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ANALYSIS OF THE CAUSE OF TRIBOLOGICAL DAMAGE TO VALVE ROCKERS IN A DIESEL ENGINE

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Abstract: This describes the consequences of a Volvo V70 diesel engine failure, as well as the development of this failure and its immediate cause. The engine was damaged 68 km after the timing belt had been changed. Preliminary analysis demonstrated strong material wear at the rocker arms of the exhaust valves, while not showing a similar wear on the intake side. Analysis of the timing belt replacement process shows that when the prescribed repair procedure is not followed, the timing system on the floating wedge can be set incorrectly and this may cause the exhaust valves to collide with the pistons. The collision caused cyclic overload in the friction nodes between the valves and rocker arms, resulting in engine damage. The aim of this paper is to indicate possible methods for determining the actual causes of tribological damage in internal combustion engine components. In addition, it is intended to serve as an example of the consequences that may result from non-compliance with the service instructions.

Keywords: rocker arm damage, incorrect timing system setting, exhaust valves, tribological wear.

1. INTRODUCTION

The consequences are described of the failure of a diesel engine used as the power unit of a Volvo V70 passenger car. It also reconstructs the course of the failure and identifies the direct cause of the damage.

The failure occurred after 68 km of operation following a timing belt replacement, which was performed at a European-wide workshop network that lacked the vehicle manufacturer's authorization. Initial inspection of the damage revealed a collision in the engine's timing system, causing it to lock up and preventing full crankshaft rotation. However, the timing belt was neither broken nor loose, it still maintained the proper tension. Upon removing the cylinder head cover, it was found that one of the exhaust valves had fallen into the cylinder, while the valve rocker had been punctured by the valve stem. The immediate cause of the engine lockup and failure was identified as the perforation of the valve rocker by the valve stem. The valve rocker pressed against the valve spring retainer and unlocked the valve keepers. However, preliminary analysis did not reveal the root cause of the valve rocker damage, prompting further investigation to determine the direct cause of the failure.

In seeking the root cause of the damage, an analysis of available scientific articles describing similar failures was conducted, resulting in the identification of one comparable case. The authors of the article [Soffritti et al. 2018] encountered an almost identical failure of the valve rockers; however, it affected both the intake and exhaust rockers, and no information was provided regarding the engine's operational history apart from the total operating time (1000 hours). Due to these limitations, a direct comparison between the two cases was not possible, and it was therefore decided to carry out an independent analysis. An inspection revealed that the mechanic did not maintain proper care or adhere to the replacement procedure when changing the timing belt. The procedure requires locking the camshaft and flywheel with appropriate locking tools, conducting a specific verification process to ensure correct timing alignment, and replacing the crankshaft pulley bolt. At least some of these steps were not performed according to the instructions. The mechanic only used the camshaft locking tool and locked the flywheel by inserting a screwdriver blade between the flywheel and the engine housing, according to his testimony and demonstration the engine disassembly, justifying it as a standard practice. This method carries a significant risk of unintended crankshaft rotation, such as when loosening the crankshaft pulley bolt. Such movement could have been detected and corrected by performing the verification procedure outlined in the official timing belt replacement instructions. These instructions specify performing four full crankshaft rotations and reinstalling the engine locks. If the timing phases have shifted, the locks cannot be reinstalled.

Another deviation from the original replacement procedure was the reuse of the old crankshaft pulley bolt, a typical Torque-To-Yield bolt. These bolts are used in timing systems or for mounting valve heads, for example. A more detailed description of the phenomena occurring during the tightening of such bolts has already been studied and described in the literature [Nassar and Bickford 2025], demonstrating [Lee et al. 1995] the contraindications to reusing these bolts. Due to the high tightening torque and the additional specified angle of rotation, this bolt is subjected to significant torsional stress during both tightening and loosening. These stresses cause structural changes in the metal, meaning that reusing the same bolt does not provide the required clamping force. The vehicle manufacturer anticipated this issue and mandates replacing the crankshaft pulley bolt with a new one each time.

The engine is typically used in Volvo 2.0 D vehicles, designated as D4204T, as well as in Peugeot 2.0 HDI and Ford 2.0 TDCi vehicles. Strict adherence to the timing belt replacement procedure is essential due to the presence of a floating key that determines the position of the timing gear on the crankshaft. Incorrect positioning of the gear on the floating key may result in an advanced or delayed timing phase. This, in turn, can cause piston-to-valve collisions – either with the intake valves in the case of advanced timing or with the exhaust valves in the case of delayed timing. Such a collision, especially if minimal, may not lead to an immediate timing system failure but can increase the stress at the valve stem–rocker friction points, potentially exceeding the scuffing load limit. Exceeding this limit leads to scuffing at the friction node and material loss in the contact area. The material loss from the valve rocker reduces its structural strength, eventually leading to perforation.

The car travelled 68 km after the timing belt replacement until the failure occurred. For a four-stroke engine, assuming an average engine speed of 1500 RPM and an average vehicle speed of 60 km/h, the exhaust valves would have undergone approximately 51,000 opening and closing cycles. If even a slight piston-to-exhaust valve collision occurred in each cycle, it could have gradually caused scuffing and material wear at the contact point between the valve stems and the valve rockers.

2. RECONSTRUCTION OF THE GEOMETRIC RELATIONSHIPS

To verify the hypothesis presented in the introduction, the geometric relationships within the combustion chamber were examined. According to Volvo service data [Volvo Cars Corporation], the free gap height during piston movement ranges from 0.056 to 0.103 mm. This represents the distance from the piston at TDC to the open exhaust valve. This parameter is crucial since any timing shift causing a delay in the exhaust valve closing beyond this clearance can lead to a piston-to-valve collision.

The angle of possible timing misalignment due to the floating key was calculated using CAD software based on the measured dimensions. Figure 1 illustrates the extreme positions of the timing gear on the crankshaft, while Figure 2 presents a geometric representation of these relationships. The correct positioning of the timing gear relative to the crankshaft is achieved by centrally aligning the key within the machined slot of the gear. The gear can rotate by 10.86° to the right, advancing the timing relative to the crankshaft, or by the same amount to the left, delaying the timing. However, considering the correct reference position, the actual misalignment would be half of this value: 5.43° in either direction.

Since the camshaft rotates at half the speed of the crankshaft [Wajand and Wajand 1993; Witkowski 2017] a 5.43° misalignment of the crankshaft gear results in a 2.715° shift of the camshafts. In this case, the misalignment of the timing gear relative to the crankshaft could have been caused by the reuse of the old crankshaft pulley bolt, insufficient tightening of this bolt, or crankshaft rotation due to the absence of proper flywheel locking during the timing belt replacement.

The exhaust valves open after the power stroke and close after the exhaust stroke, once the piston has passed top dead center (TDC). At the moment the piston passes through TDC, the valves remain open. According to the service manual for this engine type, the exhaust valves close 15.45° after TDC, which corresponds to 7.725° on the camshaft.

To assess the impact of timing phase adjustment on the exhaust valve lift, the exhaust cam profile was measured and referenced against the delayed valve closing angle, taking into account the rocker arm ratio. Figure 3 shows the measured cam profile from the maximum lift point to the end of the profile.

The camshaft rotation angles used to determine the exhaust valve lift are 7.725° before valve closure, which corresponds to the piston's TDC position, and a delay of 2.715° relative to the crankshaft caused by repositioning the sprocket on the crankshaft.

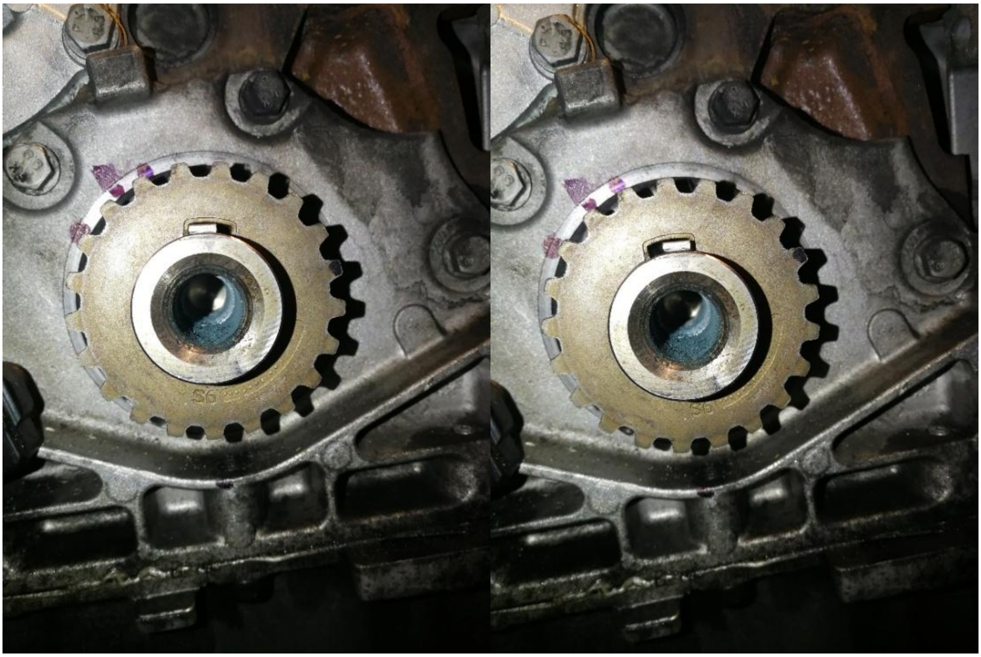

Fig. 1. Extreme positions of the sprocket on the crankshaft.
On the left side, the timing is advanced relative to the crankshaft.
On the right side, the timing is retarded relative to the crankshaft

The cam profile was measured at 2° intervals, so for the specified camshaft rotation angles, the valve lift values were derived using linear interpolation between two adjacent measurement points.

The calculated exhaust valve opening height at the moment the piston passes through top dead center (TDC) is 0.143 mm. When the timing system is retarded by 2.715° relative to the crankshaft, this height increases to 0.214 mm. The difference between these two values is 0.071 mm, which is 0.015 mm more than the specified clearance between the piston at TDC and the open exhaust valve [Volvo Cars Corporation].

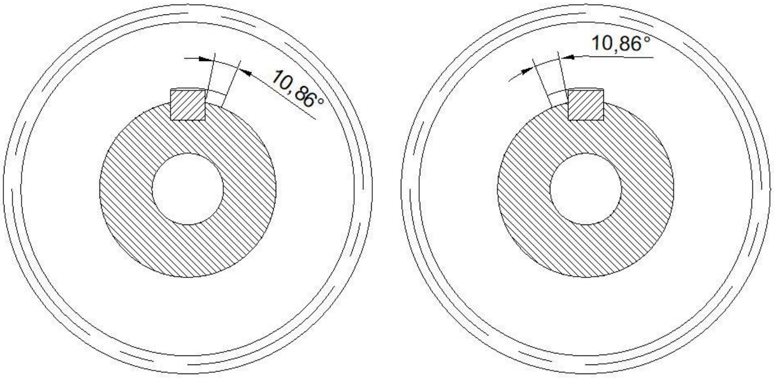

Fig. 2. Graphical representation of the sprocket displacement relative to the crankshaft

The presented results are based on precise service data and geometric measurements, which are subject to errors stemming from the accuracy of the measuring instruments, reading errors, and limited access to certain surfaces. However, it should be emphasized that all measurements were carried out with the utmost care and, where possible, were verified geometrically and against service documentation.

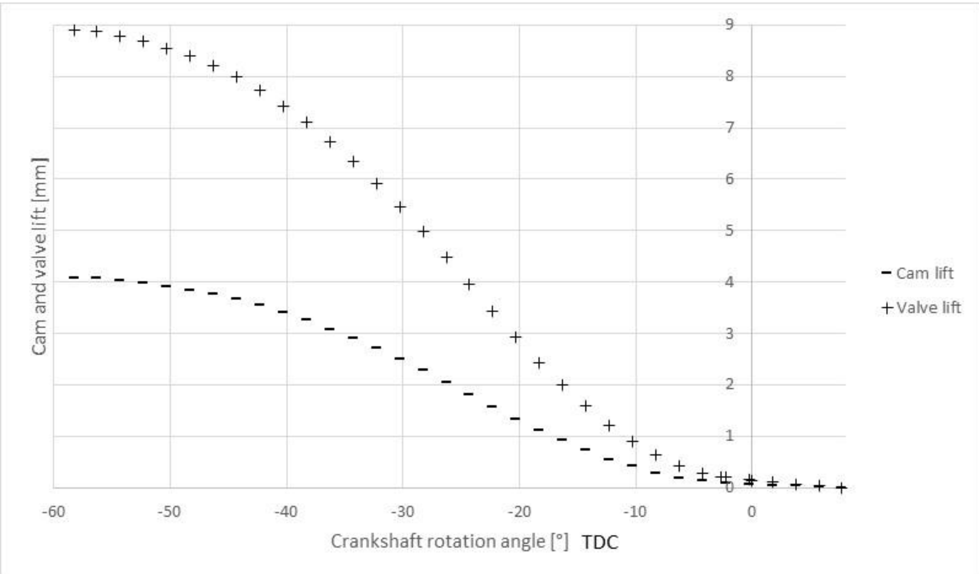

Fig. 3. Cam lift and valve opening height as a function of camshaft rotation

The analysis does not account for actual operating conditions, such as oil pressure effects or thermal expansion of the piston and valve. Nevertheless, the obtained results indicate that repositioning the sprocket on the crankshaft's floating key by 5.43° may cause timing retardation and lead to a collision between the piston and the exhaust valves.

3. OPTICAL EMISSION SPECTROSCOPY

The geometry tests of the timing system presented in the previous section allow for the possibility of a collision between the pistons and the exhaust valves. Measurements of other diagnostic parameters will help verify this hypothesis. One such diagnostic test is the measurement of trace element content in the oil.

Both fresh oil and the oil sampled from the engine after the failure were analyzed. The repair preceding the engine failure included an oil change, so the sampled oil was taken after driving 68 km following the replacement.

Measurements were performed five times for both the fresh and used oil, and the results were consistent. The average values from these measurements are presented in Table 1. Values marked as Δ represent the difference in trace element content between the fresh oil and the used oil sampled after the failure.

Table 1. Elemental contents in fresh and used oil

Element	Ag	Al	B	Ba	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	Si	Sn	Ti	V	Zn
Fresh oil [ppm]	0.644	1.638	67.714	0.078	58.14	0.527	0	0	0.755	0.157	632.29	6.943	6.406	0.785	3.462	863.07	3.258	6.584	0	2.174	0.492	606.06
Used oil [ppm]	0.796	3.453	50.983	0.113	284.02	0.554	0	0.294	36.386	0.457	236.95	11.487	3.801	0.014	4.197	750.65	1.802	12.792	0	2.462	0.669	457.2
Δ [ppm]	0.152	1.815	-16.731	0.035	225.88	0.027	0	0.294	35.631	0.3	-395.34	4.544	-2.605	-0.771	0.735	-112.42	-1.456	6.208	0	0.288	0.177	-148.86

Some of the trace elements that increase during operation originate from the wear processes, while those that decrease include the components of oil additives. A trace element that typically does not occur in fresh oil, or appears only in very small amounts, is iron. An increase in iron content by 35 ppm after driving just 68 km indicates very intense scuffing in a friction node primarily composed of iron. Such a node consists of the valve rocker arm and the valve itself.

As shown in Table 1, tin and chromium are absent in the used oil. These elements normally appear in used oil and originate from bearing alloys or piston rings. Their absence in the analyzed oil indicates that no remnants of the old oil remained in the engine prior to refilling with fresh oil [Sikora and Miszczak 2013; 2015].

To determine the origin of specific contaminants in the used oil, spectrometric analysis was also performed on the piston and the valve rocker arm. The chemical composition of the piston is presented in Table 2, while the composition of the rocker arm is shown in Table 3. According to the chemical analysis, the piston is an aluminum-silicon alloy with additives that enhance its properties. Both aluminum and silicon were found in the oil after 68 km of operation. Their concentrations changed less than that of iron, but the changes are still relatively high considering the short distance traveled. This may indicate a collision between the pistons and valves, or between a dislodged valve and the engine head.

Table 2. Chemical composition of the piston

Element	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ni**
Content [ppm]	11.305	0.5105	2.475	0.066	0.55265	0.0275	0.054	1.5935
Element	**Ti**	**Sn**	**P**	**Pb**	**V**	**Ag**	**Sb**	**Bi**
Content [ppm]	0.042	0.017	0.008	0.078	0.1045	0.0325	0.024	0.0005
Element	**Bi**	**Be**	**Ca**	**Co**	**Ga**	**Sr**	**Zr**	**Al**
Content [ppm]	0.01595	0.00025	0.01095	0.02805	0.11	0.0015	0.1475	82.7245

Table 3. Chemical composition of the rocker arm

Element	**Fe**	**Mn**	**Pb**	**Bi**	**Ti**	**Cr**	**Cu**
Content [ppm]	98.81	0.42	0.27	0.19	0.14	0.12	0.04

The chemical composition of the valve rocker arm consists primarily of iron and manganese. Both of these elements were found in the oil sampled from the engine after the failure.

A significant change in the engine oil chemical composition is the increase in calcium content. Calcium is not an alloying element of engine components and is typically part of oil additives. Under normal engine operation, the concentration of additives decreases as they are consumed, for example, in neutralizing acidic combustion by-products. In this case, the calcium content increased, indicating that it entered the oil along with the fuel. Fuel can enter the oil through the combustion chamber in cases of incomplete combustion. Such incomplete combustion may have been caused by the timing errors. When the timing is retarded relative to the crankshaft, the fuel dose remains unchanged, but the intake valves close earlier, resulting in less air entering the cylinder. The unburned portion of the fuel escapes from the combustion chamber into the exhaust system and the engine crankcase.

The increase in calcium content clearly indicates an abnormal combustion process in the engine.

The trace element analysis, showing a significant rise in metallic elements, confirmed very intense engine wear after just 68 km of operation. The increase in calcium also demonstrated a disturbance in the combustion process. However, a definitive collision between the pistons and valves cannot be confirmed.

4. HARDNESS TESTING

Preliminary inspection of the pistons with the naked eye did not reveal any signs of contact between the pistons and the exhaust valves. However, it should be noted that in this engine, the valve surface is parallel to the piston surface, and any potential collision would occur near the piston's top dead center (TDC) – at a moment when the valve is open only to a height of 0.214 mm. Consequently, the scuffing load resulting from such a collision would be distributed across the entire surface of the valve head and would act at the interface between the valve stem and the rocker arm.

According to the spare parts catalog data, the valve stem diameter is 6 mm, while the valve head diameter is 25 mm. Therefore, the contact surface between the valve stem and the rocker arm is approximately 17 times smaller than that of the valve head. Moreover, the nature of interaction at these points differs [Czaban 2013]: the stem–rocker interface is a friction node, whereas the piston–valve interaction is impact-based.

The absence of visible contact marks between pistons and exhaust valves was justified by hardness measurements of the rocker arm and the piston. The measured Vickers hardness at a 100 kg load was 93.7 for the piston and 457 for the rocker arm, which means the rocker arm was only 4.8 times harder than the piston. In the event of a piston–valve collision, the load would be transmitted from the valve head through the stem to the rocker arm. Given the 17-fold smaller contact area and only 4.8 times greater hardness, it is natural that any collision imprint would occur on the rocker arm rather than the piston.

Any potential valve imprints on the piston could be attributed solely to surface roughness or localized carbon deposits pressed into the piston surface. Additionally, the aforementioned differences in interaction characteristics on either side of the valve suggest that collision marks are more likely to appear on the rocker arms and valve stems than on the pistons.

5. MICROSCOPIC ANALYSIS

The final tests conducted to determine the cause of tribological wear on the valve rocker arms were microscopic examinations of the piston surface and the exhaust valve rocker arms. Piston no. 3 and the rocker arms of the exhaust valves were subjected to microscopic analysis.

Figure 4 highlights a mark located in the milled section of the piston situated beneath the exhaust valves.

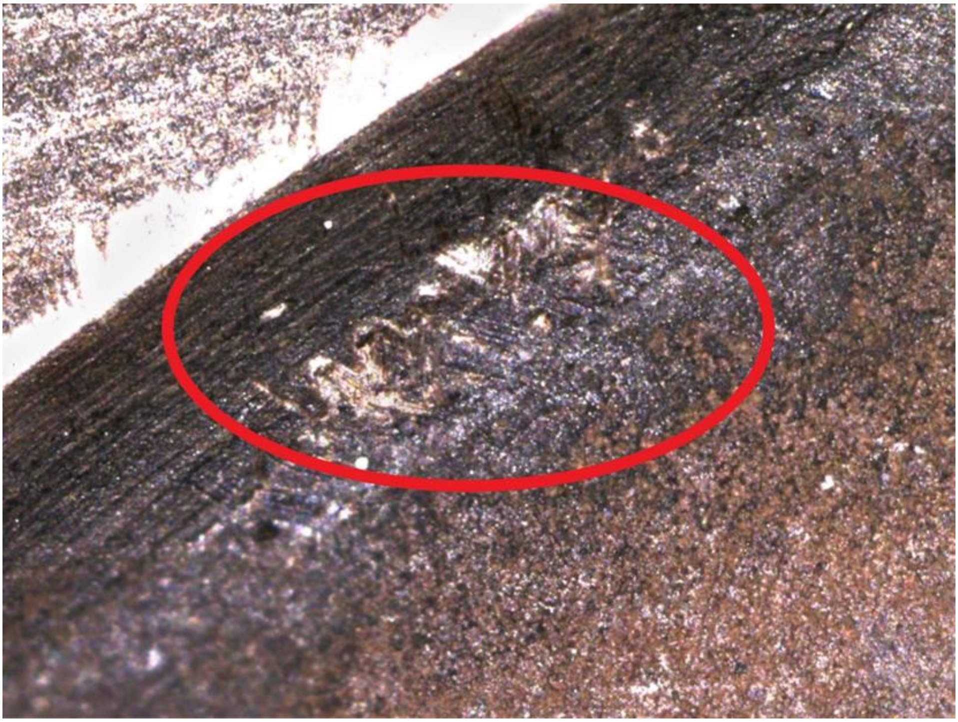

Fig. 4. Traces of piston–exhaust valve contact

The traces marked in Figure 4 could only have formed as a result of contact between the piston and an exhaust valve. The observed defect is located on the wall of the milled recess beneath the exhaust valves, and its height indicates that the valve–piston collision occurred within that range.

In other areas of the piston recess, numerous scratches and imprints were found, with arc diameters close to 25 mm. However, these marks are relatively short and faint, making their interpretation potentially subjective.

Examples of such scratches and imprints are shown in Figures 5 and 6.

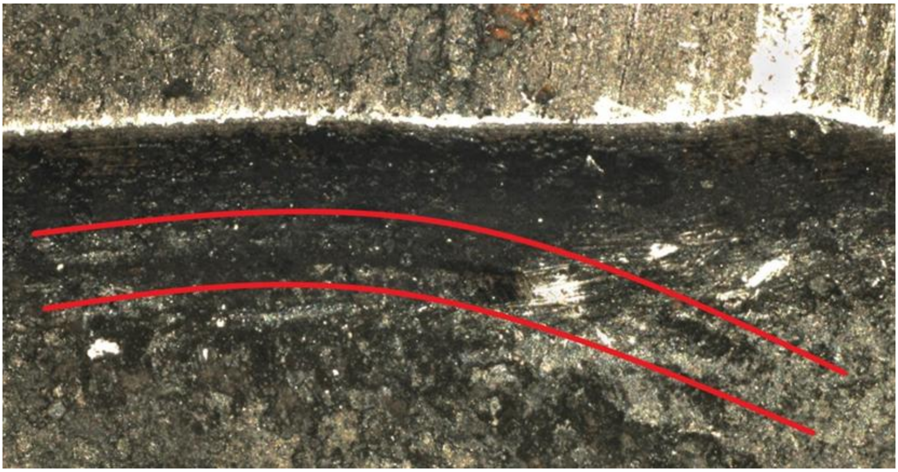

Fig. 5. Imprint from contact with the valve

Figure 6 also shows a layer of scale formed as a result of fuel injection. This scale is disrupted in multiple areas, which may indicate contact between the piston and the valve. Detached fragments of the scale could have entered the engine oil, a possibility that was addressed in the trace element analysis of the oil.

Fig. 6. Imprints with a diameter close to that of the valve head

The final conclusion regarding the cause of tribological damage to the valve rocker arms can be drawn from their microscopic examination.

Figure 7 shows the area of proper contact between the rocker arm and the valve stem. This reference image pertains to an undamaged intake valve rocker arm.

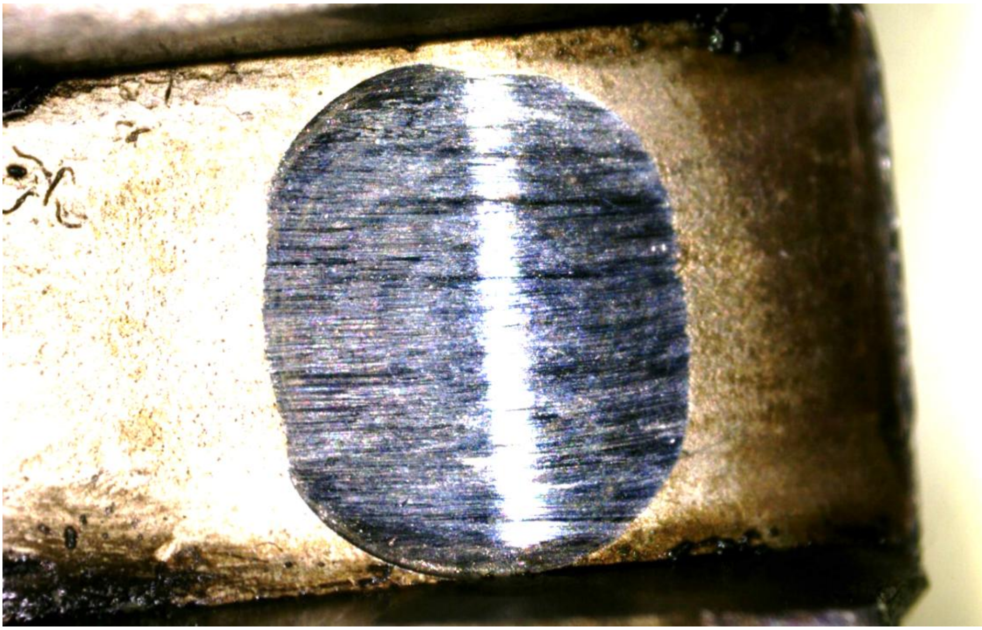

Fig. 7. Normal wear on the valve rocker arm

The microscopic image shown in Figure 7 confirms proper interaction within the friction node and aligns with findings reported in the literature [Włodarski 2006; Kułakowska et al. 2018]. It displays longitudinal scratches oriented along the direction of valve stem movement. These marks are continuous and parallel throughout the entire contact area. The valve opening cycle begins with the stem positioned on the left side, and at maximum lift, the stem shifts towards the right side of the rocker arm wear area.

Microscopic analysis was also performed on the valve rocker arm that suffered perforation and led to the engine failure, see Figure 8.

In Figure 8, material chipping is visible on the left side, indicating that the perforation occurred either at the beginning of valve opening or during valve closing. This area experienced the greatest material weakening due to loss, which correlates with increased load in the friction node at the start of valve opening or the end of valve closing [Tuszyński 2012; Wierzcholski and Miszczak 2015].

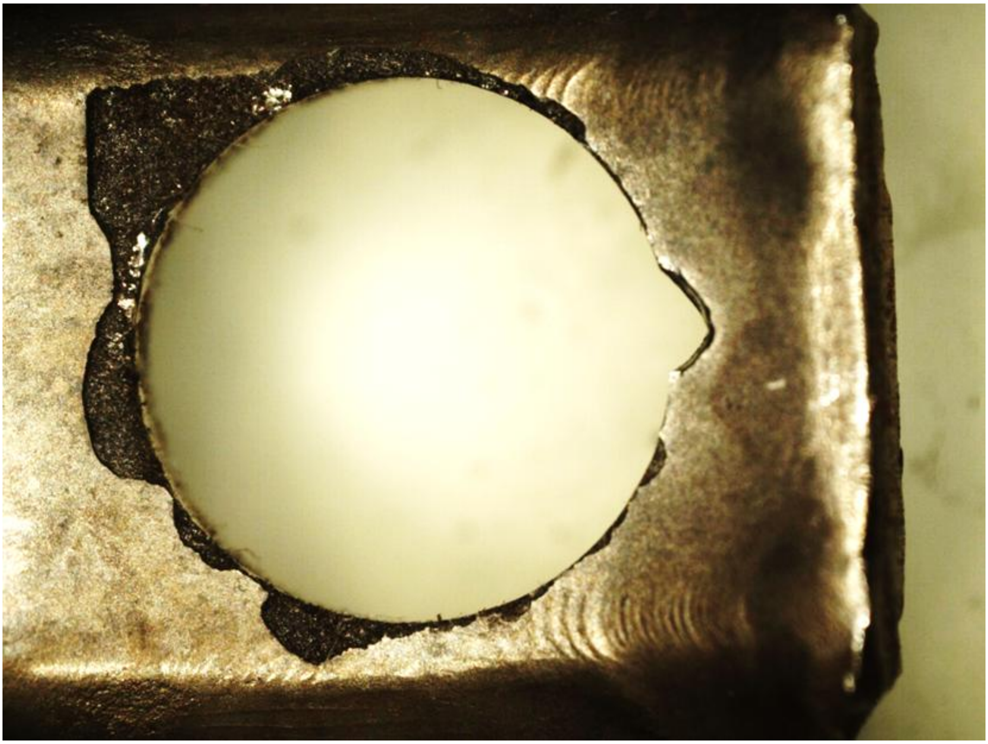

Fig. 8. Perforated valve rocker arm

The increased load during valve opening is caused by the presence of exhaust gases in the cylinder. However, this is a gradual load that varies with the camshaft rotation angle and is not impact-based. In contrast, increased load in the friction node during valve closing can only result from a collision between the piston and the exhaust valve. This is an impact load, as the piston completes a full stroke of 88 mm within the same time frame, while the valve moves only about 9 mm.

Figure 9 shows an exhaust valve rocker arm exhibiting signs of scuffing. Similar wear marks are present to varying degrees on all the rocker arms. This wear trace can be divided into three zones:

- Zone I: A scratch-free surface with varied height. The top layer is non-directional with rounded peaks, resembling plastic deformation typical of burnishing processes.
- Zone II: A swelling zone, where material from Zone I has been displaced. The increased volume in this zone is visible to the naked eye.
- Zone III: Deep, parallel scratches aligned with the direction of valve stem interaction. The depth of these scratches and the significant material loss in this zone are due to plastic deformation of the valve stem, which occurred as a result of the piston-exhaust valve collision.

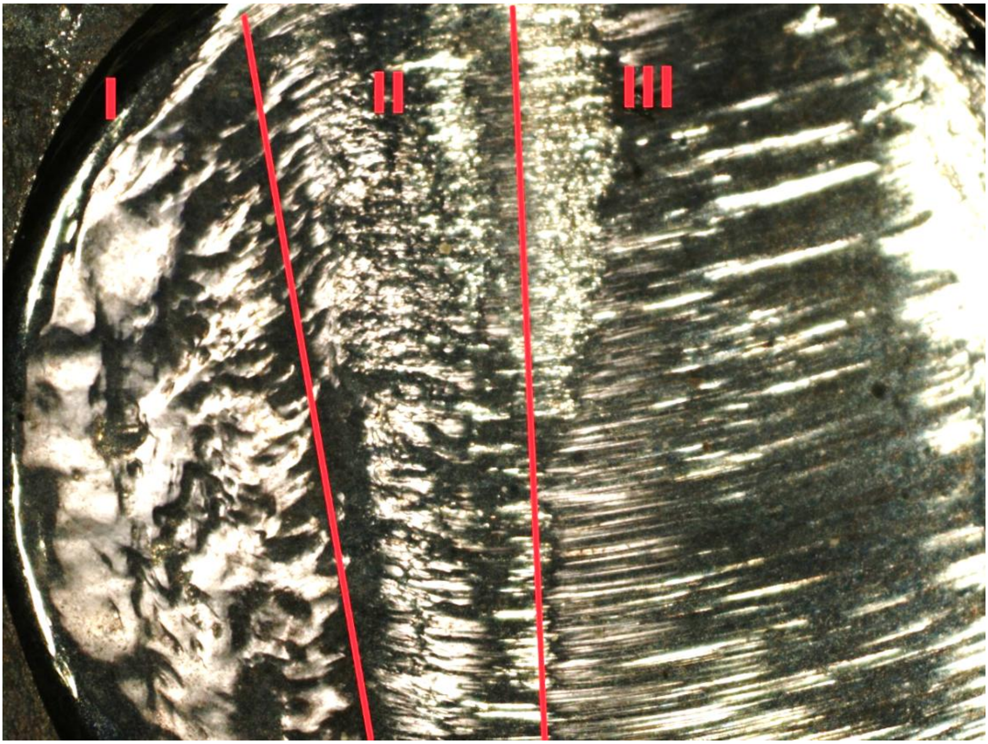

Fig. 9. Microstructure of the scuffing zone on the rocker arm at ×74 magnification

The differences observed between zones I, II, and III ultimately indicate that the cause of tribological damage to the valve rocker arms was impact-induced overload within the friction node, resulting from collisions between the piston and the valves. If the overload had occurred during valve opening and was related to exhaust gas pressure, material loss could also be expected. However, in such a case, the wear pattern at the valve stem-rocker arm interface would resemble that of the intake valves, as shown in Figure 7.

6. CONCLUSIONS

The origin of this study stemmed from the need to precisely determine the cause of damage to the valve rocker arms, which could not be accomplished under workshop conditions. Most of the laboratory tests conducted did not indicate a definitive cause of the rocker arm damage, but merely allowed for the possibility of a collision between the pistons and the exhaust valves.

Due to the lack of access to the engine's technical drawings, the geometry of the timing system had to be evaluated manually, which introduced the potential for error. This reconstruction was not feasible under workshop conditions. A comparison of the obtained results with the service data revealed the possibility of incorrect timing system alignment, which could lead to piston–exhaust valve collisions. The possibility of collision with the intake valves in the case of a reverse rotation of the crankshaft gear was not investigated, but such a scenario should be considered.

Given the wide variety of construction materials used in engine manufacturing, trace element analysis of the engine oil does not allow for precise identification of the failure location within the engine. However, it remains a highly effective diagnostic method for assessing engine condition prior to failure. An increased concentration of metallic elements in the oil immediately after its replacement indicates a serious engine fault, and the engine should not be started until the fault is located and resolved. As demonstrated in the presented analysis, periodic testing of trace element contents in the oil also enables evaluation of the combustion process within the engine.

Only a thorough microscopic analysis of the scuffing marks and piston surface features, combined with a comparison of the resulting microstructures with the literature data, allowed for a conclusive identification of the cause of scuffing.

Considering the results of all the described tests, and to a lesser extent the fact that workshop analysis of the engine's technical condition, did not reveal excessive wear in other friction nodes, it must be concluded that a mechanic's error during timing belt replacement led to misalignment of the timing system and a collision between the pistons and the exhaust valves. This collision caused cyclic overload in the friction nodes between the valve stems and the rocker arms. The overload exceeded the threshold for scuffing, resulting in progressive wear and material loss at the contact interface. As a result of this material loss, after driving 68 km, the rocker arm was perforated, leading to engine failure.

REFERENCES

Bosch, *Timing Belt Replacement Instruction for Engine D4204T.*

Czaban, A., 2013, *The Influence of Temperature and Shear Rate on the Viscosity of Selected Motor Oils*, Solid State Phenomena.

Kułakowska, A., Kukiełka, L., Kałduński, P., Bohdal, Ł., Patyk, R., Chodor, J., Kukiełka, K., 2018, *Burnishing Rolling Process of the Surface Prepared in the Turning Process*, AIP Conference Proceedings.

Lee, D.B., Foyos, J., Smith, M.L., Es-Said, O.S., Kossuth, O., 1995, *On the Reuse of Bolts Which Have Been Torqued to Yield*, Loyola Marymount University Mechanical Engineering Faculty Works, vol. 46.

Nassar, S.A., Bickford, J.H., 2025, *Handbook of Bolts and Bolted Joints*, Second edition, CRC Press.

Sikora, G., Miszczak, A., 2013, *The Influence of Oil Ageing on the Change of Viscosity and Lubricity of Engine Oil*, Solid State Phenomena.

Sikora, G., Miszczak, A., 2015, *Viscosity in Exploitation Time Analysis of the Lubricating Oil Used in the Combustion Engine of the Personal Car*, Solid State Phenomena.

Soffritti, C., Merlin, M., Vazquez, R., Fortini, A., Garagnani, G.L., 2018, *Failure Analysis of Worn Valve Train Components of a Four-Cylinder Diesel Engine*, Engineering Failure Analysis.

Tuszyński, W., 2012, *Problemy tribologicznych badań właściwości przeciwzatarciowych olejów przekładniowych*, Wydawnictwo Naukowe Instytutu Technologii Eksploatacji – PIB, Radom.

Volvo Cars Corporation, *Service Manual D4204T Engine*.

Wajand, J.A., Wajand, J.T., 1993, *Tłokowe silniki spalinowe*, Wydawnictwa Naukowo-Techniczne, Warszawa.

Wierzcholski, K., Miszczak, A., 2015, *Convergences of Cumulative Wear after Time of Bearing Operation*, Solid State Phenomena.

Witkowski, K., 2017, *The Impact of the Accuracy of Indicator Diagrams on the Heat Release Characteristics Calculation, Used in the Diagnosis of Marine Diesel Engine*, MATEC Web of Conferences.

Włodarski, J.K., 2006, *Podstawy eksploatacji maszyn okrętowych. Tarcie i zużycie*, Wydawnictwo Akademii Morskiej w Gdyni, Gdynia.