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NATIONAL TRANSPORTATION SAFETY BOARD
WASHINGTON, D.C

METALLURGIST'S FACTUAL REPORT
Report No. 97-81

Examination of Small Holes

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

April 29, 1997

METALLURGIST'S FACTUAL REPORT Report No. 97-81

A. ACCIDENT

Place : East Moriches, New York
Date : July 17, 1996
Vehicle : Boeing 747-100
NTSB No. : DCA96-M-A070
Investigator : Al Dickinson, AS-10

B. COMPONENTS EXAMINED

Test plates generated by Boeing; accident airplane structure

C. DETAILS OF THE EXAMINATION

INTRODUCTION

Various holes in the airplane structure were documented and examined to determine if they had indications of being created as a result of penetration by a high velocity fragment. At the request of the Safety Board, Boeing generated a series of holes (through penetrations) and impacts in test plates, and the features associated with these holes were used to define the characteristics of higher and lower velocity penetrations. These definitions were then applied to the holes in the accident airplane.

CLASSIFICATION OF TEST HOLES GENERATED BY BOEING

Penetration holes and damage were generated in the test plates by fragments of various sizes and materials that were fired out of a gun. The velocity of each fragment at impact with the test plate was precisely measured. Target plates consisted of various thicknesses and different aluminum materials corresponding to the structural elements of a 747 airplane in the vicinity of the wing center section. In some cases, multiple targets were used for a single shot. A total of 105 shots were made. Examination of the hole characteristics showed that the holes could generally be classified as one of two types that will be referred to as higher velocity holes or lower velocity holes (see descriptions below).

The hole classifications indicated that steel impact fragments with a size approximately equivalent to or less than the thickness of the target plate could produce holes only of the higher velocity type. However, when the impact fragment size was much larger than the thickness of the target plate, both types of holes could be produced, depending on the velocity. Only higher velocity holes were produced in the thicker target plates (0.25 inch and above) because the maximum size of the fragments used was approximately equivalent to the thickness of these plates. For thinner target plates (less than 0.25 inch) the smaller fragments would be expected to also produced only high velocity holes (testing parameters did not adequately cover this area). Larger fragments could produce penetration at lower velocities in thinner targets, and at sufficiently low velocities these holes were classified as lower velocity holes. It was also noted that at intermediate velocities, some mixed characteristics were found in individual holes. For 0.100 inch thick aluminum plate, steel fragments (1/4 inch to 3/8 inch cubes) impacting at velocities below about 1000 feet per second produced low velocity holes, while those fragments impacting at velocities above about 1500 feet per second produced high velocity holes. Small steel cubes (1/8 inch) needed very high velocities to penetrate 0.250 inch thick plate, and produced damage and holes classified as high velocity.

Titanium and aluminum fragments were also used. It was necessary to propel these less dense fragments at greater velocities to penetrate a given thickness plate. For example, 1/4 inch aluminum cubes did not fully penetrate 0.25 inch thick plate at velocities as high as 4000 feet per second and did not fully penetrate 0.375 inch thick plate at velocities as high as 5400 feet per second.

The following descriptions list the characteristics associated with the two types of holes.

CHARACTERISTICS OF HIGHER VELOCITY HOLES

1. Splash back This feature consists of material deformed opposite to the direction of travel of the penetrating object around the perimeter of the hole on the entry side of the target plate. It appears that the initial penetration is by lateral displacement of the metal of the plate under the high compression loads generated as the fragment impacts the surface. This feature can also be generated for high velocity partial penetrations and for high velocity impacts in which the fragment only dents the surface. (This feature is comparable to the raised lip of metal around a hardness measurement impression.)

2. Lack of overall deformation Higher velocity penetrations produce little overall membrane deformation in the direction of motion of the striking object.

3. Hole wall characteristics The surface of the higher velocity hole wall is characterized by melted and resolidified material adjacent to the entry side (plus

indications of transferred material from the penetrating object, even when steel), severe shear deformation, and multiple shear cracks associated with the passing of the fragment through the material.

4. Exit deformation or breakout Passage of the fragment through the targets generated local deformation (similar to splash back, but on the exit side) adjacent to the hole wall in the direction of travel of the fragment or shear breakout of material around the hole.

CHARACTERISTICS OF LOWER VELOCITY HOLES

1. No splash back Lower velocity holes have little or no splash back opposite to the direction of travel of the impacting fragment.

2. Overall deformation Lower velocity holes have a much larger amount of overall deformation associated with the hole. Generation of the hole at lower velocities appears to be primarily from membrane bending in the direction of travel of the impacting fragment.

3. Hole wall characteristics The hole wall of lower velocity holes appears to be generated by fracture of the plate, resulting in elongated ductile dimples throughout the entire thickness of the plate. No melting was found on the lower velocity holes.

In summary, higher velocity holes appear to be initiated by lateral displacement of material under very high pressures associated with impact forces. These pressures are sufficient to generate local melting of the plate material. Transfer of impacting fragment material into this melted layer indicates that some melting of the impacting fragment also occurs. Lower velocity holes appear to be created by overall deformation and then fracture under a shear or tearing mechanism, without the melting and high energy features associated with the higher velocity holes.

COMPARISON OF HOLES IN THE STRUCTURE WITH THE TEST PLATE HOLES

The pieces of the airplane were examined by the structures group; a total of 196 holes were identified. This section covers the metallurgical evaluation of these holes and compares them to the test plate holes provided by Boeing.

An initial evaluation showed that many of the holes in the structure were obvious penetrations from the inside of the structure outward, contained substantial deformation adjacent to the hole, and generally had some amount of impact damage associated with the hole, all indications of lower velocity penetration by a structural member. Other holes listed by the structures group were actually tears in structure or penetrations associated with damage and did not contain any missing material. All but

25 of the 196 holes were therefore initially determined not to have characteristics indicative of a higher velocity hole.

The remaining group of 25 holes received more detailed examinations. All holes associated with the wing center section were classified as lower velocity holes. For example, a 0.5 inch diameter hole in the front spar web (piece CW519 at RBL77) contained aftward deformation around most of the hole, a lip of metal around the aft side of the hole, and a slight burr on the lower edge of the forward side of the hole, consistent with a lower velocity hole with penetration in the aft and downward direction. The wing center section lower skin on piece CW236 contained a 0.25 inch diameter hole and a slot leading from the hole to a nearby fracture. No evidence of splashback was noted around the hole, the skin in the vicinity of the hole was deformed downward, and the upper surface of the skin contained an impact area adjacent to this hole, indicating penetration from an object moving downward at lower velocity. The damage associated with the slot adjacent to the hole in CW236 was found on only one face of the nearby fracture, indicating that the fracture was created before the hole and associated damage.

Similar examinations of the other holes in the structure indicated that most of these were also classified as lower velocity holes. However, two holes in the horizontal pressure deck above the wing landing gear bay (in pieces LF137 and RF60) contained some features of both lower velocity holes and higher velocity holes, making a field determination of the velocity characterization difficult. These two holes were each about 3/16 inch in diameter and were very similar in appearance with the following features:

1. Lack of overall deformation in the sheet around the hole.
2. No splashback.
3. Chipped out metal on the lower surface of the sheet on one side of the hole.
4. Smooth hole wall, generally perpendicular to the surface with some exit deformation on the lower surface.

The hole in piece LF137 was located in the pressure deck at STA 1457 and LBL 110. The chipped out metal on the lower surface and the exit deformation associated with this hole indicate penetration from a fragment moving downward and slightly aft. The hole in piece RF60 was located in the pressure deck at STA 1452 and LBL 62. The chipped out metal on the lower surface and the exit deformation associated with this hole indicate penetration from a fragment moving downward and slightly inboard. The lack of overall deformation in the sheet around these two holes suggests higher velocity holes, but the lack of splashback suggests lower velocity holes.

A portion of piece LF137 containing the hole was cut from the remainder of this piece and brought to the NTSB Materials Laboratory for additional examinations.[1] Figures 1 and 2 show the upper and lower surfaces of the piece cut from LF137, and figures 3 and 4 show closer views of the hole from the two sides of the piece. The sheet material containing the hole was 0.074 inch thick. Examination of the hole with a bench binocular microscope showed the presence of a crescent of deformed material on the upper surface of the piece, adjacent to one side of the hole (see opposing arrowheads, figure 3). The hole diameter was slightly larger in the direction from the center of the deformed crescent to the opposite side of the hole, measuring 0.19 inch, compared to a perpendicular diameter measurement of 0.17 inch.

The hole wall opposite from the deformed crescent contained several splits on the short transverse plane, one of which opened up to the chipped out area on the other side of the hole (see figure 4). Only part of the chipped out area was directly opposite from the deformed crescent. The dashed line in figure 4 is on the lower surface at a position corresponding to the center of the deformed crescent on the upper surface.

The optical examination also showed that the hole wall surface was largely covered by white crystalline deposits. A smaller section, about 1 inch square, was cut from the laboratory sample and ultrasonically cleaned in acetone for an extended period of time. This cleaning removed some of the deposits from the surface of the hole. Examination of the hole with a scanning electron microscope (SEM) revealed that much of the hole wall remained covered by deposits, mostly mud-cracked oxide deposits. Cleaner areas within the deformed crescent on the upper surface adjacent to the hole contained parallel lines oriented in the direction of particle travel indicative of metal deformation smearing, as shown in figure 5. X-ray energy dispersive spectroscopy (EDS) of outside edge surface of the SEM specimen after grinding generated a spectrum typical for the specified material for the sheet material (7075-T6 aluminum alloy, primary alloying elements of zinc, magnesium, and copper). EDS of a cleaner area within the deformed crescent also generated spectra consistent with the specified material for the sheet metal plus peaks for oxygen, sulfur, and chlorine. No evidence of melted and resolidified metal was noted on any portion of the hole wall.

Some of the test plates provided by Boeing were composed of 7075-T6 aluminum alloy, the specified material of the pressure deck. The test plates closest in thickness to the pressure deck material were 0.050 inch, substantially thinner that the 0.074 inch thickness of the sample from LF137. A 0.050 inch thick test plate was used as the third plate in two multiple-plate test firings[2] using ¼ inch steel cubes. The maximum initial velocity for the ¼ inch cubes was 1509 feet per second, and the holes

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[1] The hole in piece RF60 was directly adjacent to the steel framework for the reconstructed airplane and was much more difficult to cut out without removal of the entire piece. Because the two holes were so similar in appearance, only the removal and laboratory examination of the hole in LF137 was accomplished.

[2] The first two plates in both tests were 2024-T3 aluminum alloy with thickness of 0.063 inch and 0.050 inch.

made in the third plate in both tests were classified as lower velocity holes, with deformation around the hole and no splashback.

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National Resource Specialist - Metallurgy

Figure 1. Overall view of the upper surface of the laboratory sample removed from piece LF137.

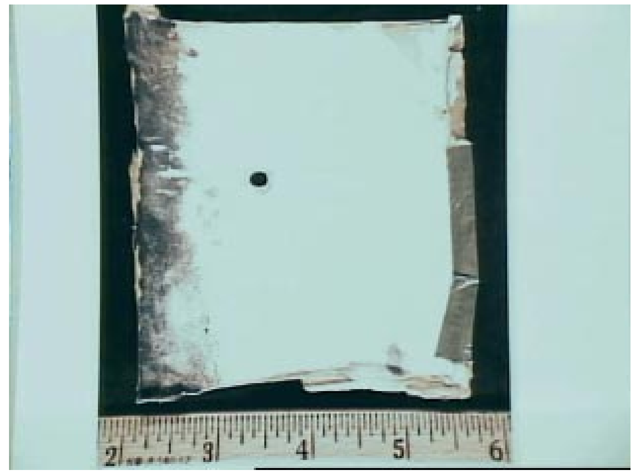

Figure 2. Overall view of the lower surface of the laboratory sample removed from piece LF137.

Figure 3. Closer view of the hole as shown from the top surface of the piece. (7.5X)

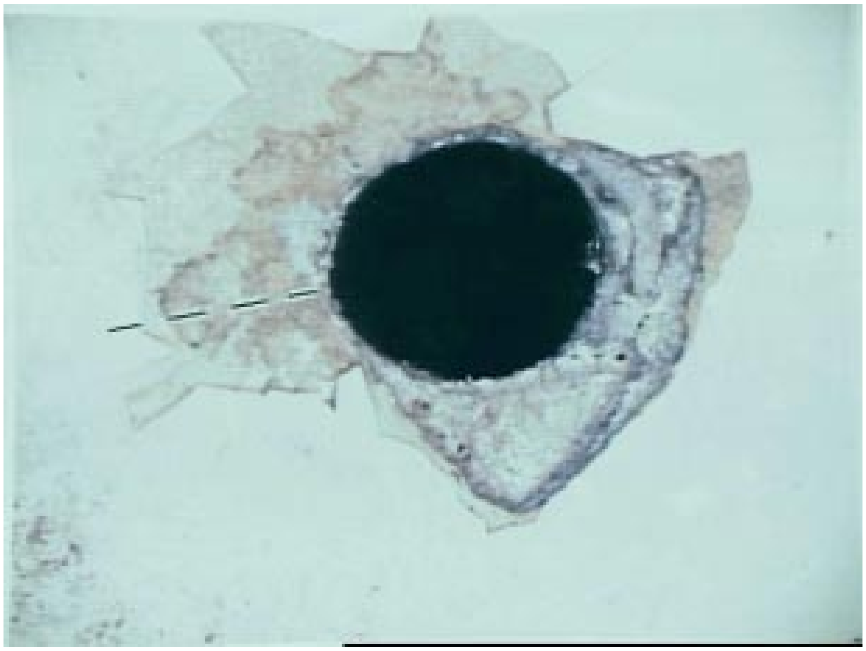

Figure 4. Closer view of the hole, as shown from the lower surface of the piece. (7.5X)

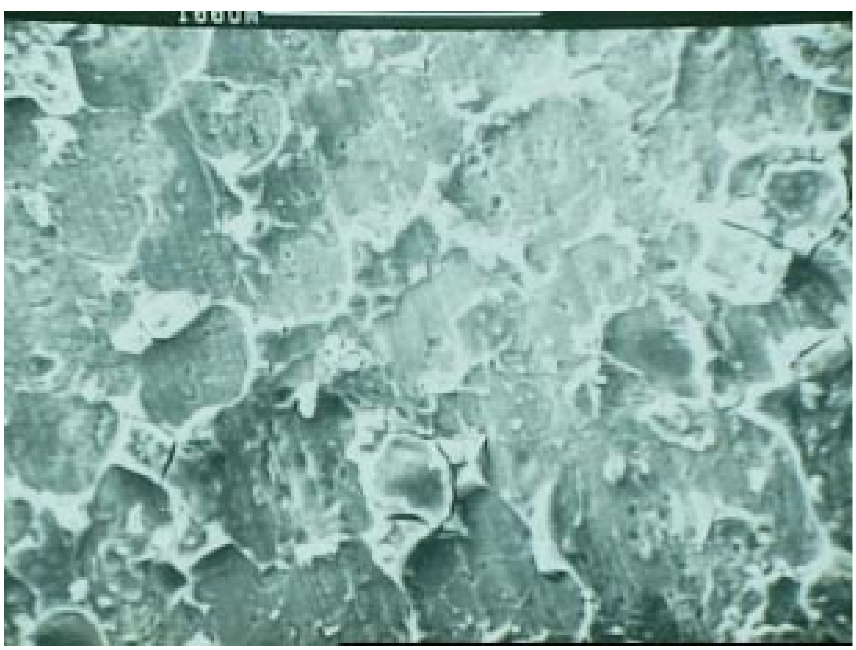

Figure 5. SEM photograph of the features within the deformed crescent adjacent to the hole on the upper surface. Remnants of the mud-cracked oxide deposits are also visible on the surface. (334X)