study had been taken out of service prematurely when numerous broken wires were detected during routine inspection (Figure 4). It was reported that a second rope within the same shaft had been rejected a few
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weeks previously for the same reason. Both ropes were of the same construction and material and were supplied from the same source.

The material of construction was a high carbon steel (0.85 to 0.90% C) without significant alloying additions other than manganese. The specified minimum tensile strength was 1 770 MPa and the actual measured value was 1 873 MPa, with acceptable ductility as measured by torsion and bend testing, which is conventional for testing wires from ropes.

When examined, it was found that the galvanised layer included a δ-layer of significant thickness, (Figure 5), which was extensively shattered, (Figure 6). It is considered probable that this shattering had occurred during the final draw pass after galvanising. The cracking had, in some cases, propagated into the substrate, (Figures 7), initiating fatigue failure of the wire.

Hot-dip galvanising is a coating of zinc applied by immersing a steel component in a bath of molten zinc at about 450 °C. The zinc layer is metallurgically bonded to the surface through the formation of an alloy layer. The alloy layer of the zinc coating – typically consisting of a 7-11% iron as an FeZn alloy – is commonly called the delta-layer (δ-layer) and is an intermetallic compound that is known to be of relatively high hardness, generally of the order of 250 to 300 HV, with poor ductility.

Formation of the δ-layer is dependent on several factors, including the temperature of the galvanising bath, where an increase in temperature of as little as 10-20 °C will result in a greatly increased coating thickness build-up and an associated increase in the thickness of the δ-layer. Similarly, the duration of the galvanising process and the chemical composition of the substrate will affect the rate of zinc deposition and will give thicker coatings and thicker δ-layers. The principal elements affecting δ-layer formation are silicon and phosphorus, with recommended maxima of 0.12% and 0.010% respectively, [3]. The levels of these two elements in this case study, being 0.20% Si and 0.024% P, were found to be excessive and will have contributed to the formation of the thick δ-layer observed. The effects of cracking of this layer of a galvanised coating will have contributed to a reduction in fatigue strength, particularly because of the high strength of the base material, [4].

In addition, the thickness of the galvanised zinc layer, measured at about 35.5 μm, is considered to be much thicker than would normally be expected, a coating thickness of about 15-20 μm would be considered normal for this application. This suggests that the temperature at which galvanising was carried out was too high. An increase of 10-20 °C above the normal bath temperature can give a dramatic increase in coating thickness and δ-layer formation. The higher than optimal levels of silicon and phosphorus would also have contributed to the thicker than expected coating.

As was the case with chromium plating, while the presence of a crack in the substrate was invariably associated with the presence of a crack in the δ-layer, the converse was not true. Many instances of cracking of the δ-layer did not propagate.

In both of these cases, the fatigue life of the component was adversely affected by the application of a surface coating, and led to failure. It is of interest to note that the reduction in fatigue life is very similar for two very different coatings, indicating that the effect is a function of the notch sensitivity of the substrate rather than of the nature of the coating.

Conclusions

In the two cases examined here both, fortunately, occurred without injury, loss of life or serious damage to property. But neither aircraft landing gear nor winding ropes can be considered inexpensive. It could, however, have been very different.

So, before hard-chrome plating or hot-dip galvanising a fatigue sensitive, critical, high strength part, it is essential that a thorough analysis is done to ensure that the coating does not compromise the component integrity.

References