1. **INTRODUCTION**

A. After an uneventful landing, the crew of the subject aircraft reported a sudden drag load, whilst performing the final taxi turn onto stand. Subsequent walk round inspection showed that the number 15 wheel (figure [1]) was at an abnormal angle (figure [2]). Closer examination revealed that the axle had fractured just inside the truck bushing (figures [3] to 5). This test was requested to determine the cause of failure.

B. The subject axle had entered service as original fit to a particular aircraft, on delivery to the airline. After 3,701 landings in 7.5 years of service, it was removed from the aircraft for routine overhaul. After a full overhaul, in accordance with the manufacturer's manuals, it re-entered service on a different aircraft. At the time of failure, it had endured 2 landings / 11 flight hours on that aircraft, since overhaul. It is estimated that the weight of the aircraft had been on the landing gear for a cumulative total of 3-4 days since the overhaul had taken place.
2. **WORK CARRIED OUT**

A. **Visual Examination**

(1) A preliminary examination was performed on the entire truck assembly, minus the wheels and brakes. The brake sleeve was then removed from the inboard portion of the fractured axle and the fractured end was sectioned from the remainder, to facilitate more detailed examination. The fracture surface was then examined at magnifications up to x50, using a stereomicroscope.

B. **Fractography**

(1) The area identified as the origin of the fracture was sectioned from the remainder of the fracture surface. It was then ultrasonically cleaned in acetone, prior to examination in a scanning electron microscope, at magnifications up to x5000.

C. **Hardness Testing**

(1) Hardness readings were taken on the outer diameter of the axle, at locations both close to and remote from the fracture origin. This was performed with the chromium plating in place, using the superficial Rockwell 15N scale. It was then repeated, using the Rockwell C scale, after the plating had been electrolytically removed.

D. **Surface Temper Etch Inspection**

(1) Once the chromium plating had been removed, a region of the outer diameter of the axle, adjacent to the fracture origin, was subjected to surface temper etch
inspection. This was performed using a 10% w/v solution of ammonium persulphate.

E. **Magnetic Particle Inspection (MPI)**

(1) With the chromium plating removed, the fractured end of the axle was subjected to magnetic particle inspection, for the purpose of crack detection.

F. **Metallography**

(1) Cross sections were taken at several locations through the region of fracture origin. These sections were prepared for examination using contemporary metallographic techniques. The prepared samples were examined at magnifications up to x500, using a metallographic microscope. This was performed both before and after etching with 2% nital.

3. **RESULTS**

A. **Visual Examination**

(1) The fracture had occurred approximately 1in (25mm) inboard of the brake axle sleeve flange (figures 3-5). The primary plane of fracture was approximately normal to the major axis of the axle. The fracture surface was predominantly clean and free of oxidation. Some minor post-fracture damage was evident at the 9 o’clock* position but otherwise, the fracture surface was in good condition.

---

* The “o’clock” positions described refer to the orientation of the axle, as it was fitted to the truck.
(2) Radial marks present on the fracture surface indicated that the fracture had initiated at the 6 o’clock* position (figure 8). Closer examination of this region indicated that crack initiation had occurred at multiple sites on the outer diameter of the axle (figure 9 and 10). Traces of oxidation products were present at the initiation sites. The numerous, incipient cracks had coalesced after a short distance, to form four primary crack fronts, separated by ridges on the fracture surface. These were evident as thumbnail shaped regions with a markedly coarser texture than the remainder. The above fracture morphology was consistent with stress corrosion crack initiation and growth, leading to final, overload fracture.

(3) A spiral pattern was evident on the chromium plated outer diameter of the axle. This was consistent with abusive grinding of the chromium plating.

B. Fractography

(1) Within the thumbnail shaped regions detailed at 3.A.(2) above, the fracture was brittle and intergranular, consistent with stress corrosion cracking (figure 11). However, there was no evidence of corrosive attack or oxidation products on the majority of the surface.

(2) Remote from the thumbnail shaped regions, the fracture mode was ductile separation, by microvoid coalescence, characteristic of static overloading (figure 12).

C. Hardness Testing

(1) There were randomly located variations in the hardness of the chromium plating within the range 89-91HR15N, which approximates to 57-62HRC. The minimum hardness specified for this type of plating was 55HRC.

* The “o’clock” positions described refer to the orientation of the axle, as it was fitted to the truck.
(2) With the plating removed, the hardness of the parent alloy was measured to be 55HRC, which approximates to an ultimate tensile strength (UTS) of 300ksi (2,068MPa). The specified UTS for the axle was 275-300ksi (1,896-2,068MPa).

D. **Surface Temper Etch Inspection**

(1) Several dark bands of overtempered martensite were present on the outer diameter of the axle, adjacent to the fracture surface (figure 13). These dark bands appeared to be coincident with the spiral pattern observed on the chromium plating (3.A.(3), above). This was consistent with abusive grinding of the plated diameter.

E. **Magnetic Particle Inspection**

(1) A network of numerous, fine cracks was present on the outer diameter of the axle, adjacent to the fracture. The location of the cracked regions was coincident with the dark bands of overtempered martensite detailed at 3.D.(1), above.

F. **Metallography**

(1) The fracture path within the initiation region was confirmed as intergranular, consistent with stress corrosion cracking.

(2) Numerous secondary cracks were present on the outer diameter, adjacent and extending parallel to the fracture surface (figures 14 and 15). They appeared to be intergranular in nature and were 0.004-0.005in (0.10-0.13mm) in depth.
(3) The microstructure of the initiation region was found to be tempered martensite (figure 15), consistent with 4340M steel, heat treated to 275-300ksi (1,896-2,068MPa).

(4) The etch indications detailed at 3.D.(1) above, could not be detected in depth, indicating that they were a surface specific condition.

4. DISCUSSION

A. The axle base alloy was AISI 4340M high strength, low alloy (HSLA) steel, heat treated to a UTS of 275-300ksi (1,896-2,068MPa). To attain this strength level, the axle would have been subjected to a three stage heat treatment process during manufacture.

(1) **Hardening / Austenitising**: The part is heated and held for a period of around 30 minutes at a temperature of 1,575-1,625°F (860-885)°C. This causes the microstructure of the alloy to change entirely to a crystal structure, known as “austenite”.

(2) **Quenching**: The part is cooled rapidly from the austenitising temperature. This is often achieved by immersion in oil held at room temperature. Such rapid cooling is necessary to form a crystal structure known as “martensite”, which has very high strength and hardness but is also very brittle.

(3) **Tempering**: The part is heated for 2 hours at a temperature of 575°F (300°C) and air cooled to room temperature. This process is performed twice. Tempering relieves some of the brittleness of untempered martensite but also causes a slight reduction in strength. This is the finished condition for the part.

B. Improper maintenance practices can also cause heating of the part to temperatures, which can cause microstructural changes of the type detailed at 4.A. above. In the case of abusive grinding, excessive feed rate of the part, speed of the grinding wheel or
insufficient coolant can result in local heating of the surface of the part. If the maximum temperature attained lies between that used for tempering (575°F (300°C)) and that used for austenitising (1,575°F (860°C)), then a condition known as “overtempered martensite” (OTM) will be formed at the surface. The presence of OTM results in a local reduction in tensile strength. More importantly, the very high temperature gradients which occur during its formation can result in high levels of residual stress within the affected areas. In some cases, the magnitude of these stresses may be high enough to cause surface cracking.

C. On the subject axle, the spiral pattern on the chromium plating (3.A.(3)), presence of bands of overtempered martensite (3.D.(1)) and associated cracking (3.E.(1)) are all typical of abusive grinding of the chromium plated outer diameter of the axle. This indicates that the grinding wheel feeds / speeds used in this operation were excessive, causing significant, momentary heating of the surface of the axle, as detailed at 4.A. and B. above.

D. During the routine overhaul, operations were undertaken to remove corrosion from the outer diameter of the axle. These operations are summarised in figure 16. The abusive grinding and introduction of an array of associated small cracks in the outer diameter would have occurred during operation 12. The subsequent MPI operation (14) was not able to detect these cracks through the chromium plating. However, the spiral pattern visible on the ground surface (3.A.(3)), should have been sufficient reason to strip the chromium plating and perform surface temper etch and magnetic particle inspection of the base alloy.

E. Cadmium plating (figure 16, operation 13) was performed after the cracks had been introduced into the outer diameter of the axle, at operation 12. As a result, aggressive cleaning and plating chemicals were able to enter into the cracks. Post plate baking would have evaporated off any liquid, leaving solid chemical residues within the grinding cracks. When the axle re-entered service, atmospheric moisture was able to enter the cracks, allowing the chemical residues to go back into solution.
F. The normal operating stress in the axle, imposed by the weight of the aircraft on the wheels, was concentrated by the presence of the grinding cracks. This, coupled with the aggressive chemical environment within the cracks, resulted in an extremely rapid rate of stress corrosion crack (SCC) growth. The abnormally high rate of growth explains the general lack of oxidation products on this portion of the fracture surface. Once the SCC cracks had penetrated to a depth of approximately 0.47in (12mm), the stress concentration associated with them became sufficient to cause catastrophic fracture of the axle, in static overload.

5. CONCLUSIONS

A. The fracture of the subject axle was initiated by grinding cracks, introduced during an abusive grinding operation of its chromium plated outer diameter. This operation was performed during the most recent overhaul of the axle.

B. Once the axle re-entered service after overhaul, stress corrosion cracks propagated from the grinding cracks detailed above, as a result of the conjoint action of:

(1) Normal operating stresses imposed by the weight of the aircraft on the wheels.

(2) The stress concentration associated with the presence of the grinding cracks.

(3) The presence of aggressive cleaning / plating chemical residues within the cracks.

C. Factors 5.B.(2) and (3) above, resulted in an unusually high rate of SCC growth. After a cumulative period of only 3-4 days with the weight of the aircraft on the landing gear, the stress concentration associated with the advancing stress corrosion cracks reached a critical value. At this point the axle underwent catastrophic fracture in static overload.
Figure 1 - Wheel numbering diagram, showing the no.15 wheel in red.

Figure 2 - Aft view of the starboard WLG, after arrival on stand. The no. 15 wheel was at an abnormal angle, due to failure of the axle.
Figure 3 - Close view of the fracture location.

Figure 4 - Truck assembly, after removal from the aircraft.
Figure 5 - Closer view than figure 4 above, showing the fracture location approximately 1-2 inches outboard of the edge of the truck / axle bush.

Figure 6 - Inboard portion of the fractured axle, after removal of the wheel and brake assembly.
Figure 7 - Inboard portion of the fractured axle, after removal of the wheel and brake assembly.

Figure 8 - Fracture surface, after removal from the inboard portion of the axle. At least four stress corrosion crack (SCC) fronts were present, penetrating up to 0.47in (12mm) inwards from the outer diameter. The stress concentration associated with these crack fronts initiated overload fracture, which travelled in both directions around the axle. Final separation occurred diametrically opposite the SCC crack fronts.
Figure 9 - Close view of the initiation region. Stress corrosion crack initiation occurred from multiple sites on the outer diameter. A number of minor cracks had coalesced, to form four primary crack fronts. Ultimate coalescence of the four primary crack fronts resulted in catastrophic failure (see also figure 8).

Figure 10 - Close view of the region shown in figure 9. Stress corrosion crack initiation occurred from multiple sites at the outer diameter. Note the markedly coarser texture in the region of sub-critical, stress corrosion crack growth, compared with that of final, catastrophic failure.
Figure 11 - Close view of the approximate point indicated in figure 10. Brittle, intergranular fracture, consistent with stress corrosion cracking. However, note the general absence of oxidation products (secondary electron image).

Figure 12 - Close view of the approximate point indicated in figure 10. Ductile separation by microvoid coalescence, consistent with static overload fracture (secondary electron image).
Figure 13 - View on the region of the outer diameter shown in figure 9 after removal of the chromium plating and surface temper etch inspection. Shows several dark bands of overtempered martensite, an indication of abusive grinding.

Figure 14 - Section through the outer diameter, adjacent to the initiation region, as polished, x500. Shows a secondary stress corrosion crack, approximately 0.004in (0.1mm) deep.
Figure 15 - Section through the outer diameter, adjacent to the initiation region, etched, x500. Shows a secondary stress corrosion crack, approximately 0.004in (0.1mm) deep. The microstructure was tempered martensite, consistent with 4340M steel at 275-300ksi (1,897-2,968MPa).
Figure 16 - Summary of the corrosion removal processes specified in the Component Maintenance Manual for the landing gear.