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Damage Investigation of a Stork Wärtsilä 6SW280 Engine Valve Exhaust – A Case Study

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ABSTRACT

The loss of steerage in maritime vessels often stems from main engine failures, as expounded in the present article. The focal incident involves a cascading engine breakdown initiated by a single exhaust valve fault. Subsequent consequences encompass the fragmentation of the second exhaust valve, structural damage to the engine components, including the head and piston, cracking of valve seats, and the inadvertent entry of cooling water into a cylinder. The ensuing plastic strain on the cylinder surface, coupled with valve fragments infiltrating the turbocharger, leads to additional, albeit minor, damage. Notably, the high degree of plastic strain obfuscates the original features of the cracked elements, necessitating the author to delineate a hypothetical cause and progression of the destruction process. In the conclusive remarks, the author underscored the paramount importance of continuous engine operation monitoring and meticulous fault diagnosis to uphold the safety standards of maritime transport.

Keywords: failure, marine engine, valves, diagnostics, maintenance, reliability.

INTRODUCTION

The loss of steerage in maritime vessels can result in catastrophic consequences, including collisions, grounding, and sinking, leading to loss of life, environmental damage, and economic loss [1]. These accidents often arise from various factors, with propulsion or steering system failures being significant contributors, rendering a vessel unmanageable. Among these systems, the propeller shaft is particularly susceptible to damage [1]. This vulnerability stems from dynamic elements like bending moment, torque moment, axial thrust force, temperature fluctuations, and exposure to corrosive environments. An illustrative case [2] highlights the impact of propeller shaft failure, where a fracture occurred due to corrosive effects and variable torque moments, necessitating costly repairs and operational downtime. While propulsion system failures contribute to maritime immobilizations, failures in the main engine also pose frequent challenges. For instance, a crack in an exhaust valve pin triggered catastrophic engine damage in one case, leading to extensive repair and towing [3]. Examination of diesel engines reveals a prevalent focus on exhaust valve faults due to their operation under extreme thermomechanical loads, often resulting in fatigue failure. Various studies delve into the causes of valve failures, including cyclic loads in high temperatures and accelerated corrosion [4–7]. Selected research employs advanced techniques such as fractographic examination and optical microscopy to investigate failure mechanisms [4, 5]. These studies highlight factors contributing to reduced valve service life, such as impurities from combusted fuel and lubrication oil depositing on valve surfaces.

In addition to post-failure analyses, experimental studies on valve and valve seat wear using simulating testers shed light on failure mechanisms, emphasizing the role of elastic and plastic deformation, spalling, and fatigue micro-cracks [8]. Interactions among engine components, particularly valves and cylinder heads, are crucial considerations, as evidenced by studies highlighting their influence on engine durability [9]. Finite element method (FEM) analyses align with experimental tests, suggesting potential issues like cylinder head cracking, affecting valve operation [9].

Proper failure monitoring and diagnosis are emphasized to prevent emergency shutdowns and ensure marine engine reliability [10]. Acoustic emission (AE) technology shows promise in detecting valve faults, although its full potential remains underutilized [11]. Integrating engine function details and failure mechanisms into comprehensive frameworks aids in identifying and monitoring incipient combustion-related faults in diesel engines [12].

Studies on gas scavenging, cylinder untightening, and geometric parameters in internal combustion engines offer insights into engine operation and maintenance [13–15]. Explorations into maritime failures underscore the importance of proactive measures, innovative technologies, and a deep understanding of failure mechanisms in fortifying the maritime industry [16–21].

The aim of this study was to investigate the chain of events leading to the loss of steerage in maritime vessels resulting from a cascading engine breakdown initiated by a single exhaust valve fault. By examining the failure of two valves as well as the condition of the cooling conduit and the presence of impurities within, this research aimed to bridge a significant knowledge gap in maritime engineering. It provides a nuanced understanding of the factors contributing to valve failures in maritime vessels, highlighting the roles of thermal stresses, impact forces, and cooling system conditions. These insights are valuable for addressing specific engineering challenges and implementing preventive measures to avoid similar failures in the future, such as mitigating impact forces and managing thermal stresses in critical engine components.

Subject of the study

There is a lack of research on the specific role of main engine failures in the loss of steerage, particularly in the context of a cascading engine breakdown initiated by a single exhaust valve fault. In this article, a case was presented in which initially one of the exhaust valves was damaged. As the engine continued to operate, further damage occurred to another exhaust valve, the cylinder, piston, and cylinder head. The vessel, having lost the ability to move independently, had to be towed to the shipyard.

The main engine of the Stork Wärtsilä 6SW280 vessel (serial number: 80336) underwent overhaul in September 2015, which involved replacing the inlet valve spindles, exhaust valve spindles, and seats. On 8th July 2016, while en route to Wolgast, Germany, and cruising at 65% of its maximum continuous rating (MCR), white smoke was observed coming from the funnel. The Captain promptly reduced the load to Dead Slow; however, the main engine had already ceased operation without triggering any alarms. During the maintenance of the Stork Wärtsilä 6SW280 engine (Fig. 1) a total of ten irregular steel masses were extracted from the engine, revealing themselves to be fragments of exhaust valves. This issue extended to the turbocharger area, resulting in minor damages. Specifically, valve no. 1 fractured into seven components—comprising the pin and six head fragments—while valve no. 2 broke into three parts, including the pin and two head fragments.

The as-received failed exhaust valve was at first examined visually by naked eye and under magnifying glass. Photographs in the as-received condition were taken and preserved for future reference during analysis. Subsequently, representative fracture surfaces were selected and extracted delicately without damaging the fracture surfaces for further in-depth examination for tracing out existence of any surface corrosion debris and/or contamination and its composition as well as observation on fracture features under scanning electron microscope (SEM). A similar methodology was adopted in the work by Hazra et al. [22]. Analysis of pollutants from the cooling channel of an internal combustion engine using EDS can provide significant diagnostic information that may be crucial for identifying and addressing the issues leading to failure. EDS analysis reveals the distribution of elements present in the damaged engine components. The purpose of this examination is to elucidate the causes of failure.

The investigation detailed in this article is based on the examination of research materials available to the author, as depicted in Figures 2 and 3. Figure 2 illustrates that, for valve no. 1, the material included the pin and a singular head fragment. Conversely, for valve no. 2, the material comprised the pin and two head fragments. Notably, the larger fragment of the latter valve had been dissected into four pieces during a prior

Figure 1. Stork Wärtsilä 6SW280 engine (production date: 1993)

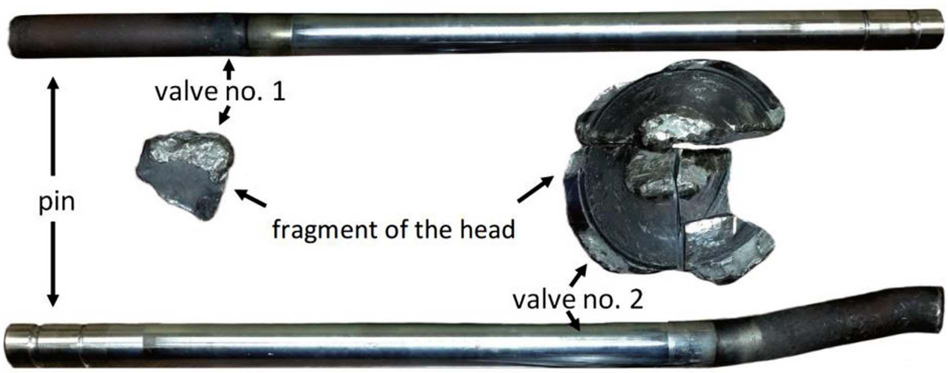

Figure 2. Examined exhaust valves parts valve no. 1 and 2

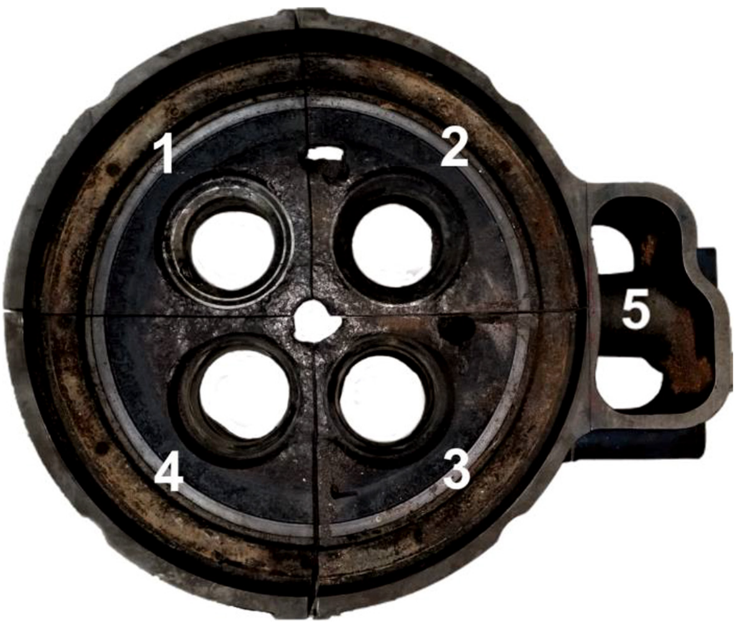

Figure 3. A fragment of the head of the marine engine cylinder no. 1 cut into five pieces numbered 1 to 5

study; however, one of these fragments is omitted from the visual representation. Examinations were additionally carried out on the cylinder no. 1 head, along with the valve seats housing the malfunctioning valves. To facilitate a thorough visual inspection, the lower section of the head was trimmed due to its substantial mass and subsequently divided into five distinct pieces (refer to Fig. 3). The numerical labels 1 and 2 in Figure 3 correspond to the identification of the exhaust valves (Fig. 1).

RESULT OF THE STUDY

The failure of the two exhaust valves did not occur simultaneously, as evident from the distinctive fractures observed on the valve pins, illustrated in Figure 4. The fracture pattern strongly suggests that valve no. 1 was the first to experience failure. It is reasonable to consider two equally probable scenarios for the deterioration of valve no. 1.

In the first scenario, dynamic loads acting at the location of maximum stress concentration—specifically, where the pin with a smaller cross-sectional area penetrated the head with a considerably larger cross-sectional area—induced material fatigue, resulting in a fatigue fracture. Subsequently, the entire head descended into the cylinder while the engine continued to operate. Over successive compression and exhaust strokes, the piston repeatedly impacted the pin, resembling a forging process. This extended interaction caused plastic deformation on the surface perpendicular to the pin axis, erasing the typical features of a fatigue fracture. Simultaneously, this surface provided no discernible information regarding the root cause of the damage. The freely moving head was also struck by the piston, leading to the fragmentation of the head into six pieces.

The second scenario envisions that the process of fatigue fracture initiated at a site where a pre-existing local fault existed. Over time, segments of the head crumbled, disrupting the axial symmetry of the dynamic valve load. With ongoing operation, the valve underwent simultaneous stretching and bending, inducing fatigue in the valve pin material. The subsequent destruction of the valve unfolded in a manner consistent with the aforementioned steps.

The likely sequence of events leading to the destruction of valve no. 2 unfolded as follows: while the valve was in the open position, a fragment from the head of valve no. 1 became lodged between the valve head and seat. Subsequently, during the valve-closing phase, the combined forces acting on the valve resulted in the head breaking into two pieces and the pin bending, as illustrated in Figure 3.

The fracture observed on the pin of valve no. 2, depicted in Figure 4, exhibits characteristics consistent with a typical brittle fracture, manifesting within a relatively brief timeframe under a load surpassing the tensile strength, particularly during the valve-closing operation. Unlike the fracture surface of the pin of valve no. 1, which is predominantly perpendicular to the pin axis and indicative of a fatigue fracture, the fracture surface of the pin of valve no. 2 displays a less

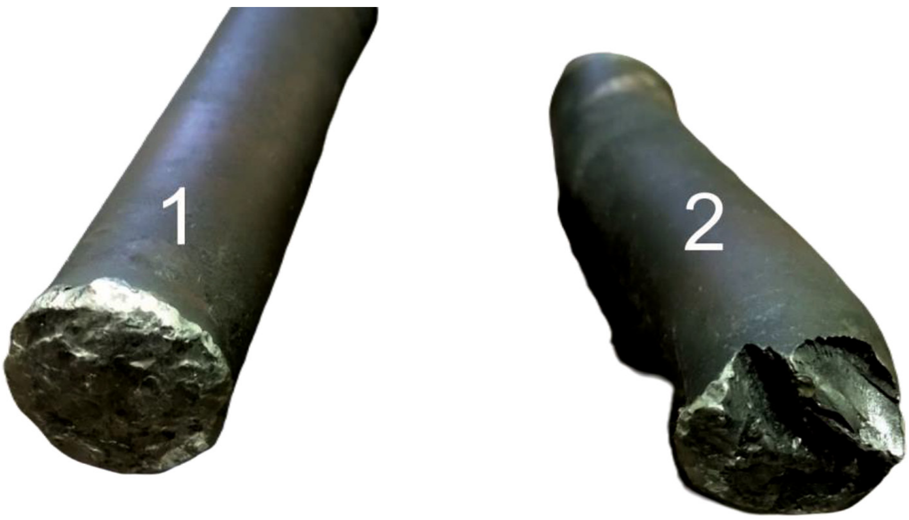

Figure 4. Fractures of the pins of valves no. 1 and 2

pronounced perpendicular orientation. Furthermore, in contrast to the fracture of the pin of valve no. 1, the fracture of the pin of valve no. 2 underwent minor deformation during subsequent engine operation, as depicted in Figure 4. The fractures observed in the heads of valve no. 1 (refer to Fig. 5) and valve no. 2 (refer to Fig. 6) manifest distinct characteristics attributable to different types of loads, as substantiated by the outer structures of the valves.

In Figure 5, the surface of the fracture exhibits hallmark features indicative of a fatigue fracture. Characteristic markings of a nucleation point, from which crack fronts radiate, are evident on this surface. As the dynamic load cycles increase, the fatigue crack systematically propagates deeper into the material. This fracture pattern aligns with typical fatigue behavior where repeated loading over time induces crack initiation and propagation.

Conversely, the fracture surface displayed in Figure 6 possesses notable roughness, with irregular bands spreading predominantly parallel to the valve axis. The shape and characteristics of these irregularities strongly suggest extensive plastic deformation of the head material in this region. Regarding the presented fracture of the head of the valve number 2 (Fig. 6), there is no visible focal point where fatigue crack initiation occurred due to deformation. This fracture is emblematic of a type that occurs under transient or temporary loads, indicating a distinct mechanism compared to the fatigue fracture observed in Figure 5.

During the investigative phase, an alternative hypothesis was considered to explain the cause of the destruction of valve no. 1. The proposition posited that the vessel failure might have originated from the unstable mounting of the valve seat within the engine head, allowing the seat to undergo movement relative to the head. Subsequent examination, however, did not substantiate this hypothesis.

The seats of the exhaust valves, affixed within the openings in the engine head, were found to be securely fixed in parts 1 and 2, as depicted in Figure 3. These seats displayed no propensity for movement under the influence of applied forces. To conduct a visual inspection of the outer surfaces of the valve seats and the openings in the engine head, kerfs were introduced on parts 1 and 2 using a chainsaw. Following impact with a hammer, part no. 1 of the head fractured into three pieces (refer to Fig. 7), while part no. 2 split into two (refer to Fig. 9). The exhaust valve seat from part no. 1 was extracted intact (refer to Fig.

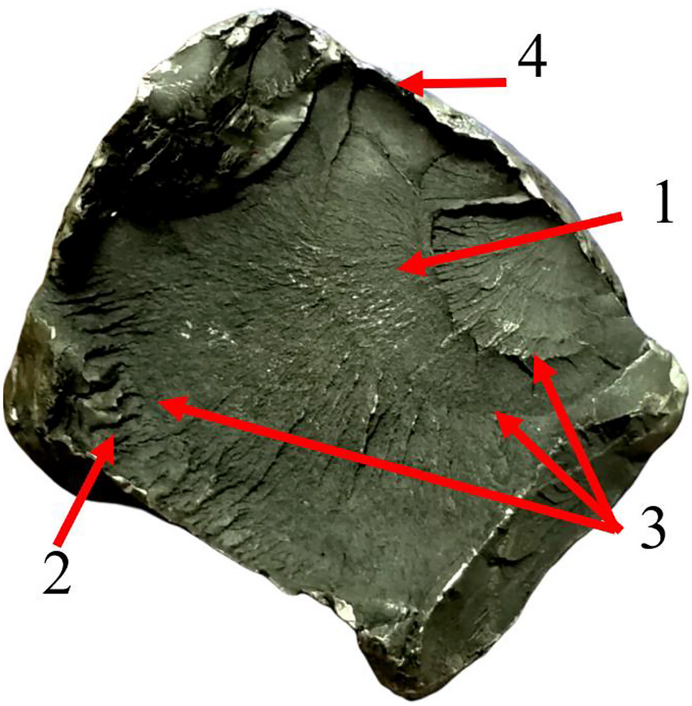

Figure 5. A photograph showing the fracture of the head of the valve no. 1: 1 – fatigue part of the fracture, 2 – immediate part of the fracture, 3 – front lines propagating the fracture, 4 – plastically deformed outer surface of the head of valve no. 1

Figure 6. A photograph showing the fracture of the head of the valve no. 2:1 – the fracture is characterized by significant roughness; its shape indicates significant plastic deformation, which is characteristic of acute fractures

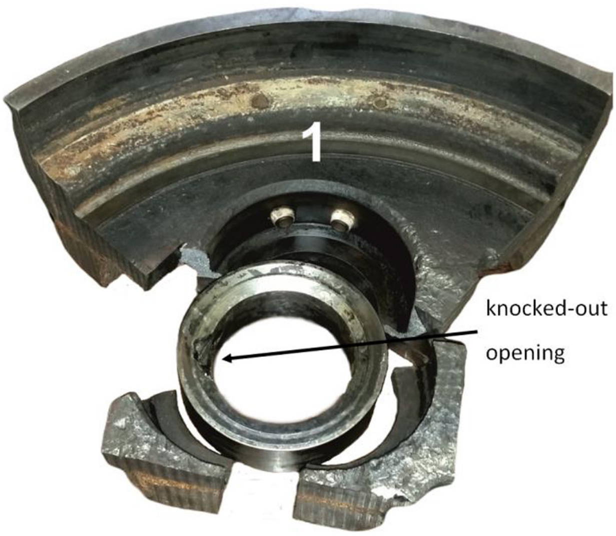

Figure 7. Part no. 1 of the head (Fig. 3) split into three pieces, along with loose valve seat no. 1

Figure 8. The seat of the exhaust valve no. 1 after having been extracted from the engine head

7 and 8), while the valve no. 2 seat was extracted in three pieces (refer to Fig. 10). Figure 8 displays the outer surface of the valve seat from part no. 1, and Figure 10 reveals the surface of the opening in part no. 2. The tarnished layer observed on both the valve seats and the openings, primarily resulting from cooling water seepage and exposure to high-temperature exhaust gases, hinted at the absence of relative motion during engine operation. If two elements experience relative motion, friction forces generate. Initially, this results in the removal of a thin layer, such as oxides or scale, from the surface. Subsequently, the surfaces undergo a process of grinding, becoming metallic,

Figure 9. Part no. 2 of the head (Fig. 3) divided into two pieces and the loose seat of the valve no. 2

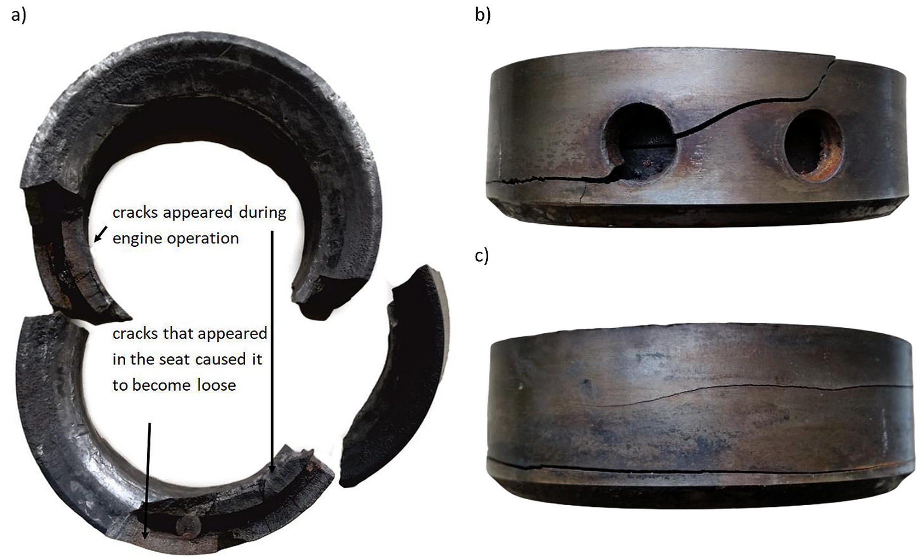

Figure 10. The seat of the exhaust valve no. 2 after having been extracted from the engine head – three shots showing the size of the cracks

smooth, and shiny. However, in this case, the surfaces of both the valve seats and the openings retained a layer of tarnish. This suggests that the seats of the exhaust valves remained stationary in relation to the engine head during engine operation, exhibiting no discernible traces of axial or rotary movement. Moreover, the ports of the conduits supplying water to the seats showed no signs of damage or visible strains, as depicted in Figures 7 and 9.

Upon extracting the seat of valve no. 1 from the engine head, the author noted a crack extending for more than half of the seat's perimeter, as illustrated in Figure 8. The cracks in the valve seat no. 2, which manifested during engine operation, were of such magnitude (refer to Fig. 10) that when the seat became dislodged, it fractured into three distinct pieces.

These cracks in the valve seats emerged due to thermal stresses, particularly in the regions where there were significant variations in cross-sectional areas. Such cracks did not appear under normal engine operating temperatures. This implies that the temperature of the valve seats exceeded permissible levels, likely due to anomalies in the working cycle within cylinder no. 1. Additionally, the discrepancy in thermal expansion coefficients between steel (seat) and cast iron (head) contributed to the generation of thermal stress. According to the manufacturer's data, the engine block is made of nodular cast iron. The cylinder liner is made of centrifugally cast special cast iron and is equipped with anti-bore polishing grooves or an anti-polishing ring. The connecting rod is forged from alloyed steel. Its large end is split diagonally to allow the removal of piston and connecting rod parts upwards via the cylinder liner. The cylinder head, a triple-deck design, is crafted from alloyed cast iron and houses two inlet valves, two exhaust valves, valve rotators, a starting air valve, and a safety valve. It is affixed to the engine block using only four hydraulically tensioned cylinder head studs to facilitate quick maintenance. All valve seats are replaceable, with the exhaust valve seats being water-cooled.The conical surface of the valve seat no. 2 exhibits numerous instances of high plastic deformation, a consequence of the piston impacting the seat with fragments of valve heads in between. This underscores that, aside from thermal stress, impact forces played a substantial role in the seat cracking process. Conversely, the surface of the valve seat of valve no. 1 displays minor plastic deformation compared to the surface of the seat of valve no. 2, which, however, features a knocked-out opening (refer to Fig. 7), allowing the ingress of cooling water. The presence of cracked valve seats prompted an investigation into whether the cracks resulted from inadequate head cooling or potential obstructions in the cooling water conduit. To address these queries, the head was strategically sectioned to allow a comprehensive inspection of the entire conduit. Figure 11 illustrates a segment of the conduit where an accumulation of impurities was discovered. Initially, it might appear that these impurities obstructed water flow during engine operation, potentially leading to an uncontrolled rise in cylinder temperature. A conglomeration of impurities (refer to Fig. 12) was extracted from the conduit (refer to Fig. 11), followed by an analysis of its chemical composition.

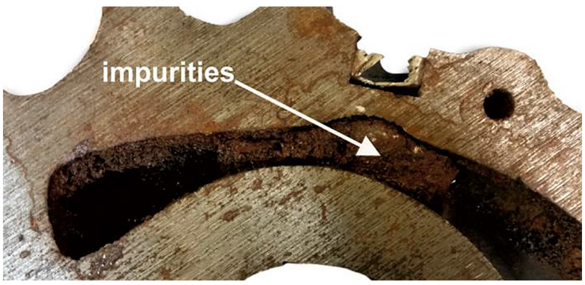

Figure 11. Uncovered cooling conduit in the engine head, partially filled with a mixture of swarf and rust

The chemical analysis was performed utilizing energy-dispersive spectrometry (EDS) with a Hitachi field emission scanning electron microscope, equipped with the Noran 7 microanalysis system by ThermoScientific. The analyzed material was mounted in Struers' PolyFast conductive resin, and a standard metallographic specimen was produced. Even at low magnification, it was evident that the impurities comprised a mixture of swarf and rust. Consequently, measurement points for analyzing the chemical composition were situated on the swarf and within the rust area. The analysis of impurities in the cooling channel of the engine was conducted using (EDS) on a sample taken from the locations marked in Figure 13 that depicts the destruction of a mixture of shavings and rust. Points 1 and 2 correspond to locations on the cross-section of the shaving, while Points 3 and 4 represent the areas on the cross-section of the material exhibiting a rusty color. The results of the analysis are presented in Figure 14 and Table 1.

The analysis clearly indicates that such impurities only took this particular form during the chainsaw cutting of the head. They represent a blend of cast iron chips generated during the head cutting process and rust spalled from the inner surface of the conduit. The chip surfaces exhibit no corrosion, and their chemical composition aligns with the iron from which the head was cast. The rust, on the other hand, contains elements from both cast iron and cooling water. It had been accumulating on the inner surface of the conduit over an extended period. Subsequent spalling resulted in the rust and swarf accumulating in the lower part of the conduit, a phenomenon triggered by the head-cutting process.

On the basis of these considerations, it can be concluded that the cooling conduit remained unobstructed, with its cross-section experiencing only a minor reduction due to the layer of rust deposited on the inner surface of the conduit.

As a result of the conducted "swarf" analysis, it is determined that the examined element is made of cast steel. The analysis revealed a carbon content not exceeding 2%, with manganese and silicon present in the material. The EDS method poorly identifies the carbon

Figure 12. A lump of swarf and rust extracted from the cooling conduit in the engine head

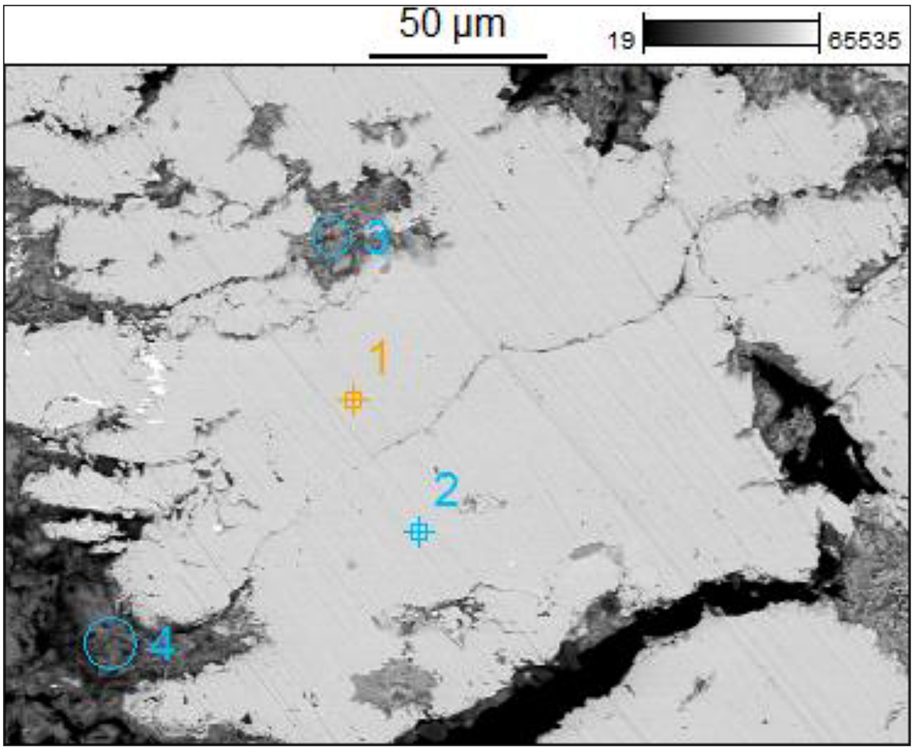

Figure 13. Points 1–4 of performing EDS analysis on the component extracted from the cooling channel of the analyzed engine. Marked locations of the destruction of a mixture of shavings and rust.

content; however, according to the authors, at carbon values above 1%, the measurement error is not significant. (EDS analysis allows for the identification of elements with an atomic number greater than 3 (i.e., starting from boron, where Z=4)). Alloying elements (Cr, Mo, Ni) are responsible for the resistance to elevated temperatures and corrosive environments. Knowing the manufacturer's data on the materials used for engine components production, the carbon content in the EDS investigation is not significant. The concentrations of other elements and impurities were important. In the "rust," elements such as oxygen, phosphorus, sulfur, and chlorine indicate a typical corrosive environment, such as exhaust gases.

DISCUSSION

The consequences of even a seemingly minor fault in a marine engine part can result in the

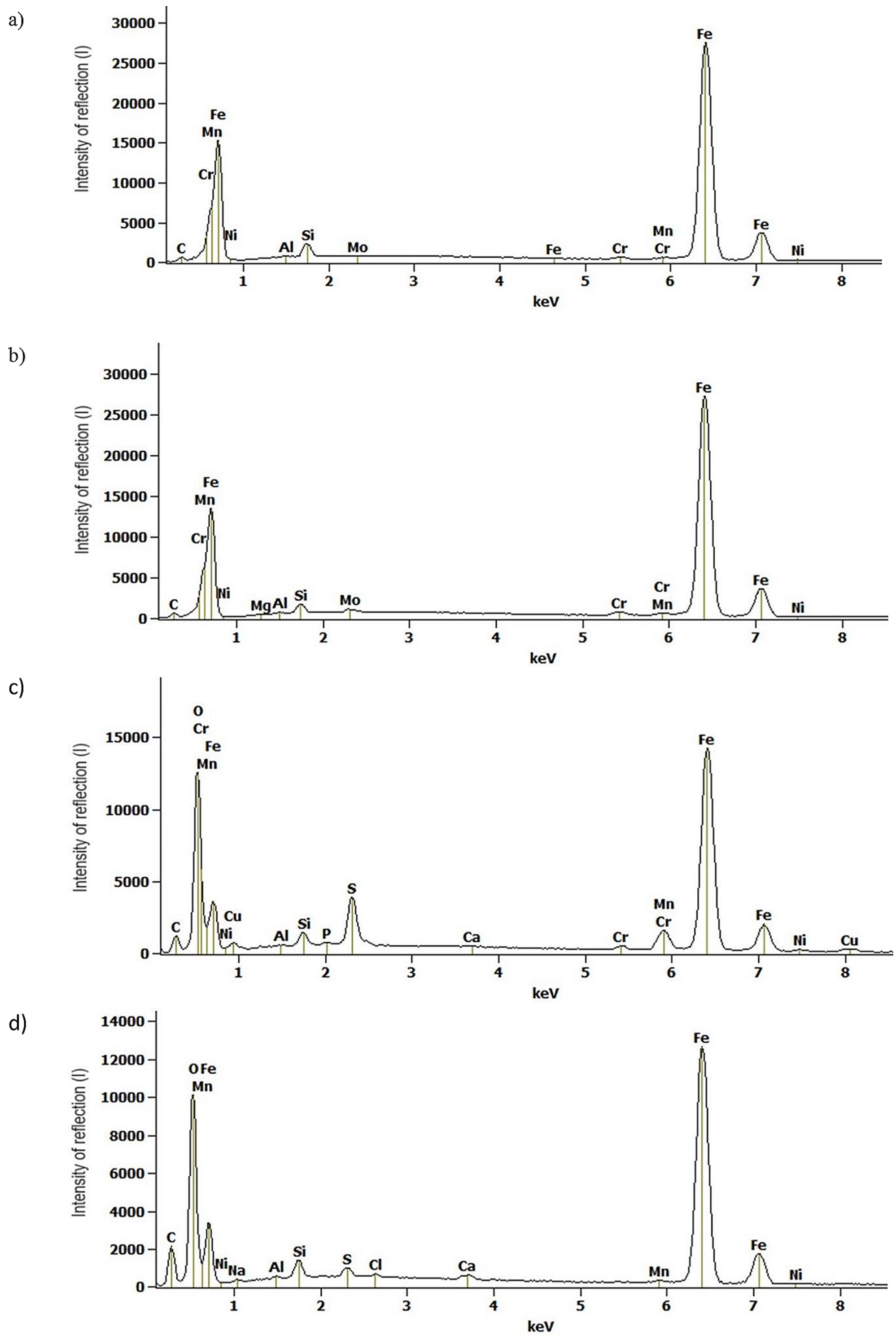

Figure 14. Results of chemical composition of the impurities from the cooling conduit in the head: a) and b) measuring points on swarf, c) and d) measuring points on rust

immobilization of a vessel at sea if not promptly detected and rectified. The incident recounted above serves as a poignant illustration, wherein a vessel lost steerage and necessitated towing to a shipyard for repairs. The root cause, impurities in one of the exhaust valves, triggered a cascade of damage, ultimately leading to engine shutdown. The critical nature of the situation became evident when the captain, prompted by the observation of white smoke from a chimney due to tailwind, swiftly reduced the engine speed to "Dead slow ahead." Notably, the engine ceased operation

Table 1. The percentage of elements in the components of the impurities from the cooling conduit in the engine head by weight %

Area of analysis	Weight %													
	C	O	Al	Si	P	S	Cl	Ca	Cr	Mn	Fe	Ni	Cu	Mo
1-swarf	1.49		0.15	2.09					0.35	0.47	94.56	0.71		0.18
2-swarf	1.68		0.13	1.42					0.73	0.55	93.98	0.54		0.85
3-rust	4.62	25.01	0.12	1.13	0.12	3.73		0.07	0.45	4.93	57.65	0.70	1.46	
4-rust	8.30	26.61	0.12	1.36		0.70	0.23	0.47		0.46	60.95	0.44		
~RSD of the method %	±1.0	±0.5	±0.1	±0.1	±0.1	±0.1	±0.1	±0.1	±01	±0.1	±0.1	±0.1	±0.1	±0.1

without emitting emergency signals, and subsequent attempts to restart it proved unsuccessful. It is noteworthy that the servicing personnel had not preemptively reported any anomalies and struggled to interpret the acoustic signals generated during the piston impacting the valve heads and their subsequent deterioration. This highlights the inherent difficulty in fault detection, necessitating a considerable level of experience from the crew, given the broad spectrum of potential faults and their combinations. In instances where human senses fall short, reliance on sophisticated systems for monitoring engine operation and diagnosing failures becomes paramount to ensuring the safety of both the crew and the vessel itself.

Folsberg [23] pointed out that in engine valves, the sliding distance and wear on the valve sealing surface vary among different designs, and the contact angle has the most significant impact on sliding length, surpassing other changes in parameters. The cause of failure may also be oil residue forming tribo-films on valve surfaces, covering and protecting the underlying structure. A recommended solution could be applying PVD coatings to the valve surface. Hard PVD-coated valves show potential for low wear but fail due to a too-soft supporting substrate. In order to avoid failures, the author suggests considering alterations to the surface chemistry of valve sealing surfaces in future valve designs. Vardar and Ekerin [5] stated that diesel engine exhaust valves are exposed to thermal and mechanical stress, potentially leading to failures. Fractures were observed around the impact area at the table of the failed exhaust valve. Exhaust valves commonly fail due to wearing, fatigue, and corrosion (the carbon content in the material of the failed valve decreased). According to the authors, deposits on exhaust valves are attributed to the reaction of fuel-borne contaminants and lubricating oil during combustion. The buildup of deposits can insulate the valve, slow cooling, and lead to hot corrosion. The work by Vera-Cardenas et al. [24] on the sensitivity study of a valve recession model emphasized that modeling applied to tribological systems serves as a reliable alternative. This is particularly true when experimental processes are challenging. The sensitivity analysis led to the conclusion that impact wear played a crucial role in valve recession for light-duty engines. Blau [25] focused his research on the wear processes occurring in the valve-seat area. He conducted a wear analysis of exhaust valves tested on engines and production-grade valves. In his model, he assumed that the abrasion rate increases over time or with the number of cycles. Additionally, the results of friction experiments showed variations in sliding resistance and the associated work with changes in temperature. Smoleńska et al. [26] described in their work the possible mechanical factors associated with valve failure. Irregular wear of the seat in the undamaged area of the valve may imply improper valve fitting. Incorrect grinding-in could lead to valve leakage and subsequent blowing of hot exhaust gases, causing local temperature increase and intense destruction. Bałon et al. [27] designed a non-standard solution in the form of a bean-shaped hole along the width of the drive shaft of the injection pump, allowing for maintaining the appropriate strength of the structure. The methodology presented by the authors, utilizing finite element analysis (FEM) and experimental validation, could verify the design of the Stork Wärtsilä 6SW280 engine. To improve engine construction, one might consider employing coatings made of TiN, TiCN, TiAlN applied via the PVD method as described in the work by Niemczewska-Wójcik et al. [28].

The use of predictive models and tools to analyze engine operation, along with the knowledge contained in the referenced publications, should contribute to an innovative approach to engine design. The implemented solutions and research methods will enable the prediction of failures or help avoid design flaws.

CONCLUSIONS

This research aimed to bridge an important knowledge gap by examining the chain of events that can lead to the loss of steerage in maritime vessels as a result of a cascading engine breakdown, as well as provide a comprehensive understanding of the chain of events that can lead to the loss of steerage in maritime vessels as a result of a cascading engine breakdown initiated by a single exhaust valve fault. The investigation into the failure of valve no. 1 and valve no. 2, as well as the examination of the cooling conduit and impurities within, yields several key conclusions:

1. Valve failure causes – the failure of valve no. 1 and valve no. 2 was influenced by a combination of factors, including thermal stresses and impact forces. Thermal stress, indicated by cracks in the valve seats, played a role, especially in the regions with significant cross-sectional variations. Impact forces, evidenced by plastic deformation on the conical surface of valve seat no. 2, were substantial contributors, particularly during the piston's interaction with valve fragments.
2. Comparison of valve seats – valve seat no. 1 exhibited minor plastic deformation, while valve seat no. 2 displayed more pronounced plastic deformation and a knocked-out opening, allowing the ingress of cooling water. These differences suggest varying loading conditions and modes of failure for the two valves.
3. Cooling conduit investigation: an investigation into the cooling conduit revealed the presence of impurities, including swarf and rust, in the conduit. Chemical analysis showed that these impurities represented cast iron chips from the head-cutting process and rust spalled from the inner surface of the conduit.
4. Implications for cooling system – contrary to the initial concerns of cooling system obstruction, the impurities observed during the head-cutting process did not obstruct water flow during engine operation. The cooling conduit remained largely unobstructed, with only a minor reduction in cross-section due to rust deposition.
5. Functional cooling system – the presence of rust on the inner surfaces of the cooling conduit suggests a prolonged accumulation, but the cooling system remained functional. The rust deposition did not significantly hinder the water flow or cause the observed valve failures.

In summary, while thermal stresses and impact forces were identified as contributors to the valve failures, the cooling system analysis rules out major obstructions, affirming that the system remained operational. The nuanced understanding of these factors provides valuable insights for addressing specific issues and preventing similar failures in the future. Further considerations may include the measures to mitigate impact forces and manage thermal stresses in critical areas of the engine components.

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