Case Study: Aluminum Hoist Failure

By

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Opinion

It is my opinion, based on the findings given in this case study, that failure of the aluminum hoist used on this trailer was the result of a significant design error. The patents that this hoist was based on showed a clear lack of understanding of the mechanical and fatigue properties of aluminum alloys, and the comparison with steel alloys.

The manufacturer of the hoist is still in business, but no longer manufactures and markets an aluminum hoist.

Subject

Determination the cause of failure of an aluminum hydraulic hoist on an aluminum trailer which was manufactured in April of 2006. The hydraulic hoist failed on August 4, 2006, while attempting to dump a load of gravel. The failure of the hydraulic hoist was one of the clearest engineering design failures that I have ever examined. The aluminum hydraulic hoist was examined by visual examination, chemical analysis, mechanical testing, scanning electron microscopic examination, and metallographic examination.

Visual Examination

Figure 1 – Trailer, September 2, 2006

Figure 1 shows the condition of the trailer when it was examined on September 2, 2006. The failed hydraulic hoist was in the trailer bed. It had been removed after its failure.

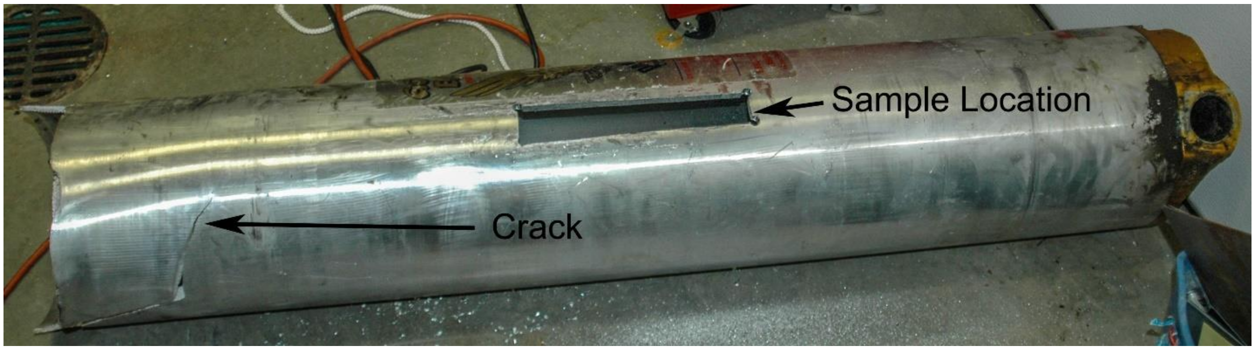

Figure 2 – Failed Aluminum Hoist Outer Cylinder after Test Sample Removal

Figure 2 shows the outer cylinder of the aluminum hoist after the removal of the test sample for chemical analysis and mechanical testing. The crack in the cylinder is also indicated.

Figure 3 – Sheared Threads on Cylinder End Cap

Figure 4 – Failed End of Cylinder

Figure 3 shows the sheared threads on the end cap of the failed cylinder. The end cap was also the reducer for the next stage of the hoist assembly. The threads failed after the start of the failure of the cylinder.

Figure 4 shows the failed end of the hydraulic cylinder. The approximate location of the fracture origin is indicated. The fracture origin was on the top end of the cylinder. It does not appear that side loading was a major factor in the cause of the cylinder failure.

Chemical Analysis

Chemical analysis was done according to ASTM Specification E227. The results of the analysis are given in the table that follows.

Chemical Analysis of Hydraulic Cylinder Material (Percent by Weight)		
Element	Cylinder	Specification
Silicon	0.57	0.40 – 0.80
Copper	0.20	0.15 – 0.40
Magnesium	0.95	0.8 – 1.2
Iron	0.13	0.7 Max.
Titanium	<0.05	0.15 Max.
Zinc	<0.05	0.25 Max.
Manganese	<0.05	0.15 Max.
Lead	<0.05	0.05 Max.
Tin	<0.05	0.05 Max.
Nickel	<0.05	0.05 Max.
Chromium	0.12	0.04 – 0.35
Others each	<0.05	0.05 Max.
Other total	<0.15	0.15 Max.
Aluminum	Balance	Balance

The chemical analysis showed that the cylinder had been fabricated from 6061 aluminum alloy tubing.

The hoist manufacturer's international patent application for the aluminum hydraulic hoist states that the preferred aluminum alloy is 7005, which is a stronger and more fatigue resistant alloy than 6061.

Mechanical Testing

The tensile testing was done according to ASTM B557, and the hardness testing was done according to ASTM B384, using a Knoop indenter and a 500 gram load.

Mechanical Testing Results of Cylinder Material		
Test	Result	Specification for T6
Tensile Strength	44,700 psi	42,000 psi Min.
Yield Strength	41,200 psi	35,000 psi Min.
Elongation	13.9%	9% Min.

Hardness test Sample 1 was a longitudinal sample, and Sample 2 was a transverse sample.

Hardness Test Data for Hydraulic Cylinder Material				
Sample	Knoop	Std. Dev.	Range	Typical Hardness
1	119.00	4.88	114.00 - 126.00	120 Knoop
2	123.00	5.50	117.00 - 136.00	120 Knoop

The chemical and mechanical testing showed that the material used in the cylinder was 6061, T-6 or T-651 temper. 6061 T-6 aluminum alloy is the typical high strength aluminum alloy used for non-aircraft applications.

Scanning Electron Microscopic Examination

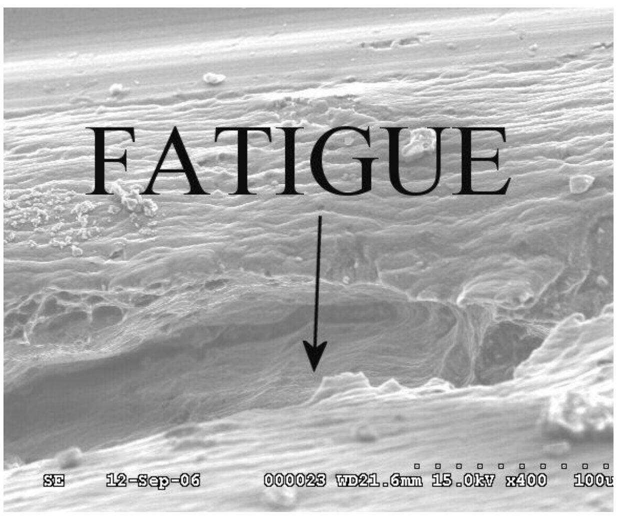

Figure 5 – 400X Fatigue Crack in Thread Root

Figure 6 – 40X Fissile Fracture

Figure 5 shows clear evidence of a low cycle fatigue crack starting in a thread root.

The arrows in Figure 6 indicate fissile fractures perpendicular to the fracture surface. Cracks of this nature are the result of very high stress levels, that exceeded the tensile strength of the material. The primary fracture mode in the area is ductile rupture. The owner of the trailer indicated that the hoist bound-up at least once during dumping of a load. He further stated that he had contacted the manufacturer and had reported the situation.

The combined presence of fatigue and ductile rupture indicates that the fatigue was low cycle. The fatigue endurance limit for 6061-T6 aluminum is 14,000 psi at 500 million cycles. The fatigue life at 24,000 psi is approximately 20,000 cycles. The Dawson aluminum hydraulic hoist is rated at 35 tons, where most of the principle stresses in the area of the failure are at, or very close to 14,000 psi. This does not allow for any loading that may result from irregularities in the dumping operation. There is virtually no safety factor for fatigue when using 6061T-6 aluminum alloy in this application.

Metallographic Examination

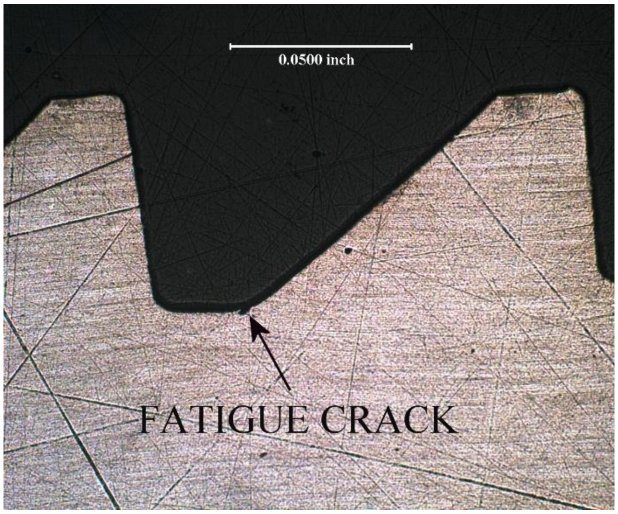

Figure 7 – 25X Fatigue Crack Thread Root

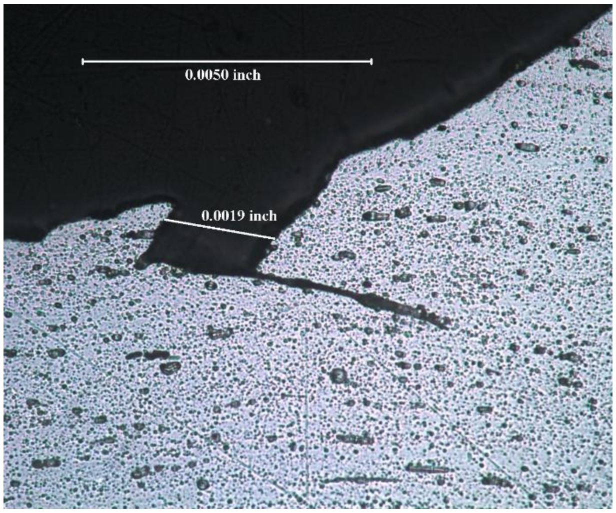

Figure 8 – 400X Fatigue Crack Thread Root

A fatigue crack was found in one of the thread roots, Figure 7. Figure 8 shows that there was a 0.0019 inch displacement in the crack opening, indicating that the material had been stressed beyond the yield point.

Discussion

The manufacturer has been granted three United States patents for the aluminum hoist. The abstract of Patent Number 6,899,014, states: “A telescoping hydraulic hoist with tube stages formed from a heat treated aluminum alloy from one of the series 2000, 6000 or 7000 aluminum alloys. These alloys retain good "memory" properties, and under the force of a pressure spike undergoes a momentary elastic deformation which acts as a shock absorber, expanding the tube wall to absorb the peak stresses and resist buckling. The hoist of the invention is thus much lighter than a comparably rated steel hoist, and much more resistant to corrosion.” Pressure spikes that exceed the elastic limit of material used can result in fissile fracturing, shown in Figure 6, or plastic deformation that will cause the hoist bind during operation as stated by the owner.

In the patent it is also stated: “In further aspects of the preferred embodiment: the hoist s selected from one of the series 2000, 6000 or 7000 aluminum alloys, preferably a 70005-T53 aluminum alloy; and the tube stages have a wall thickness of 1/2 inch or less.”

They had a typing error in the patent specifying 70005-T53, which should be 7005-T53. The actual measurement of the wall thickness of the failed cylinder was 0.375 inches and was reduced to 0.250 inches in the threaded section.

The patent goes on to say: “Certain aluminum alloys, particularly the 2000, 6000 and 7000 series, are heat treatable and can thus be processed to have a strength comparable to steel. However, the modulus of elasticity remains relatively constant even after processing, so that the heat treated aluminum alloy is considerably more elastic than steel, often referred to as "memory."

In reality, the lower elastic modulus in aluminum means that aluminum is less elastic than steel. This same characteristic also makes aluminum alloys susceptible to fatigue. Fatigue is a strain related fracture process, and the lower elastic modulus results in a much larger strain in aluminum than the same stress level would put into steel. Therefore, this results in the lower fatigue strengths and the greater susceptibility to fatigue for aluminum alloys as opposed to steel under the same loading conditions. The statement in their Patent also shows that the manufacturer was fully aware of short term overloading of their cylinders, but did not understand the characteristics of the materials that they were working with. The quoted sections are pasted directly from the patent itself.

The table that follows compares the properties of a pressure vessel quality steel, A738 Grade A, with 6061-T6, and 7005-T53.

Material Properties Comparison			
Property	Pressure Vessel Steel A738 Grade A	6061-T6 Typical	7005-T53 Typical
Tensile Strength	75,000 psi Min.	45,000 psi	56,600 psi
Yield Strength	45,000 psi Min.	39,900 psi	50,000 psi
Elongation	20% Min.	12%	15%
Shear Strength	37,500 psi	29,700 psi	43,500 psi
Fatigue Strength*	22,500 psi	13,800 psi	20,300 psi
Modulus of Elasticity	30,000,000 psi	10,000,000 psi	10,300,000 psi

*Fatigue Strength for steel is at an infinite number of cycles, and for aluminum is at 500,000,000 cycles.

6061-T6 is not directly substitutable for 7005-T53. The thickness would need to be increased by 26% to compensate for the lower tensile strength, by 25% to compensate for the lower yield strength, and by 47% to compensate for the lower fatigue strength. Fatigue strength is always the primary design consideration for aluminum products that are subjected to cyclic loading. At an infinite number of cycles the fatigue strength of most aluminum alloys is less than 10,000 psi.

At the hoist-rated load of 35 tons, the hoop stress in the cylinder is 13,800 psi. For 7005-T53, there is a burst safety factor of 4.1:1, and for 6061-T6 the burst safety factor is 3.26:1. For fatigue, the safety factor for 7005-T53 is 1.47:1, and for 6061-T6 is 1:1. It is apparent that the fatigue safety factor is not large enough for 7005-T53, and definitely not large enough for 6061-T6.