

NATIONAL TRANSPORTATION SAFETY BOARD

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



February 2, 2021

MATERIALS LABORATORY FACTUAL REPORT

Report No. 19-078

A. ACCIDENT INFORMATION

Place : Cashiers, North Carolina
Date : March 14, 2019
Vehicle : Mooney M20C; N6075Q
NTSB No. : ERA19FA130
Investigator : Eric Alleyne, AS-ERA

B. COMPONENTS EXAMINED

Vacuum pump, a portion of the separated vacuum pump driveshaft, and a portion of a directional gyroscope

C. DETAILS OF THE EXAMINATION

On March 14, 2019 at 1815 eastern daylight time, a Mooney M20C, N6075Q, departed controlled flight and collided with mountainous terrain near Cashiers, North Carolina. The commercial pilot was fatally injured, and the airplane was destroyed. Day instrument meteorological conditions prevailed, and an instrument flight rules (IFR) flight plan was filed for the personal flight which was conducted under the provisions of Title 14 Code of Federal Regulations Part 91. The flight departed Knoxville Downtown Island Airport (DKX), Knoxville, Tennessee, at 1724, and was in route to Aiken Regional Airport (AIK), Aiken, South Carolina. A vacuum pump and a portion of a directional gyroscope instrument were recovered and submitted to the NTSB Materials Laboratory for examination. Figure 1 shows the vacuum pump components and figure 2 shows the portion of directional gyroscope, as received.

1. Vacuum Pump

According to the identification placard affixed to the vacuum pump (dry air pump) the part was a RAPCO, Inc. FAA-PMA Dry Air Pump with part number RA215CC and serial number A22252. There was soil residue adhered to the outer part surfaces as well as packed inside of the inlet port and inside of the tube connected to the outlet port. A portion of the inlet connection was retained in the threaded inlet port but separated at the outer surface of the pump housing. The fracture surface exhibited shear lip ¹features, consistent with overstress separation of thin tube sections. A white, stringy material was protruding from between the retained fitting piece and the pump housing port. A 90° pipe-to-tube elbow fitting (stamped "AN822") with a coupling nut, sleeve, and approximately 4

¹ A narrow, slanting ridge along the edge of a fracture surface.

inches of metal tube was connected to the outlet port. The tube was fractured at the free end, bent in a C-shape, and deformed throughout. The fracture surface exhibited mechanical damage and smearing consistent with post fracture impact damage, however there were slanted areas observed which were consistent with shear lips. The observed condition of the fractured outlet tube was consistent with buckling and overstress separation.

The vacuum pump was carefully disassembled to examine the interior of the housing. The outlet cover was secured by two bolts with washers, one with a purple torque stripe material applied. The inlet cover was also secured to the housing by two bolts with washers both containing a purple torque stripe material. In all observed cases, the torque stripe material exhibited a crazed appearance and was aligned on the bolt head and pump housing on the outlet side and on one of the two fasteners on the inlet side. The other bolt head on the inlet side did not contain any torque stripe as it was only present on the washer and housing. The inlet cover was removed to reveal the interior of the housing which contained the pump rotor, vanes, rotational shaft, and drive shaft assembly. Figure 3 shows an exploded view of the partially disassembled pump from the inlet side. The cylindrical pump rotor consisted of six wedge shaped fins with an approximately 0.13-inch slot in between each fin, which contained a rectangular vane, each of which was intact. The vane widths were measured in three locations: near the outlet side, near the inlet side, and at approximately mid-height. These values were recorded in table I and figure 4 shows the vanes after removal from the pump. The vane walls exhibited a parallel scratch pattern on the sidewalls consistent with radial sliding within the slots during rotor rotation. The rotor sidewall was marked with a handwritten letter "P", followed by a curved character obscured by a vane slot, followed by "# 2" on the adjacent fin sidewall and a "2" on the outlet side of the rotor on the same fin. Using the fin marked with a handwritten "2" designated as 2, the fins and vanes were each labeled 1 – 6 in the direction of rotation for the purposes of this report. There were three axial through-holes evenly spaced around the hub at approximately mid-radius which engaged with the drive shaft assembly studs. The rotor was fractured into four larger pieces around the central hub with axial cracks spanning between the internal edge of the vane slots and the central hub through-hole as highlighted by yellow dashed lines in figures 3 and 5. Several smaller fragments from the rotor were recovered from inside the pump housing after the rotor was removed. The smaller fragments were predominantly from the area of the rotor located between fins 1 and 6. The fracture surfaces of the rotor pieces exhibited a rough morphology with a dull luster—these features were consistent with overstress failure of brittle materials.

Figure 5 shows a view of the rotor and vanes inside of the pump housing with the housing cover removed from the outlet side. Cracks were observed spanning between the central hub and vane slots which traversed axially through the rotor to the inlet side and are highlighted with yellow dashed lines. A larger portion of the hub between fins 1 and 6 was fragmented into smaller pieces that were recovered from the pump housing during disassembly. The outlet side of the rotor displayed a circumferential wear pattern of fine scratches consistent with rotation, however, a linear pattern of deeper parallel scratches was observed over an area from near the leading edge of fin 6 spanning counterclockwise around the rotor to near the trailing edge on fin 4 as indicated by the

red arc. The red double arrows indicate the direction of the parallel scratches. These parallel scratches were consistent with a non-rotational, sliding wear pattern.

Figure 6 shows a view of the rotor removed from the housing and approximately reassembled with the inlet side facing up. The outer diameter surface of the rotor exhibited a visually non-directional surface finish except at the inlet side there were visible circumferential marks around the entire diameter. The most prominent marks were measured to be 0.041, 0.072, 0.096, 0.124, 0.171 and 0.256 inch from the inlet side of the rotor. A wider shiny band of circumferential marks was observed spanning from near the trailing edge of fin 1 through fins 6, 5, and near the trailing edge of fin 4 (listed in order by which an observer from the outside would witness the rotor fins pass by during pump rotation, as labeled in this report) which ranged from 0.26 inch to 0.46 inch from the inlet side of the rotor. The widest section of the shiny circumferential mark was observed between fins 6 and 5. The corner of vane 1, where the outer surface and inlet side surface intersected, exhibited a tinted appearance as shown in the left image of figure 6 indicated by a black arrow.

The outlet cover contained an integral shaft concentric with the rotor hub about which the rotor rotated. Closer examination of the integral shaft on the housing cover revealed witness marks that matched the profile of the fracture surface between fins 1 and 6 and between fins 1 and 2. Figure 7 shows a view of the rotor fragments partially reassembled on the housing cover and pulled away slightly from the central shaft with the portion containing fin 1 removed to reveal the dark gray witness marks indicated by red arrows which aligned with the edges of the exposed fracture surfaces.

The inlet cover was examined and exhibited an elliptical area of circumferential scratches consistent with rotation of the rotor and sliding vanes. The inlet cover contained a central bearing where the drive shaft assembly passed through to engage the two-piece drive shaft. The drive shaft bearing exhibited multiple circumferential score marks around the end nearest the pump mounting flange as indicated in figure 8 with red arrows.

The interior surface of the pump housing sidewall was visually examined and exhibited a translucent brownish-gold appearance which was crazed throughout, consistent with the presence of an anodic coating. Figure 9 shows a digital microscope image of one side of the interior of the pump housing along the minor diameter of the elliptical shape. Circumferential scars which revealed bare base metal were observed and examples are highlighted with red arrows. Figure 10 shows a digital microscope image of one side of the interior of the pump housing along the major diameter of the elliptical shape. Axial bands, along the full height of the sidewall, of circumferential wear scars were observed around the housing wall, consistent with impact and dragging of sliding vanes being forced radially outward and inward relative to the rotor rotation within the elliptical housing shape.

The pump driveshaft, which connected the pump rotor to the accessory drive gear, consisted of a two-piece splined shaft coupled via a translucent, light amber colored urethane shear coupling with a flanged cylindrical shape. The fractured shear coupling is

shown in figure 11. The flanges on both sides of the reduced section each contained a circular pattern of 8 through-holes which were keyed to each portion of the split drive shaft. The flange of the drive side exhibited an approximate 90° section of edge damage consistent with impact and abrasive wear. The reduced section of the urethane shear coupling was fractured transversely into two pieces and exhibited post fracture mechanical and thermal damage. The fracture surface features were heavily obscured by a swirled circumferential pattern of stringy and flowing opaque whitish-gold material consistent with melted and resolidified shear coupler material. A circular cup-shaped burnished region was observed locally around the center axis of rotation on the fracture surface of the drive side of the coupler and a corresponding cone shaped region was observed on the pump side of the fractured coupler and both exhibited circumferential material flow lines consistent with thermal stresses which exceeded the melting temperature of the shear coupler and contact during rotation, after separation. A small undamaged area on the fracture surface of the pump side of the shear coupler displayed slanted crack planes formed by radial marks² which produced a stepped profile with the adjacent surface of the outer diameter of the reduced section, consistent with torsional loading during fracture, as highlighted by red arrows and a dashed yellow line in figure 11. The surfaces of these fracture planes exhibited faint river patterns³ consistent with a radial fracture direction near the edge of the part.

When the drive side portion of the translucent shear coupler was observed from the flanged end using transmitted illumination as shown in figure 12, multiple radially oriented internal fracture planes were observed slanted at approximately 45° from the axis plane, consistent with torsional loading during fracture. Two of these cracks were observed on the flange surface spanning between the center hub and outer holes and are highlighted with dashed yellow lines. Examples of internal radial marks and crack arrest lines that were observed are highlighted with dashed black lines. Multiple complexly oriented fractures were observed.

2. Directional Gyroscope

According to the heavily obscured identification placard affixed to the portion of the directional gyroscope that was received, the legible information was consistent with an Aeritalia part number 31100 C. The portion of the directional gyroscope housing was crushed around the gimbal set which was separated from the deformed and fractured frame and is shown in figure 2. The rotor housing rotated about the inner gimbal axis to the extent limited by interference with the deformed drive gear. The rotor rotated freely about the spin axis within the rotor housing when viewed through the outlet port, but a slight amount of orthogonal play was observed between the rotor axis and rotor housing.

² Lines on a fracture surface that radiate from the fracture origin(s) and are visible to the unaided eye or at low magnification. Radial marks result from the intersection and connection of brittle fractures propagating at different levels.

³ River patterns describe a characteristic pattern of cleavage steps running parallel to the local direction of crack propagation on the fracture surfaces which resemble smaller tributaries feeding into larger rivers.

The gyroscope housing was disassembled to examine the rotor and interior of the housing. Figure 13 shows the rotor housing as removed from the inner gimbal which exhibited deformation and mechanical damage consistent with crushing due to impact. Figure 14 shows a closer view of the rotor housing. One of the housing end caps which supported the rotor axis, shown on the left in figure 14, was easily removed by hand from the housing, the other end cap, shown on the right in figure 14, was slightly deformed, wedged tightly in the housing, and was not removed. A scar was observed on the corner of this end cap, consistent with mechanical impact damage. The inner race of one of the bearings about which the housing rotated was fractured, as indicated in figure 14. The fracture surface exhibited a dull, rough appearance, consistent with overstress separation at impact.

The rotor, as shown in figure 15, exhibited faint circumferential scarring around the outer diameter surface. The scar highlighted with the single arrow was apparent around the entire circumference and was closely aligned with the edge of the housing end cap that was easily removed during disassembly. The two other scars highlighted with black brackets were not continuous around the entire rotor. The crescent shaped fins on the rotor had a dark speckled appearance near the rounded end. The interior surface of the housing exhibited evidence of circumferential scoring as highlighted by yellow arrows in figure 16. One continuous circumferential score mark was observed on the inner surface of the chamfered surface of the end cap, but a corresponding mark was not observed on the rotor. The inner surface of both housing end caps exhibited a uniform circumferential machined appearance on all surfaces with alternating sectors of contrasting reflectivity observed on the surface normal to the rotor axis.

Closer examination inside of the air inlet port of the rotor housing revealed small gouges consistent with tool marks or foreign debris damage and inconsistent with laminar flow damage/wear. Figure 17 shows views of these gouges from both inside and outside of the housing.

Michael Meadows
Materials Engineer

Table I: Vacuum Pump Rotor Vanes - Width Measurements

Vane ID	Outlet Side	Mid-Height	Inlet Side	Average
1	0.7945	0.7965	0.7965	0.7958
2	0.7965	0.7980	0.7985	0.7977
3	0.7985	0.7995	0.7985	0.7988
4	0.8010	0.8025	0.8025	0.8020
5	0.7995	0.8010	0.8010	0.8005
6	0.7970	0.7975	0.7970	0.7972

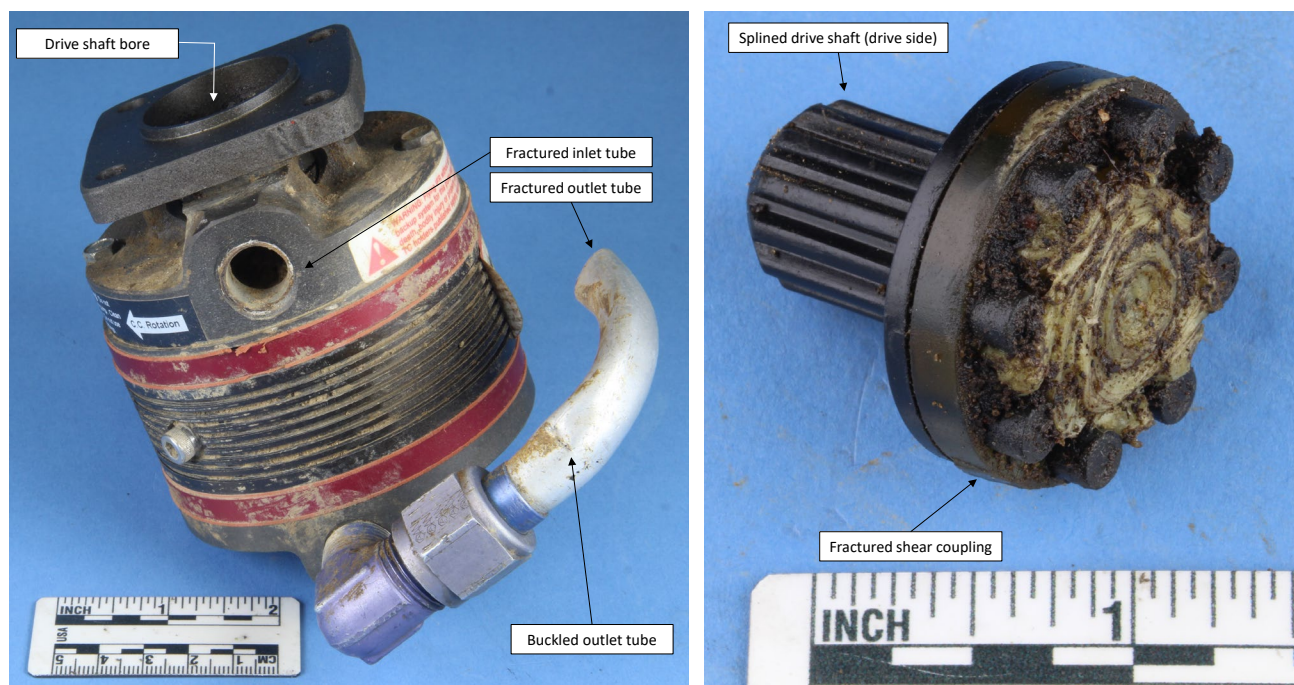


Figure 1: Photographs of the as received vacuum pump components prior to cleaning. The photograph on the left shows the vacuum pump oriented with the engine accessory case mounting flange located at the top. The photograph on the right shows the drive side of the splined two-piece drive shaft and fractured shear coupling which engaged the pump through the drive shaft bore when installed.

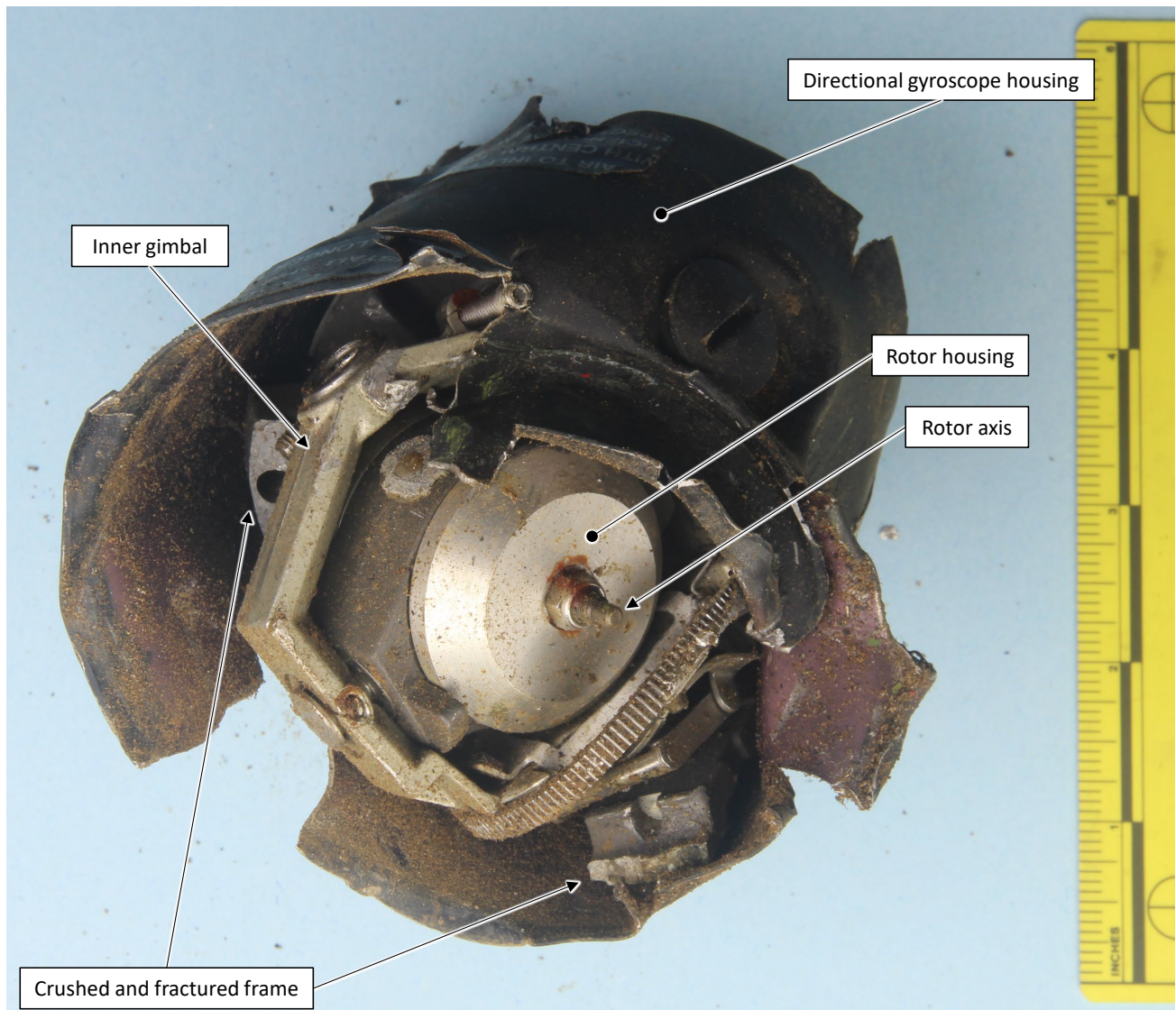


Figure 2: A photograph of the portion of the directional gyroscope as received with crushed, buckled, and torn housing. The inner gimbal, containing the drive gear and rotor housing, was observed separated from the crushed and fractured frame.

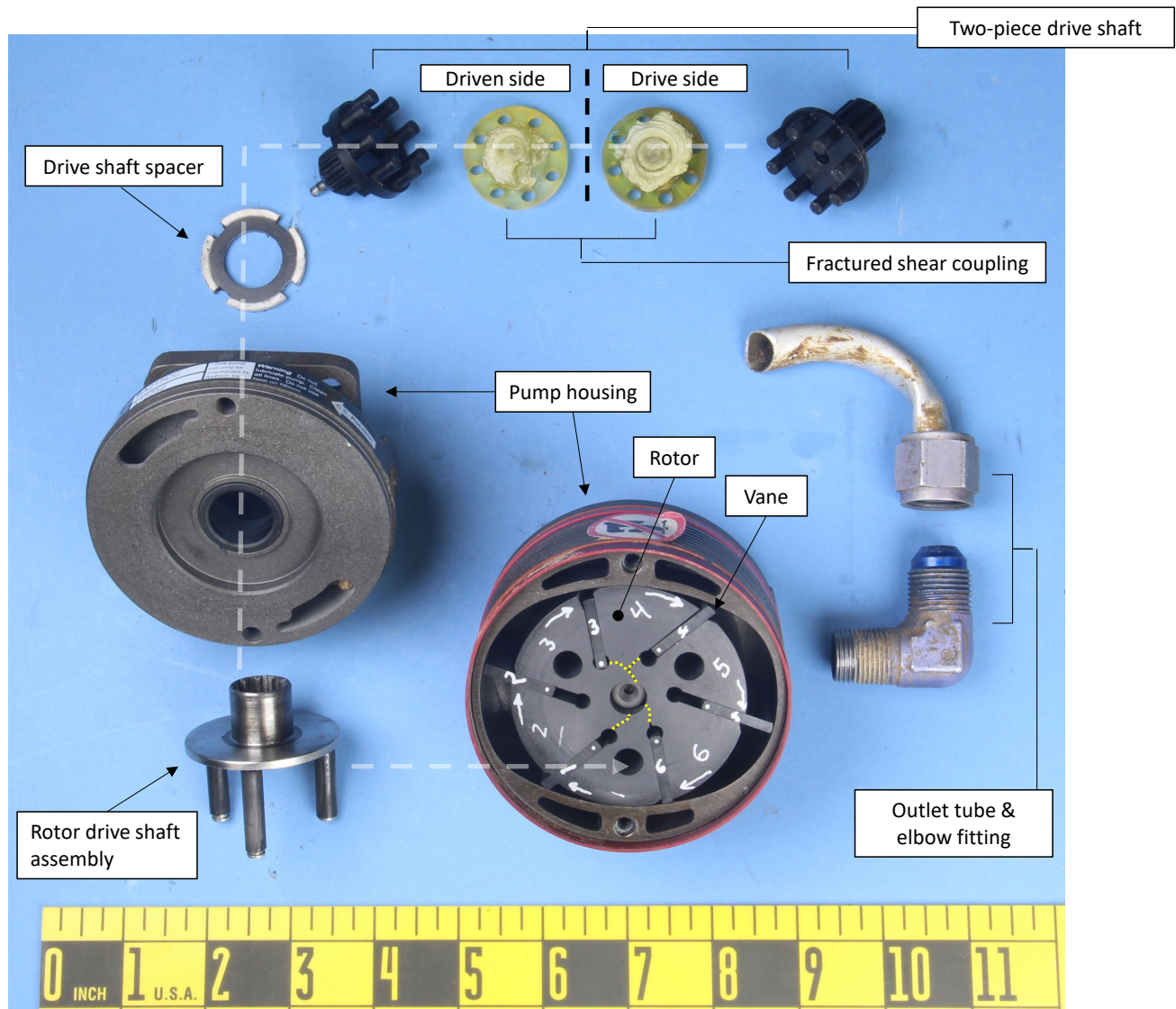


Figure 3: A photograph showing an exploded view of the vacuum pump after partial disassembly with the inlet side of the pump housing removed. The translucent white arrow indicates the connection pathway when assembled. The mating fracture surfaces of the shear coupler are visible showing the lighter swirled morphology consistent with thermal damage (melting). The dotted yellow lines at the rotor hub indicate the locations of cracks which traversed axially through the rotor. The silver arrows marked on the rotor indicate the direction of rotation and the silver numbers indicate the identification convention used for the rotor fins and vanes for the purposes of this report.

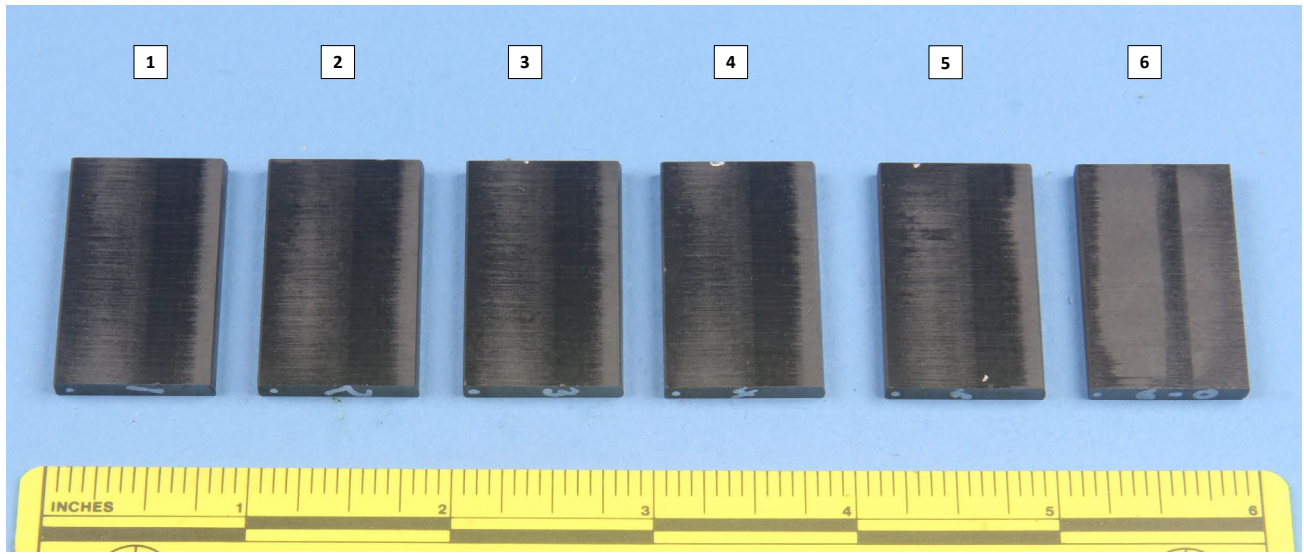


Figure 4: A photograph showing the six intact vanes removed from between the rotor slots. Vane identification numbers were assigned based on the sequential rotor fin as observed in the rotation order. Horizontal wear scratches consistent with sliding contact with rotor slot faces during rotation were observed.

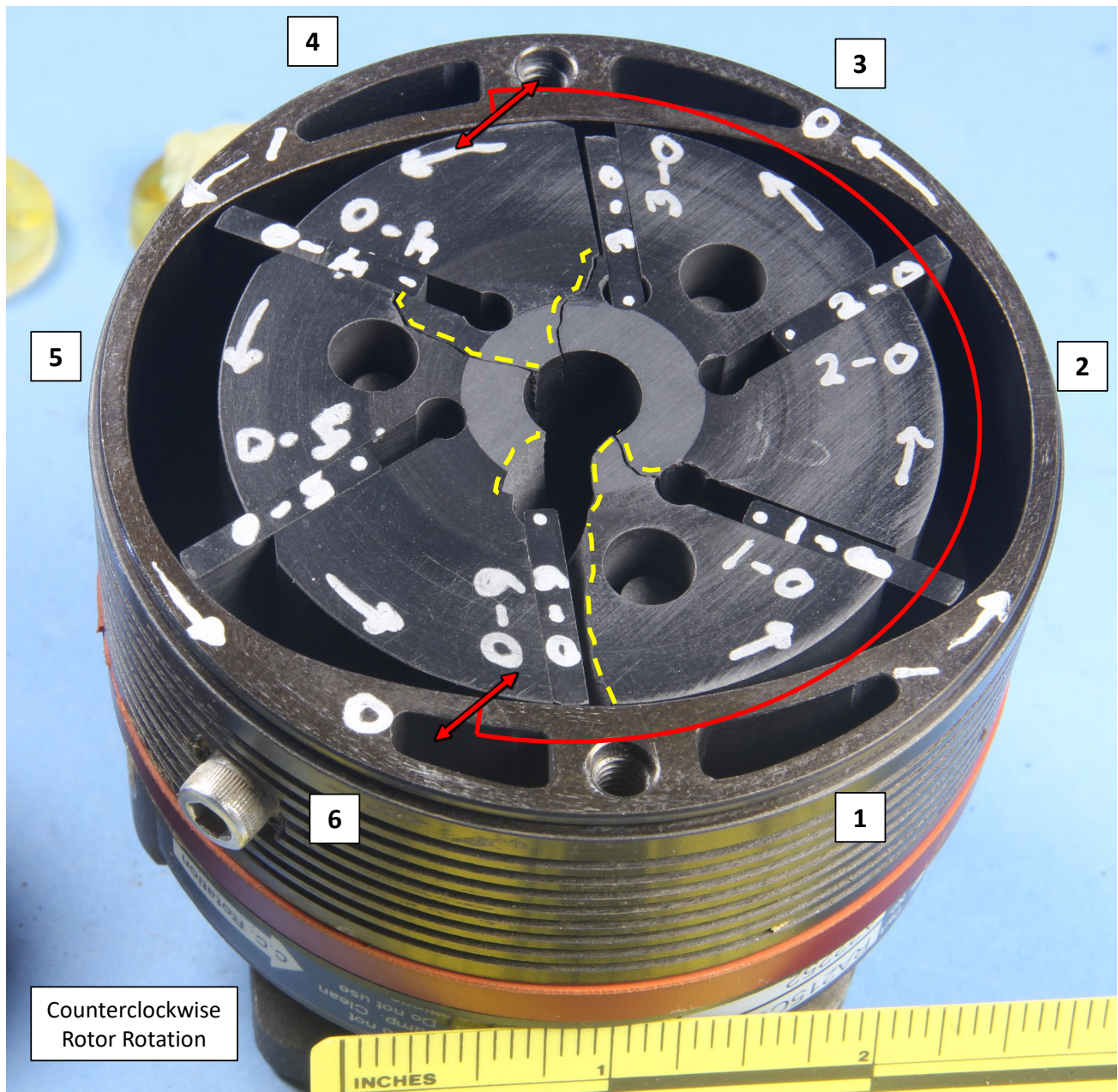


Figure 5: A view of the labeled rotor and vanes within the pump housing as observed with the outlet cover removed. Cracks in the rotor emanating from the central hub were observed and are highlighted by yellow dashed lines. The red arrows indicate the direction of parallel scratches consistent with sliding motion and inconsistent with rotational motion that were observed over the area of the rotor face indicated by the curved red bracket.

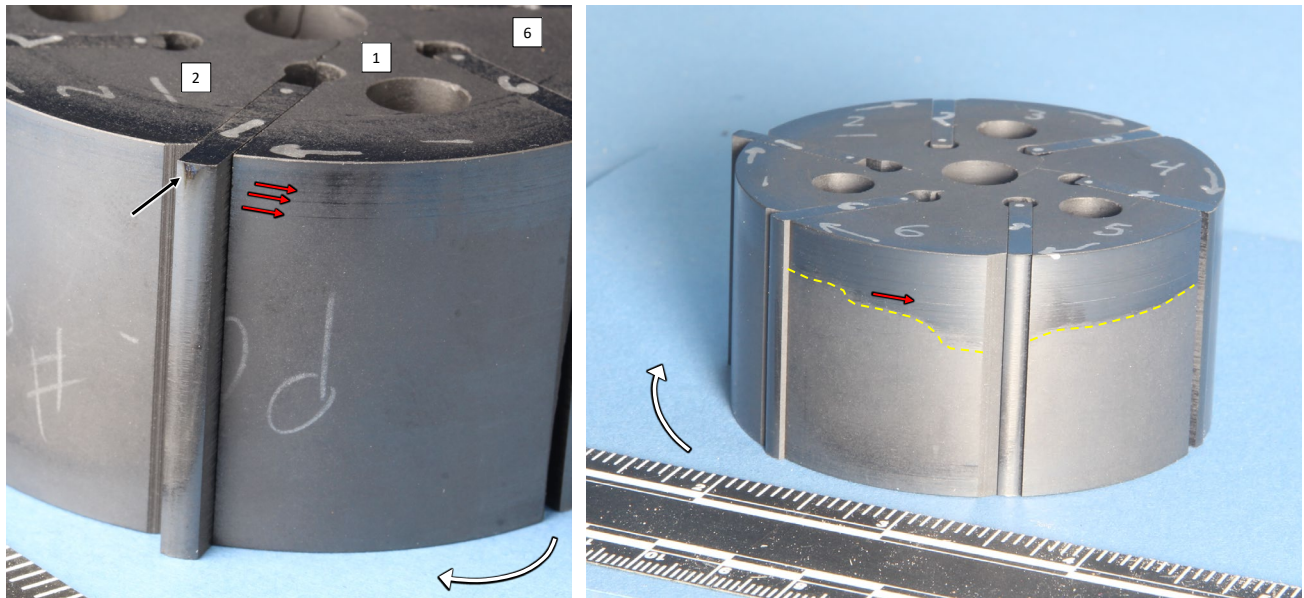


Figure 6: A pair of side views of the rotor as removed from the pump housing. The rotor rotation is indicated by the white curved arrows. The left image shows a close-up view of the rotor, oriented with the inlet side facing up, near fin and vane 1. The red arrows indicate circumferential marks measured at 0.096, 0.124, and 0.171 inch from the inlet side of the rotor face. The black arrow indicates a tinted area observed on the edge of vane 1. The right image shows a view of the entire rotor with the red arrow indicating a circumferential mark measured at 0.256 inch from the inlet side of the rotor face. The yellow dashed line highlights the boundary of the shiny band of circumferential marks.

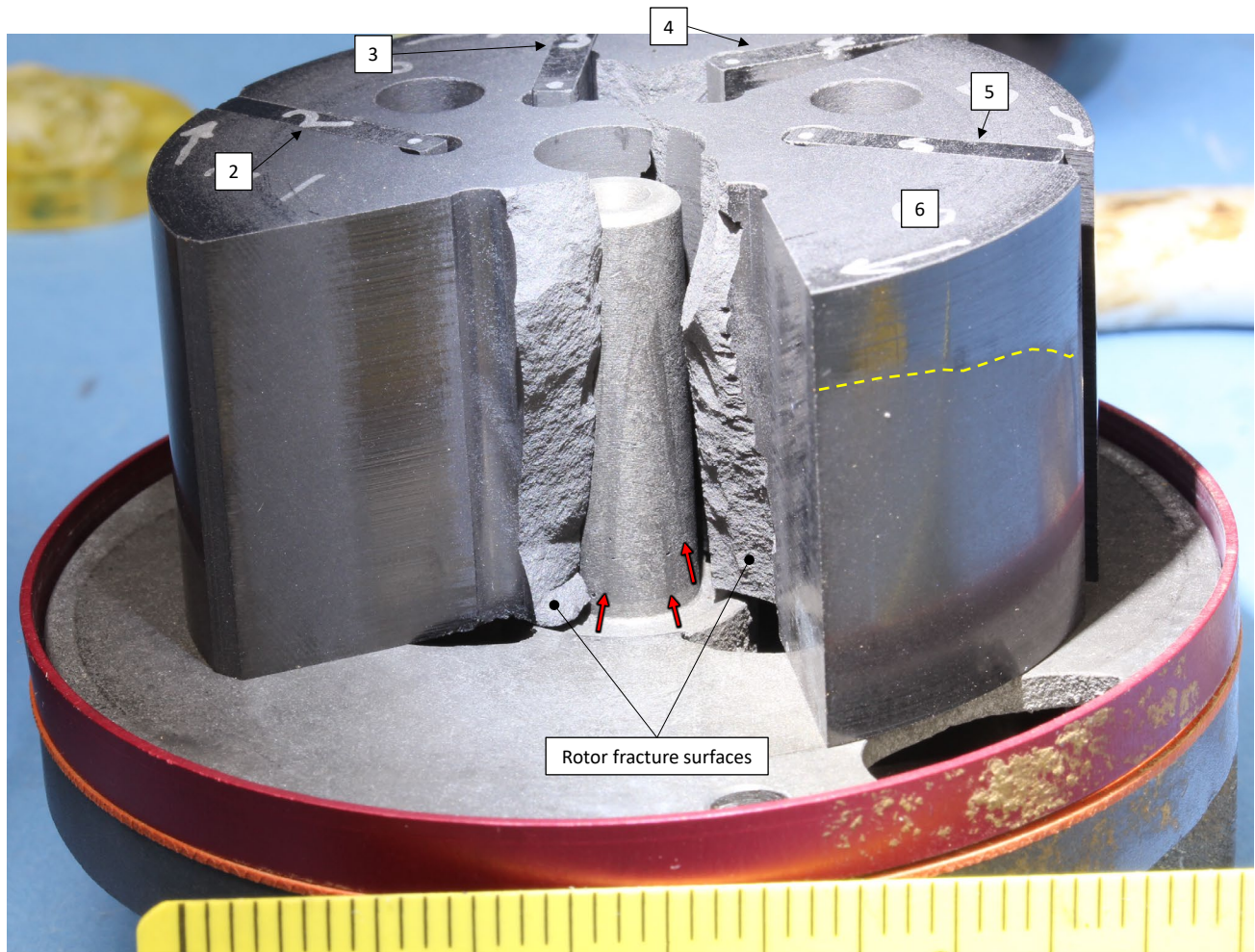


Figure 7: A view of the fractured rotor partially reassembled on the outlet cover with the portion containing fin 1 removed (vanes 1 and 6 are also removed). The numbered labels and arrows correspond to the applicable fin and vane, respectively. The fractured pieces were pulled away slightly from the central shaft to reveal dark gray witness marks (highlighted with red arrows) that match the profile of the rotor fracture surfaces. Witness marks were consistent with impact damage. The dashed yellow line on the outer diameter surface of fin 6 marks the boundary of a shiny circumferential wear pattern.

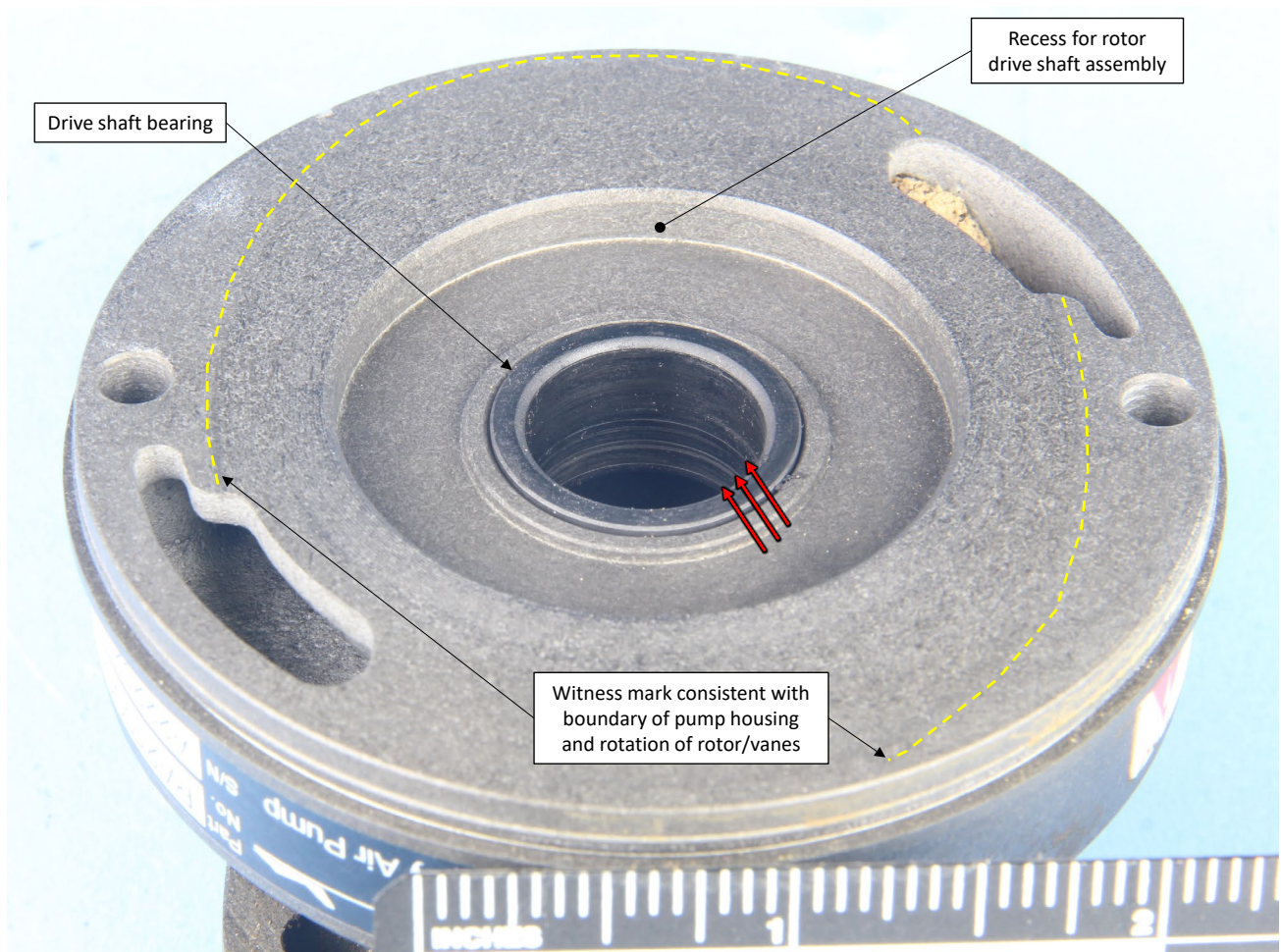


Figure 8: A view of the inside of the pump housing on the inlet cover with the sidewall of the housing, rotor, and rotor drive shaft assembly removed to reveal the drive shaft bearing. A yellow dashed line marks the inner boundary of the elliptical sidewall of the housing, within which, circumferential marks were observed. Red arrows highlight circumferential scars observed on the inner surface of the drive shaft bearing.

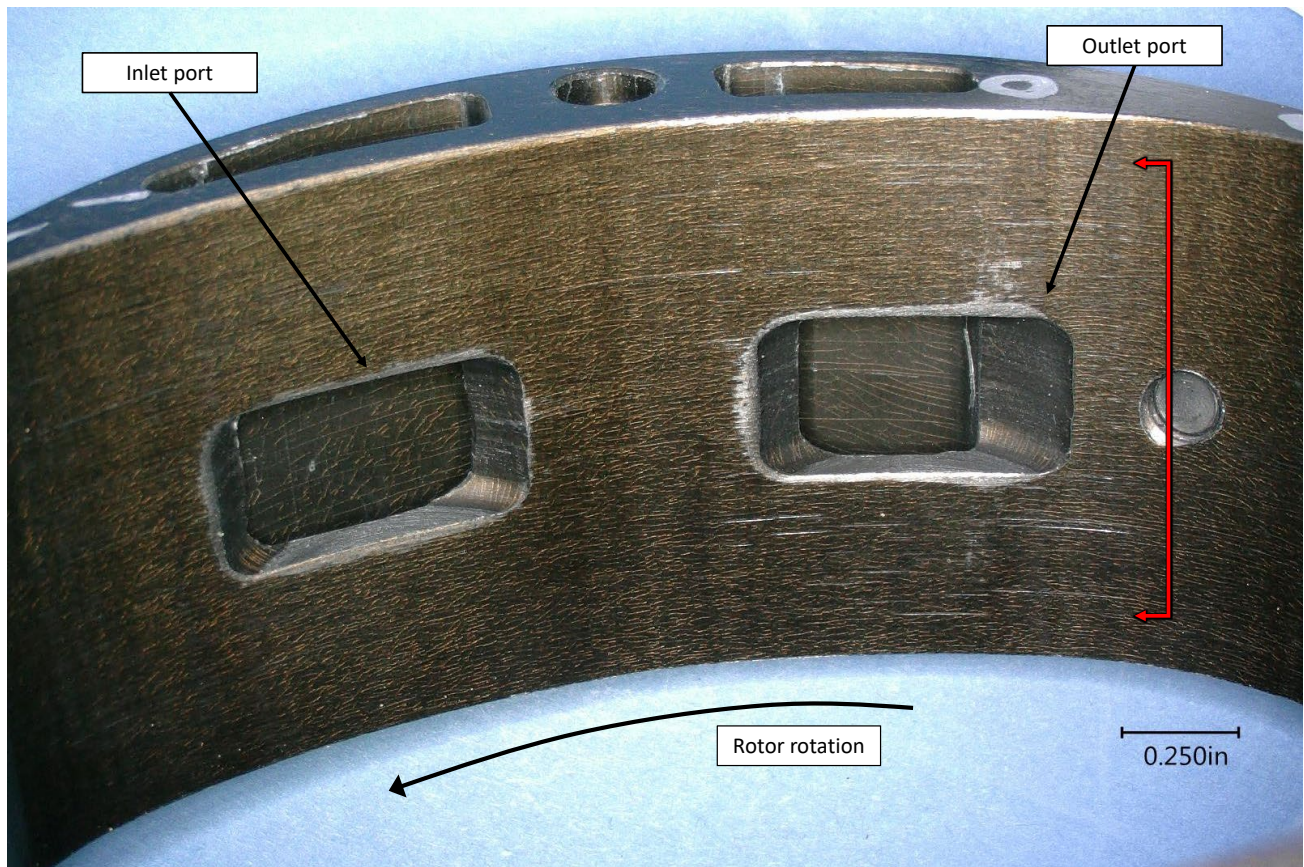


Figure 9: A view of the inside of the pump housing along the minor diameter showing the crazed brownish-gold coating layer. Circumferential scratches were also observed, and typical examples are the horizontal silver streaks observed within the area highlighted by the red brackets. The area surrounding the rectangular shaped inlet and outlet ports also exhibited coating wear and circumferential scratches.

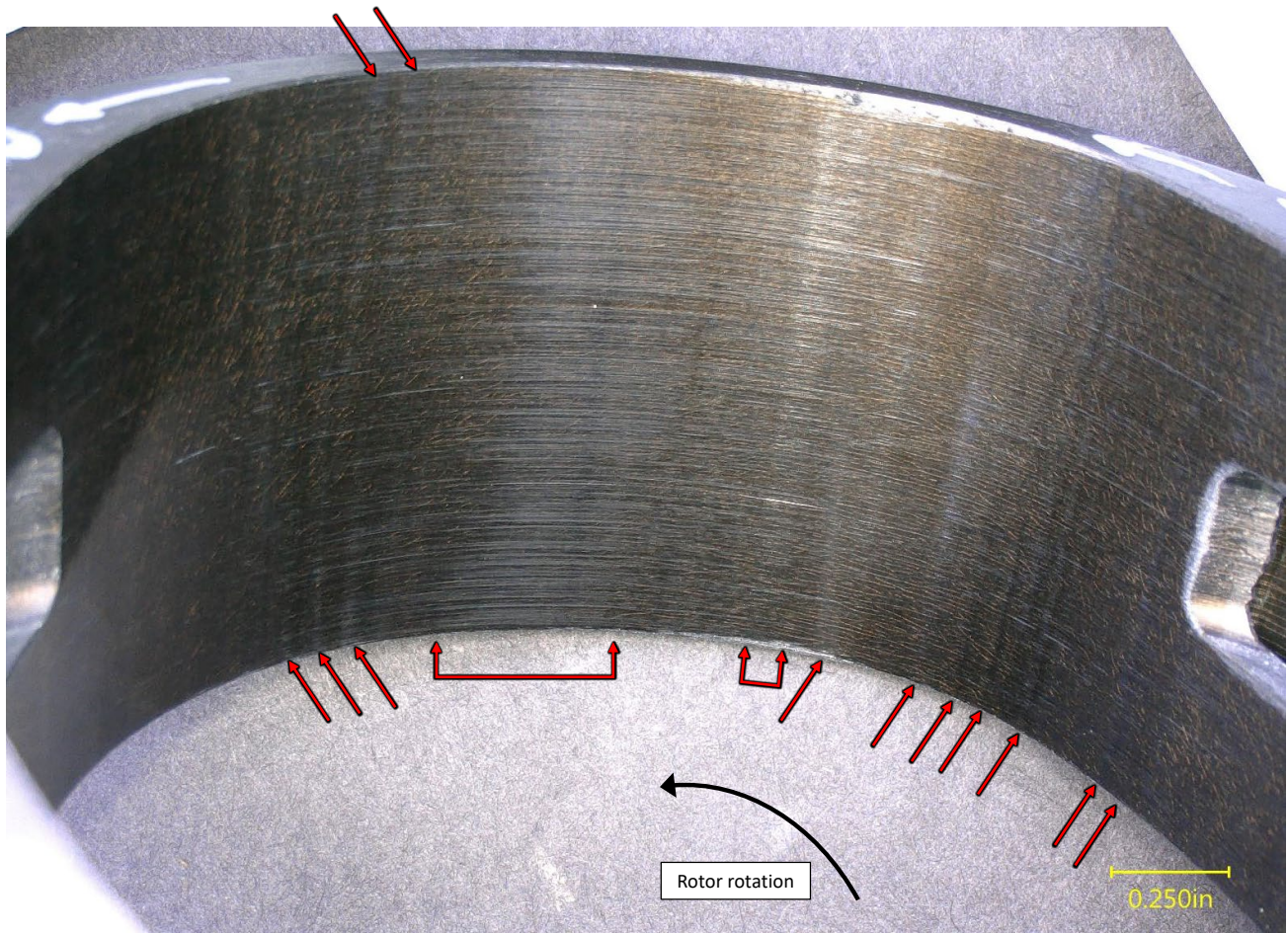


Figure 10: A view of the inside of the pump housing along the major diameter with the rotor and both covers removed. Red arrows and brackets highlight vertical bands of horizontal scratches consistent with vane edge impact and dragging from radial sliding during rotor rotation.

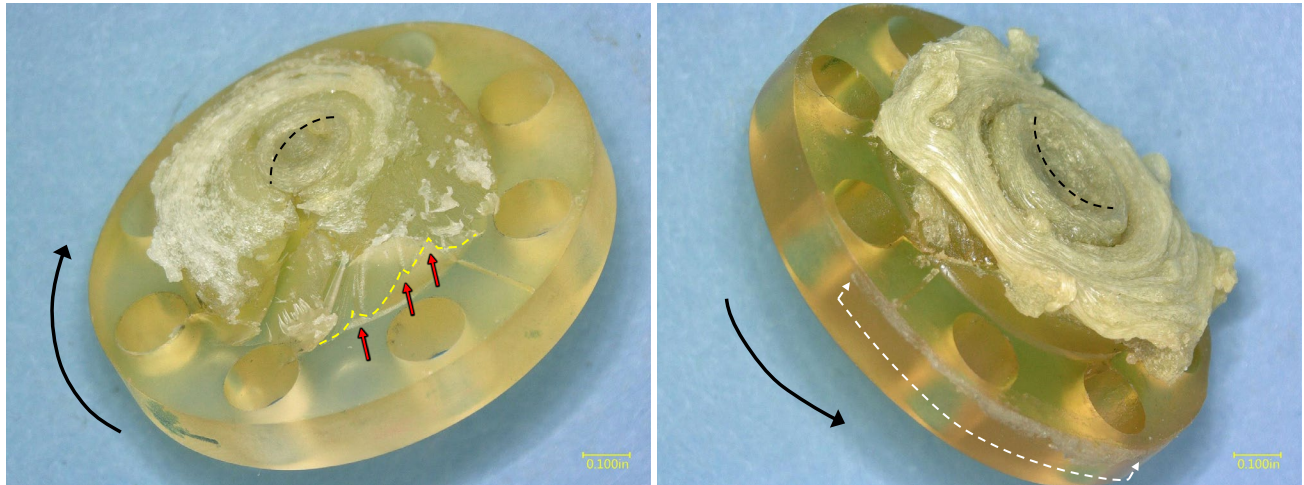


Figure 11: Digital microscope images showing side views of the fractured and partially melted and resolidified shear coupling with the driven side interface on the left and the drive side interface on the right. The black arrows indicate rotation direction. The yellow dashed line on the driven side highlights the slanted edge between the fracture surface and adjacent surface of the reduced section. Red arrows indicate step shaped features corresponding to radial marks. Faint river patterns were observed on the undamaged area of the fracture surface at this location. The dashed white bracket on the right photograph highlights an area of the shear coupling flange where damage consistent with impact and abrasive wear was observed. The black dashed lines highlight the cup profile (right photograph) and the cone profile (left photograph) observed at the central region of the fractured shear coupling.

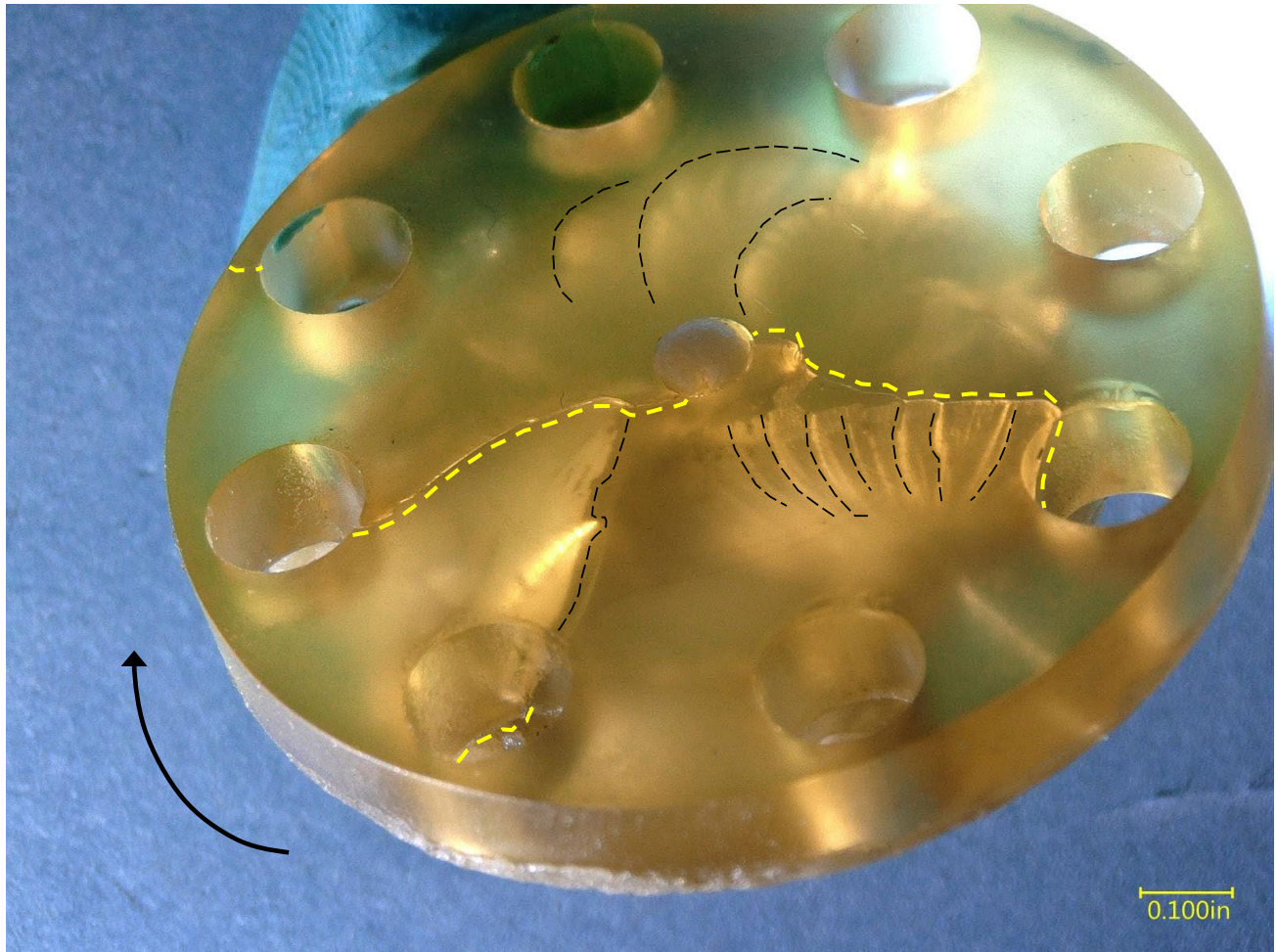


Figure 12: A digital microscope image of the opposite side of the drive side interface of the shear coupling shown in figure 11 (right photograph). The black arrow indicates rotation direction. Yellow dashed lines highlight cracks observed on the surface of the shear coupling spanning between the central hub and outer flange holes. Black dashed lines highlight internal crack arrest and radial marks visible through the translucent shear coupling. Crack orientations were slanted approximately 45° relative to the rotation axis.

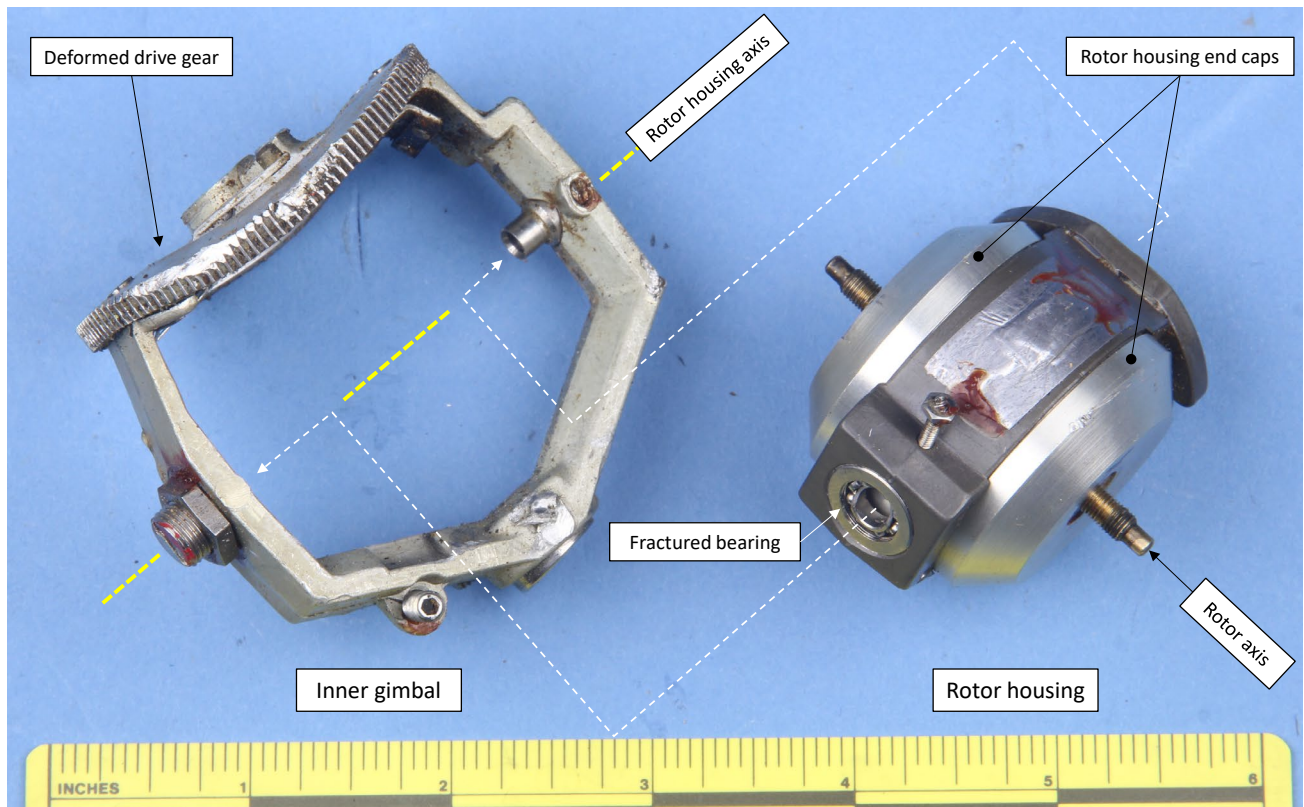


Figure 13: A photograph of the partially disassembled directional gyroscope internal gimbal and rotor housing. White dashed arrows indicate the assembled position where the rotor housing rotated about the axis indicated by the yellow dashed line. The drive gear and gimbal frame were mashed and deformed, consistent with crushing damage at impact. The inner race of one of the rotor housing bearings was fractured, a closer view is shown in figure 14.

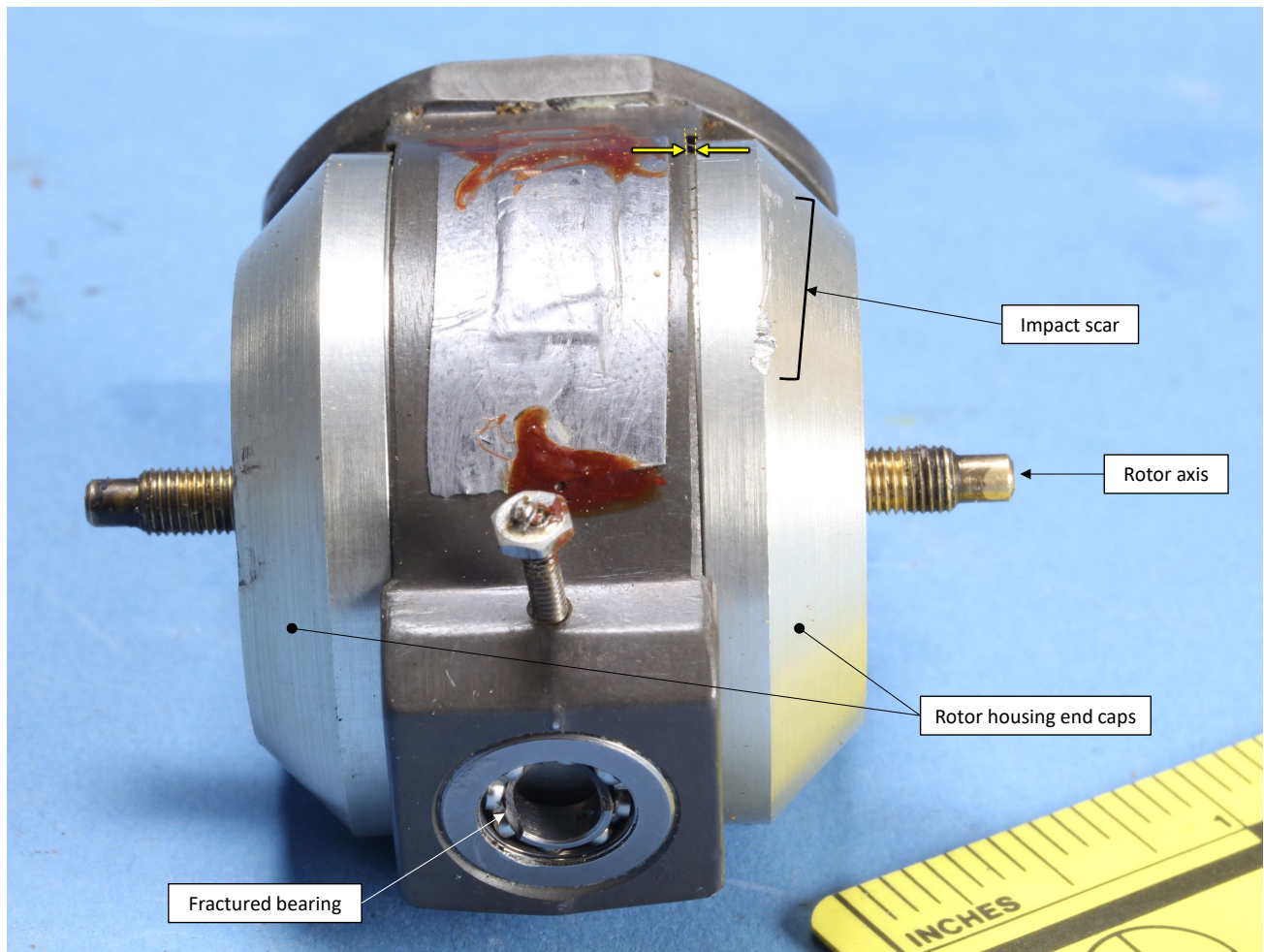


Figure 14: A closer view of the rotor housing, with the fractured bearing shown at the bottom. The fracture surface was dull and rough, consistent with overstress due to crushing at impact. The yellow arrows and dashed lines indicate a wedge-shaped gap observed between the housing end cap and sidewall, the cap was seized within the sidewall and unable to be removed. An impact scar was observed on this endcap as shown bounded by the black bracket. The cap on the left side of the photo exhibited a uniform gap at the interface with the sidewall and was easily removed by hand during subsequent disassembly.

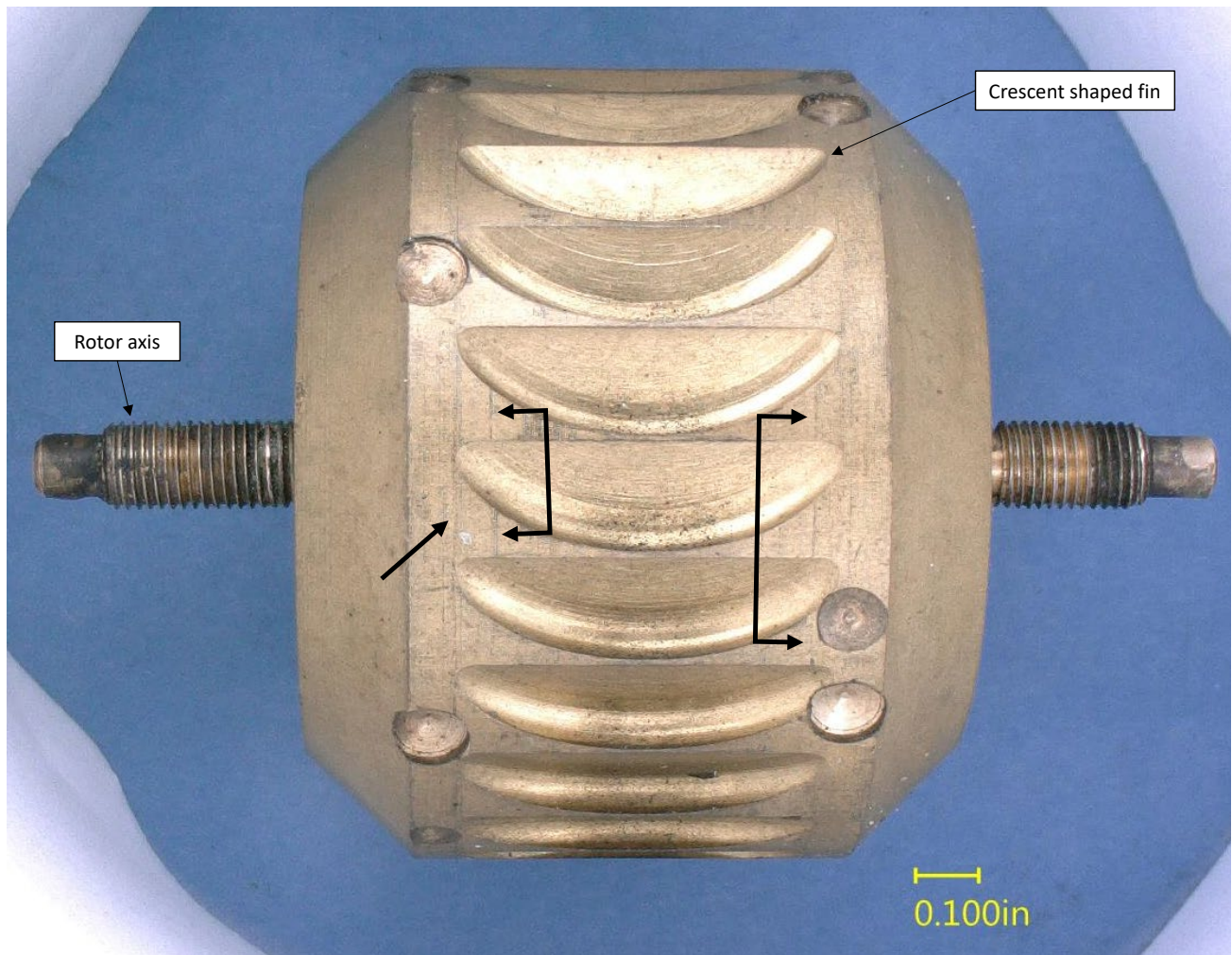


Figure 15: A digital microscope image of the rotor after removal from the housing. The single black arrow indicates a continuous circumferential score mark observed around the entire rotor which corresponded to the location of the edge of the housing cap when installed. The brackets indicate the extent of two prominent local circumferential score marks.

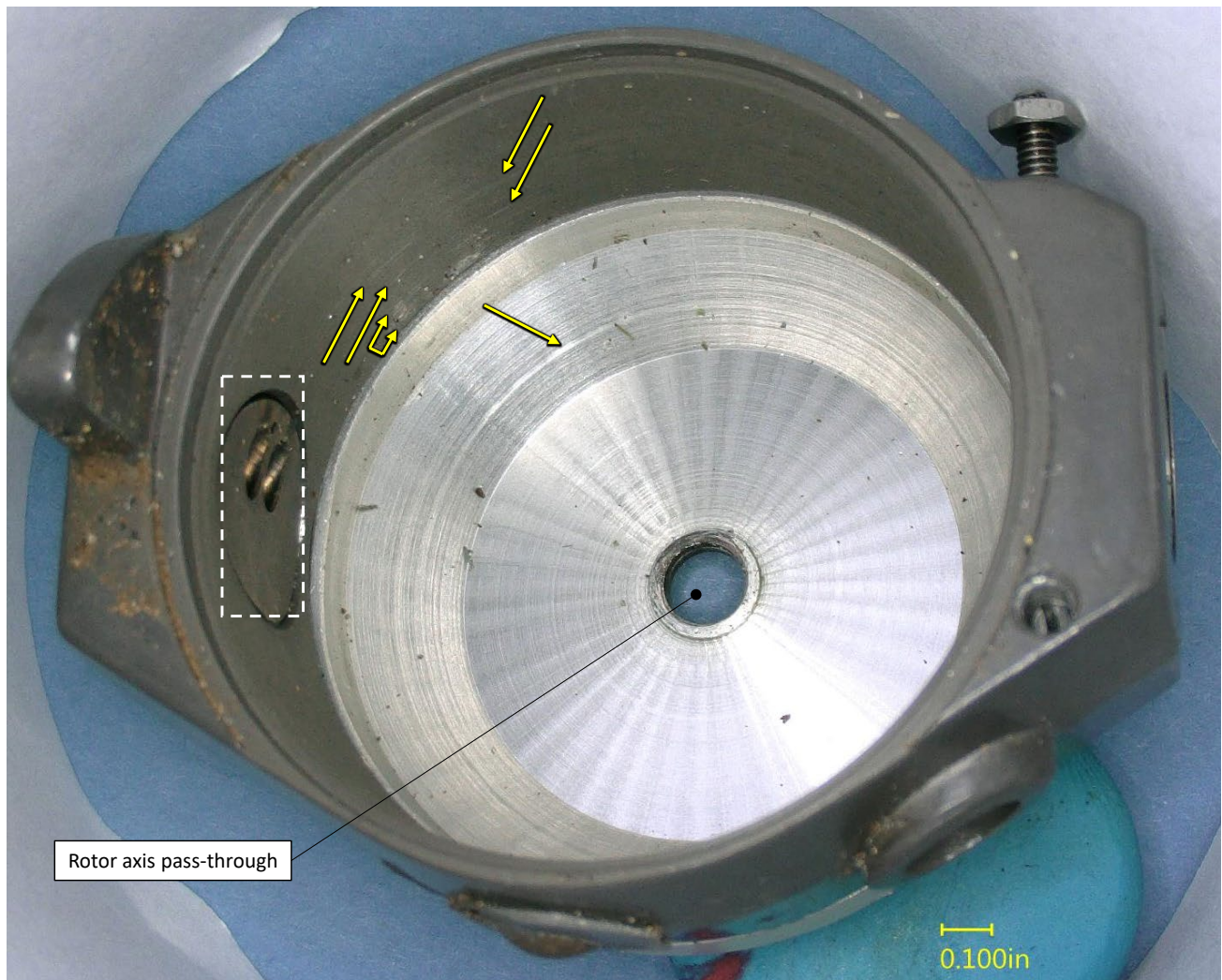


Figure 16: A digital microscope image of the inside of the rotor housing with one of the end caps removed. Yellow arrows indicate circumferential scratches observed on the housing sidewall and end cap. The indicated circumferential mark on the end cap was continuous around the chamfer surface. A corresponding mark was not observed on the rotor. The pattern observed on the interior surface of both caps consisted of circumferential machining marks and sectors of alternating reflectivity on the surface normal to the rotor axis. A closer view of the area within the white dashed box is shown in figure 17.

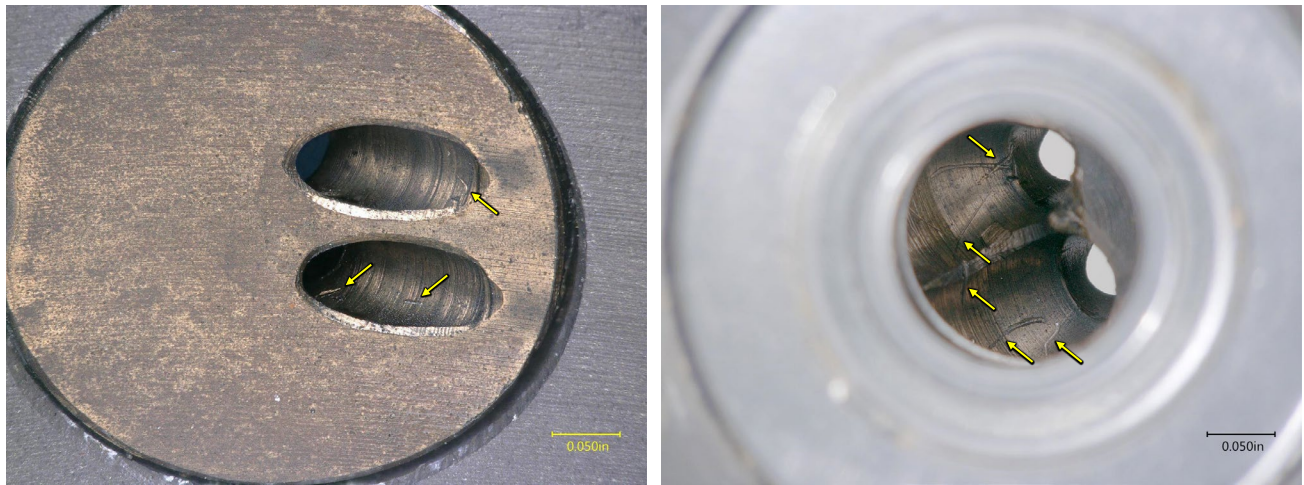


Figure 17: A digital microscope image of the directional gyroscope rotor housing air inlet port from the interior (left) and exterior (right) of the housing. Yellow arrows indicate irregular shaped gouges observed on the flow surfaces.