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Failure Analysis of a Ruptured Cast Aluminum Alloy Fire Hose Manifold

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In 2009, a cast aluminum large diameter hose appliance with adjustable pressure relief valve suddenly ruptured during a training drill in New Jersey, injuring a firefighter. The part had been in service for several years prior to rupture. The NJ Division of Fire Safety provided the part to Corrosion Testing Laboratories, Inc. for destructive failure analysis in order to determine the cause of the sudden rupture.

The manifold ruptured into two large pieces, Figure 1. Cracking was present all around the part and was roughly flush with the threads at the threaded inlet connection. To the unaided eye, the fracture surface appeared reasonably uniform. However, using oblique lighting and stereomicroscopy, casting voids were revealed near the inlet connection. In places, there was a white substance in the voids, Figure 2. As-cut and polished cross-sections at this location showed that the voids spanned a significant percentage of the wall, thus reducing the effective wall thickness. Prior to polishing, the white substance was analyzed by energy dispersive x-ray spectroscopy (EDS) in the scanning electron microscope (SEM). It was consistent with slag from the casting process.

A cross-sectional metallurgical mount was prepared through the fracture surface, Figure 3. The microstructure consisted of aluminum dendrites with angular second phases of silicon and intermetallic phases of iron and magnesium. These phases are brittle and the cross-section showed evidence of cracking through them, especially at the long needle-like particles. This is consistent with the overall morphology of the fracture surface as revealed by SEM, which showed brittle fracture plus casting voids.

Samples of the material were tested for strength and ductility. Mechanical testing showed that tensile and yield strengths were typical of alloy 356 T6 castings [1]. However, Charpy V-notch impact testing showed that the material had virtually no toughness (ductility) at room temperature. This means that the material had very little ability to resist a sudden impact or load. A sample of material was chemically analyzed and was consistent with aluminum casting alloy 356.

The hose manifold ruptured when a brittle fracture propagated through the material. Several factors contributed to the failure. Numerous casting voids were present within the part, some of which contained a substance consistent with slag. These factors point to poor manufacturing control during casting. The microstructure was typical of an unmodified aluminum-silicon casting alloy and contained long, brittle, needle-like intermetallic phases. This microstructure does not impart good fracture toughness properties to the material. These factors – the voids which reduced the effective wall thickness and the brittle needle-like second intermetallic phases within the microstructure – allowed fracture to occur at lower stresses than would normally be anticipated for the casting. Once initiated, the crack propagated rapidly through the brittle material.

Better process control to minimize voids and slag within the casting would help improve properties. In addition, aluminum casting alloy A356 reportedly has better fracture toughness than alloy 356. It contains less iron, which reduces the presence of brittle second phases. Also, microstructural modification through the addition of chemical modifiers and control over solidification rates can help to improve fracture toughness by refining the morphology of second phases within the alloy [2]. These measures are routinely employed in aluminum castings to produce alloys with more desirable mechanical properties.

References:
[1] ASTM B26/26M-14, Standard Specification for Aluminum-Alloy Sand Castings, ASTM International, Conshohocken, PA.
[2] Kaufman, JG, and Rooy, EL, “Aluminum Alloy Castings – Properties, Processes, and Applications,” (ASM International, Materials Park).

Figure 1. Several views of the ruptured hose manifold. Box in middle photograph shows location of right photograph as well as photographs in Figure 2. Right photograph shows voids in casting wall (arrows).

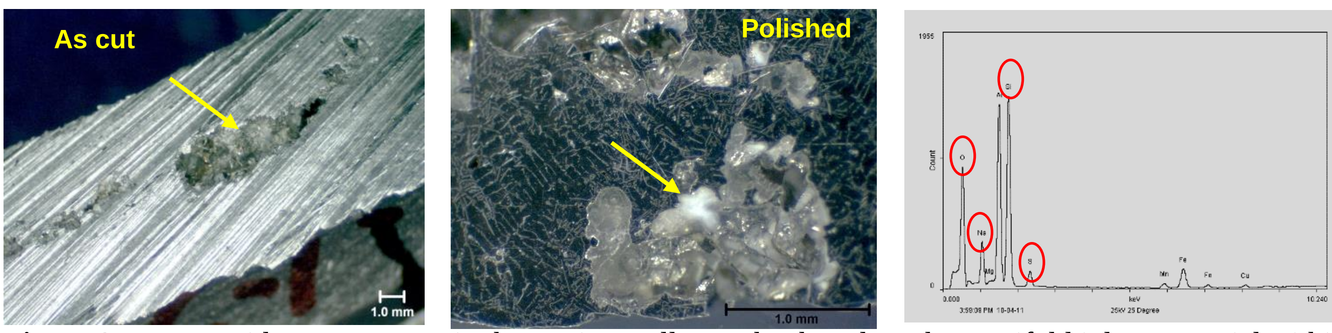

Figure 2. Large voids were present in the casting wall near the threads at the manifold inlet. Material within the voids (arrows) was high in silicon, sodium, oxygen and sulfur, as determined by EDS (right).

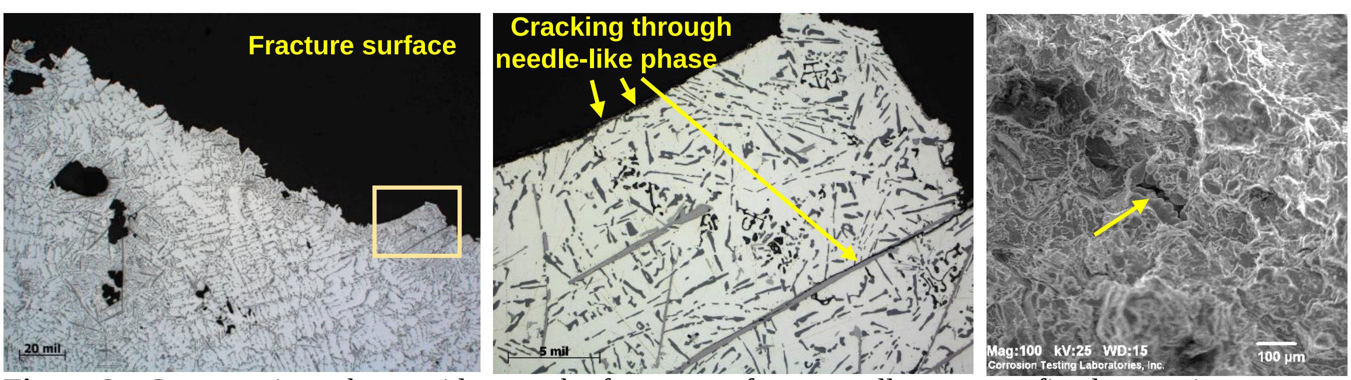

Figure 3. Cross-sections show voids near the fracture surface as well as an unrefined cast microstructure containing needle-like brittle intermetallic particles, through which cracking propagated (arrows). Box shows location of middle photo. SEM imaging reveals typical brittle fracture, plus casting voids (arrow).

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