



Failure analysis of an intake valve in a gasoline engine

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ABSTRACT

This paper presents a failure analysis on a failed intake valve in a gasoline engine. During an endurance test, an intake valve was broken and caused some damages on the piston. Material examinations (by a light microscope and also a scanning electron microscope) were conducted on the fracture surface of the intake valve shaft. Results showed that no pores or defects could be observed and the microstructure and the hardness of the material were conformed to the specification (the standard map extracted by the manufacture). But a mechanical factor caused the damage which consisted of a reversal bending load due to the misalignment of the valve shaft. The misalignment was caused by the thermal deformation in the valve shaft. The engine was working in a hot condition. Also, it was a reversal condition (with zero mean stress) due to the rotation of the valve shaft during engine working. Also, the fracture surface demonstrated beach marks due to cyclic loadings. In this case study, it was found that cracks initiated from the outer surface of the valve shaft and propagated through the inside of the fracture surface.

1) Introduction

Valves are important components in internal combustion engines which are responsible for the air entrance and the smoke exit from the combustion chamber [1]. Their operation has a direct effect on performance parameters (power, torque, fuel consumption and etc.) and also the engine emission. Applied stresses on valves during its service lifetime are generated by valve train dynamics and the combustion pressure [1]. During the combustion process, the temperature of the intake valve reached to about 550°C. This temperature for the exhaust valve is between 700 to 900°C, dependent on the engine [1, 2]. Also, due to this nature of work, valves are subjected to severe cyclic loading stresses which are applied by the cam shaft. Therefore, the material should have proper fatigue strength.

Fatigue failures can occur in three cases. One can be at the head area of valves which leads to radial cracks due to stresses generated by temperature gradient. This is a thermal fatigue failure. The second one can be near to seat face which leads to transversal cracks due to mechanical bending stresses. The other can be in the groove area which leads to transversal cracks due to the stress concentration [1]. Other failures in engine valves can occur due to oxidation or corrosion phenomena.

In the case of the failure analysis and the fatigue analysis of valve systems, there are several investigations. Voorwald *et al.* [1] presented the fatigue strength of X45CrSi93 stainless steel which is used in internal combustion engine valves. Their results illustrated significant increase of the axial fatigue strength in the martensitic X45CrSi93 steel after nitriding, compared to results of chrome-plating specimens. Ipohorski *et al.* [3] conducted a failure analysis of a steam valve stem. They demonstrated that the failure was attributed to the low toughness of the material and a nitrided layer on roots of the threaded zone.

A failure analysis of the exhaust valve stem in a gas engine was performed by Kwon and Han [4]. They showed that the failure was a result of the overheating. The significant hardness loss, the extensive surface oxidation and fretting/galling on the valve stem were indicative of the overheating. Yu and Xu [5] performed a failure analysis and metallurgical investigations of diesel engine exhaust valves. Their fractographic studies indicated that the fatigue was the dominant mechanism of the failure in the exhaust valve.

This article presents a case study for a failure analysis of a broken intake valve. This fracture took place in a gasoline engine (designed for passenger cars) during an endurance test (entitled 500 hours general cycle). During this durability test, the engine torque reduced sharply and therefore, the test was stopped after 161 hours. After more investigations, it was observed that one of intake valves in the

cylinder number 1 was broken. This event also caused other damages on the piston and the cylinder head. These failures in the intake valve are shown in Figures 1 and 2.



Figure 1: The broken intake valve in a gasoline engine during an endurance test



Figure 2: Damages on piston and cylinder head faces according to the failure of the intake valve

Such this damage in the valve was repeated three times in the same engine. The first time occurred after 242 hours of such a durability test. This failure took place in the intake valve of the cylinder number 1 at the same condition. It means that the failure location in the intake valve was the same in two cases. The second time occurred after 60 hours of another test (entitled 165 hours over-speed cycle). In this case, the exhaust valve (in the cylinder number 1) was broken. According to this failure history, the damage mode was chosen for accurate investigations due to its repeatability.

2) Investigation methods

For the failure analysis of the intake valve, two types of root causes were considered which include mechanical and material phenomena.

Mechanical problems include:

- Non-conformance of the geometric dimension and the tolerance of the intake valve in comparison to the specification (the standard map).
- A problem in the oil lubrication of the valve system.

- Increasing in the clearance of the valve shaft and guide.
- Misalignment of the valve seat with the valve guide.
- Non-planar of the valve guide on the combustion chamber (of the cylinder head).
- Other mechanical problems due to piston crashing, valve opening according to un-correct timing and etc. causes.

Material problems include:

- Non-conformance of the chemical composition with the specification (the standard map).
- Defects in the microstructure of the intake valve.
- Low hardness of the intake valve and the valve guide.
- The existence of inclusions in the intake valve.

To investigate these factors, specimens were taken from the failed intake valve and prepared by standard methods for metallurgical examinations (including the microstructure investigation and the fractography). The chemical composition of the intake valve was determined by a spectroscopy chemical analysis.

The valve shaft was cut near the fracture surface to measure the hardness. A Rockwell C test with 150 Kg force was performed for 15 seconds and it was repeated for 4 times according to ASTM-E18-08 standard [6].

According to the specification (the standard map), the material of the intake valve shaft is made of 1.4718 steel (X45CrSi9-3) which includes chrome and silicon elements [7]. It should be mentioned that the heat treatment process of the valve system has two types. One process is annealing at 780-820°C and the other consists of solution at 1000-1050°C, quenching in hot oil and tempering at 780°C in the water or the air [7]. The first one is for the intake valve shaft according to the specification (the standard map of the component). It should be mentioned that the exhaust valve shaft has both heat treatment processes.

To investigate the fractography, pictures of the material microstructure were taken by a light microscope after grinding, polishing and etching the specimen surface [8]. The microstructure of specimens and fractured surfaces were studied by a scanning electron microscopy (SEM). Also, accurate measurements on the valve system of this engine were conducted by a coordinate measuring machine (CMM).

3) Results and discussions

3-1) Mechanical investigations

Dimensions of several parts in the valve system were measured by the CMM. First accurate measurements were conducted for the diameter of the valve shaft (the external diameter) and the valve guide (the internal diameter) and also its clearance. These results are shown in Table 1.

The clearance can be calculated as a difference of the internal diameter of the valve guide and the external diameter of the valve shaft. It should be mentioned that these dimensions could not be measured for the failed intake valve (in the cylinder number 1) due to its damages.

Table 1 demonstrates that the clearance increases by performing the endurance test. Also, as another result, the clearance after the test in the cylinder number 3 was more than other cylinders. The reason can be described by occurring higher temperatures in this cylinder. It means that maximum temperature of the cylinder head occurs in the cylinder number 3 in this gasoline engine which was measured during a temperature survey test [2].

Table 1: The external diameter of the valve shaft and the internal diameter of the valve guide

Intake valve number		1	2	3	4
External diameter (mm)	Before test	7.911	7.911	7.909	7.906
	After test	7.903	7.900	7.896	7.897
Internal diameter (mm)	Before test	7.929	7.928	7.933	7.935
	After test	damaged	7.947	8.012	7.944
Clearance (mm)	Before test	0.018	0.017	0.024	0.029
	After test	-	0.047	0.116	0.047

Results of measuring the deviation value from the valve guide cylindricity and also the misalignment value of the valve seat and guide (non-concentricity) are shown in Table 2.

It should be mentioned that these measurements data are conducted after the test (there is no available data before the test) and also, could not be performed for the cylinder number 1 due to its damages. Also, accurate measurement results of the valve shaft parameters are also shown in Table 2. These parameters include the deviation value from the cylindricity of the valve shaft and the misalignment value of the valve seat and shaft (non-concentricity).

As demonstrated in Table 2, maximum value for the deviation from the cylindricity of the valve guide was measured in the cylinder number 3. Also, the non-concentricity value of the cylinder number 4 is more than other cylinders.

The maximum value of the deviation from the cylindricity of the valve shaft was measured for the cylinder number 4. But the misalignment value of the valve seat and shaft for the cylinder number 1 is more than other cylinders. These misalignments can be produced by thermal deformations. And thermal deformation can be produced when the engine is working in an ultra-hot condition according to various reasons.

Table 2: Values of parameters in the valve system which are measured after the test

Intake valve number	1	2	3	4
Deviation from cylindricity of valve guide (mm)	damaged	0.038	0.078	0.009
Misalignment of valve seat and guide (mm)	damaged	0.036	0.006	0.072
Deviation from cylindricity of valve shaft (mm)	damaged	0.005	0.004	0.012
Misalignment of valve seat and shaft (mm)	damaged	0.295	0.096	0.065

As mentioned, one important factor in these thermal deformations is the heat transfer in the engine. The temperature difference between inlet and outlet of coolant temperatures can describe thermal conditions of the engine. This value is shown in Figure 3 for two different engine speeds (3000 and 5000 rpm at full-loaded conditions) during two endurance tests on the same engine (without any failures during 500 hours of testing), comparing to this engine which the intake valve was broken at 161 hours. These results demonstrate that the temperature difference between inlet and outlet of coolant temperatures for this engine (with the failed intake valve) is higher than the other one which had no failures. This value is about 8°C for the failed engine in comparison to 6°C (as an average value) in the engine without failures.

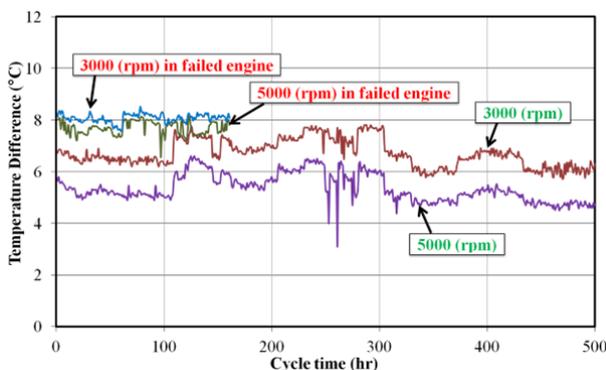


Figure 3: The value of the temperature difference between inlet and outlet of coolant temperatures

It means that the heat transfer system of the failed engine was not working in a proper situation comparably to the other engine. This phenomenon can be due to various reasons such as pump defects. In other words, the engine has worked in a hot condition and then, one reason for breaking of the intake valve can be this hot condition of the engine. Higher temperature leads to excessive thermal expansions in the valve shaft. Then, the valve can be exposed to the misalignment and therefore can be exposed to an external bending force. As the valve rotates during engine working, then this force

becomes a reversal cyclic loading in the valve shaft. At last, the valve can be locked in its guide due to an un-allowable deformation. This locking of the valve system causes the valve to remain opened and then causes crashing of the piston and therefore, leads to damages in the piston and the cylinder head (as shown in Figure 2).

3-2) Material investigations

In the first step, the fracture surface of the broken intake valve was investigated as shown in Figures 4 and 5. In these figures, beach marks can be observed due to cyclic loadings and the fatigue fracture. As it is known, the valve rotates when the engine works, a reversal bending load is applied to the valve shaft. The fracture surface on the valve shaft shows macroscopic lines which illustrate the cracks growth path. On the other side of the valve shaft, the fracture surface was damaged due to the impact after the failure in the engine.



Figure 4: The fracture surface of the broken intake valve with beach marks

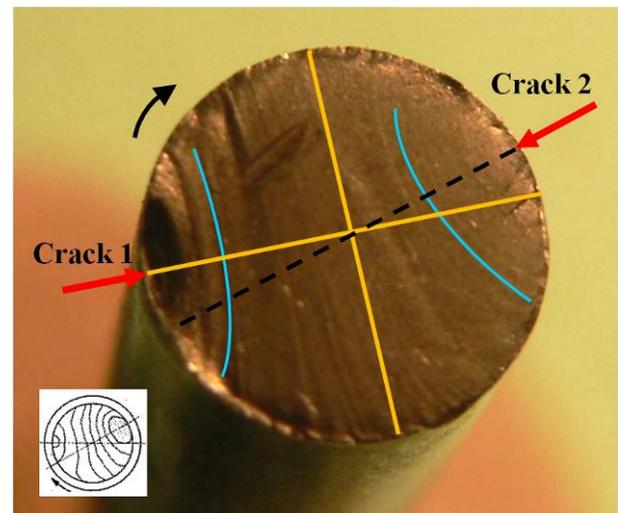


Figure 5: Beach marks and crack initiation zones on the valve shaft surface

A visual inspection of beach marks on the valve shaft surface shows two crack initiation zones (as illustrated in Figure 5, in two left and right sides). These regions are demonstrated with arrows (entitled "Crack 1" and "Crack 2") in Figure 5. As shown in Figure 5, cracks initiate at the outer surface of the valve shaft. This phenomenon occurs mostly in high cycle fatigue (HCF) regime. Then, this pattern shows a fully reversal bending as the loading

type in the valve system [9]. In other words, the mean stress is zero and the stress ratio is minus one ($R = -1$). This bending force is applied due to the misalignment, reported in Table 2. As mentioned before, this misalignment can be produced by thermal deformations due to hot working of the engine.

Scanning electron microscopy (SEM) images of the fracture surface are shown in Figure 6. A defect near the outer surface of the valve shaft (shown in the right side of Figure 6 which is that region entitled "Crack 1" in Figure 5) existed which could cause a crack initiation.

This zone is a three dimensional dislocation which has become active during the fatigue failure. Also, the oxide and carbide particles can be probably observed (shown by arrows in Figure 6) near the crack initiation zone.

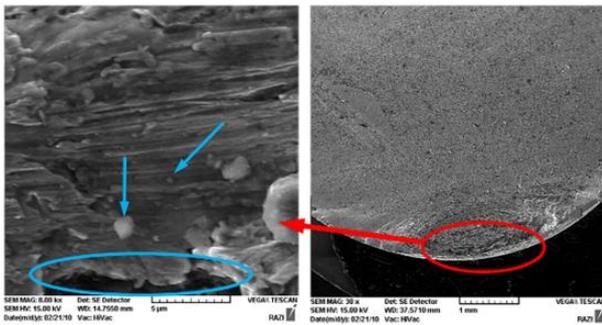


Figure 6: SEM images of the fracture surface with different magnifications

The element composition of the failed valve shaft is shown in Table 3. The result demonstrated that there is a conformation for the chemical composition of the valve shaft to the specification (the standard map of the component) and the material standard [7].

Table 3: The chemical composition of the failed intake valve shaft

Elements	Failed component	Material standard [7]
C	0.45	0.40-0.50
Si	3.24	2.70-3.30
Mn	0.40	0.80
Cr	9.15	8.00-10.00
Ni	0.17	0.60
P	0.02	0.04
S	0.01	0.03
Fe	Rem.	Rem.

The average hardness of the material was determined to be 33 HRC which is in the range of mentioned values in the specification (the standard map of the component). In this standard map, the value is mentioned as 24.8 to 34.5 HRC. Thus, there is no conformation for the hardness of the material in the valve shaft.

In Figure 7, it can be seen that the microstructure of the valve shaft material consisted of a tempered

martensite [1, 8]. This microstructure confirms the heat treatment process which is also revealed by the hardness. As mentioned before, the material of the intake valve shaft is made of 1.4718 steel (X45CrSi9-3) which includes chrome and silicon elements [7].

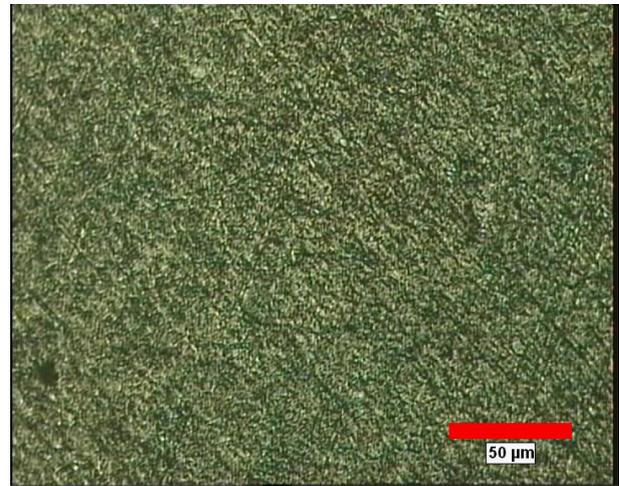


Figure 7: The microstructure of the valve shaft made of 1.4718 steel (X45CrSi9-3)

The microstructure of the material has a conformation with the specification (the standard map) of the valve system. As it can be seen in Figure 7, there exist no unusual pores or defects due to the casting process or the heat treatment process in the material of the valve shaft.

These material investigations illustrate that the damage was not due to material defects and the failure caused by a mechanical factor. In the previous part, it was shown that the heat transfer system of the engine was not working in a proper condition and therefore, a misalignment occurs in the valve shaft. Then, this phenomenon leads to an external bending force. According to the valve rotation, a reversal bending loads cause fatigue damages. At last, an un-allowable thermal deformation in the valve shaft, causes locking of the valve system and leads to failures in the piston and the cylinder head.

4) Conclusion

In the present paper, various tests and inspections (include material investigations and accurate measurements) were conducted to study reasons of the broken intake valve in a gasoline engine.

Results demonstrate that:

a) The microstructure and the hardness of the material had conformations to the specification (the standard map) of the valve system. No unusual pores or defects can be observed in the material of the valve shaft according to the casting process and the heat treatment process.

b) Cracks initiated from the outer surface of the valve shaft and propagated through inside of the fracture surface. On the fatigue fracture surface, beach marks can be observed due to a reversal

bending loads. The reversal state is due to the rotation of the valve during engine working. The bending force is also due to the misalignment of the valve shaft which was caused by a thermal deformation during testing.

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تحلیل خرابی دریچه هوای ورودی در موتوری بنزینی

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 خمش کاملاً معکوس‌شونده

در این مقاله، تحلیل خرابی یک دریچه هوای ورودی در یک موتور بنزینی بررسی شده است. در طول یک آزمون دوام، یکی از دریچه‌های ورودی، شکسته شده و باعث ایجاد خرابی روی سنبه موتور گردیده است. بررسی‌های موادی (با استفاده از میکروسکوپ‌های معمولی و الکترونی روبشی) روی سطح شکست دریچه هوای ورودی انجام پذیرفت. نتایج نشان داد که هیچ‌گونه حفره انقباضی و یا نقص مادی در سطح شکست مشاهده نشد و نوع ریزساختار و مقدار سختی ماده دریچه، مطابق با استاندارد قطعه مورد نظر بودند. اما یک عامل مکانیکی همچون یک هم‌ترازی غیرمجاز که باعث ایجاد یک نیروی خمشی کاملاً معکوس‌شونده بوده، سبب رخ دادن شکست در دریچه بوده است. این عدم هم‌ترازی به دلیل تغییر شکل‌های حرارتی رخ داده است؛ چراکه کارکرد موتور در شرایط فوق گرمی بوده است. همچنین، نوع شرایط کاملاً معکوس‌شونده (تنش میانگین صفر)، به دلیل چرخش دریچه در حین کارکرد موتور می‌باشد. تحلیل شکست خستگی نشان داد که خطوط ساحلی در اثر بارهای خستگی روی سطح شکست ایجاد شده‌اند. ترک‌ها از سطح خارجی ساق دریچه ایجاد شده و سپس به سمت داخل سطح مقطع شکست، رشد کرده‌اند.

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