

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



WPR23LA352

MATERIALS LABORATORY

Factual Report 24-069

12/5/2024

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A. ACCIDENT INFORMATION

Location: San Pedro, California
Date: September 25, 2023
Vehicle: Wayne Toddun Sling 4 TSI (N135WT)
Investigator: Stephen Stein, AS-WPR

B. COMPONENTS EXAMINED

4 cylinders and pistons from a Rotax 915iS piston engine, along with associated spark plugs and knock sensor. Cylinder components included valve train components (each consisting of a tappet, push rod assembly, rocker arm, cotters, spring retainer, spring, washer, and valve) for both the intake and exhaust valves.

C. EXAMINATION PARTICIPANTS

Specialist Brian Fuchs, Ph.D.
National Transportation Safety Board
Washington D.C.

D. DETAILS OF THE EXAMINATION

1.0 Overall Examination

Figures 1-4 show overall images of the cylinders and components submitted for inspection. The cylinder components consisted of the cylinder, cylinder head, piston, and valve train components for the intake and exhaust valves. Also submitted were the spark plugs (Figure 5) and knock sensor (Figure 6). Mechanical damage was noted in cylinder 2, cylinder 4, and the spark plugs. Cylinders 1 and 3 were largely undamaged, but their conditions are documented below.

Cylinder 1 and its associated components showed no signs of mechanical damage. The piston had hard green deposits across its face. One quadrant of the piston face had a thin layer of hard black deposit sitting on top of the green deposit (Figure 7). The composition of this black deposit was not determined. The cylinder head also showed green deposit, and a small amount of black deposit was also visible between the spark plug port and the exhaust valve port. Loose metal flakes were visible in the intake port.

Cylinder 2 showed gouges on the interior of the cylinder head, piston, and interior wall of the cylinder (Figure 8). Several fragments of metal were embedded in the cylinder head, and metal fragments were present in the intake port. X-Ray Fluorescence measurements of one fragment removed from the cylinder head showed a composition (wt%) of 81.2% Fe, 9.7% Co, 2.6% Al, 2.2% Ni, 2.2% Mo, 1.2% S, 0.52% Si, and smaller amounts of other elements. The intake and exhaust valves

showed small scratches and gouges across the faces of the valves (Figure 9). No damage was seen in the other components of the valve train.

Cylinder 3 and its associated components showed no signs of mechanical damage. Hard green deposits were present on the piston and the cylinder head. No deposits were found outside the expected areas of the cylinder.

Cylinder 4 showed the most extensive damage. The cylinder wall showed gouging and scratching, and a portion of the wall was broken off with a rough and matte gray fracture surface, consistent with overstress fracture (Figure 10). The piston showed repeated impacts across its face, to the point where a hole had been punched through the center of the face (Figure 11). The head also showed extensive damage consistent with repeated impacts. Both the intake and exhaust valve heads were broken off their stems, and the stems remained in their guides. The intake stem was bent and immobile in its guide; the guide itself was deformed and fractured. The exhaust valve stem was straight. As received, the exhaust valve stem was stuck in a 'fully extended' position. The fracture surfaces on both stems showed smearing and gouging consistent with repeated impacts after fracture. Both the exhaust and intake valve heads (Figure 12) showed similar gouging and impact damage. The center of the fracture surface of the exhaust stem was open, revealing a hollow cylindrical core. This is consistent with a sodium-filled valve.¹ Manufacturer documentation confirmed that the valves were sodium-filled.

Black residue was found on the stem of the exhaust valve near the tip, below the cotter grooves (Figure 13). This residue was hard and brittle, preventing the stem from being removed from the guide. Later examination of this residue using Energy Dispersive Spectroscopy (EDS) showed high amounts of lead and carbon, consistent with leaded fuel combustion byproduct (Figure 14).

Mechanical damage was noted at several other points in the valve train in cylinder 4. The valve cotters for the exhaust valve showed damage consistent with rubbing or vibration on the outside of the sleeve (Figure 15). This damage was localized to four areas around the circumference of the valve, spaced roughly 90° apart when the two halves were assembled. Similar damage was seen on the inside of the valve spring retainer. The locations of the damage in the retainer roughly lined up with the locations on the outside of the cotter, where the two components would have been in contact during typical use. The foot of the exhaust rocker arm had a

¹ Sodium-filled valves have a hollow cylindrical chamber in the stem is partially filled with sodium metal. During engine operation, the sodium transfers excess heat from the valve head to the stem. Contact between the valve stem and valve guide transfers heat to the cylinder head via conduction. F. Lai, S. Qu, Y Duan., et al. "The wear and fatigue behaviours of hollow head & sodium filled engine valve," *Tribology Int* 128 (2018). Retrieved from <https://www.sciencedirect.com/science/article/abs/pii/S0301679X18303438>

light coating of gray residue (Figure 16).² This residue resembled lighter residues found on the intact exhaust valves from other cylinders. Finally, damage was noted on the tip of the intake valve. One edge of the tip was dented as though by impact, but no corresponding mark was seen on the foot of the intake rocker arm. The oil return sleeve on the intake side of the engine was ovalized and dented along the body, and one of the valve push-rod assemblies showed damage consistent with buckling.

The eight spark plugs were submitted all together, and it was not possible to identify the cylinders that they came from (Figure 5). Four plugs showed damage to the electrode and grounds; in two plugs, the plugs and grounds were eroded away, and the surfaces showed damage consistent with repeated impact. Two other plugs had bent contacts and grounds. A fifth plug showed damage to the opposite end, where the terminal had bent and a piece of the insulator had broken off. The knock sensor showed no damage.

2.0 Comparison of Exhaust Valves

The black residue near the tip of the exhaust valve in cylinder 4 was scraped off with a metal razor blade. This allowed the tip of the stem to slide through the guide to be removed from the cylinder head. The stem showed black and brown discoloration starting at the fracture surface and extending towards the tip (Figure 17). Short (approximately 0.25 inch) longitudinal scrape marks were visible in the brown discoloration. The discoloration remained on the valve after cleaning in an Alconox solution in an ultrasound bath and after rinsing with ethanol. EDS spectra were taken of the base material (shiny metal stem material) and the discolored area (Figure 18). Higher amounts of carbon, bromine, and lead were detected on the discolored surface compared to the base material, consistent with aviation gas exhaust deposits. In a further inspection of the valve from cylinder 3 (documented further below), it was found that similar discolorations could be removed with an Alconox solution and scrubbing with a plastic scrubbing pad.

All exhaust valves taken from the cylinders are visible in Figure 19. For brevity, the valves will be referred to by the cylinder they were taken from (e.g. the valve from cylinder 1 shall be referred to as 'valve 1', cylinder 2 as 'valve 2', etc.). Per the Rotax Maintenance Manual Heavy, the surface of the stem that contacts the valve guide is known as the 'running surface.'³ The ends of the surface are not defined with dimensions in the manual, but the location of surface wear (primarily consisting of shallow longitudinal scratches) on all the valve stems is consistent with the manual's

² The foot is the location where the tip of the exhaust valve would have been in contact with the rocker arm.

³ "Rotax Maintenance Manual Heavy for Rotax Engine Type 915 i A / C24 Series" Issue 0, Rev 2. Ref No.: MMH-915. Retrieved from <https://www.flyrotax.com/p/service/technical-documentation> on 11/24/2024.

graphical depiction (Figure 20). The measured running surface on the intact valves was approximately 1.85 inches.

The three intact exhaust valves showed a buildup of hard black, white, and green deposits on the back of the face and the lower portion of the stem. On valve 4, a shiny silver-colored circumferential ring was noted on the stem approximately 0.75 inch from the fracture surface. When the stem was lined up next to other intact exhaust valves, this ring approximately lined up with the upper edge of the thick deposits on the intact valves.

Brown and black discoloration was noted on the stems of all valves above the deposit build-up. The discoloration was most uniform and extended up the stem furthest on valve 4. Table 1 notes the appearance and extent of the discoloration seen on all four valves. A warning in the maintenance manual states that oil residues are permissible on up to 20% of the running surface, else the valve may be at risk of failure at the weld point due to overheating. The manual further states that any valve showing higher amounts of residue must be replaced due to increased risk of failure at a weld in the valve.

Table 1. Appearance and length of discoloration seen on the exhaust valves, measured from the lower end of the running surface.

Valve	Appearance	Length, inch (% running surface ⁴)
1	Dark brown/black	0.19 (10)
2	Light brown patina	0.30 (16)
3	Patchy black/brown, some light areas	0.74 (40)
4	Uniform black or brown	1.11 (60)

The diameter of each valve stem was measured at two locations on each valve, at 0.12 inch from each end of the running surface, in accordance with the inspection outlined in the Rotax maintenance manual. These measurements, as well as callouts and tolerances listed in the manual, are shown in Table 2. The stems were thinnest at the lower end of the running surface (closest to the face). At this location, valve 3 was at and valve 4 was below the 100% tolerance limit for measurements near the lower end of the running surface. Valves 1 and 2 were within the 50% tolerance limit at all measured locations.

⁴ Average running surface length of 1.85 inches used for calculation of percentage.

Table 2. Measurements of the diameter of the stems at two locations. Measurements are documented by distance from the valve tip. Reported values are the averages of at least 4 measurements. Items in italics are tolerances from the maintenance manual.

Valve	Exhaust Stem Diameter (inch)	
	0.60 inch from tip	2.05 inches from tip
1	0.2743	0.2740
2	0.2744	0.2741
3	0.2742	0.2732
4	0.2743	0.2711
<i>“Current Measurement (max)”</i>	0.2748	
<i>“Tolerance Limit (50%)”</i>	0.2737	
<i>“Tolerance Limit (100%)”</i>	0.2732	

Complementing measurements were also taken of the exhaust valve guides in the cylinders 3 and 4. A combination split-ball gauge and flat-faced micrometer were used to measure the inner diameter of the exhaust valve guides. Measurements were taken near the top, middle, and bottom of each guide. Further, measurements were taken vertically (d_v) and horizontally (d_h) to check for uneven wear or deformation of the guides (Figure 21). The measurements and associated tolerances (listed in the maintenance manual) are shown in Table 3. The valve guides were widest at the bottom; at this location, cylinder 3 was outside the 50% tolerance limit. Cylinder 4 was at or was outside the 100% tolerance limit at all measured locations in the valve guide.

Table 3. Measurements of the inner diameter of the valve guides. Reported values are the averages of at least 4 measurements. Items in italics are tolerances from the maintenance manual.

Valve	Location	Inner Diameter (inch)	
		d _v	d _h
3	0.2 inch from top	0.2757	0.2763
	0.71 inch from top	0.2786	0.2782
	0.2 inch from bottom	0.2806	0.2805
4	0.1 inch from top	0.2831	0.2815
	0.71 inch from top	0.3014	0.2943
	0.2 inch from bottom ⁵	0.3178	0.3040
<i>"Current Measurement (max)"</i>		--	0.2763
<i>Tolerance Limit (50%)</i>		--	0.2789
<i>Tolerance Limit (100%)</i>		--	0.2815

The minimum and maximum backlash (the spacing between the valve stem and valve guide) was calculated from the valve stem diameter and valve guide diameter measurements and is displayed in Table 4. Both valves are above the 100% tolerance limit for the maximum backlash, which was found near the face end of the running surface.

Table 4. Backlash calculation for the exhaust valves based on measurements of the valve stem diameter and valve guide inner diameter.

Valve	Backlash (inch)	
	Minimum	Maximum
3	0.0015	0.0073
4	0.0063	0.0467
<i>Current Measurement (max)</i>		0.0021
<i>Tolerance limit (50%)</i>		0.0040
<i>Tolerance limit (100%)</i>		0.0059

Valve 4 was cross-sectioned and a portion of the stem was mounted and polished for Vickers microhardness tests. Five measurements were taken across the surface. The average hardness measured as 376±14.8 HV0.5, consistent with a hardened chrome steel.

Valve 3 was cleaned and subjected to further inspection. A scrubbing pad and Alconox solution were used to remove the black residue on the stem near the face of the valve, in the region where valve 4 had failed. Removal of the caked-on residue revealed dispersed imperfections on the surface of the valve (Figure 22). The largest such imperfection was approximately 0.01 inch across. Examination of this imperfection in a field-emission scanning electron microscope (SEM) did not show

⁵ Mechanical damage was noted in the cylinder head around the bottom edge of the valve guide.

any cracks extending from the imperfection (Figure 23). EDS scans showed increased amounts of lead and carbon in the imperfection, consistent with exhaust residue (Figure 24).

3.0 Further Examination

The valve train includes a washer placed between the valve spring and the cylinder head. The Rotax maintenance manual recommends inspection of the washers for damage and wear. The washers from the intake and exhaust valves on cylinder 4 were examined. The washer from the exhaust valve is shown in Figure 25. Each washer showed a dark gray ring on one face. The ring was circumferential around the approximate center of the face. A dial thickness gauge was used to measure the thickness of the washer at four locations on both washers, shown schematically in Figure 25. The measurement closest to the inner edge was used to establish the baseline thickness, and subsequent measurements closer to the outer edge were to check for a change in thickness. Measurements are detailed in Table 5. The maintenance manual states that a change of 0.0016 inch should result in valve train component replacements. No measurements showed a thickness change of that magnitude.

Table 5. Measurements of the washer thickness (inch), shown schematically in Figure 25.

<i>Intake Washer</i>	Inner	1	2	3
East	0.0393	0.0393	0.0391	0.0390
North	0.0397	0.0397	0.0393	0.0390
West	0.0391	0.0391	0.0391	0.0390
South	0.0391	0.0391	0.0391	0.0390
<i>Exhaust Washer</i>	Inner	1	2	3
East	0.0389	0.0389	0.0389	0.0385
North	0.0391	0.0390	0.0390	0.0389
West	0.0389	0.0389	0.0389	0.0389
South	0.0389	0.0389	0.0389	0.0389

Submitted by:

Brian Fuchs, Ph.D.
Materials Engineer



Figure 1. Cylinder 1 components; intake components on the left side of the image, and exhaust components on the right.

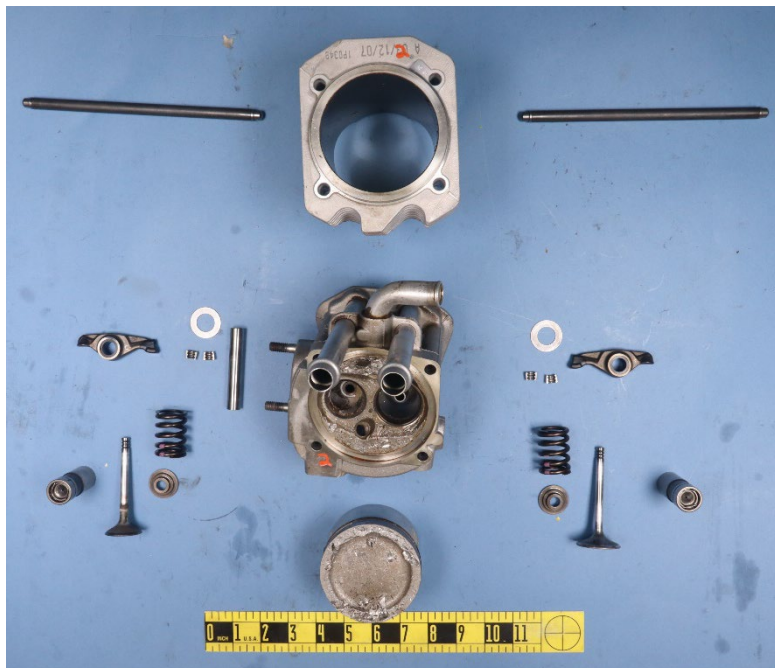


Figure 2. Cylinder 2 components; exhaust valve train components on the left side of the image, and intake valve train components on the right.

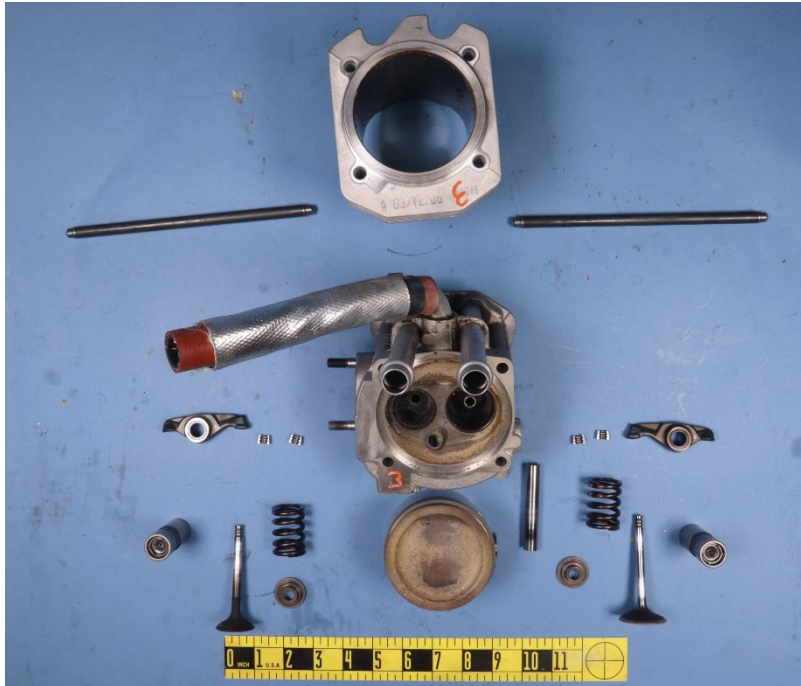


Figure 3. Cylinder 3 components; exhaust valve train components on the left side of the image, and intake valve train components on the right.

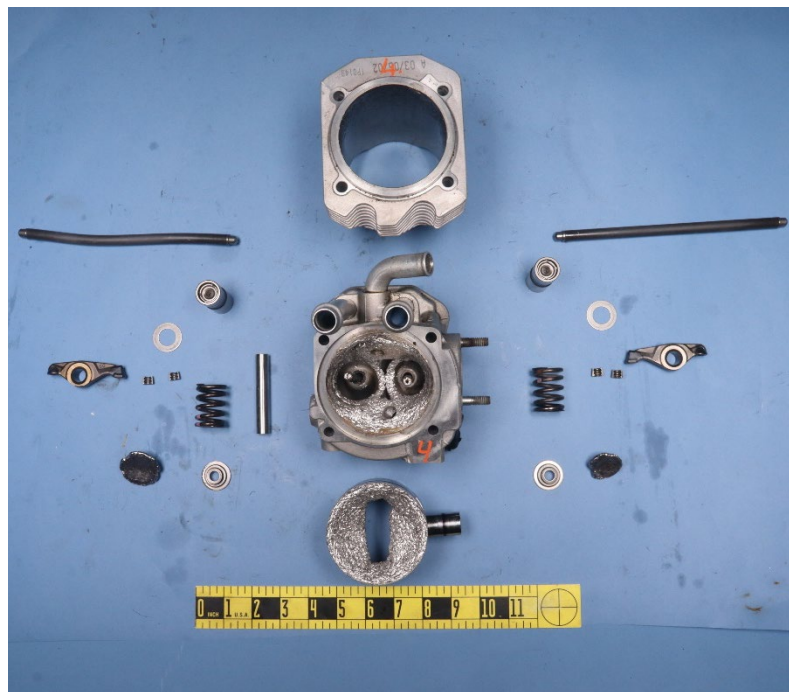


Figure 4. Cylinder 4 components; intake valve train components on the left side of the image, and exhaust valve train components on the right.

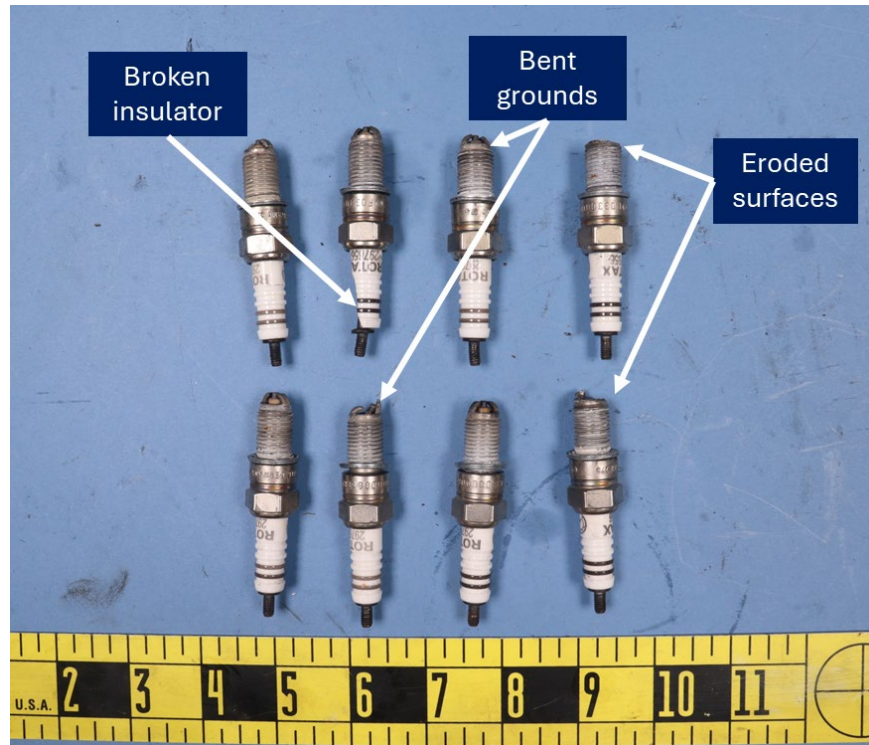


Figure 5. Four spark plugs showed damage to the ground and terminal surface. One spark plug had a broken insulator.



Figure 6. Knock sensor and attachment bolt.



Figure 7. Black residue on the (left) piston and (right) cylinder head for cylinder 1.



Figure 8. (Left) The cylinder head and (right) piston for cylinder 2 showed gouges across the surfaces. Metal fragments were embedded in the cylinder head.



Figure 9. Both the (left) intake and (right) exhaust valves from cylinder 2 showed small gouges and scratches across their faces.

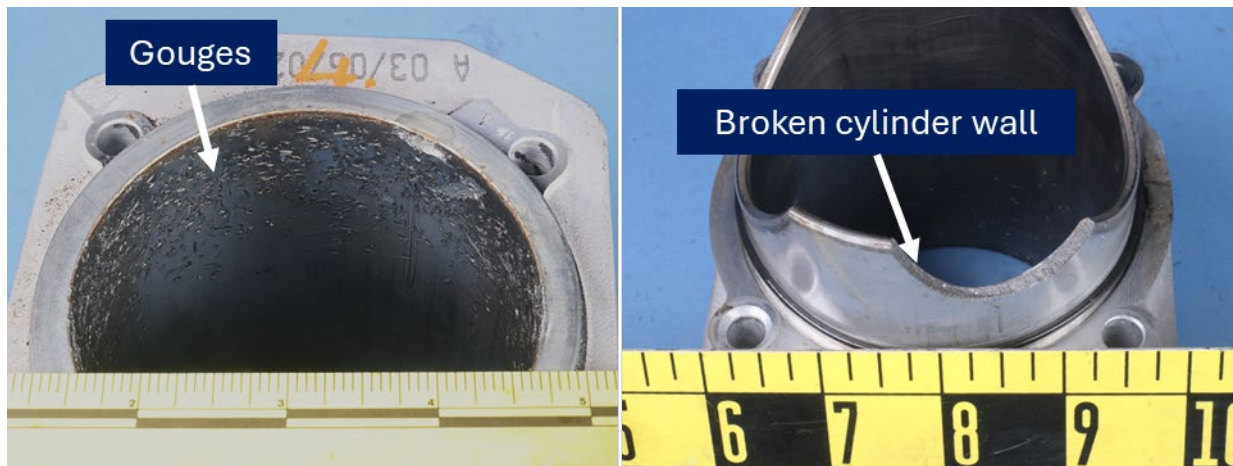


Figure 10. (Left) Gouges in the wall of cylinder 4 near the cylinder head. (Right) fractured section of cylinder wall.



Figure 11. (Left) The piston and (right) cylinder head from cylinder 4 showed significant impact damage across their faces. The fracture surfaces of the valve stems showed similar damage.

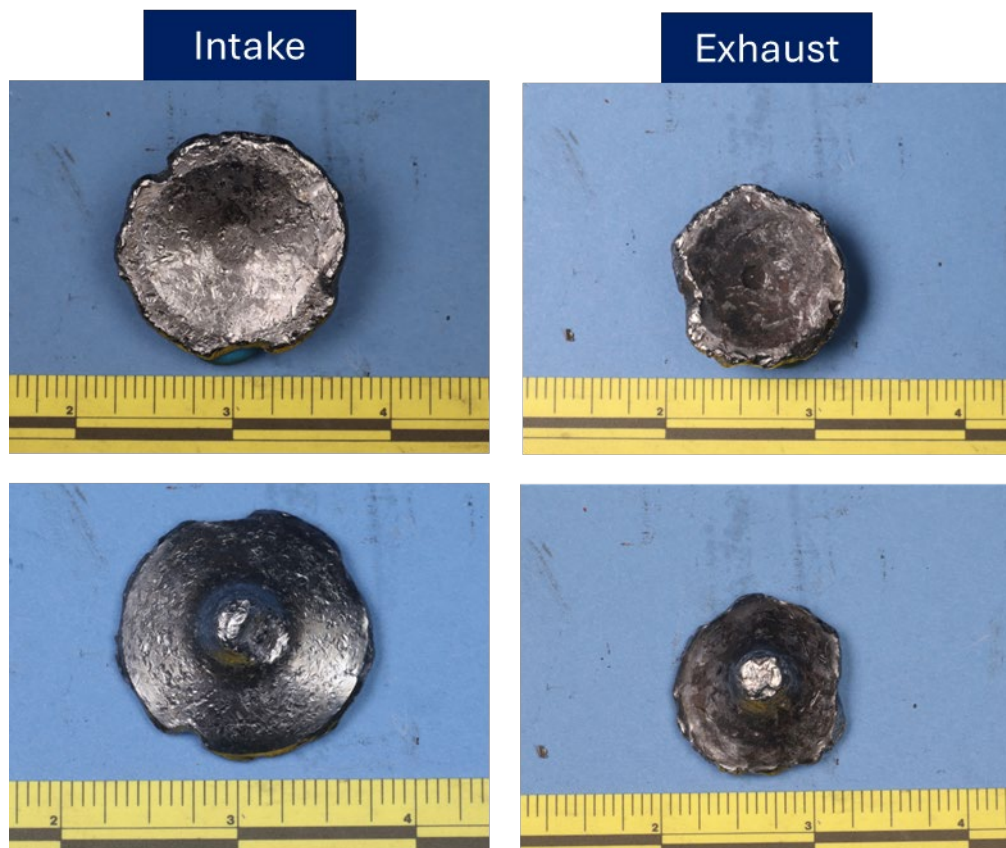


Figure 12. (Upper left) Intake valve face and (lower left) rear face. (Upper right) Exhaust valve face and (lower right) rear face. Both pieces showed significant gouging and impact damage.

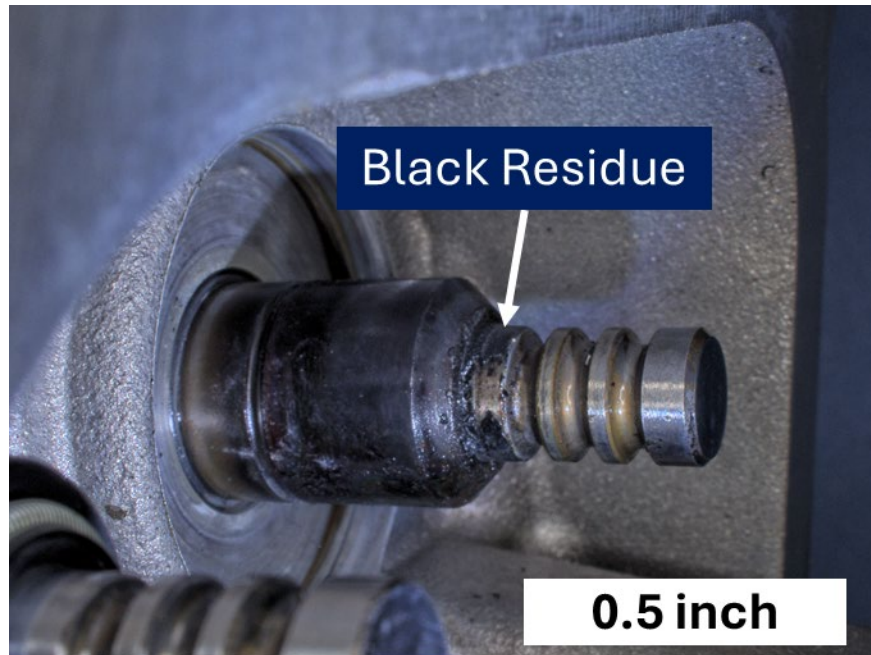


Figure 13. A black residue was visible below the tip of the exhaust valve.

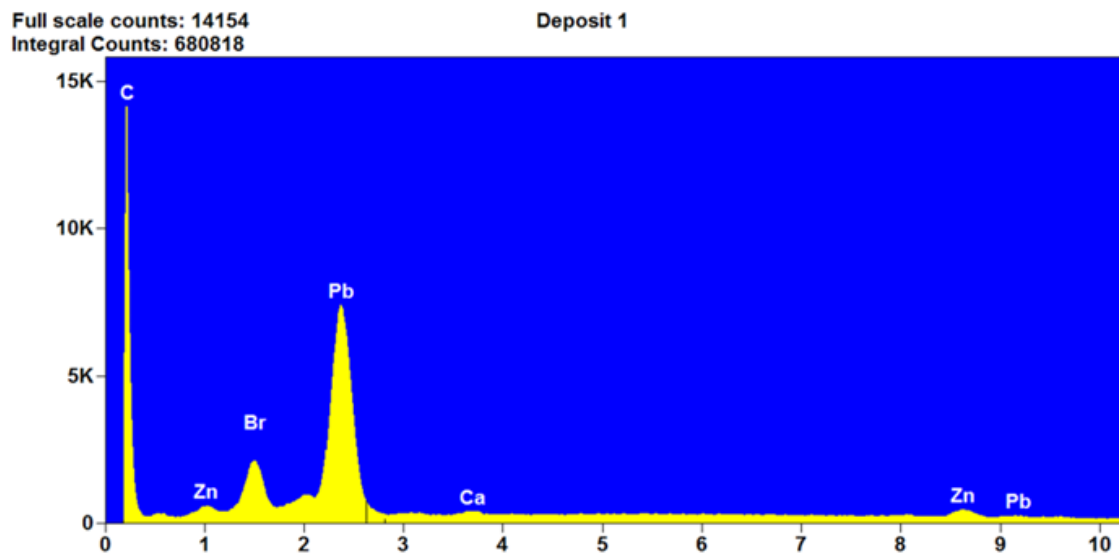


Figure 14. The EDS spectrum of the black deposits on the tip of the exhaust valve showed high amounts of lead and carbon.

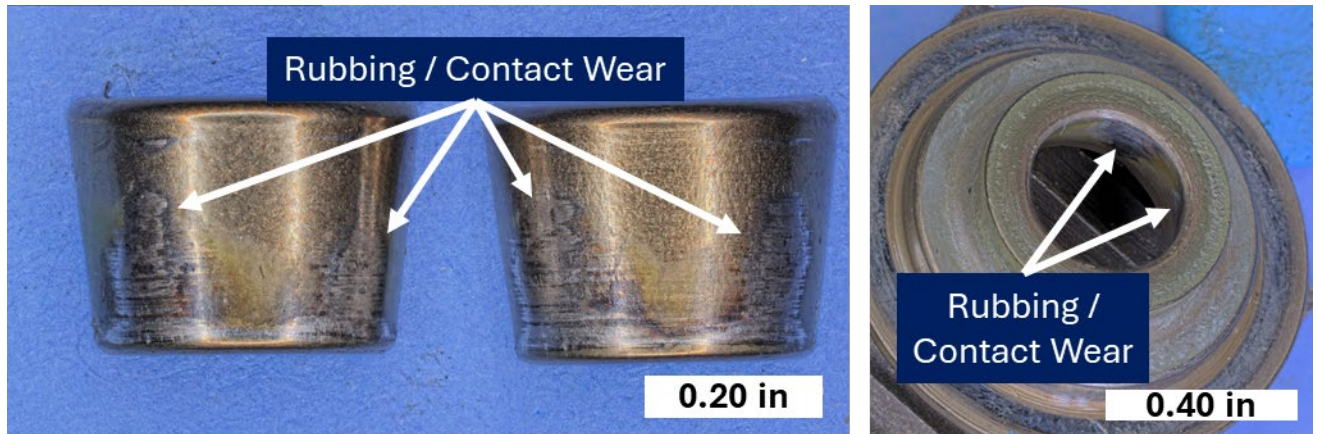


Figure 15. (Left) The outer surface of the cotters from the exhaust valve on cylinder 4 showed contact wear localized to 4 areas approximately 90° apart. (Right) Contact wear on the interior wall of the valve spring retainer roughly lined up with the wear on the cotters.

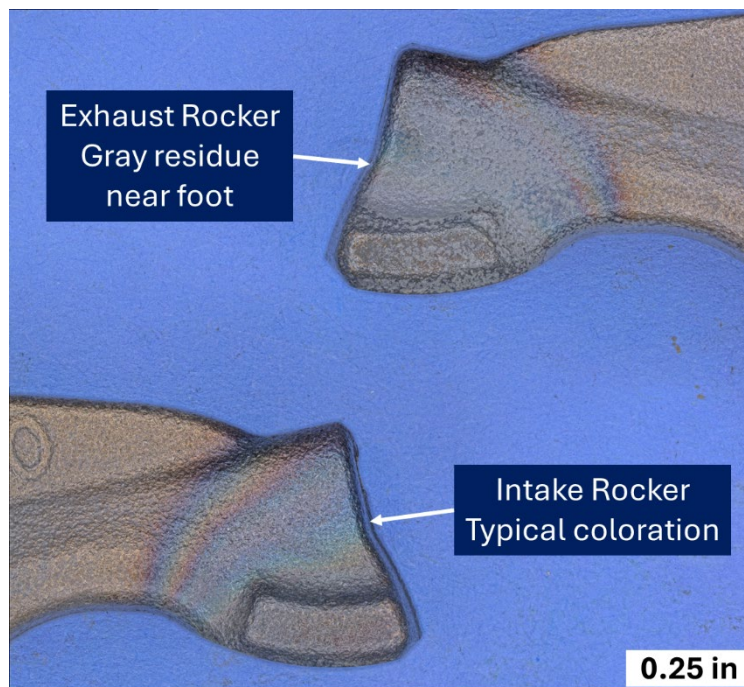


Figure 16. A light coating of gray residue was seen on the foot of the exhaust rocker arm from cylinder 4. The intake rocker arm shows the typical coloration.

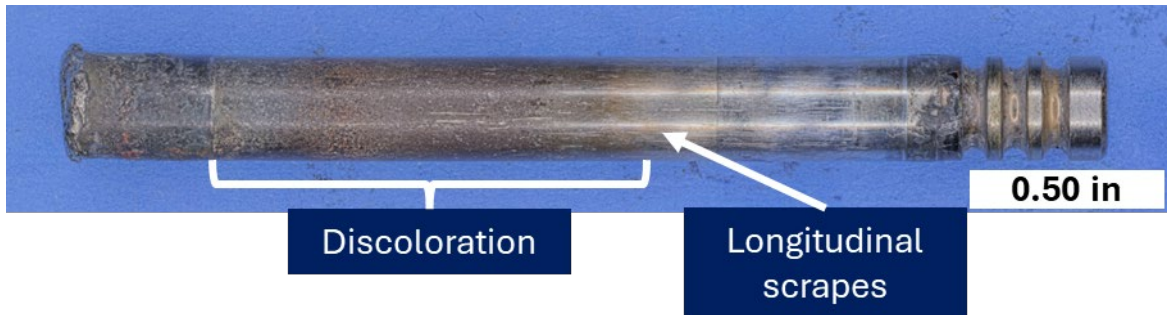


Figure 17. The exhaust valve stem from cylinder 4 after removal from the cylinder head.

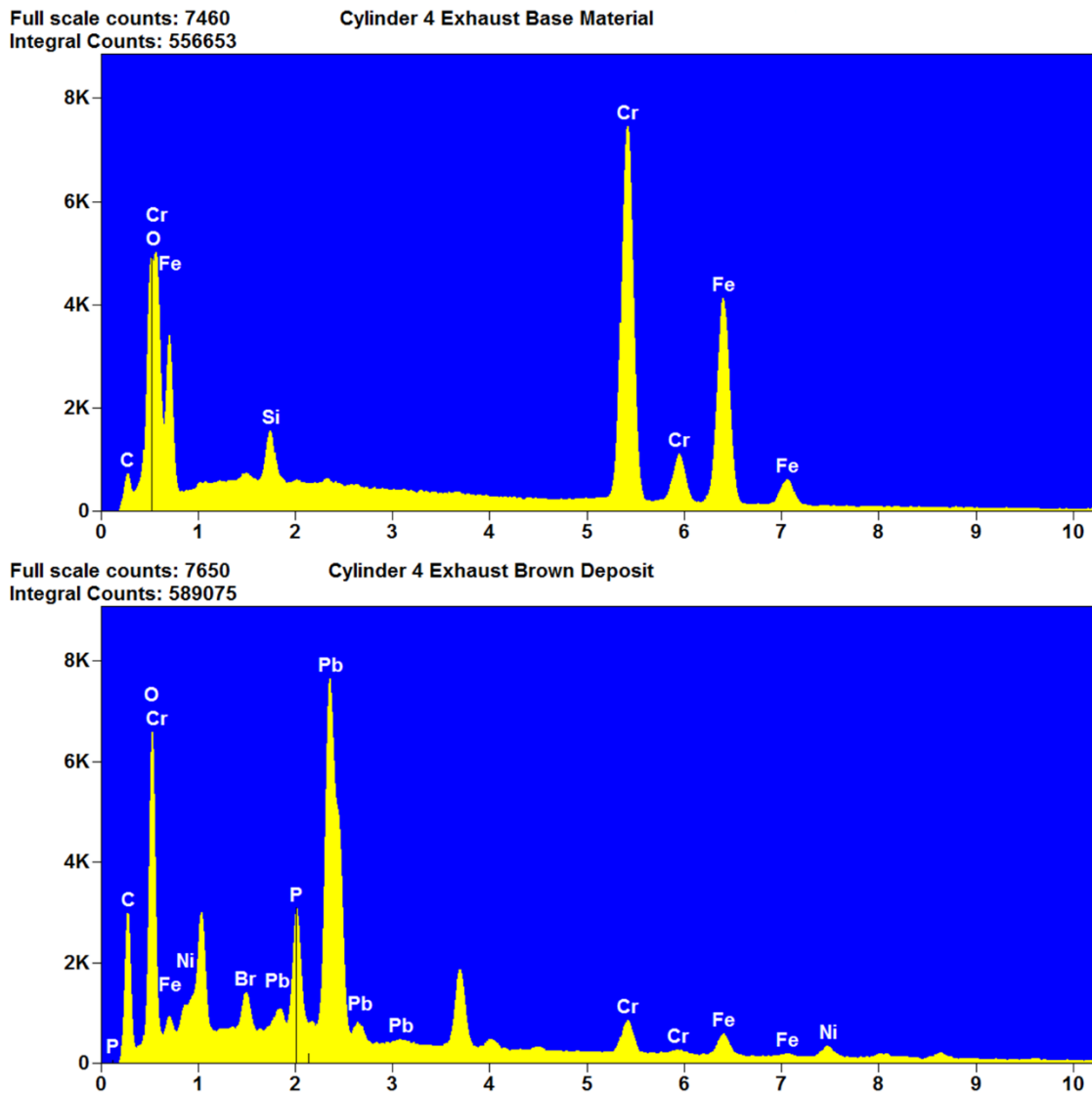


Figure 18. (Top) EDS spectra of the base material for the exhaust valve stem from cylinder 4. (Bottom) The EDS spectra of the brown deposit on the stem showed increased amounts of lead, bromine, and carbon.

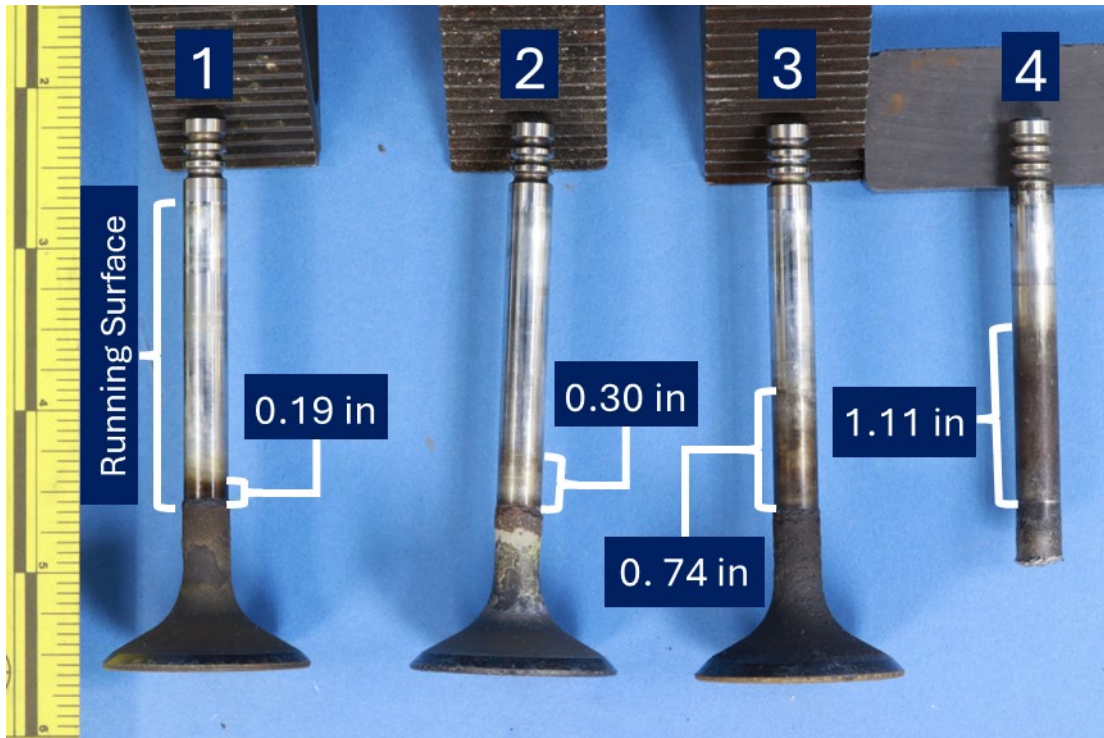


Figure 19. The four exhaust valves (three intact, one fractured) from the cylinders had brown discoloration(s) on the stem above the faces of the valve.

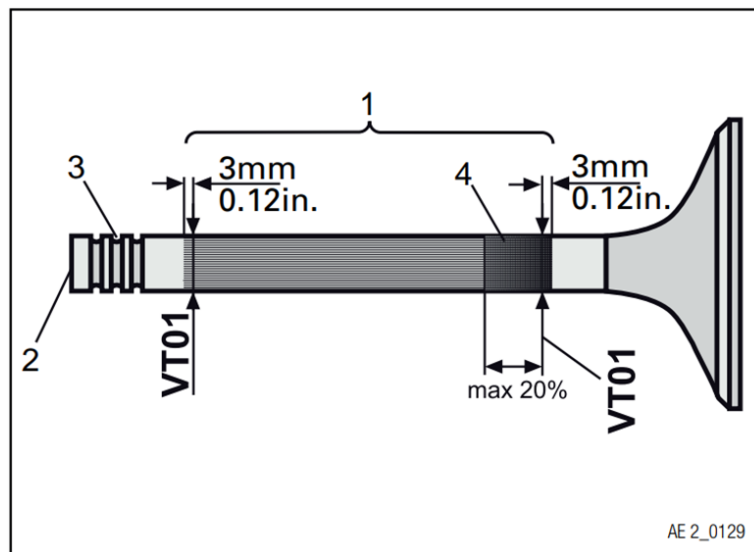


Figure 20. Schematic depiction of the valves taken from the Rotax Maintenance Manual Heavy. Measurements and markings indicate areas of necessary inspections described in the manual. The bracketed area demarcated by '1' is referred to as the 'stem' and the 'running surface' in the manual.

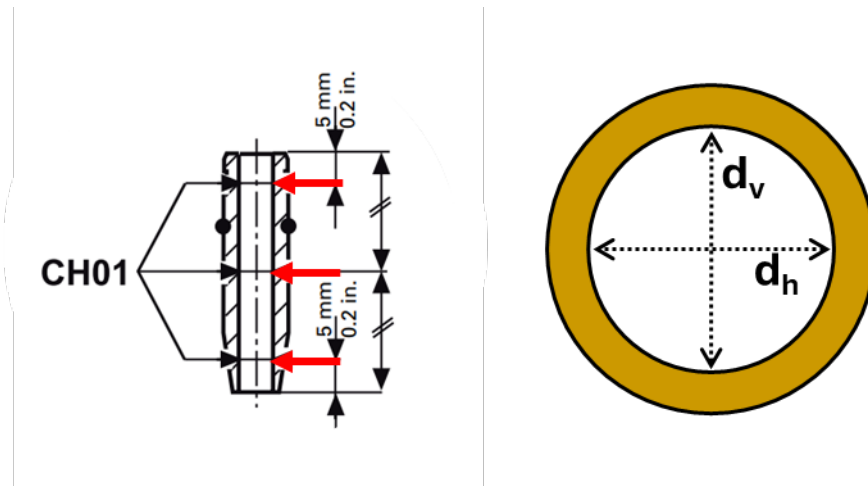


Figure 21. (Left) Schematic depiction of the locations to measure the inner diameter, adapted from the Rotax Maintenance Manual Heavy. (Right) Measurements were taken in two perpendicular directions. The vertical direction aligns with the nominal orientation of the cylinder when mounted.

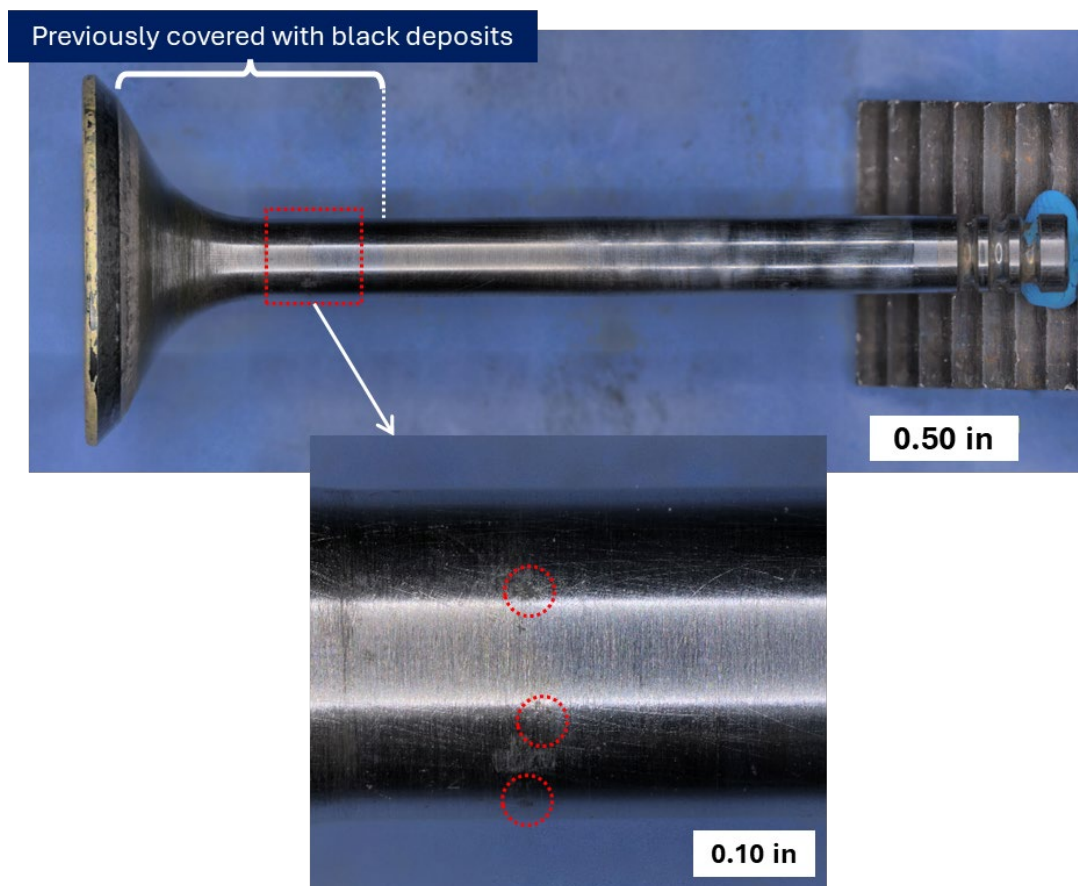


Figure 22. Valve 3 after cleaning with a scrubbing pad and Alconox solution. Red circles in the inset show visible surface imperfections.

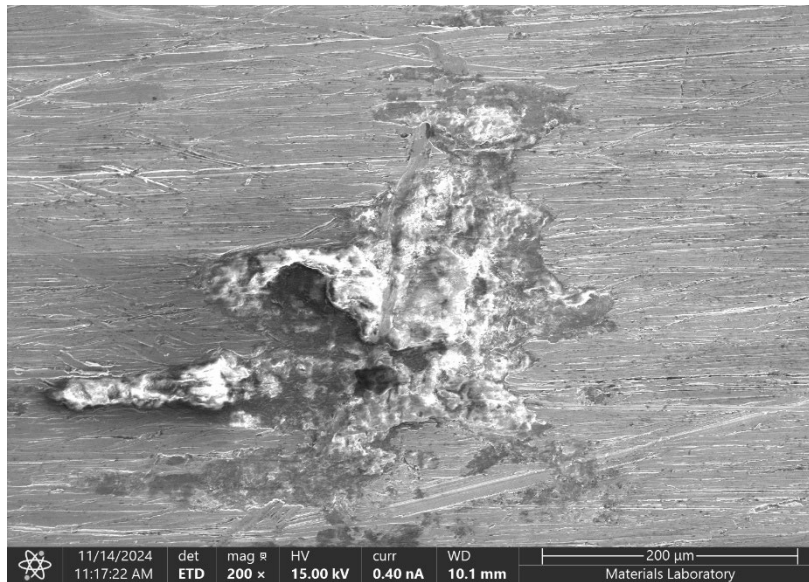


Figure 23. Backscattered electron image of the largest surface imperfection seen on the surface of valve 3.

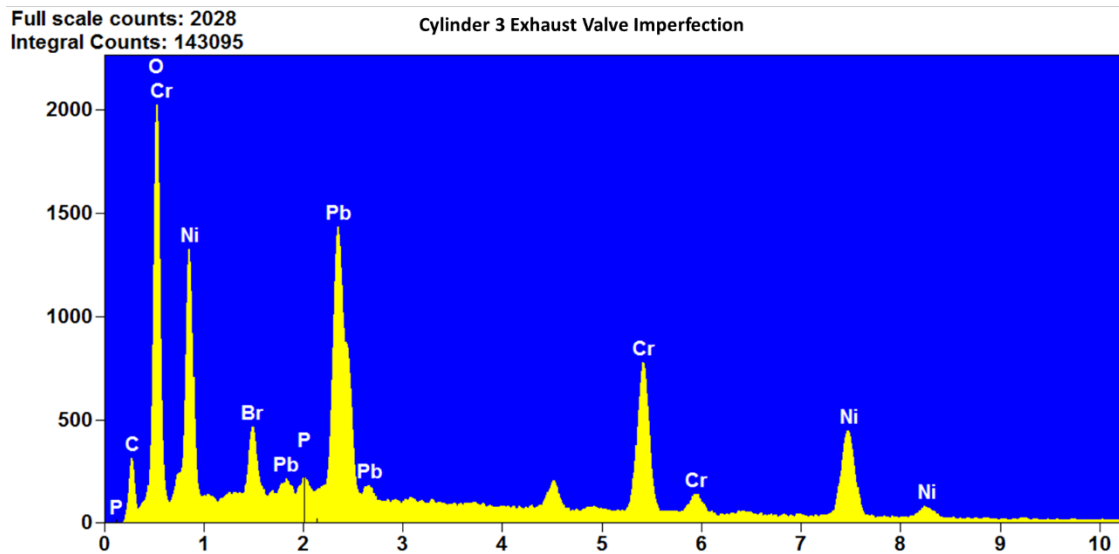


Figure 24. EDS spectrum of the surface imperfection in Figure 23.

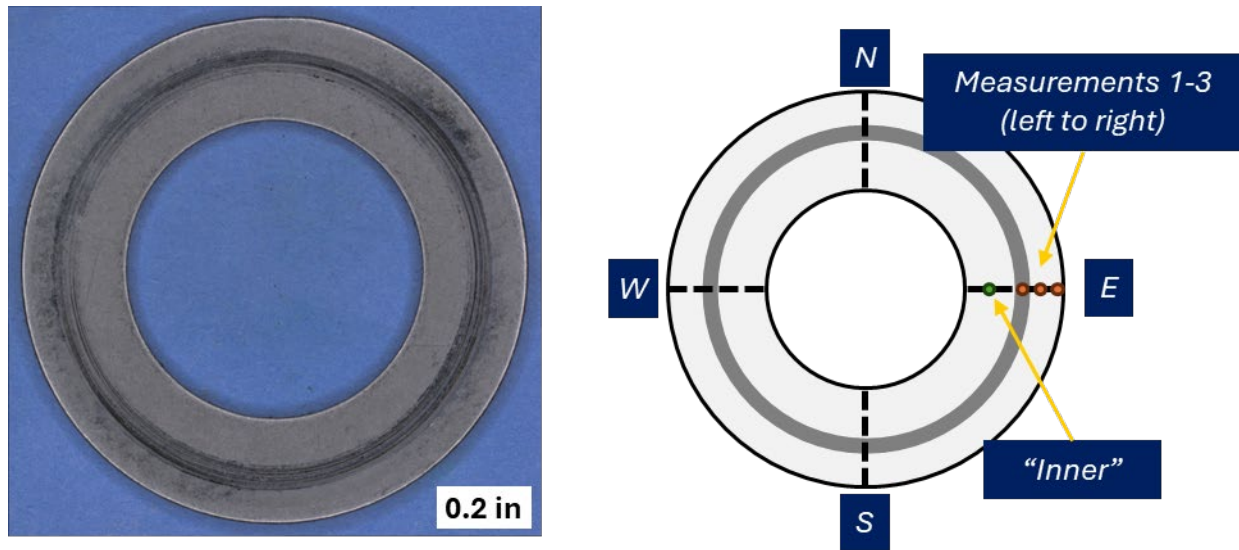


Figure 25. (Left) Exhaust valve washer from cylinder 4. (Right) Schematic depiction of measurements taken on the intake and exhaust washers. The green dot represents the baseline 'inner' thickness and the orange dots are the points checked for a change in thickness. Measurements were taken at 4 locations around the washers, marked by letters in the schematic.