

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



ERA24LA066

MATERIALS LABORATORY

Factual Report 24-072

October 11, 2024

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A. ACCIDENT INFORMATION

Location: Asheville, North Carolina
Date: December 14, 2023
Vehicle: Diamond Aircraft Industries Incorporated, DA 40 NG airplane, N907L
Investigator: Leah Read (AS-ERA)

B. COMPONENTS EXAMINED

- Engine block;
- Cylinder head;
- Crankshaft;
- No.1 piston (wrist pin not recovered);
- No 2 piston was not recovered;
- Unidentified connecting rod (by default is either a “#1” or “#2” connecting rod), fractured fragment of an attachment bolt that remained attached to each arm portion of the connecting rod (the cap, two bearing halves, and wrist pin from the unidentified connecting rod were not recovered);
- No.3 piston with connecting rod, cap, two bearing halves, and wrist pin;
- No.4 piston with connecting rod, cap, two bearing halves, and wrist pin;
- No. 1 thru No. 4 main journal caps and their respective bearings (2 halves each);
- Two pieces of crankshaft shims from the #4 cylinder;
- Bag of miscellaneous fractured pieces that were found in the oil sump;
- All from engine model E4-A-6603 manufactured by Austro Engine GmbH, Austria.

C. EXAMINATION PARTICIPANTS

Sr. Metallurgist	Frank Zakar NTSB Washington, DC
Investigator-In-Charge	Leah Read NTSB Alton Bay, New Hampshire
Engineering Technician	Ed Komarnicki NTSB Washington, DC
Party coordinator	Sean Gallinat Lyft Academy Indianapolis, Indiana

Costumer Support Manager	Ray Kolyn Diamond Aircraft Woodstock, ON, Canada
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Engine inspection	Marcel Handl Austro Engines Wiener Neustadt, Austria
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Customer Support	Amirhossein Eshtehardi Austro Engines Wiener Neustadt, Austria
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D. DETAILS OF THE EXAMINATION

Figures 1 through 5 show photographs of the as-received engine pieces from a 4 cylinder diesel engine, model E4-A-6603, that was manufactured by Austro Engine GmbH, Austria.¹ The crankshaft is numbered from aft to front, starting with the #1 main journal (#1MJ) and #1 rod journal (#1RJ), and ending with the #5 main journal (#5MJ), see figure 1.

Fractured Main Bearing Screw from the #2 Main Journal (#2MJ)

The engine was installed with a total of ten main bearing screws, Austro Engine part number (P/N) E4A-10-100-201. Examination of the as-received engine revealed a main bearing screw fragment from the #2MJ was attached to the engine (see figure 5), but the remaining (nine) main bearing screws were not submitted with the engine. The main bearing screw fragment from the #2MJ fractured in the area below the head, at the transition radius between the screw head and nonthreaded shank portion (see figure 6). The fractured screw head was not recovered. The fracture face of the screw fragment was located approximately 1.6 inch [41 mm] above the flat land (parting plane) for the #2MJ.² The screw fragment could not be turned by hand relative to the engine and it was disassembled from the engine block with the aid of pliers. Care was taken not to touch the fracture face during disassembly. The fractured screw was brush cleaned with Alconox, a commercial detergent, followed by ultrasonic cleaning in acetone.

Bench binocular microscope examination of the disassembled main bearing screw fragment revealed the fracture face contained evidence of beach marks, typical of fatigue cracking, that emanated from multiple origins at the transition radius

¹ E4-A designation refers to the engine model number and the 6603 designation refers to the engine serial number.

² The specified nominal length of a main bearing screw is 66 mm (2.6 inch), from head to end of the threaded portion.

between the head and non-threaded shank, on one side of the screw, see figure 6. Scanning electron microscope (SEM) examination of the screw fracture face revealed the fatigue crack propagated through approximately 95% of the screw cross section. Typical fatigue striations are shown in figure 7. The origin of the fatigue crack showed no evidence of corrosion damage. The fatigue origin in several areas contained post-accident mechanical damage. The fatigue crack terminated in the area indicated by a dashed line in figure 6. The remaining portion of the fracture face exhibited evidence of microvoid coalescence features typical of overstress separation.

The threads of the screw fragment contained evidence of two minor cracks. The cracks were located on the diametrically opposite side of the fatigue origin and on the root of the first two threads below the head area. The circumferential length of the crack on the first thread root adjacent to the head measured approximately 0.115 inch (2.9 mm) and that of the crack on the second thread root measured approximately 0.171 inch (4.3 mm).

A longitudinal-radial section was made through the origin of the fatigue crack. The section was encased in a metallurgical mount, ground and polished in accordance with standard laboratory procedure, and the prepared section was etched with 2% Nital reagent. The section exhibited a microstructure of tempered martensite. The tempered microstructure grains at the core showed evidence of preferred rolling direction which was parallel to the length of the screw (see figure 8). No evidence of corrosion or material anomalies were noted at the origin of the fatigue crack. The areas adjacent to the threads (root and crest areas) showed evidence of mechanical deformation consistent with rolled threads. The section incorporated the circumferential cracks (described earlier) that were located at the root of the first two threads adjacent to the head. The depth of the two cracks measured approximately 0.425 mm (0.017 inch), each.

Specification for the Main Bearing Screws

The Austro Engine engineering drawing for the P/N E4A-10-100-201 main bearing screw specified a strength class 8.8 screw with the following exceptions: screw is to be made from 1.7033 (34Cr4) steel³; the specified ultimate tensile strength (R_m) is in the range 800 – 950 N/mm² [116,030 - 137,786 psi]; the yield strength (R_{EL}) is calculated from the formula $0.85 - 0.90R_m$, where R_m in the formula is the measured tensile strength of the tensile specimen; percent elongation after fracture (A_5) is 12% minimum; and reduction in area after fracture (Z) is 50% minimum. The mechanical properties of the screws are verified by tensile testing a select batch of screws. The screws receive a surface treatment called "thin-layer phosphating." The head of the

³ Grade 34Cr4 (Material number 1.7033) steel is a material code designation in the German standard DIN EN-10083-3.

screws manufactured for Austro Engine are not marked with the class or manufacturer designation.

Labelling the Main Bearing Screws for Testing

After the group examination and at the request of the IIC the salvage facility shipped the remaining (nine) main bearing screws to the NTSB Materials Laboratory. NTSB arbitrarily labeled the nine main bearing screws as "A1" through "A9" and the main bearing screw fragment from the #2MJ was labelled "A10". Lyft Academy also submitted six disassembled main bearing screws, arbitrarily labelled by NTSB as "E1" through "E6", from an airplane engine that was not involved in this accident. The main bearing screws were arbitrarily labelled because the position of the screws were not recorded. Chemical analysis, tensile testing, and hardness testing of the main bearing screws were conducted by Applied Technical Services (ATS), Marietta, Georgia, with the exception that hardness testing of screw fragment "A10" was conducted by NTSB.

Chemical Analysis of the Main Bearing Screws

Results of the chemical analysis for the main bearing screws are shown in table 1. The chemical composition of all the accident and exemplar screws were within the elemental limits specified by the Austro Engine engineering drawing.

Tensile Testing of the Main Bearing Screws

Each intact main bearing screw was machined by ATS into sub-size tensile specimens and tested to fracture. Results of the tensile testing are shown in table 2. The measured ultimate tensile strength (UTS) of the "A7" main bearing screw was 795 N/mm², slightly less (by 5 N/mm²) than the specified range (800-950 N/mm²). The yield strength of screws "A2", "A3", "A5", and "A9", were greater than the calculated range (0.85-0.90R_m) specified by the Austro Engine engineering drawing. The measured yield strength of the remaining screws were within specified range. The elongation and reduction in area values for all the screws were within the engineering drawing specifications. The tensile values of all the exemplar screws were within the specified range.

Hardness Testing of the Main Bearing Screws

For reference purpose, hardness tests were conducted on all the submitted main bearing screws. International Organization Standard (ISO) 898-1 is a standard for grading bolts and screws. An example is class 8.8 screw. The fifth edition, dated 2013-01-15, of this document is titled "Mechanical properties of fasteners made of carbon steel and alloy steel, Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread". According to this document, hardness properties for class 8.8 screws are based on the diameter of the screw. Hardness for

screws having a diameter equal to or less than 16mm should be in the range between 22 HRC and 32 HRC.⁴ The diameter of the accident and exemplar screws fall into this category. For diameter that exceeds 16mm, the hardness should be in the range between 23 HRC and 34 HRC.

After tensile testing, a longitudinal saw cut was made at ATS by an abrasive cut-off wheel through the grip portion of each tensile specimen ("A1" through "A9" and "E1" through "E6"). The abrasive wheel and specimen were cooled by water jet spray. Hardness testing was conducted on the grip portion of the exposed saw cut surface. The hardness tests were reported in the HRC and HRA scale and are shown in table 3. The hardness of four screws ("A1", "A2", "A3", and "A7") from the accident airplane were lower than 22HRC (by 1 HRC). The hardness of all the exemplar screws was greater than 22HRC.

As indicated earlier, hardness testing of main bearing screw fragment "A10" was conducted by NTSB. Two transverse (radial-circumferential) cuts were made by a water-cooled abrasive wheel through the thread portion of screw "A10" that resulted in the removal of a disc piece. The cuts were made at approximately 0.6 inch [15.25 mm] and 1 inch [25.5 mm] away from the fracture face. Hardness tests were performed on both cut surfaces of the disc piece, at the core of the screw (more precisely in the area between the longitudinal axis and the half-radius position). Rockwell "C" hardness testing of the cut faces produced an average hardness of 19 HRC. According to ASTM A 370, titled "Standard Test Methods and Definition for Mechanical Testing of Steel Products", this hardness value is extremely low on the HRC scale and it cannot be reliably converted to an approximate tensile strength value. Rockwell "A" hardness testing covers hardness values that are lower than 20 HRC and can be converted to an approximate tensile strength value. Rockwell "A" hardness testing of the screw produced an average hardness of 60 HRA, which converted to approximately 110,000 psi (768 N/mm²), less than the minimum tensile strength for the screw (800 – 950 N/mm²).

For comparison, hardness testing was also performed in the longitudinal-radial section (previously prepared for examination of the microstructure). The section was encased in a metallurgical mount. Rockwell "C" hardness testing directly on the longitudinal-radial section produced an average hardness of 23 HRC. This hardness value converted to an approximate tensile strength of approximately 119,000 psi (820 N/mm²), which was within the specified tensile strength for the screw.

EASA Airworthiness Directive Regarding Main Bearing Screws

The European Union Aviation Safety Agency (EASA) issued an Airworthiness Directive (AD) 2024-0037R1, dated 6 February 2024, regarding replacement of main

⁴ HRC is an abbreviation for Rockwell "C" hardness. HRA is for Rockwell "A" hardness.

bearing screws.⁵ This AD enforces Austro Engine Mandatory Service Bulletin No. MSB-E4-042, dated 31 January 2024.⁶ According to the Austro Engine MSB, “occurrences of E4 series engines have been reported recently. Investigation of the occurrences has shown in some cases the failure of one inner main bearing cap screw. Subsequent investigations have determined that certain batches of inner main bearing cap screws were produced at the lower end of the material strength tolerance for class 8.8 screws having P/N E4A-10-100-201. Depending on the magnitude of the screw’s strength properties, the potential for screw failure, leading to engine failure, exists in cases where abnormal operating conditions are experienced such as fuel quality issues or significant deviations from the fuel system requirements. To address this possible unsafe condition, the MSB requires the replacement of the inner main bearing cap screws, with screws having highest safety factor”.⁷ The replacement screw is a class 12.9 screw, having P/N E4A-10-100-202, where the head portion of the replacement screw is identified by the imprint “12.9”. According to ISO 898-1, the ultimate tensile strength of a class 12.9 screw is specified as between 1,200 N/mm² and 1,220 N/mm², and the hardness is indicated as in the range between 39 HRC and 44HRC.⁸

According to Austro Engine MSB, instructions for installing the replacement screws are found in Austro Engine Work Instruction WI-MSB-E4-042, titled “Main Bearing Screw Replacement”. Per WI-MSB-E4-042, only the 6 inner screws are replaced, while the outer 4 screws (2 forward and 2 aft) remain in place. The 6 replaced screws are torqued to 55 Nm, followed by tighten them to another 90° turn. The torque for the outer 4 screws remain the same as originally specified.

The time for replacement of the main bearing screws is based on the serial number of the engine listed in the MSB, which for certain airplanes requires immediate action; whereas as on other airplanes require replacement before accumulating 300 flight hours or with the next scheduled maintenance action, whichever occurs first. The AD applies to E4 and E4P engines which are known to be installed on, but not limited to, Diamond Aircraft Industries DA 40 NG, DA 42 NG, DA 42 M-NG and DA 62 airplanes. According to an article in “Pilot”, as of March 2022, more than 3,000 E4-series engines had been produced.⁹

⁵ The “R1” indicates this AD revises EASA Emergency AD 2024-0037-E dated 02 February 2024.

⁶ The Federal Aviation Administration (FAA) released an AD [Docket No. FAA-2024-0456; Project Identifier MCAI-2024-00084-E; Amendment 39-22691; AD 2024-05-01], in response to the EASA AD.

⁷ Recent review by Austro Engine shows a total of 9 screw fatigue fracture cases, always involving a single inner screw.

⁸ In the ISO898-1 standard, the units for UTS and YS are specified in MPa whereas those in the Austro Engine engineering drawing are specified in N/mm². There is no need to perform a mathematical conversion from one unit the other. The numerical values for each of these two units of measurement are equivalent (the same) because 1 N/mm² is equal to 1 MPa, and vice-versa.

⁹ <https://pilotweb.aero/news/easa-issues-ad-affecting-austro-engined-diamond-aircraft/>

Connecting Rods

Three of the four connecting rods were submitted. Two of them were labelled “#3” and “#4”. The third connecting rod arm was not labelled and for the purpose of this report will be referred to as the “unidentified” connecting rod. By default, the third connecting rod is either a “#1” or “#2” connecting rod. The fourth connecting rod was not recovered from the accident site. The connecting rod attachment bolts are installed in an orderly sequence and the final torque is specified as 25 Nm followed by a 90° turn.

Examination of the “unidentified” connecting rod revealed the cap and bearing halves were not submitted (not recovered). The connecting rod contained two extending arms and, in turn, each extending arm contained a bolt hole. The bolt hole in each extending arm contained a fractured fragment of the attachment bolt. For the purpose of this report, one fractured connecting rod bolt fragment was arbitrarily labelled “A” and the other was arbitrarily labeled “B”. The fractured bolt fragments were removed from the connecting rod arms (after portions of the connecting rod arms were partially cut with an abrasive wheel to dislodge the bolt fragments). The fractured attachment bolts were ultrasonic cleaned with Alconox. The length of bolt fragment “A” measured approximately 0.9470 inch (24.06 mm), and length of bolt fragment “B” measured approximately 0.3820 inch (9.70 mm).

Figure 9 shows the fracture face of connecting rod attachment bolt “A”. SEM examination of bolt “A” revealed the fracture face exhibited beach marks, typical of fatigue cracking, that emanated from multiple origins at the root of the thread, on one side of the bolt. Fatigue crack propagation was through approximately 30% of the bolt cross section. The fracture outside of the fatigue zone contained microvoid coalescence features typical of overstress separation.

Figure10 shows the fracture face of connecting rod attachment bolt “B”. SEM examination of bolt “B” revealed the fracture face contained beach marks, typical of fatigue cracking, that emanated from multiple origins at the root of the thread all around the bolt. The fatigue crack propagated through approximately 70% of the bolt cross section. The remaining portion of the fracture exhibited microvoid coalescence features typical of overstress separation.

As indicated earlier, the cap, two bearing halves, and wrist pin for the unidentified connecting rod were not recovered.

The #3 connecting rod was submitted with the cap and bearing halves. The bearing halves showed evidence of severe scoring¹⁰ that extended all around its circumference.

The #4 connecting rod was submitted with the cap and bearing halves. The bearing halves showed evidence of severe heat tinting (blue-brown color) with minor scoring that extended around its circumference. One of the bearing halves was bonded to the connecting rod arm. Both bearing halves showed evidence of severe deformation.

Pistons

Examination of the #1 piston revealed a major portion of the skirt had fractured and the fractures intersected the bore for the wrist pin (see figure 2). The bore for the wrist pin showed no evidence of scoring. The outer surface of the skirt contained severe scoring damage (orientation of the scoring marks were parallel to the length of the bore for the piston). The piston contained three metallic split rings (two compression rings and one oil control ring) that were attached to the outer diameter of the piston. The three piston rings were intact and free to move within their respective grooves. The surface of the head exhibited evidence of pitting and mechanical damage. The head contained four pockets (round) areas corresponding to the location of the valve heads. The pockets for the inlet valves contained circumferential machine impression marks (in areas between the arrows in figure 11) corresponding to circumferential machine impression marks found on the head of the valve heads.

The #2 piston was ejected from the engine and was not recovered.

A small portion of the skirt for the #3 piston had fractured. The fractures were located at the bottom portion of the skirt and none of the fractures intersected the bore for the wrist pin. The bore for the wrist pin showed no evidence of scoring. The outer surface of the skirt contained minor scoring damage (orientation of the scoring marks were parallel to the length of the bore for the piston). The three rings were intact. The head portion showed no evidence of mechanical damage. The outer surface of the wrist pin was smooth and showed no evidence scoring or a crack.

The #4 piston exhibited mechanical damage was similar to that on the #3 piston, with the exception that the outer surface of the skirt contained severe scoring damage. The outer surface of the wrist pin was smooth and showed no evidence scoring or a crack.

¹⁰ Scoring is a type of abrasive wear and refers to a rough surface that usually appears as long scratches in the direction of motion.

When examined by a binocular microscope, the fracture faces on the #1, #3, and #4 pistons exhibited coarse features on slant planes typical of overstress separation.

The three pistons were shipped to Austro Engine, Austria, for hardness testing of the head portion. The results of the testing are found in Austro Engine report "Doc. No. AIR-2024-004 rev 2", titled "Inspection of engine components", subject "Aerospace Inspection Report", "Engine S/N: E4-A-06603" (for details see Appendix 1, pages 27 to 34 of the Austro Engine report).¹¹

Engine Block

Figure 4 show two views of the engine block. The engine block contained a total of four punctures in the wall. The wall on the counterpressure side in the area of the #1 cylinder contained a puncture measuring approximately 4x2.5 inch (101x64 mm). The wall on the counterpressure side in the area of the #2 cylinder contained a puncture measuring approximately 4x2.5 inch (101x64 mm); and on the pressure side a puncture measuring approximately 2.5x1.5 inch (64x38 mm). The wall on the pressure side in the area of the #3 cylinder contained the smallest puncture measuring approximately 1.5x1 inch (38x25 mm).

The engine block contained a total of four bores, one for each piston. The top surface of the engine block contained evidence of corrosion stains in several areas around each bore (see figure 12). When looking down into the #2 piston bore, the wall contained four areas of severe scoring damage along its length, in the areas between arrows (see figures 13 and 14). When looking up at the #1 piston bore, the bottom corner edge of the bore on diametrically opposite sides exhibited evidence of mechanical damage (dents) in areas indicated by arrows in figure 15 (these areas correspond to the general location of the respective connecting rod arms.) The #2 piston bore contained a similar dent damage in the same respective area as in the #1 piston bore but only on one side of the bore (see figure 15).

Engine Head

The engine head contained four internal chambers; the crown portion of each chamber incorporated four valves. Out of all the four cylinders, the crown portion of the #2 cylinder, and the four valve heads within this chamber, exhibited the most severe mechanical damage (multiple impact marks), see figure 16. The crown portion of the #1 cylinder showed next to the most severe mechanical damage, see figure 17. The crown portion of the #1 cylinder in the area surrounding outtake valves heads 1.1 and 1.2 contained evidence of minor pitting and mechanical damage, see figure 17. The crown portion of the remaining cylinders, and their corresponding valve heads,

¹¹ The first part of the report discusses inspection of the injectors (they were not examined by NTSB Materials Laboratory) and the second part discusses hardness testing of the three pistons.

exhibited no evidence of mechanical damage, see figure 18. Examination of the exhaust ports for all the cylinders located at the end of the head revealed no evidence of debris or molten metal.

The four valves for the #2 cylinder were disassembled from the head. This was achieved by removing the washer, two shim halves, and springs from the upper end of the #2 valves, see figure 19. The length of the exposed end of the valve stems were measured (distance between top end of valve stem and bottom washer referred as distance "X" in figure 19), and the results of those measurements are shown in table 4. The valve seats were examined after the valves were disassembled from the engine head. The exposed surface of the valve seats from outtake 2.1 and 2.2 valves exhibited a lustrous appearance, consistent with the head of the valves contacting their respective valve seats. A sliver of deformed metal from the engine head, in the general area indicated by an arrow in figure 16, extended into the valve seat. The remaining valve seats for this cylinder were free of debris.

A photograph of the disassembled valves from the #2 cylinder is shown in figure 20. Examination of the disassembled valves revealed they contained no evidence of scoring damage along the length of their respective stem. The stem portion of the outtake 2.1 and 2.2 valves showed evidence of severe bending deformation in the area near the head. The valves from the #1, #3, and #4 cylinders were not disassembled from the engine head.

Main Journals Caps and Bearing Halves

The #1 through #4 main journal caps and their respective bearings (2 halves each) were submitted for examination, including two pieces of crankshaft shims from the #3 cylinder (see figure 2). The bearings for the main journals exhibited scoring, deformation, and heat damage (heat tinting), the severity of which increased from the #1MJ to the #4MJ; with the #4MJ having the most severe damage. The caps were intact and showed no evidence of damage.

The bearing halves for the #5MJ, as shown in figure 1, showed moderate scoring damage with no evidence tinting (heat damage).

Crankshaft

Visual examination of the crankshaft revealed the #1 rod journal (#1RJ) contained evidence of severe scoring and dent damage. The crank cheeks¹² in the area of the #1RJ at the outer edges also showed indications of severe dents. The #2RJ exhibited metal transfer (build-up) in many areas around the circumference of

¹² The crank cheek connects the crankpin to the main journal. In some designs, the cheek extends beyond the journal and carries a counterweight.

the rod journal. The #3RJ contained minor scoring all around its circumference. The #4RJ exhibited blue-black heat tint all around its circumference.

Fractured Pieces Found in the Oil Sump

Fractured pieces recovered from the oil sump were ultrasonic cleaned with acetone. Detailed binocular microscope examination of these pieces revealed most of the fracture faces contained severe mechanical damage. The portion of the fractures that did not contain deformation damage exhibited coarse features on slant planes typical of overstress separation with no evidence of fatigue cracking.

Submitted by:

Frank Zakar
Sr. Metallurgist

Table 1: Chemical analysis (Weight %)

Element	C	Si	Mn	Cr	S	P
Specified (1)	<u>0.30</u> 0.37	0.40 max	<u>0.60</u> 0.90	<u>0.90</u> 1.20	0.035 max	0.025 max
A1	0.37	0.10	0.78	1.11	0.003	0.009
A2	0.37	0.08	0.76	1.07	0.003	0.009
A3	0.31	0.10	0.76	1.10	0.003	0.012
A4	0.34	0.09	0.77	1.10	0.003	0.011
A5	0.34	0.10	0.74	1.11	0.003	0.011
A6	0.37	0.10	0.77	1.09	0.003	0.011
A7	0.37	0.11	0.76	1.09	0.003	0.011
A8	0.37	0.10	0.73	1.08	0.003	0.009
A9	0.37	0.10	0.76	1.09	0.003	0.010
A10	0.36	0.10	0.78	1.11	0.003	0.008
E1	0.35	0.32	0.84	1.15	0.004	0.014
E2	0.37	0.30	0.84	1.12	0.004	0.013
E3	0.37	0.29	0.84	1.15	0.004	0.014
E4	0.35	0.28	0.84	1.13	0.004	0.011
E5	0.35	0.31	0.82	1.12	0.004	0.013
E6	0.33	0.28	0.74	1.03	0.029	0.014

(1) Specified by Austro Engine: Grade 34Cr4 (Material number 1.7033) steel, a material code designation in the German standard DIN EN-10083-3.

Table 2: Tensile, Round Reduced Section, Ambient Temperature

Sample	Measured UTS (N/mm ²)	Calculated YS (N/mm ²)	Measured 0.2% YS (N/mm ²)	Measured Elongation (%)	Measured Reduction Area (%)
A1	810	689-729	730	20	68
A2	805	684-725	740	16	68
A3	800	680-720	745	19	69
A4	810	689-729	705	22	69
A5	805	684-725	740	21	69
A6	805	684-725	725	21	68
A7	795	676-716	680	22	69
A8	815	693-734	710	21	67
A9	800	680-648	730	19	69
E1	890	757-801	780	21	62
E2	900	765-810	790	21	65
E3	890	757-801	770	18	66
E4	885	752-797	775	19	66
E5	895	761-806	780	20	64
E6	880	748-792	780	21	66
Customer Specifications	800-950	0.85-0.90 of UTS		12 Min	50 Min

Note: Red value indicates test results that are lower than the specified UTS range whereas green values indicate those that are greater than the specified YS range.

Table 3: Rockwell Hardness Testing

Sample	Hardness (HRC)	Hardness (HRA)
A1	21	61
A2	21	61
A3	21	61
A4	22	62
A5	23	62
A6	22	61
A7	21	61
A8	22	61
A9	23	62
E1	23	62
E2	23	64
E3	27	64
E4	30	65
E5	27	64
E6	27	64

Table 4. Length of exposed end of valve stem (mm)	
Valve position	Area extending between the upper end of stem and washer; referred to distance "X" in figure 19
Intake 2.1	43.45
Intake 2.2	42.58
Outtake 2.1	42.33
Outtake 2.2	42.20

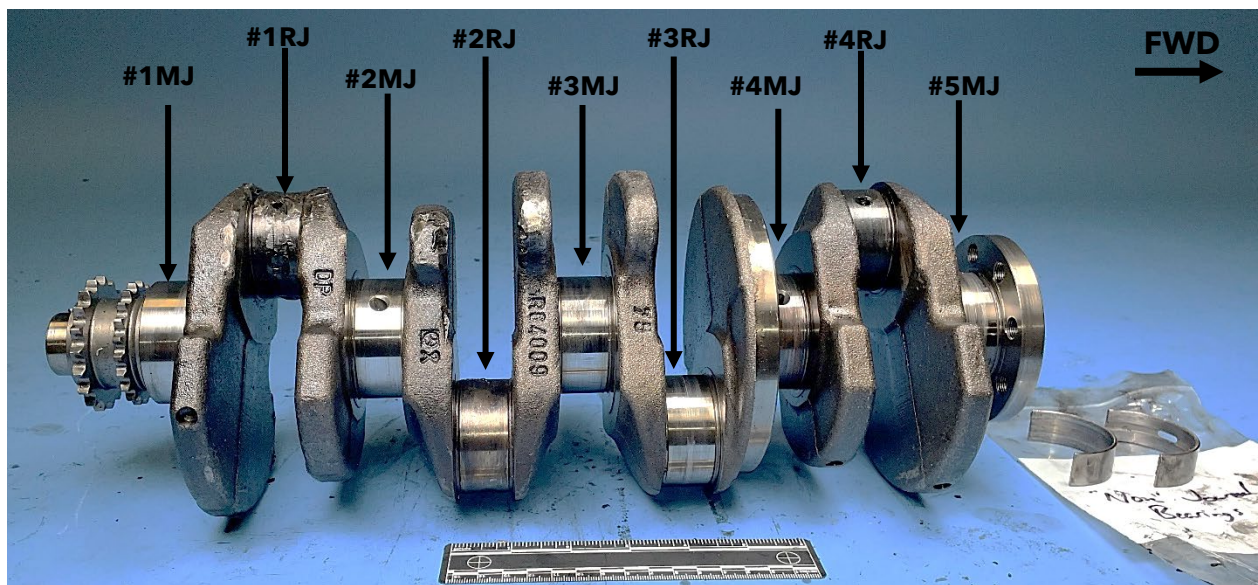


Figure 1. As-received crankshaft and bearing halves from the #5MJ. The crankshaft is numbered from aft to front, starting with the #1 main journal (#1MJ) and #1 rod journal (#1RJ) at the aft end, and ending with the #5 main journal (#5MJ) at the front end. The main bearing (two halves) for the #5MJ is shown on the right side of the photograph. Units on the top side of the ruler are inches and at the bottom side are metric (mm).

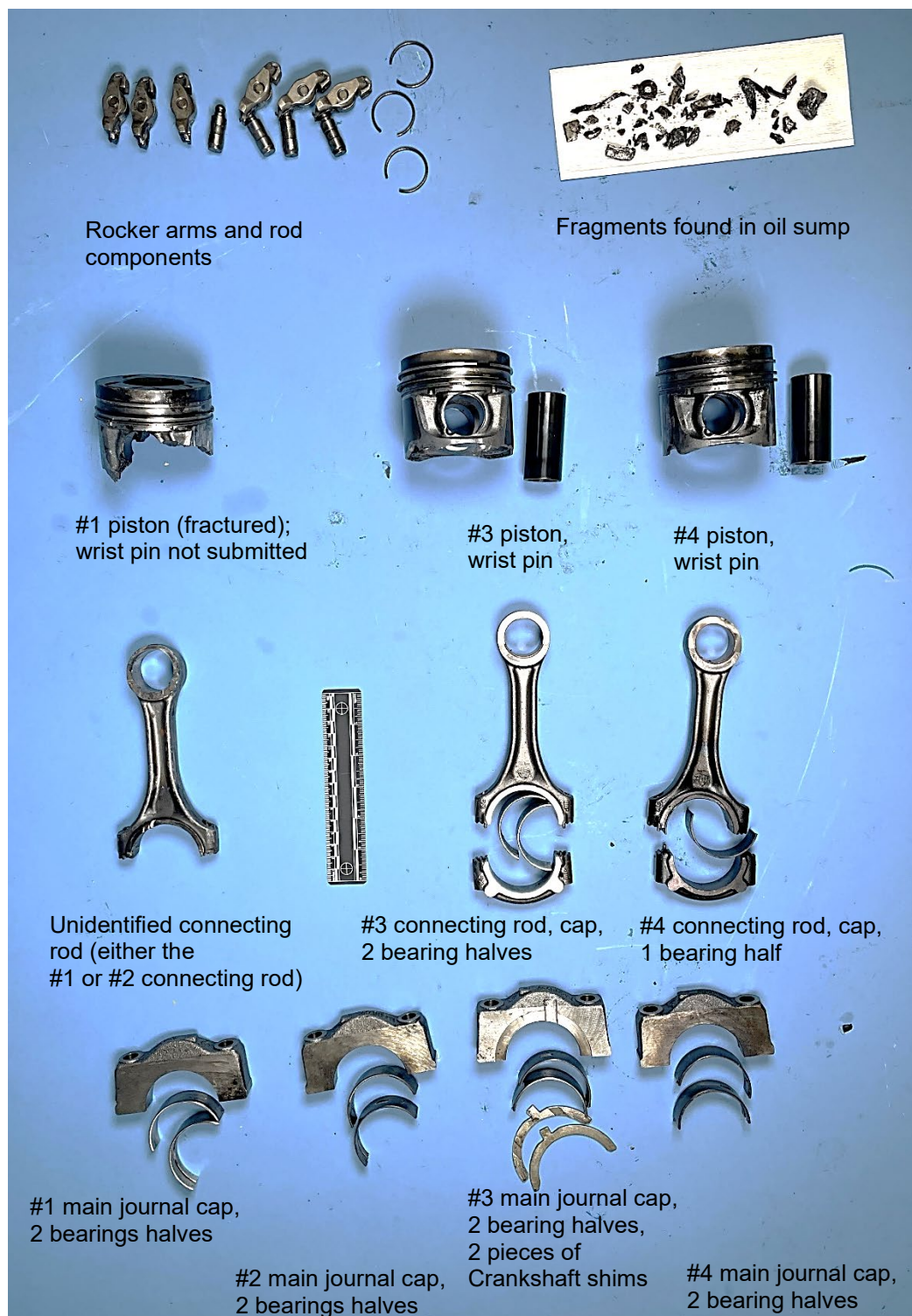


Figure 2. As-received pieces from the engine.

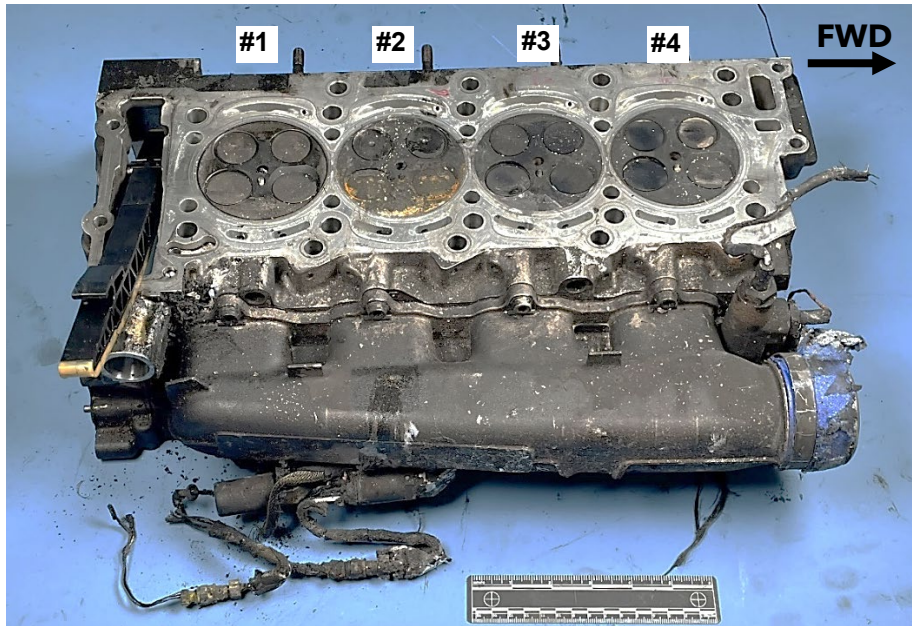


Figure 3. As-received cylinder head showing the bottom surface. Cylinders are numbered #1 through #4.

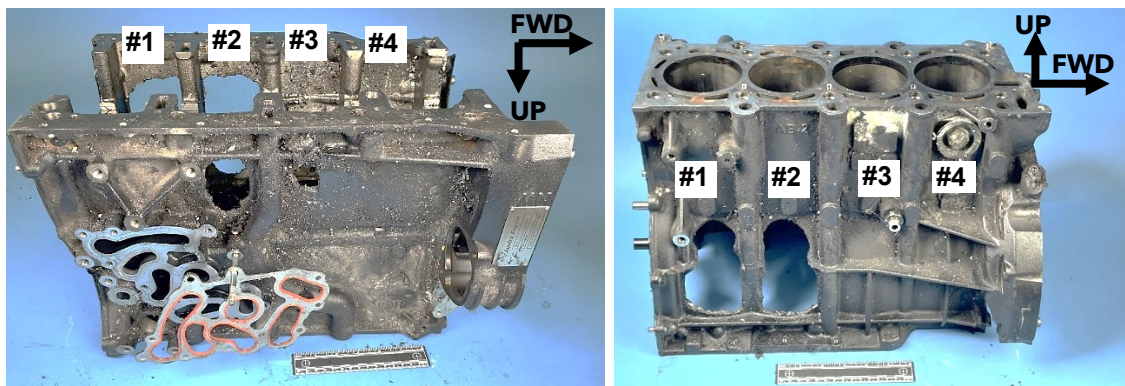


Figure 4. As-received engine block looking at the pressure side (left side of page); and looking at the counterpressure side (right side of page).

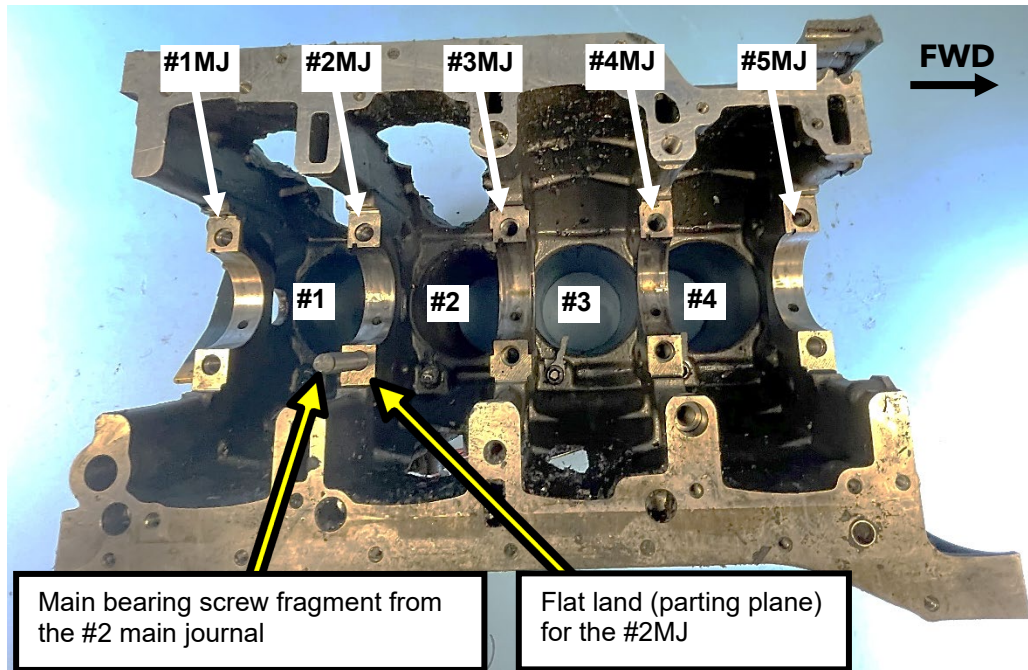


Figure 5. As received engine block looking at bottom surface. Cylinders are numbered #1 through #4. A main bearing screw fragment from the #2MJ remained attached to the flat land (parting plane) portion of the engine block.

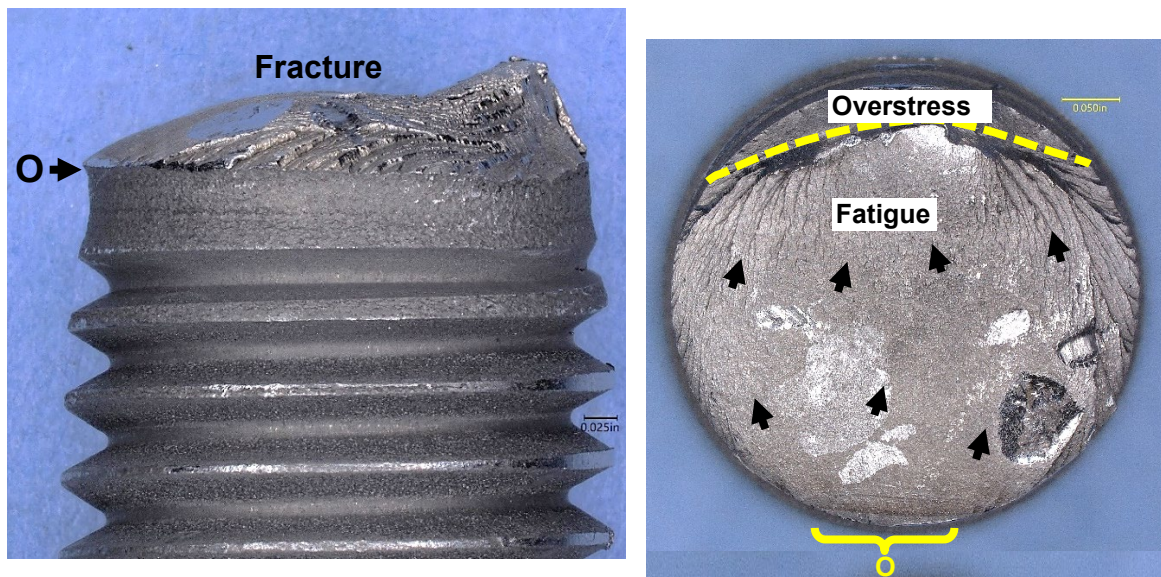


Figure 6. Main bearing screw fragment from the #2 main journal showing side view of the fracture where the fatigue origin is indicated by arrow "O" (left image) and head-on view of the entire fracture face where the same fatigue origin is indicated by bracket "O" (right image). The fatigue crack terminated in the area indicated by a dash line. Fracture areas outside of the fatigue region exhibited features typical of overstress separation. The luster (reflective) features on the fracture face are mechanical damage areas.

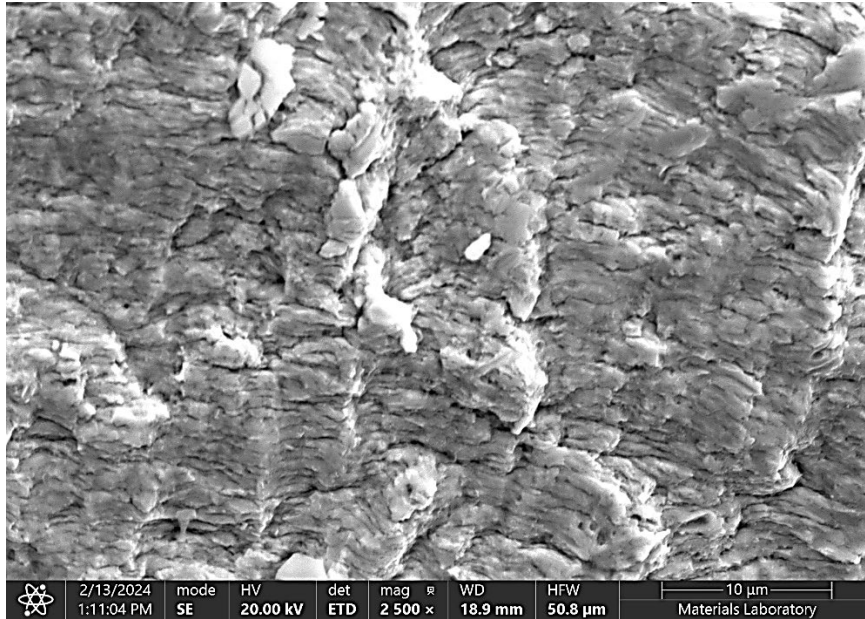


Figure 7. SEM image of the fractured main bearing screw from the #2 main journal showing typical fatigue striations in the area near the origin of the fatigue crack.

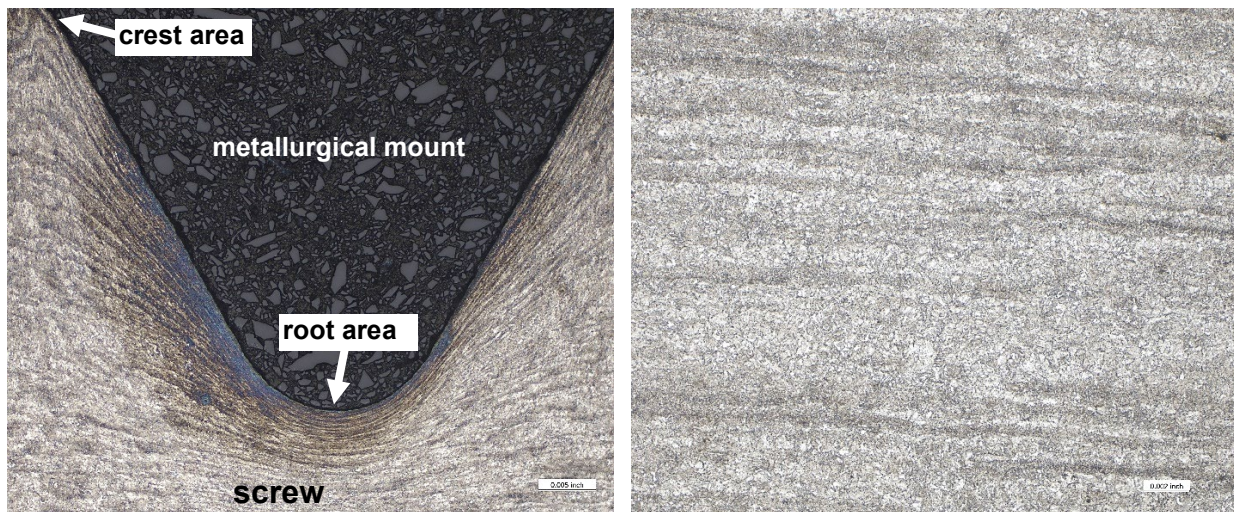


Figure 8. Longitudinal sections through the #2MJ main bearing screw fragment showing evidence of rolled threads at the root and crest areas (left image); and microstructure at the core of the screw (right image). These sections from the screw showed a microstructure of tempered martensite. Etched with 2% Nital. The brown/blue color at the surface of the thread area is residual staining from the etchant and is not an anomaly in the microstructure.

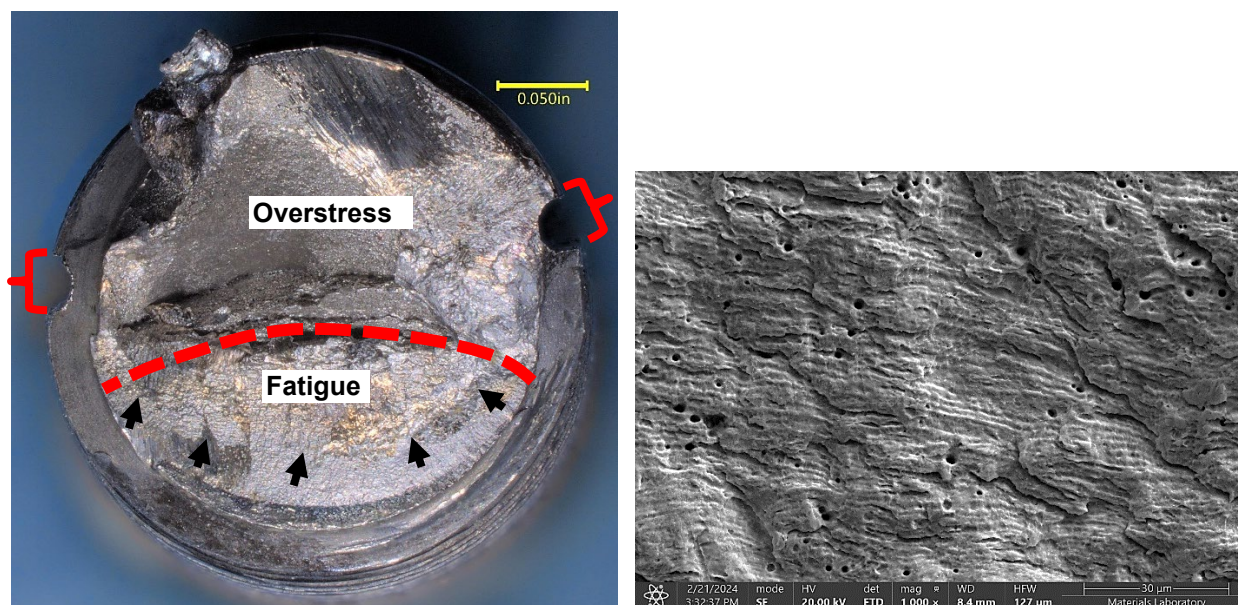


Figure 9. Fracture face of connecting rod bolt "A" from the unidentified connecting rod arm (either from the #1 or #2 connecting rod). Fatigue crack emanated from multiple origins at the root of the thread, propagated in direction indicated by arrows and terminated in the areas indicated by a dashed line (left image); and SEM photograph of typical fatigue striations (right image). Brackets indicate location of saw cuts that were made to dislodge screw from threaded hole.

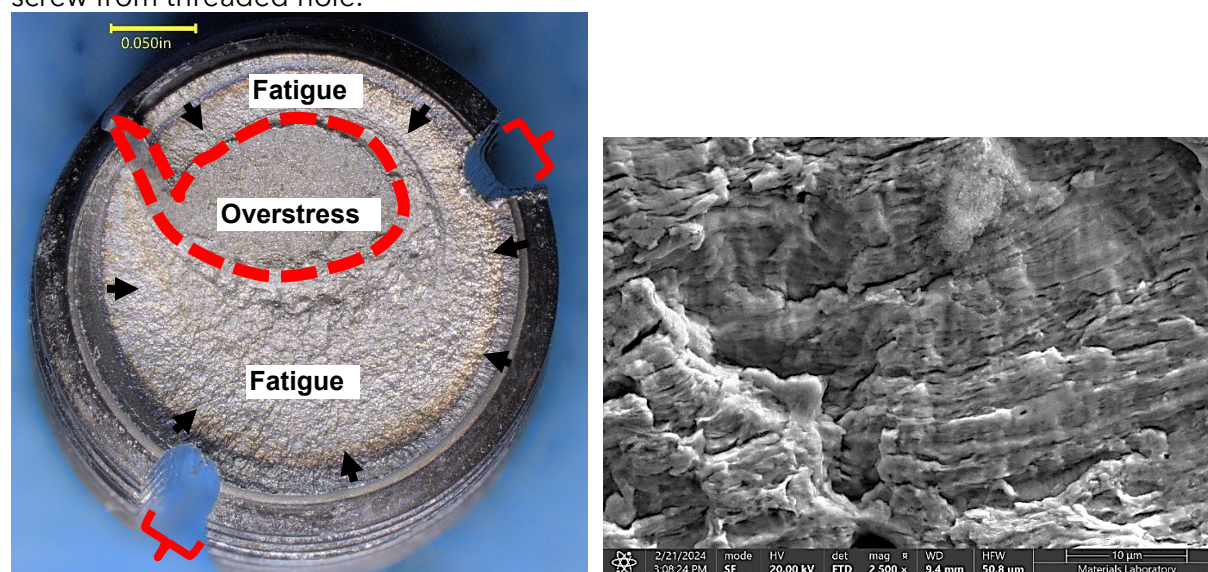


Figure 10. Fracture face of connecting rod bolt "B" from the unidentified connecting rod arm (either from the #1 or #2 connecting rod). Fatigue crack emanated from multiple origins at the root of thread in areas all around the screw, propagated in general direction indicated by arrows, and terminated at the core in the area indicated by a dashed line (left image); and SEM photograph of typical fatigue striations (right image). Brackets indicate location of saw cuts that were made to dislodge screw from threaded hole.

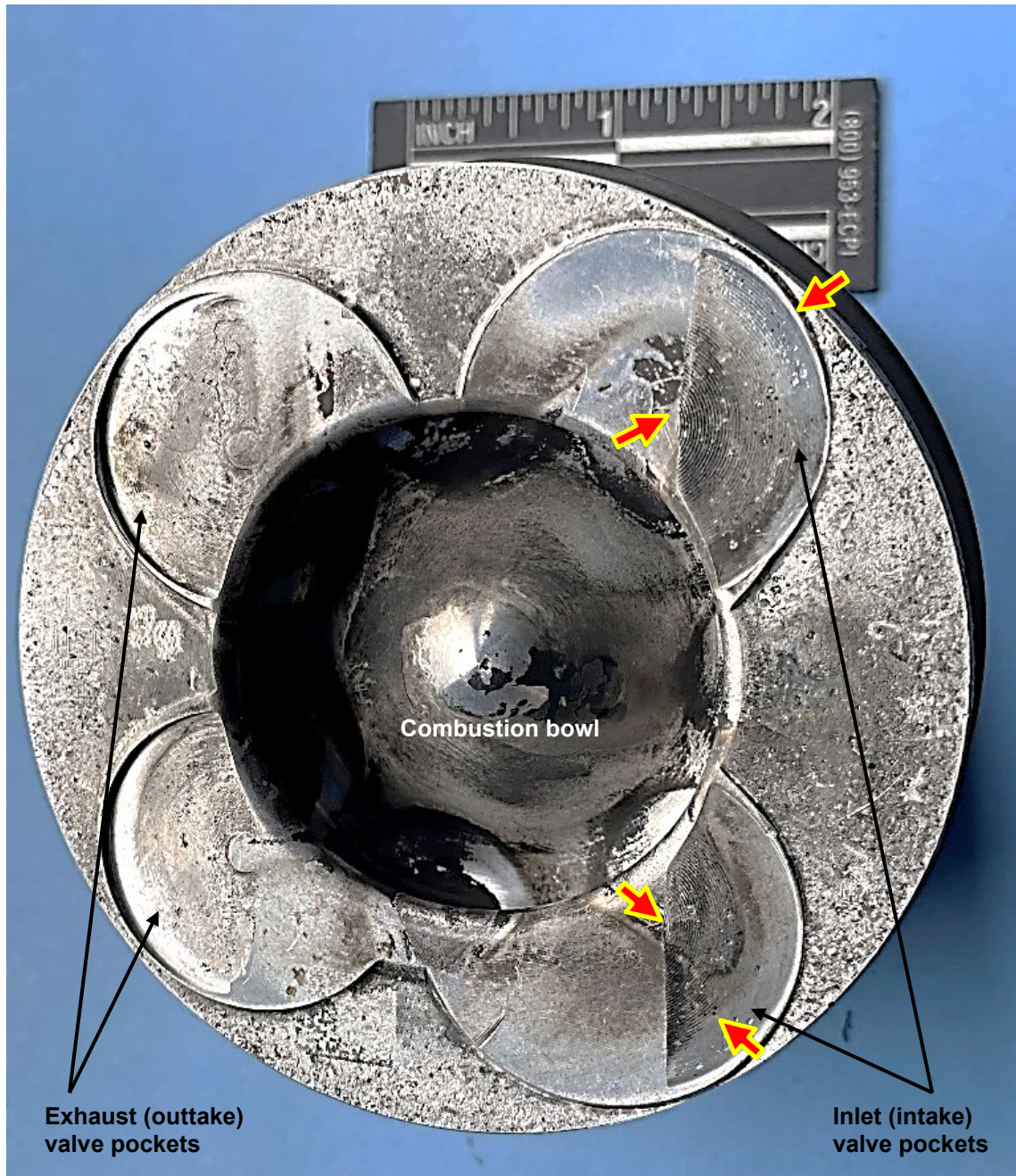


Figure 11. Head portion of the #1 piston showing four valve pockets that correspond to the location of the valve heads. The surface of the head also contained pitting and mechanical damage. Circumferential machine impression marks (between arrows) were found in the inlet pocket areas that correspond to those found on the head of the valve heads.

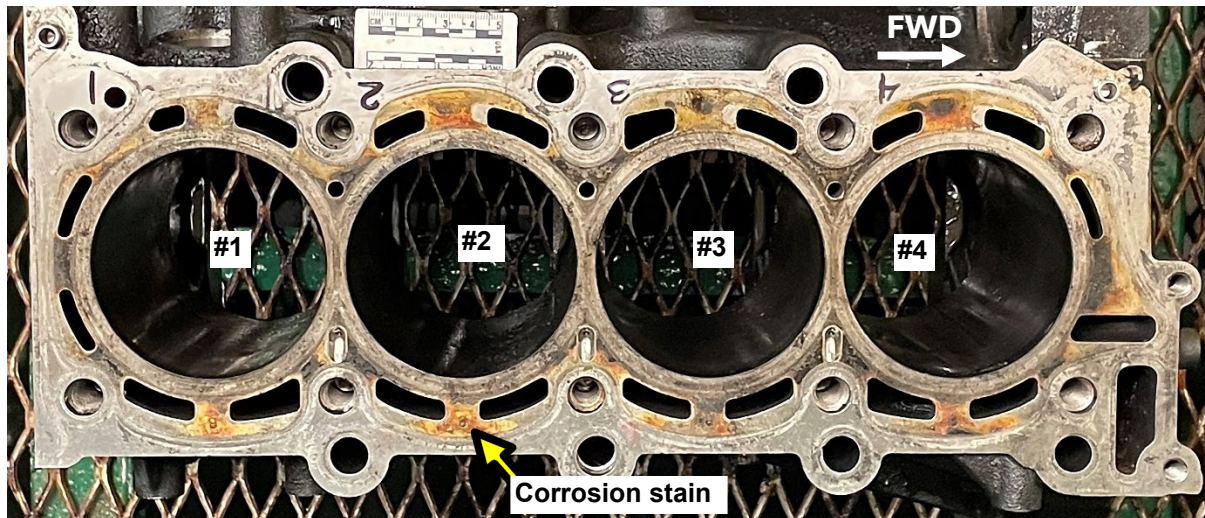


Figure 12. Top face of the engine block showing corrosion stains (brown areas) in the areas surrounding the piston bores; shown after cleaning in a degreaser tank. Piston bores are numbered #1 through #4.

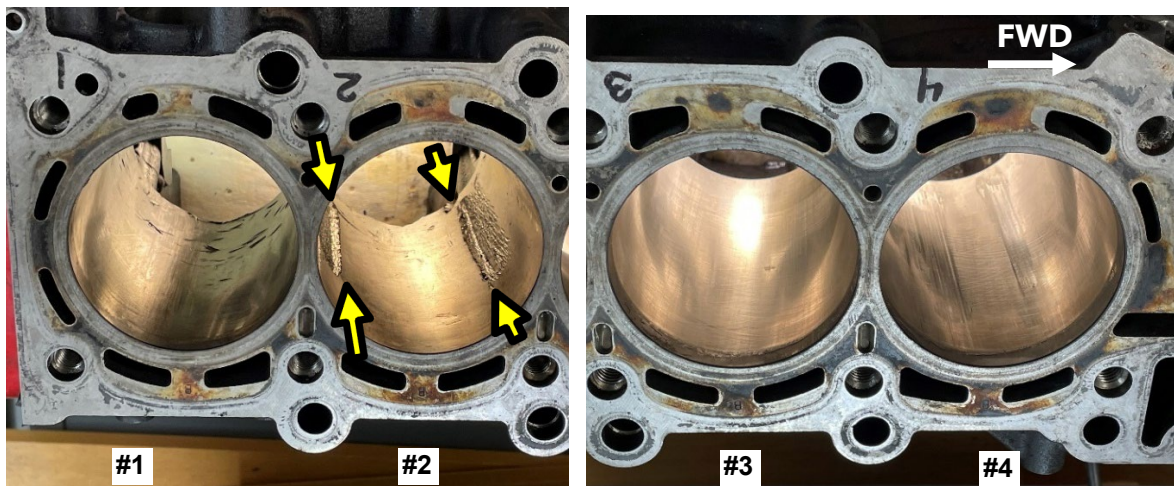


Figure 13. View of the top face of engine block with the piston bores exposed to background lighting. In this view, the #2 piston bore shows two of four severe scoring damage areas along the length of the bore in the areas between arrows; shown after cleaning. Piston bores are numbered #1 through #4.

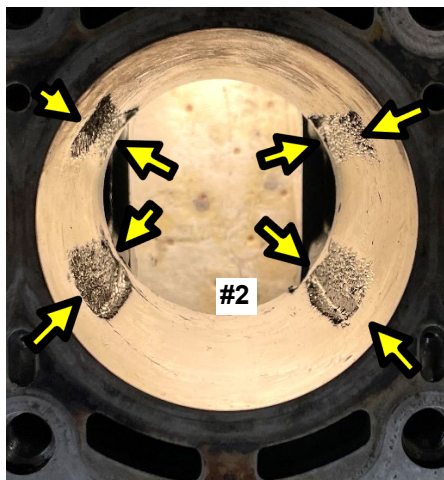


Figure 14. View looking down into the #2 bore showing four severe scoring damage areas along the length of the bore in the areas between arrows; after cleaning.

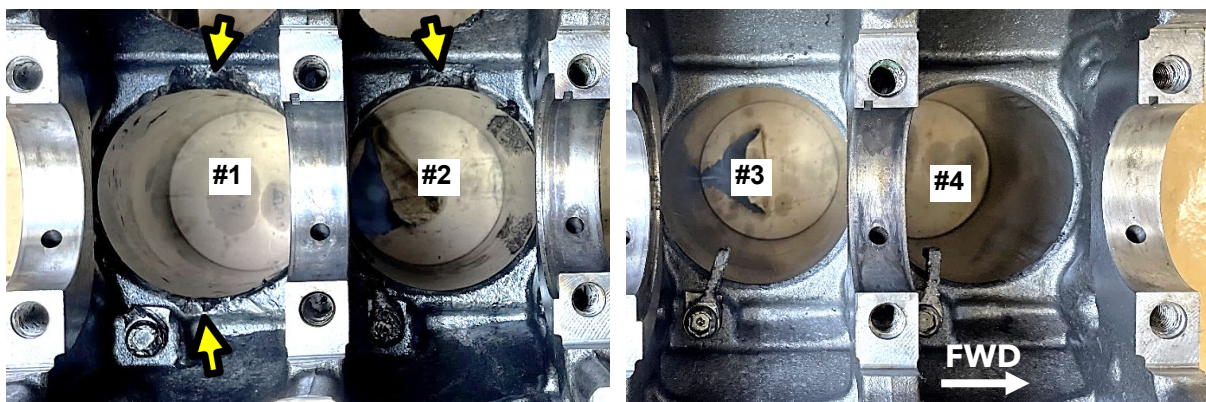


Figure 15. View looking up at the piston bores showing mechanical damage (dents) in areas that correspond to the location of the respective connecting rods, in areas indicated by an arrow.

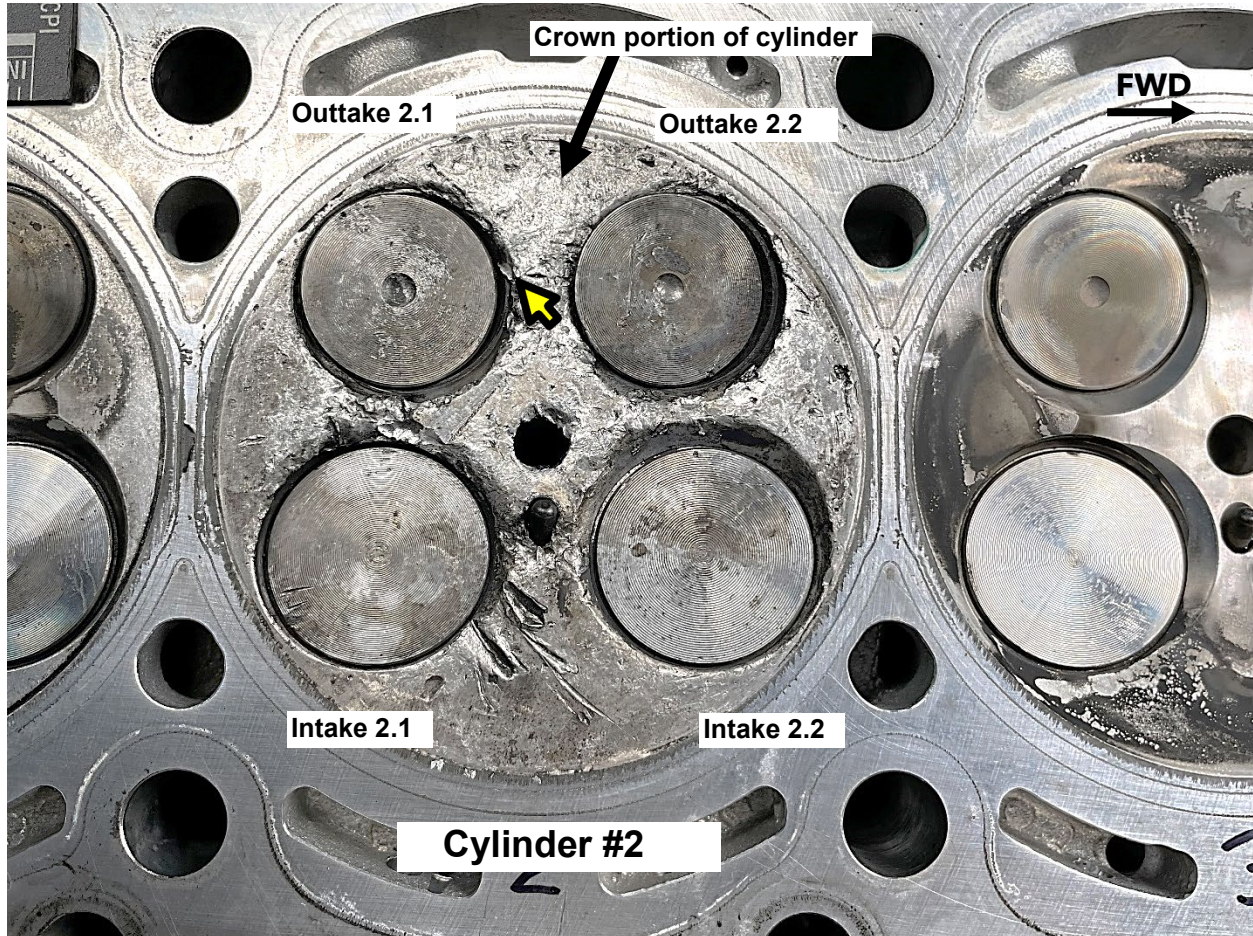


Figure 16. View of the intake and outtake valves for the #2 cylinder. A sliver of metal, indicated by an arrow, extended from the chamber into the seat of outtake valve 2.1. The crown portion of the chamber for this #2 cylinder showed severe mechanical damage compared to the crown portion of the chamber for the #1, #3 and #4 cylinders.

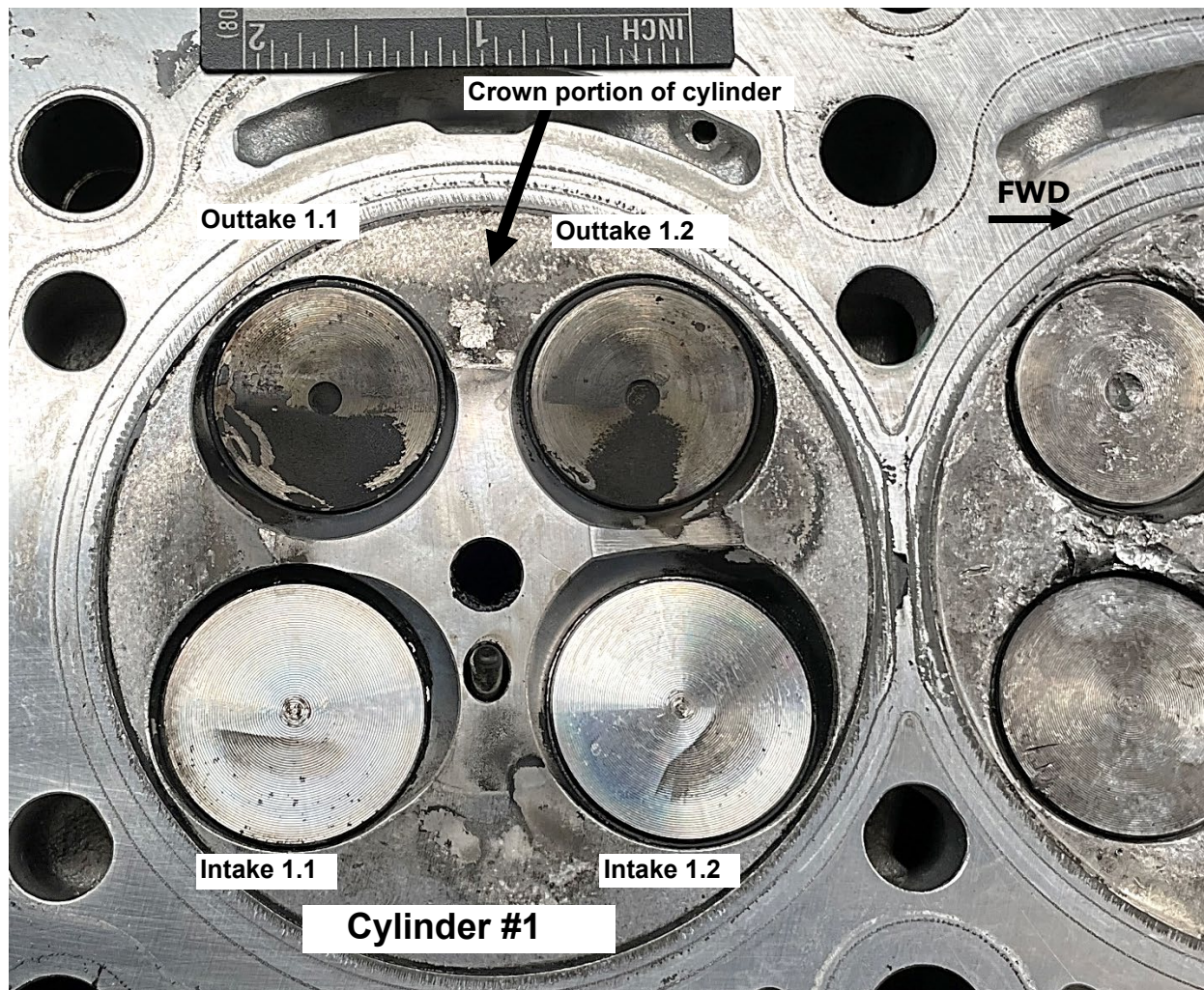


Figure 17. View of the intake and outtake valves for the #1 cylinder.

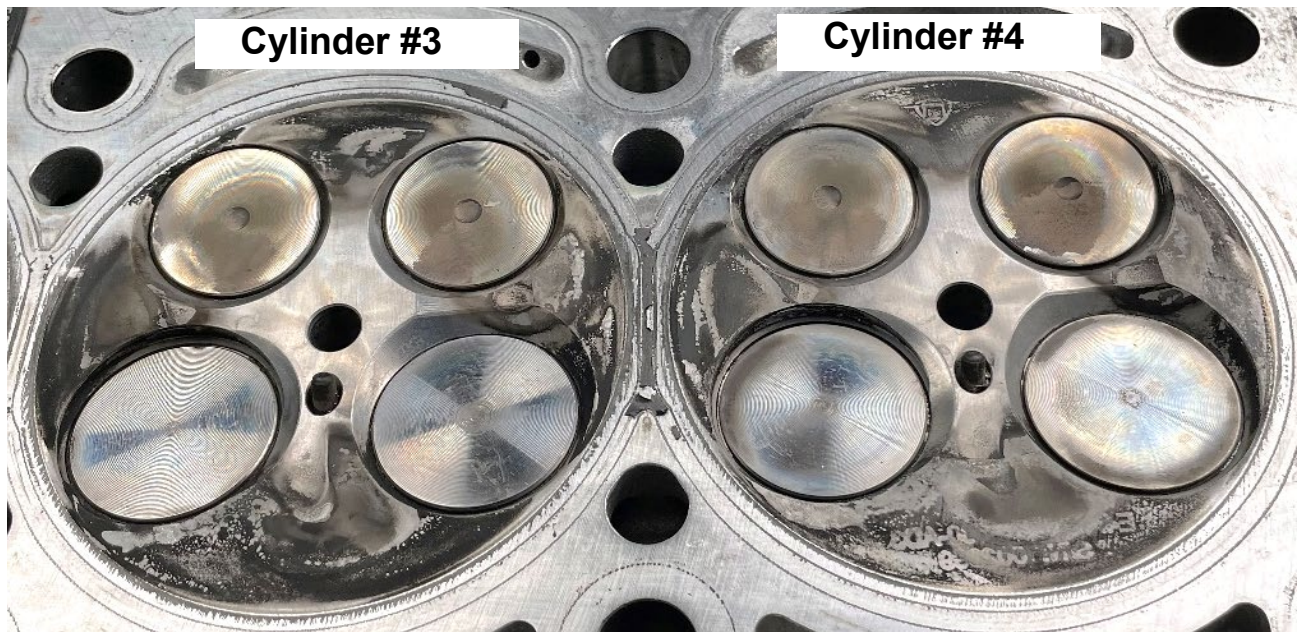


Figure 18. View of the intake and outtake valves for the #3 and #4 cylinders.

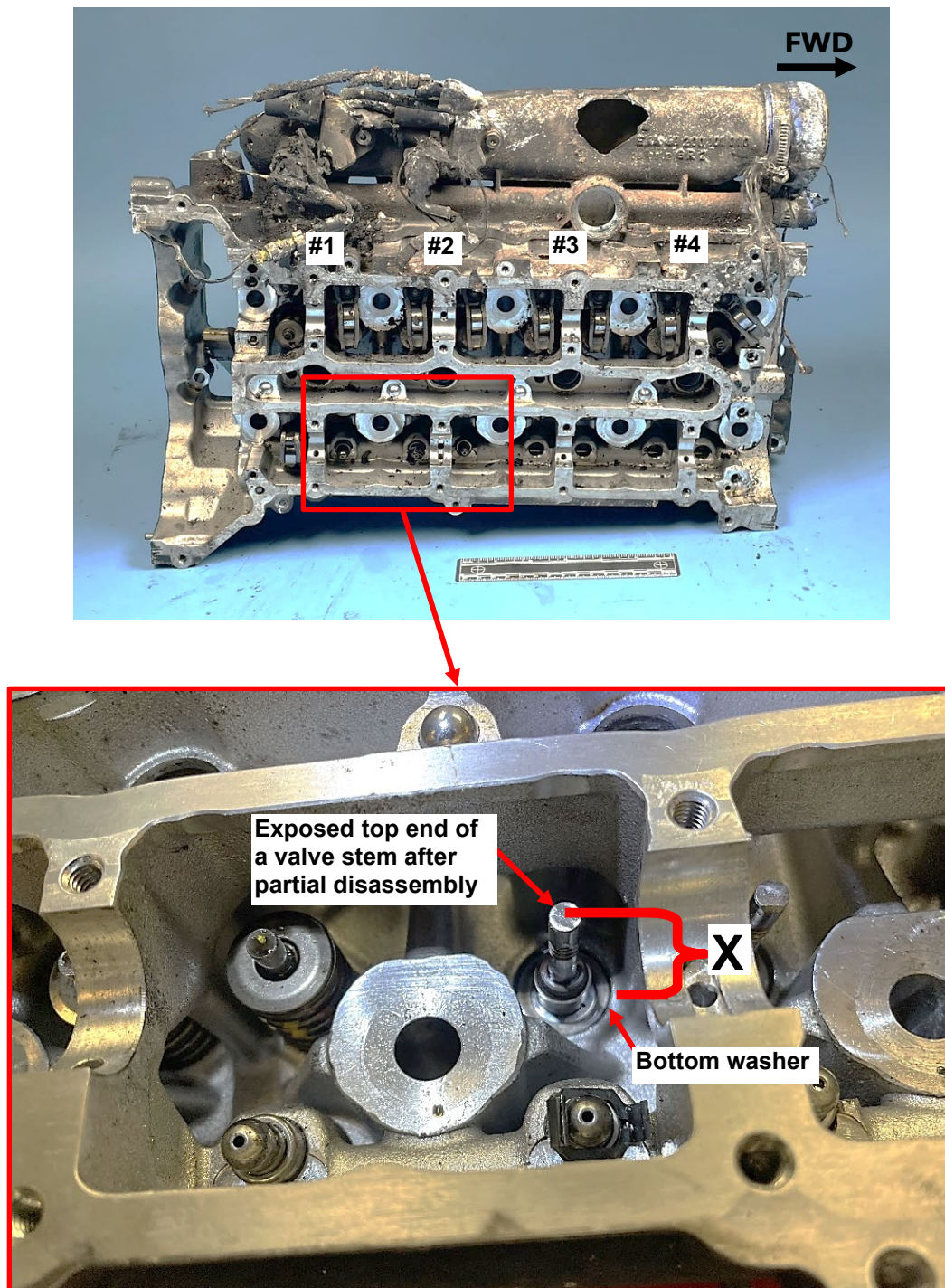


Figure 19. View of the top side of the as-received cylinder head (top image); and close-up view of the exposed top end of a valve stem from the #2 cylinder without the spring, washer, and shim halves after partial disassembly (bottom image).

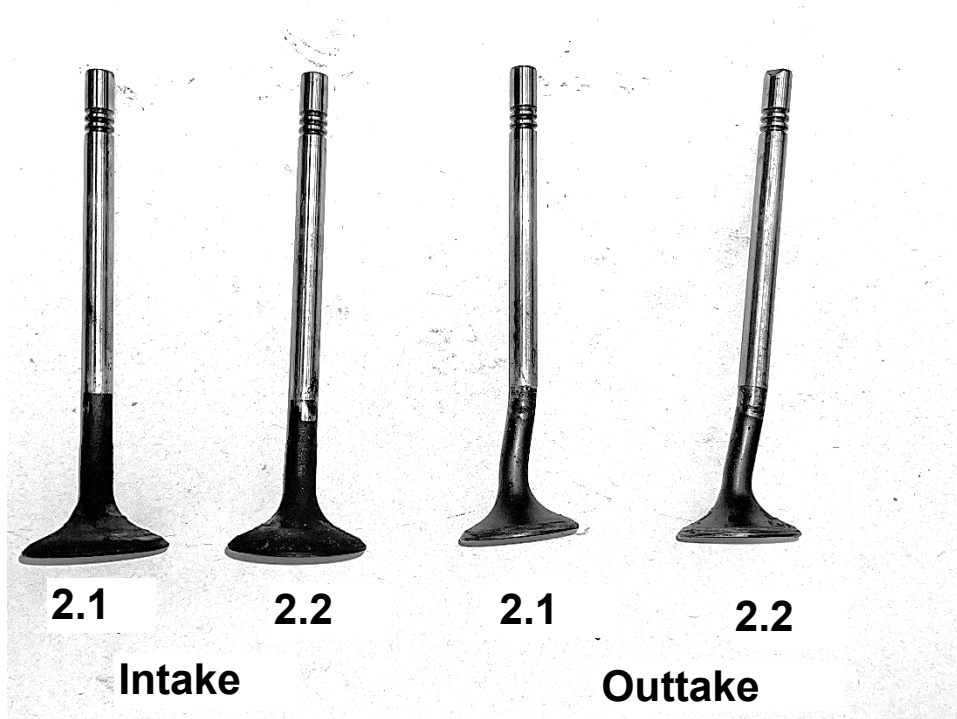


Figure 20. Side view of the disassembled valves from the #2 cylinder. Outtake valves 2.1 and 2.2 show evidence of bending deformation at the stem in the area near the head.

APPENDIX 1

Austro Engine report Doc. No. AIR-2024-004, Rev 2

(total of 34 pages)

 Austro Engine	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 1 of 34
	Type: E4	

Doc. No. AIR-2024-004

Inspection of engine components

Engine S/N: E4-A-06603

	Name / Position:	Date:	Signature / Stamp:
Prepared:	HANDL Marcel	04. MRZ. 2024	 
Checked/ Verified:	HONGENBESSER/LDE	06.03.2024	 



- o Position: the jobholders position in the company signing the document e.g. LDE (Lead Design Engineer) or CVE Hardware (Compliance Verification Engineer responsible for Electronic Hardware)
- o Prepared: preparation of this certification report under the CE responsibility
- o Checked/Verified: checking and verification of the content of this certification report and checking that the defined requirements (e.g. CS-E) are met.
- o For details refer to: AE-VA-T-12-03 / Erstellen von Berichten zur Nachweisführung

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 2 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

TABLE OF CONTENT

1. INJECTOR TESTING..... 6

1.1 Unboxing of the injectors..... 6

1.2 Injector test 9

2. INJECTOR DISASSEMBLY11

2.1. Injector function description12

2.2. Injector disassembly13

2.3. Microscopic inspection.....17

2.3.1. Injector 117

2.3.2. Injector 219

2.3.3. Injector 321

2.3.4. Injector 423

2.4. Conclusion.....25

3. PISTON HARDNESS TESTING27

3.1. Delivery condition27

3.2. Hardness measurement.....29

3.3. Conclusion.....33

4. APPENDIX.....34

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 3 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

Table of figures

Figure 1 Shipping cardbox	6
Figure 2 Cardboard box content	7
Figure 3 Separate packaging	7
Figure 4 Injector 1	7
Figure 5 Injectors 1-4	8
Figure 6 Injector clamping during test	9
Figure 7 DISU 6000 2500 bar	9
Figure 8 Injector connections	9
Figure 9 - Injector 1-4	11
Figure 10 - Schematic picture of injector	12
Figure 11 - Solenoid valve and spring	13
Figure 12 - Injector armature	13
Figure 13 - Ball valve	13
Figure 14 - Armature, bottom side	13
Figure 15 - Armature, top side	13
Figure 16 - Injector 3, armature removed	13
Figure 17 - Armature guide injector 3, top side	13
Figure 18 - Armature guide injector 3, bottom side + ball valve	13
Figure 19 - Injector 3, armature guide removed	13
Figure 20 - Nut to secure the injector nozzle	14
Figure 21 - Nut to secure the injector nozzle removed	14
Figure 22 - Injector nozzle	14
Figure 23 - Screw with secures the A-throttle	14
Figure 24 - Injector 3, injector nozzle removed	14
Figure 25 - A-throttle	14
Figure 26 - Injector needle	14
Figure 27 - Disassembled injector 3	14
Figure 28 - Control piston, injector 3	14
Figure 29 - Armature guide injector 1, bottom side	15
Figure 30 - Injector 1, armature removed	15
Figure 31 - Injector 1, armature guide removed	15
Figure 32 - Control piston, injector 1	15
Figure 33 - Armature guide injector 2	15
Figure 34 - Injector 2, armature removed	15
Figure 35 - Injector 2, armature guide removed	15
Figure 36 - Control piston, injector 2	15
Figure 37 - Armature guide injector 4	16
Figure 38 - Injector 4, armature removed	16
Figure 39 - Injector 4, armature guide removed	16
Figure 40 - Control piston, injector 4	16
Figure 41 - Injector 1, A-throttle	17
Figure 42 - Injector 1, A-throttle ~35° left	17
Figure 43 - Injector 1, A-throttle ~ 35° right	17
Figure 44 - Injector 1, armature guide x20	18

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 4 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

Figure 45 - Injector 1, armature guide	18
Figure 46 - Injector 1, armature guide x50 (1)	18
Figure 47 - Injector 1, armature guide x50 (2)	18
Figure 48 - Injector 1, corrosion on control piston.....	18
Figure 49 - Injector 2, A-throttle	19
Figure 50 - Injector 2, A-throttle ~35° left	19
Figure 51 - Injector 2, A-throttle ~35° right	19
Figure 52 - Injector 2, armature guide top side x20	20
Figure 53 - Injector 2, armature guide	20
Figure 54 - Injector 2, armature guide x20	20
Figure 55 - Injector 2, armature guide x50	20
Figure 56 - Injector 2, control piston x30	20
Figure 57 - Injector 3, A-throttle	21
Figure 58 - Injector 3, A-throttle ~35° left	21
Figure 59 - Injector 3, A-throttle ~35° right	21
Figure 60 - Injector 3, armature guide x20	22
Figure 61 - Injector 3, armature guide x150	22
Figure 62 - Injector 3, control piston x50	22
Figure 63 - Injector 4, A-throttle	23
Figure 64 - Injector 4, A-throttle ~35° left	23
Figure 65 - Injector 4, A-throttle ~35° right	23
Figure 66 - Injector 4, armature guide top side x20	24
Figure 67 - Injector 4, armature guide	24
Figure 68 - Injector 4, armature guide x20 (1)	24
Figure 69 - Injector 4, armature guide x20 (2)	24
Figure 70 - Injector 4, control piston x20 (1)	24
Figure 71 - Injector 4, control piston x20 (2)	24
Figure 72 - Example cavitation	25
Figure 73 - A-throttle injector 1	25
Figure 74 - Close up, A-throttle injector 1.....	25
Figure 75 - 2nd close-up, A-throttle injector 1	25
Figure 76 - Comparison roughened surface injector 3 (top) to corroded injector (bottom) ..	26
Figure 77 Delivered parcel top.....	27
Figure 78 Delivered parcel front	27
Figure 79 Delivered parcel back.....	27
Figure 80 Delivered parcel left.....	27
Figure 81 Parcel opened with invoice	27
Figure 82 Parcel condition opened	27
Figure 83 Piston number 1	28
Figure 84 Piston number 3	28
Figure 85 Piston number 4	28
Figure 86 Measuring equipment	29
Figure 87 Securing structure	29
Figure 88 Measuring scheme.....	30
Figure 89 Protocol 1	30
Figure 90 Protocol 2	30
Figure 91 Hardness diagram K&H	31

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 5 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

Figure 92 Hardness Comparison Average	32
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	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 6 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

1. INJECTOR TESTING

1.1 Unboxing of the injectors



Figure 1 Shipping cardboard

On the 25th of January the injectors were unpacked in the presence of the Austrian Transport Authority. The four injectors were shipped in a cardboard box with air cushions enclosed. Each injector was labeled and sealed separately in a plastic bag. The nozzle of the first injector has pierced the plastic bag and protrudes far out of the packaging. The plastic bag of the fourth injector was not completely sealed.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 7 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	



Figure 2 Cardboard box content

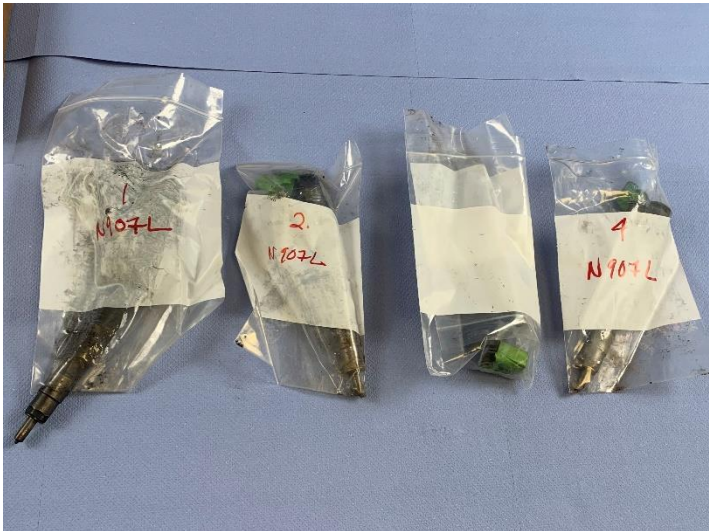


Figure 3 Separate packaging



Figure 4 Injector 1

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 8 of 34
	Type: E4	
Subject: AEROSPACE INSPECTION REPORT		



Figure 5 Injectors 1-4

Prior to testing, all injectors were visually inspected to detect any external damage. No signs of abnormal or excessive wear could be detected. Connections of the fuel inlet and return were free of dirt and debris and the electrical connection for the control unit taped off. The connector of the first injector was still connected with a cut cable. The spray nozzles were also free of dirt and debris without deformations. No excessive or abnormal wear visible.

Cylinder:	1#	2#	3#	4#
IMA:	5Z7Z6A	AZR7IN	7GRO7W	458X11

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 9 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

1.2 Injector test

After external inspection the injectors were measured with the DISU 6000 2500 bar injector tester located in the factory. The injector was not cleaned in the ultrasonic tank before testing in order to maintain the exact condition of the injector.



Figure 6 Injector clamping during test



Figure 7 DISU 6000 2500 bar



Figure 8 Injector connections

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 10 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

The final results and full reports of the injector test are attached in chapter 4: APPENDIX.

A short summary:

The engine's four injectors underwent testing on an injector test stand at Austro Engine, in which the injectors were tested electrically and hydraulically according to the manufacturer's test instructions.

The results of these tests showed that Injector Z1 exhibited a slight increase in pre-injection quantity, while Injectors Z2-Z4 were found to be functioning correctly. Slightly reduced injection quantities were measured for injector 3 and injector 4 at the full load point, although this slight reduction does not have a negative effect on the operation and service life of the engine.

It is important to note that this evaluation provides a snapshot using testing oil. However, it highlights the potential for operational issues with contaminated kerosene.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 11 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

2. INJECTOR DISASSEMBLY

On the 9th of February the injectors were disassembled and examined under the microscope VHX6000 in the presence of the Austrian Transport Authority.

The four injectors were stored in the same cardboard box in which they were shipped.

Each injector was stored in a separate labeled plastic bag.



Figure 9 - Injector 1-4

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 12 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

2.1. Injector function description

Common rail injectors rely on the flow balance between the inlet (Z) and outlet (A) throttles. The Figure shows the arrangement of the injector together with the throttle positions.

High pressure fuel from the rail is applied to the injector which is filled with fuel. The needle remains closed as long as there is a higher pressure force on the top of the needle than the force from below. Fuel flows through the orifice 'Z' to the control chamber. As long as the solenoid valve remains closed the only flow through the throttle 'Z' is that which occurs due to leakage ' q_l '. When the solenoid valve opens, the fuel in the chamber flows out through orifice 'A' to the fuel return. When the pressure in the control chamber (P_c) reduces sufficiently, the force on the needle acting on the differential area around the shaft is high enough to overcome the spring and pressure forces and lift the needle so that injection can start.

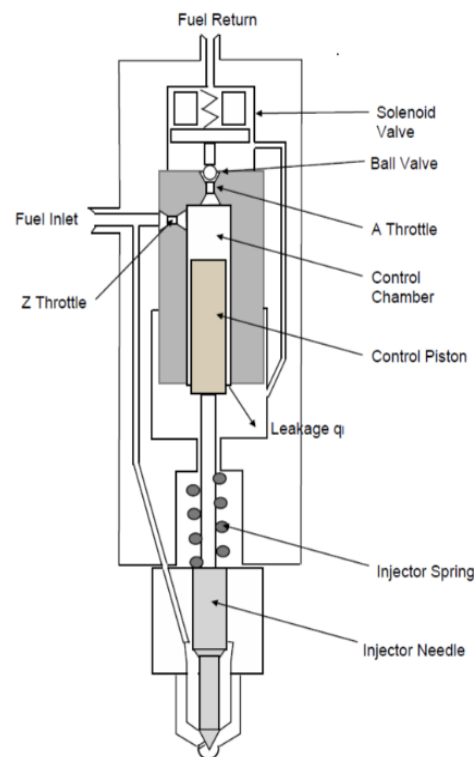


Figure 10 - Schematic picture of injector

When the solenoid valve closes, the flow through the orifice 'A' stops and the pressure in the chamber rises again until the pressure is sufficiently high to close the injector needle again. The flow rates between the inlet orifice, outlet orifice and the leakage are carefully chosen by the manufacturer to ensure correct operation of the injectors. A simple calculation demonstrates this relationship.

When the solenoid valve is closed the flow through the orifice 'Z' (q_z), is equal to the leakage flow (q_l) and the pressure in the control chamber adjusts to compensate. When the solenoid opens, the flow out of the control chamber increases by the flow through throttle 'A' (q_a), but the flow into the chamber is restricted by the throttle 'Z' so that the pressure can drop to allow the injector to open. At the end of the injection, the throttle 'A' is closed and the pressure rises again according to the flow balance between the inlet 'Z' throttle and the leakage.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 13 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

2.2. Injector disassembly

The injectors were disassembled in order from 1 to 4.
The disassembly is described below using the injector 3.

1. Solenoid valve and spring removed
(see Figure 11 and Figure 12)
2. Armature removed
(see Figure 14, Figure 15 and Figure 16)
3. Armature guide removed
(see Figure 17, Figure 18 and Figure 19)
Spots of corrosion can be clearly seen, both on the guide and in the injector itself
4. Ball valve safely packed in a lockable bag



Figure 11 - Solenoid valve and spring



Figure 12 - Injector armature



Figure 13 - Ball valve



Figure 14 - Armature, bottom side



Figure 15 - Armature, top side



Figure 16 - Injector 3, armature removed



Figure 17 - Armature guide injector 3, top side

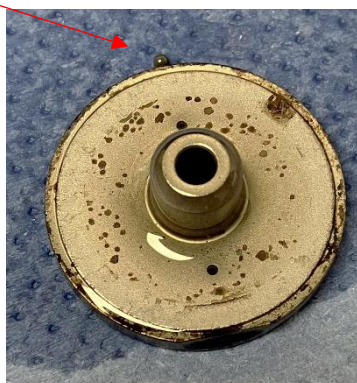


Figure 18 - Armature guide injector 3, bottom side + ball valve



Figure 19 - Injector 3, armature guide removed

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 14 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

5. Nut which secures the injector nozzle removed
(see Figure 20 and Figure 21)

6. Injector nozzle removed
(see Figure 22 and Figure 24)

7. Optional: Injector needle removed from the injector nozzle
(see Figure 26)

8. Screw which secures the A-throttle removed (see Figure 23)

9. Control piston and A-throttle removed
(see Figure 25 and Figure 28)



Figure 20 - Nut to secure the injector nozzle



Figure 22 - Injector nozzle



Figure 23 - Screw with secures the A-throttle



Figure 21 - Nut to secure the injector nozzle removed



Figure 24 - Injector 3, injector nozzle removed



Figure 25 - A-throttle



Figure 26 - Injector needle



Figure 27 - Disassembled injector 3



Figure 28 - Control piston, injector 3

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 15 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

Injector 1

Corrosion can be found on armature guide, and inside the injector.



Figure 29 - Armature guide injector 1, bottom side



Figure 30 - Injector 1, armature removed



Figure 31 - Injector 1, armature guide removed



Figure 32 - Control piston, injector 1

Injector 2

During disassembly of injector 2, corrosion was found on armature guide and within the injector as shown in the pictures below.



Figure 33 - Armature guide injector 2



Figure 34 - Injector 2, armature removed



Figure 35 - Injector 2, armature guide removed



Figure 36 - Control piston, injector 2

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 16 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

Injector 4

Corrosion on amature guide and inside the injector visible.



Figure 37 - Armature guide injector 4



Figure 38 - Injector 4, armature removed

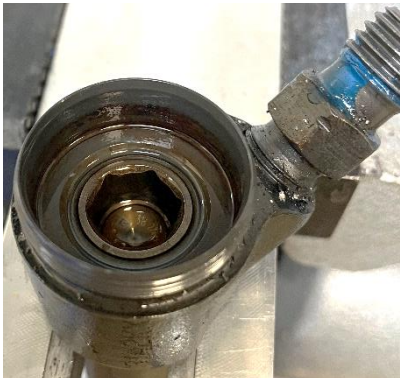


Figure 39 - Injector 4, armature guide removed



Figure 40 - Control piston, injector 4

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 17 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	

2.3. Microscopic inspection

2.3.1. Injector 1

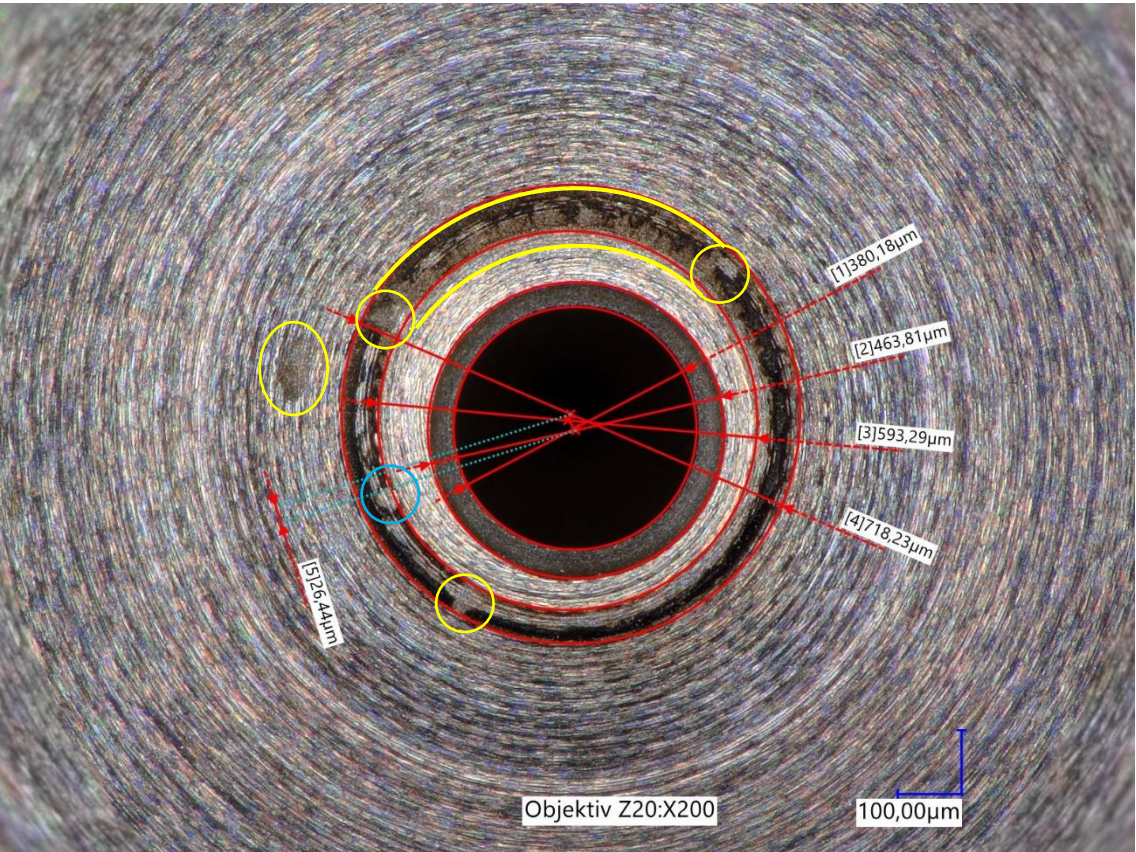


Figure 41 - Injector 1, A-throttle



Figure 42 - Injector 1, A-throttle ~35° left



Figure 43 - Injector 1, A-throttle ~ 35° right

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 18 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	



Figure 44 - Injector 1, armature guide x20



Figure 45 - Injector 1, armature guide



Figure 46 - Injector 1, armature guide x50 (1)



Figure 47 - Injector 1, armature guide x50 (2)



Figure 48 - Injector 1, corrosion on control piston

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 19 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	

2.3.2. Injector 2

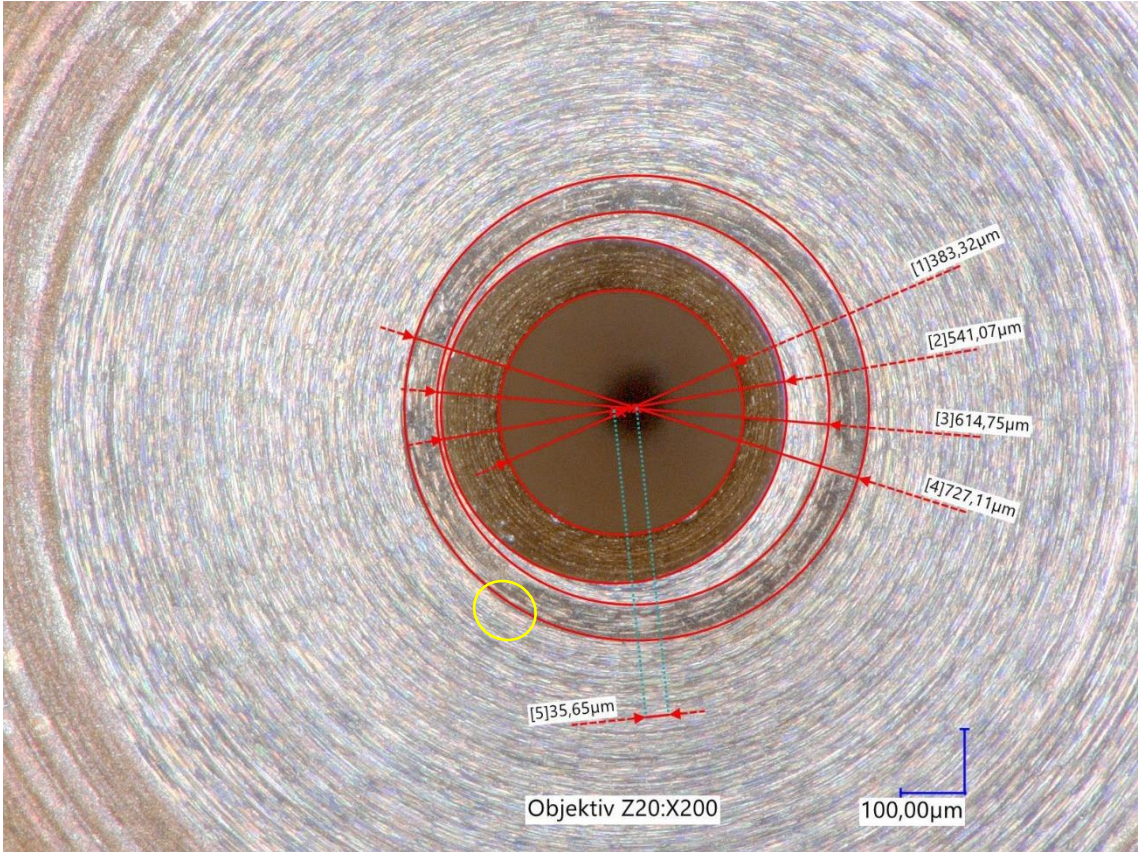


Figure 49 - Injector 2, A-throttle

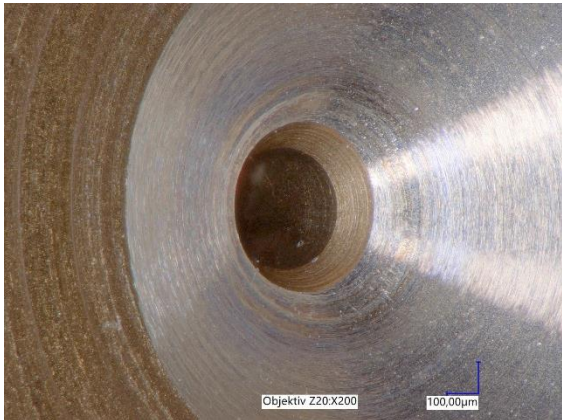


Figure 50 - Injector 2, A-throttle ~35° left



Figure 51 - Injector 2, A-throttle ~35° right

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 20 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	



Figure 52 - Injector 2, armature guide top side x20



Figure 53 - Injector 2, armature guide



Figure 54 - Injector 2, armature guide x20



Figure 55 - Injector 2, armature guide x50

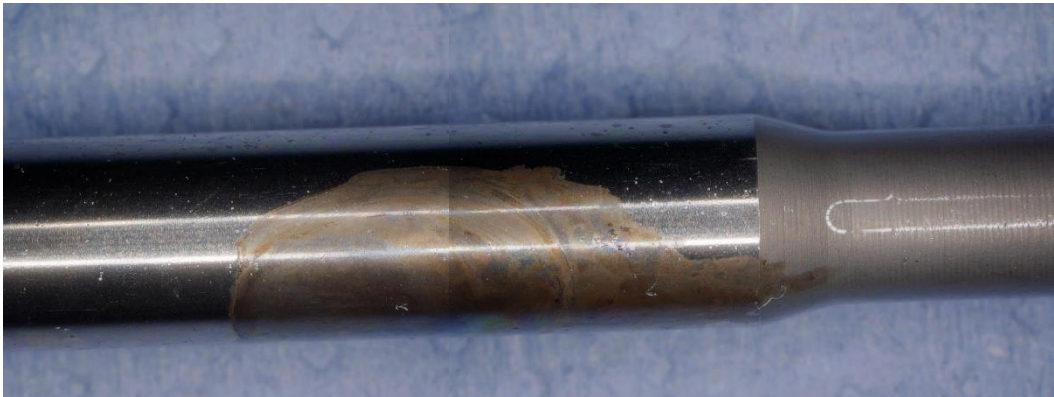


Figure 56 - Injector 2, control piston x30

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 21 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	

2.3.3. Injector 3

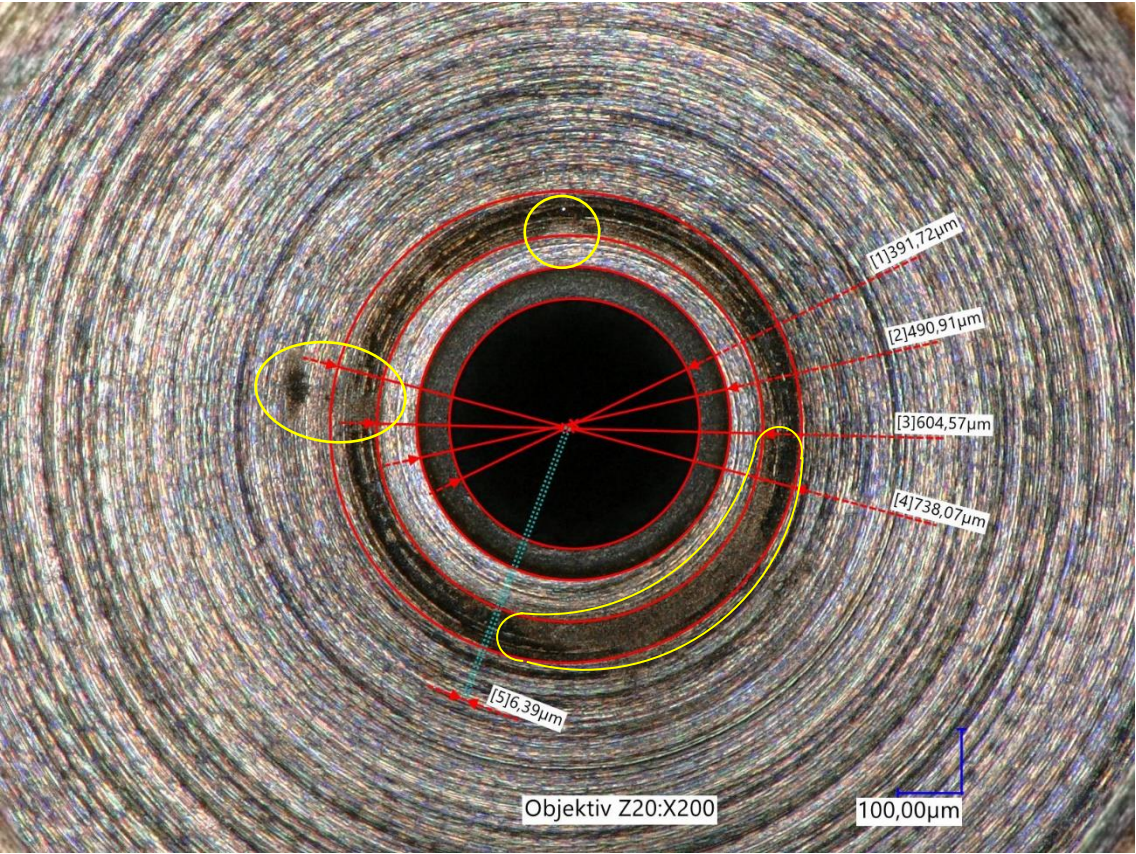


Figure 57 - Injector 3, A-throttle



Figure 58 - Injector 3, A-throttle ~35° left



Figure 59 - Injector 3, A-throttle ~35° right

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 22 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	



Figure 60 - Injector 3, armature guide x20

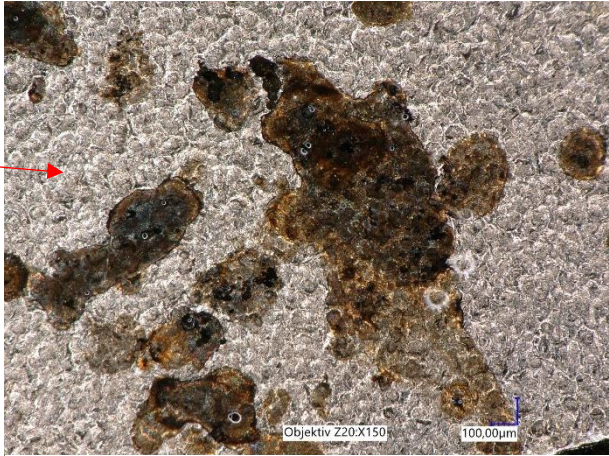


Figure 61 - Injector 3, armature guide x150



Figure 62 - Injector 3, control piston x50

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 23 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	

2.3.4. Injector 4

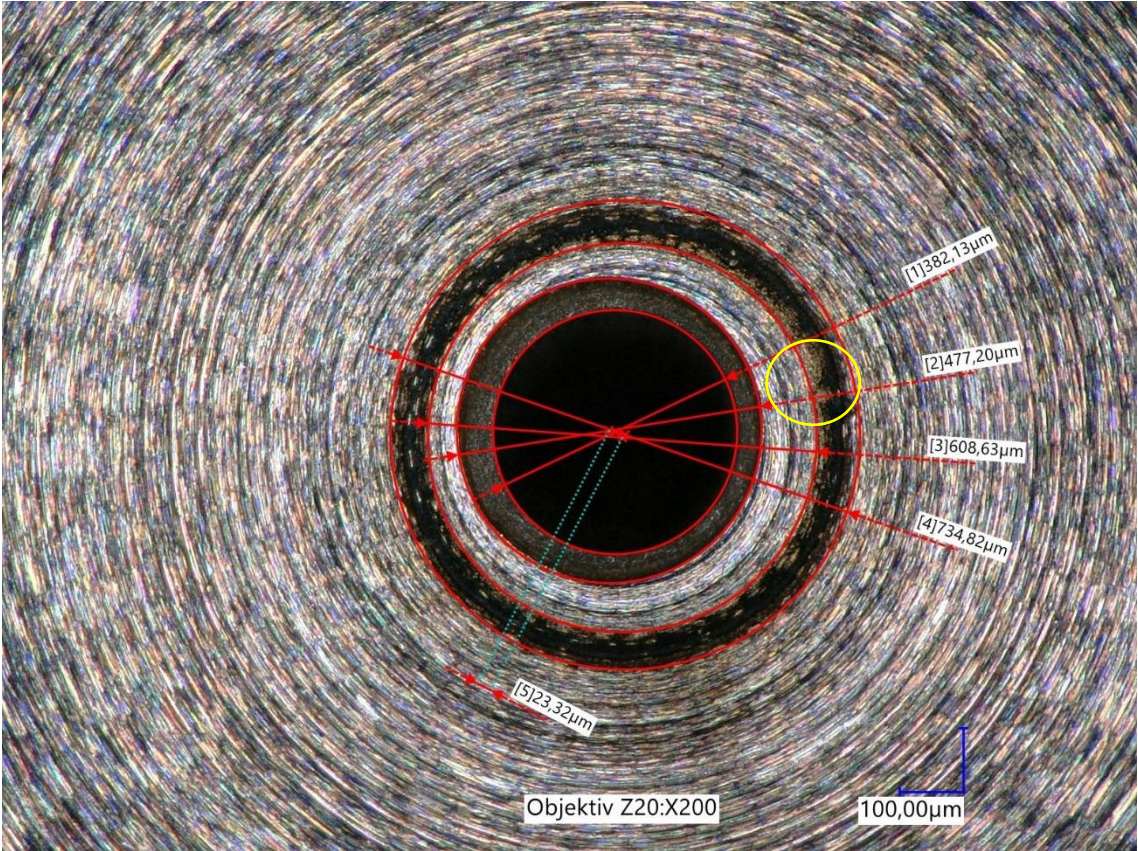


Figure 63 - Injector 4, A-throttle



Figure 64 - Injector 4, A-throttle ~35° left



Figure 65 - Injector 4, A-throttle ~35° right

 Austro Engine	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 24 of 34
	Type: E4	
	Subject: AEROSPACE INSPECTION REPORT	



Figure 66 - Injector 4, armature guide top side x20



Figure 67 - Injector 4, armature guide



Figure 68 - Injector 4, armature guide x20 (1)



Figure 69 - Injector 4, armature guide x20 (2)



Figure 70 - Injector 4, control piston x20 (1)



Figure 71 - Injector 4, control piston x20 (2)

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 25 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

2.4. Conclusion

During disassembly all 4 injectors showed clear signs of corrosion on several parts of the injector (armature guide, control piston, injector housing).

The throttles of all 4 injectors show no significant signs of cavitation erosion wear (Figure 72 shows an example of cavitation erosion wear). On all injector throttles are some irregularities (marked in blue and yellow, Figure 41-Figure 65) on the outer ring where the ball valve contacts the throttle present.

The blue marked spot at injector 1 (see Figure 41) is a small indentation on the conical surface. These indentations are mostly caused by contaminated fuel particles.

The outermost dark circle on the A-throttle (marked red on Figure 73) is the surface on which the ball valve rests. When the engine is running, the ball valve hits this area of the A-throttle so often that it usually looks polished over time.

On all 4 injector throttles, this area has some roughened spots which looks like the ball did not rest evenly. Injector 1 and 3 are the most affected, there are several places where it looks like the ball valve is hardly touching the throttle surface at all (see Figure 57, Figure 74, Figure 75). If the ball is not properly seated, the valve does not close completely and fuel can continue to enter the combustion chamber.

In practical application, these types of wear mean an uncontrolled start and end of injection. It can lead to a higher combustion chamber temperature and thereby the piston is subjected to a greater thermal load, as the firing cycle lasts longer.



Figure 72 - Example cavitation

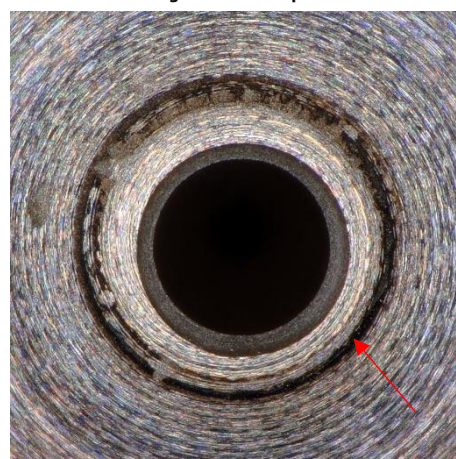


Figure 73 - A-throttle injector 1



Figure 74 - Close up, A-throttle injector 1

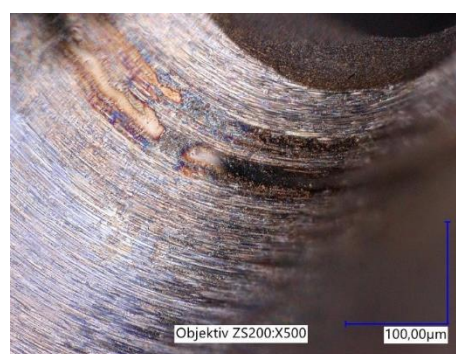


Figure 75 - 2nd close-up, A-throttle injector 1

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 26 of 34
	Type: E4	
Subject: AEROSPACE INSPECTION REPORT		

The exact cause of this roughness is difficult to determine as this damage was seen here for the first time.

Currently there are two hypotheses for the cause of this roughness:

1. The ball valve does not rest evenly on the surface, fuel continues to flow through the small openings causing the surface to roughen. Contamination of the fuel would favor this damage pattern.
2. The surface is roughened by corrosion: Is this A-Throttle compared to a throttle which clearly showed corrosion, it can be seen that the surface is similarly roughened.

However, the present wear on all four injectors do not show an influence on the performance test of the injector itself, as seen in the DISU Reports, shown in chapter 4 APPENDIX.

The DISU evaluation only provides a snapshot using testing oil.

The current wear (corrosion on injector parts) highlights the potential for operational issues with contaminated fuel.

Additionally, it is observed that the conical bores are slightly nonconcentric.

Eccentric deviations are the following:	1st Inj.	~26,44µm
	2nd Inj.	~35,65µm
	3rd Inj.	~6,39 µm
	4th Inj.	~23,32µm

It can be seen that the injector 2 is less concentric than the others.

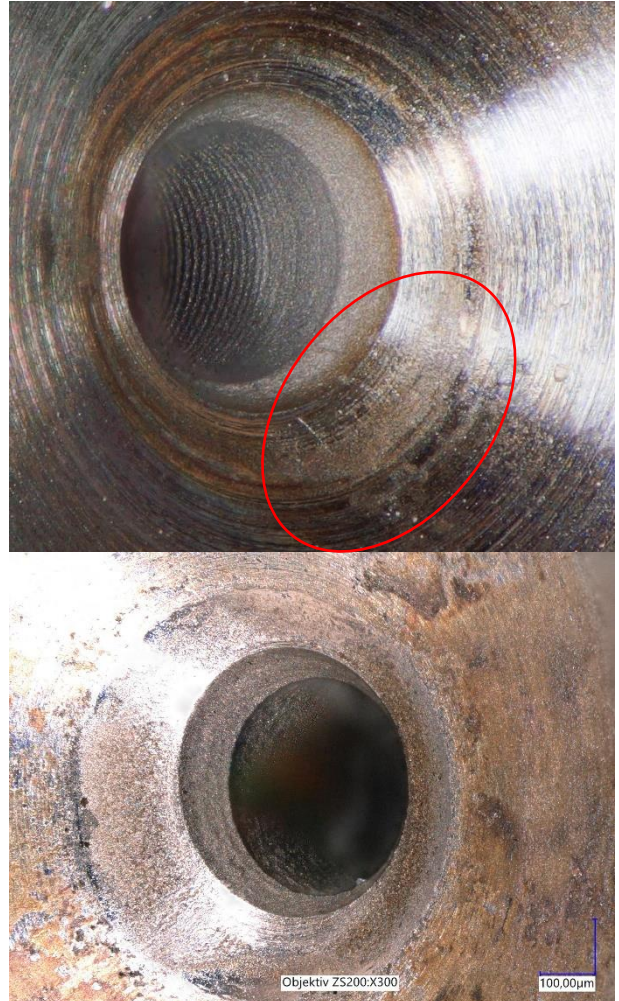


Figure 76 - Comparison roughened surface injector 3 (top) to corroded injector (bottom)

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 27 of 34
	Subject: AEROSPACE INSPECTION REPORT	

3. PISTON HARDNESS TESTING

3.1. Delivery condition



Figure 77 Delivered parcel top



Figure 78 Delivered parcel front



Figure 79 Delivered parcel back



Figure 80 Delivered parcel left

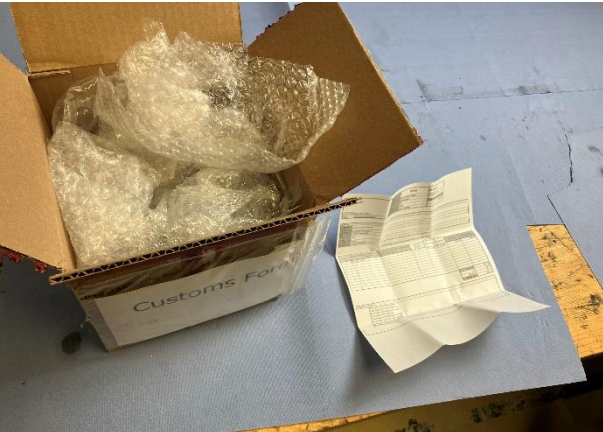


Figure 81 Parcel opened with invoice



Figure 82 Parcel condition opened

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 28 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	



Figure 83 Piston number 1



Figure 84 Piston number 3



Figure 85 Piston number 4

On February 29, the engine pistons were hardness tested in the presence of the authorities in order to determine possible effects of the injector. The delivery condition was as shown in the previous pictures. The cardboard box had several labels on the outside. No external damage could be identified. Each piston was separately packed with bubble wrap. After a quick visual inspection, the pistons were taken to Austro Engine quality assurance department to start the hardness measurement.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 29 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

3.2. Hardness measurement

Measuring equipment used:

KB Messtechnik KB250/750/3000

Test method used:

Hardness Brinell (HBW) 2,5/62,5

At the start, it was important to secure the piston against the perpendicular test force during the test procedure in order to generate a comparable value for each test. To guarantee this, clamping blocks were used, as the piston skirt could no longer be used as a base due to the damage. Great care was taken to ensure that no further damage was caused during clamping.



Figure 86 Measuring equipment

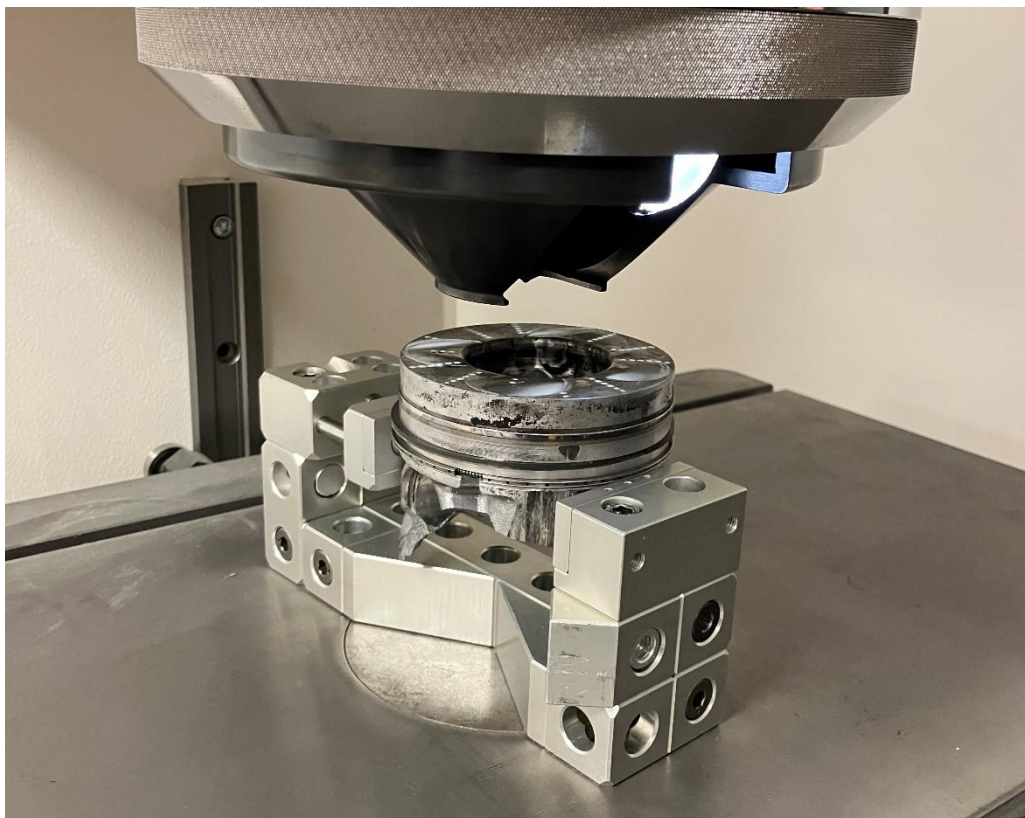


Figure 87 Securing structure

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 30 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

The hardness measurement was conducted on the first piston to investigate the probability of a malfunctioning fuel system even further.

The illustration shows the top face of the piston. Labeled are points to measure the various spray areas of the injector.

- The abbreviation "K" stands for a cold area where the injector distributes its spray directly.
- The abbreviation "H" stands for a hot area where the injector does not spray its stream directly onto the surface.

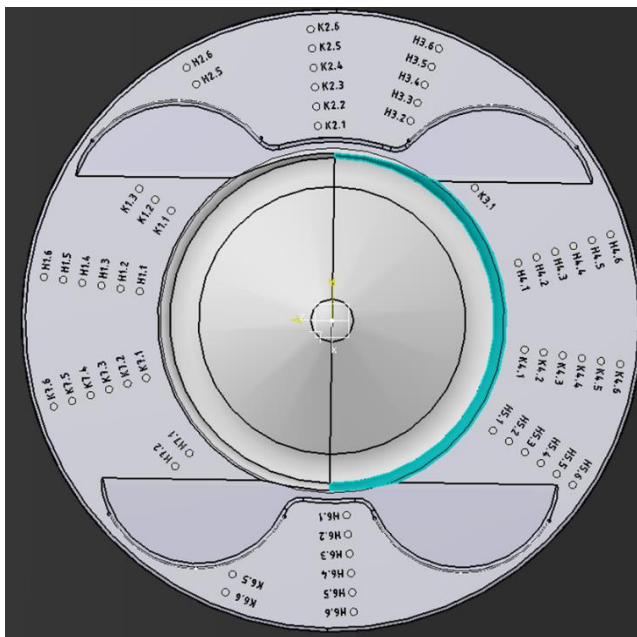


Figure 88 Measuring scheme

The values on the right-hand side were measured. Besides K4.2 & K7.3 all points were located on a level surface, therefore, a measurement was possible. Just after conducting the test, the evidence that no large differences between the different spots was present. Later, they were compared with empirically determined values and graphs were prepared.

H1.1	80,2	K1.1	77,5
H1.2	74,8	K1.2	77,1
H1.3	/	K1.3	75,0
H1.4	81,3	Mittelwert K1	
H1.5	82,7	K2.1	84,2
H1.6	82,0	K2.2	83,4
Mittelwert H1		K2.3	84,5
H2.5	80,4	K2.4	85,1
H2.6	81,8	K2.5	84,8
Mittelwert H2		K2.6	84,5
H3.2	77,0	Mittelwert K2	
H3.3	83,2	K3.1	77,8
H3.4	77,7	K4.1	75,0
H3.5	77,5	K4.2	/
H3.6	77,3	K4.3	50,8
Mittelwert H3		K4.4	77,3
H4.1	77,7	K4.5	81,1
H4.2	76,0	K4.6	77,5
H4.3	76,0	Mittelwert K4	
H4.4	77,9	Mittelwert K5	-----
H4.5	80,6	K6.5	81,5
H4.6	78,0	K6.6	78,0
Mittelwert H4		Mittelwert K6	
H5.1	75,8	K7.1	77,0
H5.2	76,0	K7.2	77,7
H5.3	77,3	K7.3	/
H5.4	77,5	K7.4	77,5
H5.5	76,0	K7.5	81,5
H5.6	78,8	K7.6	76,7
Mittelwert H5		Mittelwert K7	
H6.1	78,8		
H6.2	78,4		
H6.3	77,1		
H6.4	76,7		
H6.5	78,4		
H6.6	84,8		
Mittelwert H6			
H7.1	82,0		
H7.2	77,7		
Mittelwert H7			

Figure 89 Protocol 1

Figure 90 Protocol 2

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 31 of 34
	Type: E4	

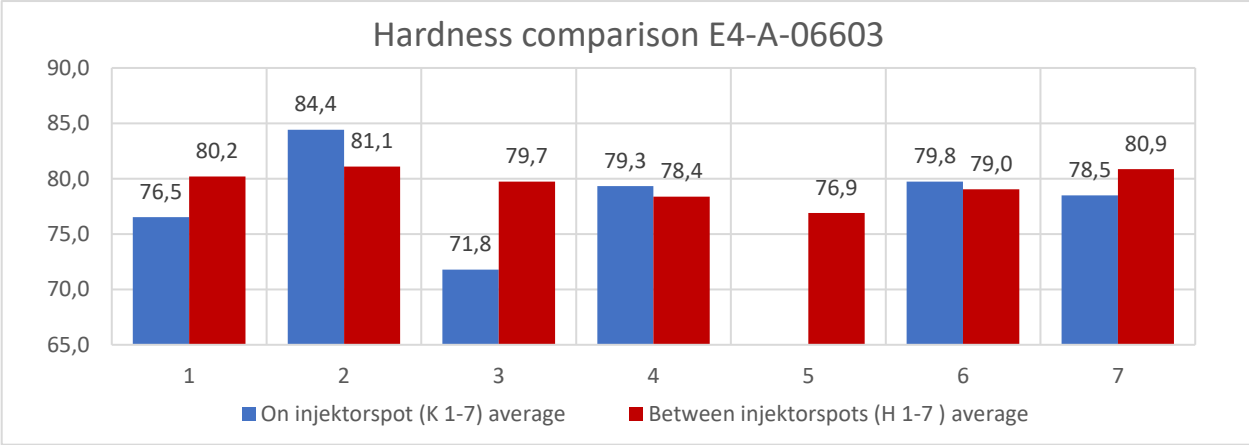


Figure 91 Hardness diagram K&H

This diagram aims to provide information about a general hardness distribution of the different spray spots. There is no big notable deviation of the areas at the injector spots and in between the injector spots. The respective K & H values are in a comparable range always between ~76,5 and ~84,4HBW except for K3, which was located on a valve notch and therefore did not provide a practical value.

If a malfunction of the injectors occurred here, the difference in hardness between K & H spots would be well over 20HBW, depending on the operation time. This is certainly not the case in this instance.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 32 of 34
	Type: E4	

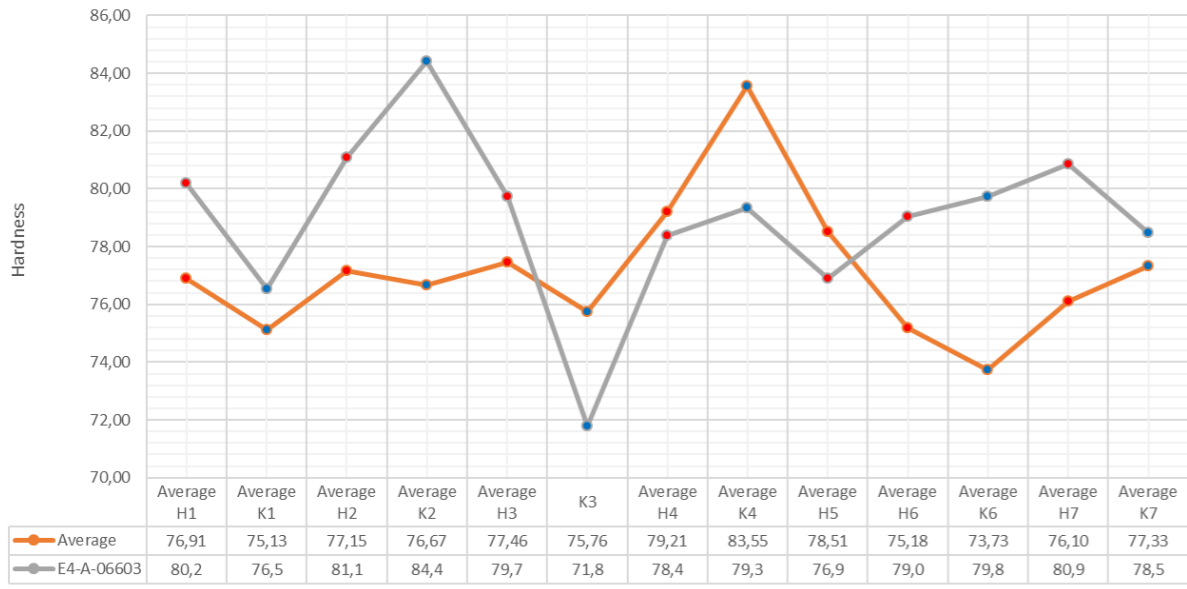


Figure 92 Hardness Comparison Average

The evaluation of the average values with empirically determined values from previous piston hardness measurements also reveals no anomalies.

The orange line shows the average hardness curve of all measured pistons. For comparison, the gray line shows the E4-A-06603 average hardness curve. All values distributed over the piston are within the expected range and also similar to the previously tested values. As previously mentioned, the value K3 cannot be used for the evaluation.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 33 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

3.3. Conclusion

After measuring the hardness of the first piston and evaluating the values, no loss of piston strength due to the fuel system can be detected on this cylinder. However, the disengagement of the second piston cannot be ignored. It is still possible that higher peak ignition pressures and/or higher combustion chamber temperatures in the second cylinder may have initiated the material fractures due to advanced wear of the injectors. Analysis of the EECU data will provide insight into this possibility.

	Title: Inspection of engine components	Doc. No.: AIR-2024-004 Chapter: OCCR/ E4-23-055 E4-A-06603 Rev.: 2 Page 34 of 34
Type: E4	Subject: AEROSPACE INSPECTION REPORT	

4. APPENDIX

- "Injector 1-4 DISU Tests"