INVESTIGATION OF SHIMANO CRANKSET FAILURES

Introduction

Two Shimano Crankset failures were investigated.

Failure 1: Bending of the Crank Arm (Figure 1)

Failure 2: Complete fracture of the Crank Arm (Figure 2)

Figure 1:

Appearance of Failure 1. Crank arm has been partly sectioned in preparation for investigation, but bending of inner/upper channel section is clear.

Figure 2:

Failure 2 indicating complete fracture of crank arm

The investigation involved:

- Carrying out a Vickers hardness test on a section of the crank arm (to determine the approximate strength of the material).
- Making general visual observations of the failures.
- Using the scanning electron microscope (SEM) to determine the approximate composition and grade of material.
- Examining the fractured crank arm in a SEM to identify the possible cause of Failure 2.

Vickers Hardness

Vickers hardness was carried out on a flat and polished section of the crankshaft arm using a 10 kg load. The measured Vickers Hardness was approximately 110 HV. A generally accepted empirical equation can be used to relate the Vickers Hardness to the Yield Strength of the material.

Vickers Hardness (in N/mm^2) = 3 x Yield Strength (in N/mm^2)

Vickers Hardness Number has units of kgf/mm^2. Therefore, the Vickers Hardness Number needs to be multiplied by 9.8 to convert its units to N/mm^2

Thus, Yield Strength is approximately 360 N/mm^2 (360 MN/m^2)

General Observations of the Failures

The Shimano crank arm has a hollow construction. It consists of two U-shaped channels interlinked to form a rectangular cross-sectioned tube as indicated in Figure 3. Investigation show that the two channels are adhered together to form the tube.

Figure 3:

The rectangular tube section comprised of two interlinked U-shaped channels

In Failure 1 (Figure 1) the inner U-shaped channel was bent inwards separating it from the outer U-shaped channel. The bending deformation caused the widespread separation of the inner and outer U-shaped channels along most of their length, in addition to some distortion (twisting) of the channel sections as seen in the cross-sectional view of Figure 4. Adhesive remains attached to the inside surface of the outer channel only (Figure 5). This indicates that during final failure the fracture path followed the interface between the adhesive and the metal substrate. No evidence of corrosion was found in the area of separation on either the inner or outer channel.

Figure 4:

Bending of the crank arm resulted in some distortion (twisting) of the component channels as clear on this cross-sectional view.

Figure 5:

Outer (undeformed) channel still retains strips of black adhesive after the failure and its separation from the inner channel.

The bending of the inner channel involved significant plastic deformation. The energy to accomplish this is far greater than that required to separate the adhered surfaces. That being so, it seems likely that the greater part of the inner and outer channel separation occurred through the bonded interface being "unzipped" during the bending of the inner channel. However, it was notable that the outer channel remained undeformed during this failure process. The indication, therefore, is that the full rectangular-box section of the crank arm is strong enough to resist deformation during normal loading conditions, and that plastic deformation of the inner U-channel can only occur if it first of all becomes detached from the outer channel along at least part of the bonded length. That is to say, that if the inner and outer channels become separated along part of their length the overall structure is weakened. The inner channel is then vulnerable to bending failure under subsequent loading which will cause it to separate further from the outer channel in the manner observed.

This assumption was tested by carrying out an approximate mathematical analysis (see Appendix 1)

The analysis, crude as it is, indicates that a mass of 43 kg could have been sufficient to cause bending failure of the upper/inner channel, if it had first been partially separated from the outer channel.

By contrast a mass of around 224 kg would be necessary to cause plastic deformation of the full as-bonded tubular cross-section.

It can therefore be concluded that the full tubular section was robust enough to resist deformation. However, in the event that the two bonded channels were to partially separate then the crank arm is significantly weakened, and the bending stresses increased over that length. Over time this could lead to a lengthening of the debonded "crack" length, such that at a critical crack length the applied bending stresses reach a magnitude sufficient to cause plastic deformation and bending of the inner channel. This failure might well occur suddenly and without warning and result in widespread "unzipping" of the inner and outer channels and the complete failure (as observed) of the crank arm. The analysis indicates that this would be possible at relatively low loads that might easily be applied during normal cycling conditions. These low loads could easily cause bending of the upper/inner channel and wide separation of the two component channels as they were torn apart.

Thus, it is suggested that the first stage in the failure process is part failure of the adhesive bond between the two channels. Unfortunately, a more complete investigation would be necessary to determine the cause of the failure. It may be that there are issues with the manufacturing process. There are several possibilities here, from lack of care in the preparation of the mating surfaces to poor mixing of the adhesive. Poor manufacturing and assembly practices could lead to the presence of defects in the adhesive bonds which could act as sources of weakness.

Other possible explanations involve environmental factors during service. Corrosion of the metal substrate can weaken adhesive bonds, although none was in evidence on the parts examined. Adhesives are also known to undergo environmental degradation when exposed to moisture. The hydrolysis reaction that the adhesive undergoes may weaken the interface between adhesive and substrate.

Finally, the variable loads placed on the crank arm during service could possibly lead to fatigue failure of the adhesive bond.

Both environmental degradation and fatigue are time dependent mechanisms. Through both these mechanisms it is possible that the length of the debonded section of the crank arm increased gradually with time until the applied load was sufficient to cause sudden catastrophic failure. I have been given no information on the service history of the failed part and its lifespan and am therefore not sure how much use it had undergone before failure occurred.

Scanning Electron Microscope (SEM) Analysis of Failed Part

X-Ray Analysis

During SEM observation the material surface is bombarded with an intense electron beam. As a consequence, X-rays are given off from the material and the energy of these are characteristic of its composition. To get a precise analysis, careful calibration is necessary. This was not done in the present study, but an estimate of the composition was obtained that was deemed sufficient for our purposes.

Indicated composition:

Aluminium: Balance

Silicon: 7%

Magnesium: 0.29%

This composition indicates an Al-Si-Mg casting alloy. Grade LM 29 has a composition similar to this, and with a yield strength compatible with that found from the Vickers Hardness measurement.

SEM analysis of the Fractured Crank Arm (Failure 2)

The second crank arm failure that was investigated had suffered complete fracture.

Visual examination of the failed inner channel indicated what appeared to be a flaw at the tip of one of the arms of the channel. This was examined further by SEM. Investigation revealed a semi-"elliptical" corner crack (Figure 6) with a major length of around 4.5 mm and a depth of around 1.5 mm (see figure). There was some evidence of what appeared to be fatigue striations on the surface of the elliptical crack, typical of a fatigue failure (Figure 7). Unfortunately, this was inconclusive, as there was also some damage to this surface, which may have occurred during or post-fracture, that partially obscured the features present. It is also possible that the crack was a casting defect. Such casting defects are common at sharp corners and can occur for a variety of reasons.

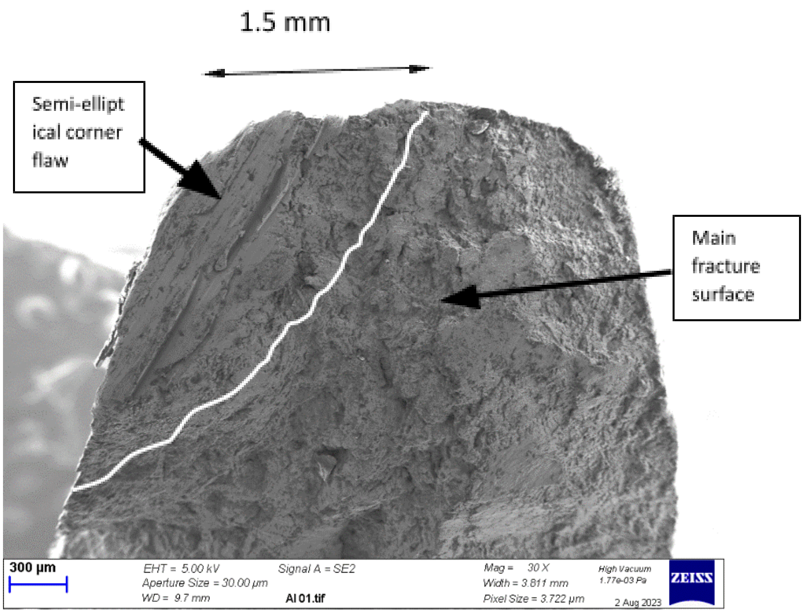


Figure 6:

Semi-elliptical flaw at the corner of one of the arms of the upper U-shaped channel (SEM photo)

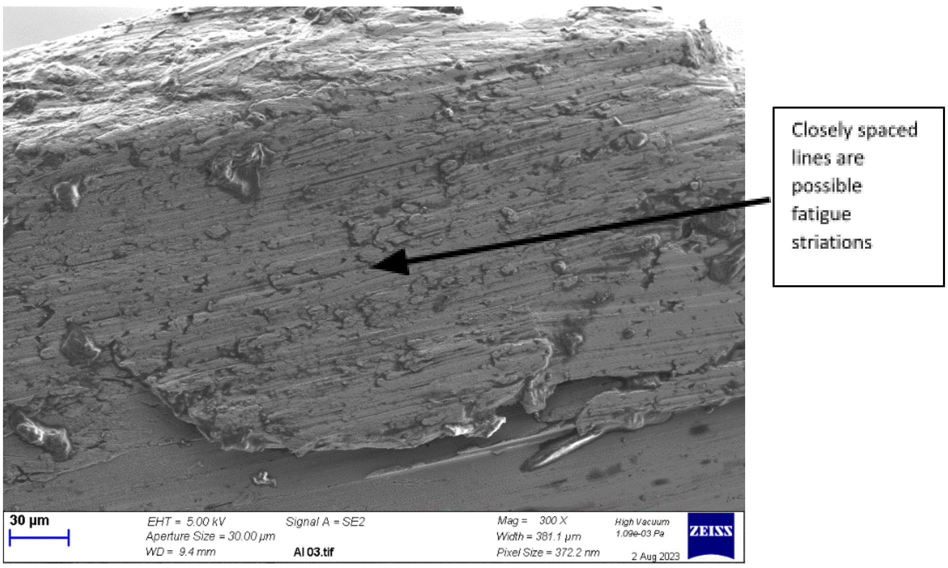


Figure 7:

Possible fatigue striations on surface of flaw

Whatever the source of the flaw it is undoubtedly the reason for the failure of the part. The remainder of the fracture surface has features typical of a failed aluminium alloy.

In Appendix 2 an analysis of the magnitude of stress responsible for the failure is carried out. The analysis is compromised by a lack of precise knowledge of the fracture toughness of the material.

Data books showed that toughness could be in the range 20-40 $MN/m^{3/2}$ depending on the specifics of the casting process and subsequent heat treatment.

A toughness at the bottom end of this range suggested a failure stress of around 310 N/mm^2, compatible with the types of tensile stresses that our previous analysis suggested was easily generated by bending loads under normal cycling conditions if debonding of the inner and outer channels had occurred. It is however unlikely that failure would have occurred in a fully bonded section of the crank arm.

Overall Conclusions

In both crank arm failures, it can be concluded that an essential preliminary stage in the failure is the partial debonding of the inner and outer U-shaped channels that together make up the rectangular tube section of the crank arm. When satisfactorily bonded the section is of adequate strength to resist any loads that it commonly sees. However, if partial debonding occurs between the parts the upper/inner channel is vulnerable to the size of loads that may commonly be applied during use.

No conclusions were possible as to how debonding between the two U-shaped channels initiated. Flaws resulting from the manufacturing process, environmental deterioration and fatigue were all considered as possibilities. Whichever was at fault, such partial debonding of the two channels is a notable weakness that might eventually lead to gross failure.

Any proposed solution to the problem will depend on how frequently failures occur. If rarely, then this might be considered acceptable by the manufacturer. If it is a frequent problem the recall of the product and a redesign will be necessary. The simplest and cheapest solution would be to reinforce the adhesive bonds with mechanical fixings. However, this might not be considered acceptable for aesthetic reasons.

APPENDIX 1

The plastic deformation of the inner channel occurred in bending mode.

The standard bending equation for the generated maximum tensile stresses σ, gives:

$$\sigma = \frac{M.y}{I}$$

Where M is the bending moment, y is the distance between the neutral axis and the outer fibres of the section, and I is the second moment of area of the section.

Let us assume that the maximum stress generated was that sufficient to cause plastic deformation. The hardness measurement indicated a yield strength of 360 N/mm^2. Assume therefore that the maximum stress was that of the yield strength.

Assume that the crank arm is a simple cantilever beam and that the bending moment M = F.L

Here F is the applied force causing bending and L is the length of the crank arm (assume 170 mm)

Taking the inner channel as a simple U-shaped channel of constant wall thickness, t (as indicated in Figure 8)

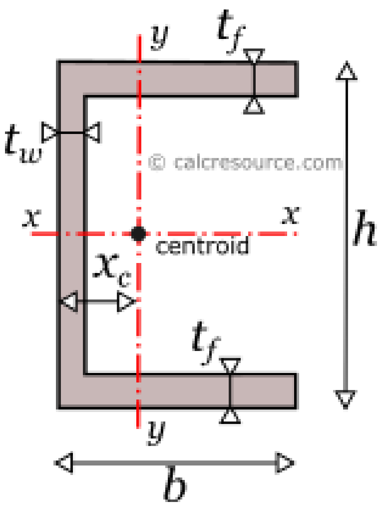


Figure 8:

U-shaped channel used for calculations of second moment of area, I (courtesy of calcresource.com)

Taking (approximate) values for the inner channel, allows the centroid position X_c and the second moment of area I_y to be calculated:

h = 30 mm

b = 12 mm

$t_f = t_w = t = 3$ mm

From this we find:

$X_c = 3.75$ mm

$I_y = 1647$ mm^4

Subsituting into the equation for bending stress gives:

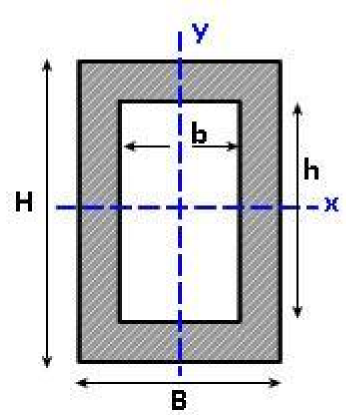
$\sigma = 360\ N/mm^2 = \frac{F(170)(12-3.75)}{1647}$

F = 422.7 N

This can be generated by a “weight” of around 43 kg which is not unreasonable when an adult is cycling.

Compare this now to the full section when the inner and outer channels are bonded strongly together.

This may be approximated to a rectangular hollow box (Figure 9)



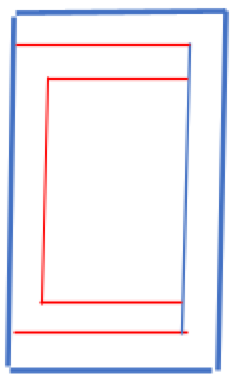


Figure 9

Upper figure shows the rectangular hollow box that the second moment of area calculation is based on.

Lower figure indicates how the crank arm cross-section corresponds to this shape

The second moment of area I_y is given by:

$$HB^3/12 = hb^3/12$$

Where:

H = 36 mm

B = 15 mm

h = 25 mm

b = 9 mm

Giving

I_y = 8606 mm^4

The fully bonded section has a second moment of area to resist bending around 5.2x that of the upper channel alone.

The “weight” required to cause plastic deformation is 5.2 x 43 = 223.6 kg

This load would not be expected to be generated during cycling.

APPENDIX 2

The flaw at the tip of the inner channel (figure xxxx) can be approximated to that of an elliptical corner crack

Stress intensity factor K of elliptical corner crack is given by:

$$K = 1.1\sigma\sqrt{\frac{\pi a}{Q}}$$

Where:

σ = applied stress

a = crack length = 1.5 mm

Q = factor related to crack shape = 1.4

Fast, catastrophic, low energy "brittle" fracture will occur when K = K_{IC}

K_{IC} is the fracture toughness of the material.

Data books indicate that K_{IC} is in between 20 and 40 $MN/m^{3/2}$ for a cast Al-Si-Mg alloy.

If K_{IC} = 20 $MN/m^{3/2}$ then failure occurs at a stress σ = 310 MN/m^2 = 310 N/mm^2

If K_{IC} = 40 $MN/m^{3/2}$ then failure occurs at a stress σ = 620 MN/m^2 = 620 N/mm^2

A stress of 310 N/mm^2 is considered possible during operation of the bike (see Appendix 1). It is a stress below that considered responsible for the bent crank arm (Failure 1)

620 N/mm^2 is above the nominal strength of the material and is therefore not possible.