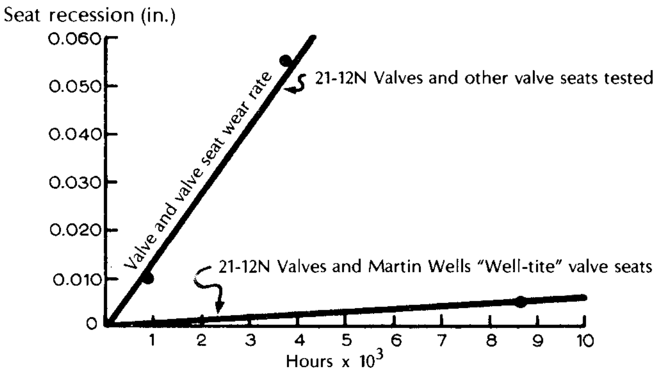
AN ANSWER TO VALVE WEAR

The following is an independent study and investigation into engine valve and valve seat wear.



Wear rates with Martin-Wells insert material.

Conclusion: It was found that the use of Martin Wells brand "WELL-TITE" valve seat inserts extend the life of valves. The wear rate is almost negligible due to the continuous oxide film which forms on the "WELL-TITE" seating surface acting as a protective mechanism to valve and seat wear.

The "WELL-TITE" valve seat delivers the total performance capability required for today's engines to insure continuing maximum compression and horsepower.

IPD manufactures Martin Wells custom valve seat inserts.

We present the following independent valve and valve seat study in order to share this research with our industry.

INVESTIGATION OF ENGINE EXHAUST VALVE WEAR

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SUMMARY

This article describes an investigation carried out to overcome a serious exhaust valve wear problem in a large spark-ignited engine.

The investigation was divided into three main parts; measurement of valve and seat temperatures, study of the dynamics of the valve mechanism and a metallurgical examination of the wearing parts.

It was found that the wear process was of a mechanical nature. Abrasion on a microscopic scale results from very small relative motion between the valve and seat insert. The wear rate was almost negligible when an oxide film could be formed on the seat insert. The formation of this film appeared to be strongly dependent on material selection and engine operating conditions.

INTRODUCTION

One of the most perplexing wear problems in internal combustion engines concerns valves. A study of the literature will reveal that practically every engine builder or user has had his share of valve wear problems. No hard and fast rules can be given to arrive at a satisfactory valve life. Each case must be painstakingly investigated, the cause or causes isolated and remedial action taken.

A closer look at the engine valve mechanism, particularly that of an exhaust valve, should convince us that the early engine builders must have been extraordinary optimists to believe that they could get it to work at all. As shown in Fig. 1, we are dealing with a mechanical system that transmits the periodic cam lift to the valve. The valve opens into the combustion chamber to let combustion gases of approximately 2000° F escape. During the actual combustion phase, the valve face is exposed to temperature flashes up to 4000° F with only the relatively small seat area and valve stem area to conduct the heat away. A typical thermodynamic engine cycle is shown in Fig. 2. It is, of course, the periodicity of the high temperature applications that saves the valve and the engine from immediate destruction. But it will be obvious that the engine builder must attempt to run his valves as cool as possible, must try to seat them as gently as possible, must select his materials not only to be compatible with these two factors but also to withstand the corrosive attack of the combustion gases.

What is satisfactory valve life? The reply to this question depends on the type of service the engine is subjected to. The average car owner, for example, would certainly not expect to have his valves reground before 80-100,000 miles. If he drives his car at an average of 30 m.p.h. this means approximately 3000 h life. On the other hand the plant man-

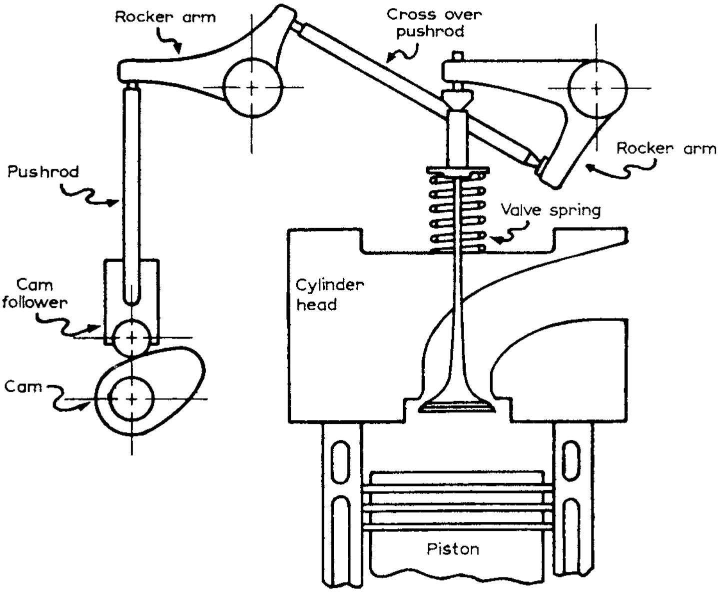


Fig. 1. Schematic arrangement of valve mechanism.

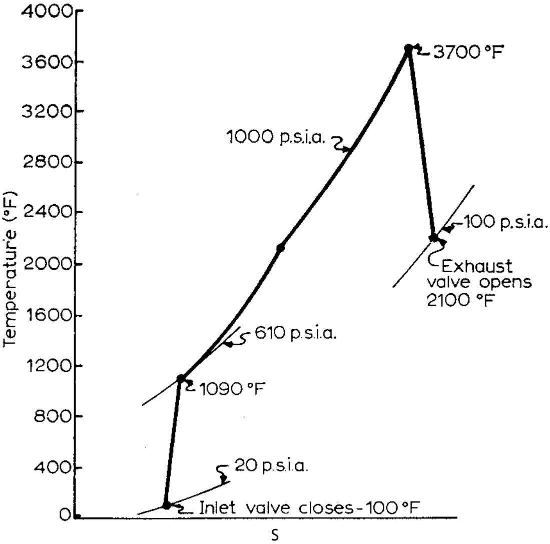


Fig. 2. T-S diagram for spark-ignited engine.

ager who runs his heavy-duty engines around the clock does not expect anything less than a full year's service. He is then willing to shut down to have the valves reground and starts up for another year of around-the-clock operation. From this it is clear that there will be as many solutions as there are applications and that it will be very risky to extrapolate experience obtained in one field to another.

The author proposes to describe the investigation of a valve-wear problem encountered on a large spark-ignited 4-cycle engine. Although a solution was found, it is still felt that a more general theory is needed to predict valve wear. The author hopes that this paper will stimulate interest in the problem of exhaust valve wear which will result in some fresh ideas with regard to this old problem.

INVESTIGATION OF EXHAUST VALVE WEAR

The exhaust-valve wear rate in this particular engine was so high that replacement became necessary in four months. Figure 3 shows that wear, measured as recession into the head, increases linearly with time. It is interesting to note that it is virtually only the valve seat insert that wears. The material specification for valve and insert are given in Table 1.

The investigation was concentrated in three main areas.

(1) Measuring insert and valve temperature,

(2) study of valve dynamics and

(3) metallurgical study of insert and valve material.

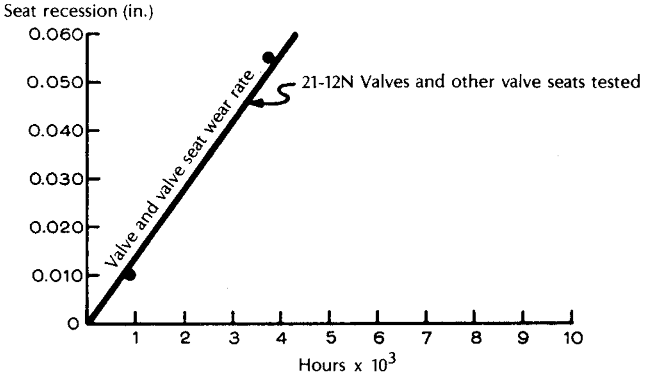


Fig. 3. Rate of valve attrition.

TABLE 1

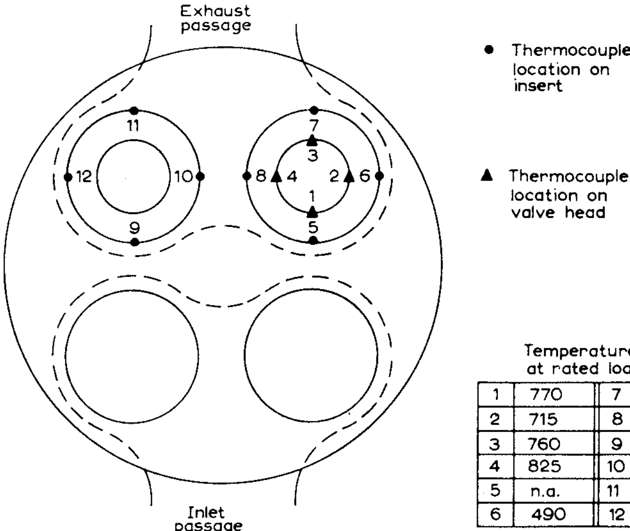
COMPOSITION OF VARIOUS VALVE AND INSERT MATERIALS

	C	*Cr*	*Ni*	*Si*	*Mn*	*Mo*	*Fe*
Valve 21-12 N	0.22	21.5	11.5	0.80	1.35		Balance
Valve 21-4 N	0.40	21.16	3	0.19	9.16		Balance
Other Seats Tested	1.0	4.0		2.5	0.60	8.5	Balance
Insert Martin-Wells	2.02	12.3	42.1	1.63	1.13	6.7	Balance

Measuring insert and valve temperature

For this purpose thermocouples were embedded in the valve head and in the insert. Figure 4 shows the location of the thermocouples and their orientation with respect to the cylinder head. Only one exhaust valve was instrumented because of the complexity. The temperatures at rated load are also shown in Fig. 4, which indicates that stations 4, 8 and 10 have the highest temperature. The insert measurements made it reasonable to expect that the two valves would also have identical temperature distributions and levels.

The temperatures at stations 4, 8 and 10 are shown in Fig. 5 as a function of the load. This type of curve is typical for a gas engine that uses a fuel-air mixture ratio control for optimum fuel consumption. Since the fuel-air ratio determines the cycle temperature, the valve temperature was also measured as a function of inlet pressure.



Temperature in °F at rated load

1	770	7	555
2	715	8	615
3	760	9	n.a.
4	825	10	635
5	n.a.	11	565
6	490	12	505

n.a.- not available

Fig. 4. Location of thermocouples in valve and seat insert.

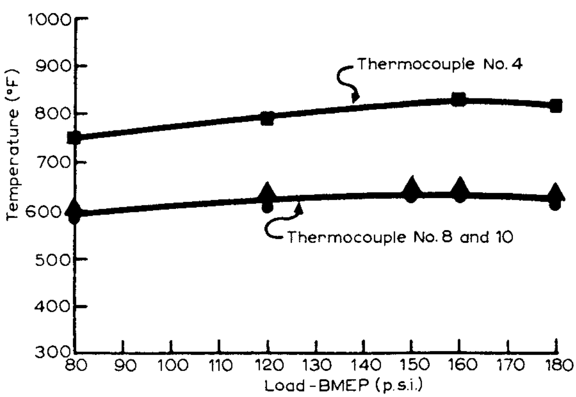


Fig. 5. Valve and insert temperatures as a function of load. (BMEP stands for Brake Mean Effective Pressure. This is in contrast to IMEP which stands for Indicated Mean Effective Pressure.)

This is shown in Fig. 6. Inspecting the data we see that under normal conditions the highest temperatures on valve and insert are 825˚F and 625˚F respectively. The circumferential difference in temperature is approximately 100˚F for both valves and inserts. Even under extreme throttling conditions, the temperature reaches only 940˚F on the valve and 690˚F on the insert.

Figure 7 shows temperature-stress characteristics for valve and insert material[1]. From these curves it would appear that the temperature was not causing any significant reduction in mechanical properties and thus was discounted as a major influence on the excessive valve wear.

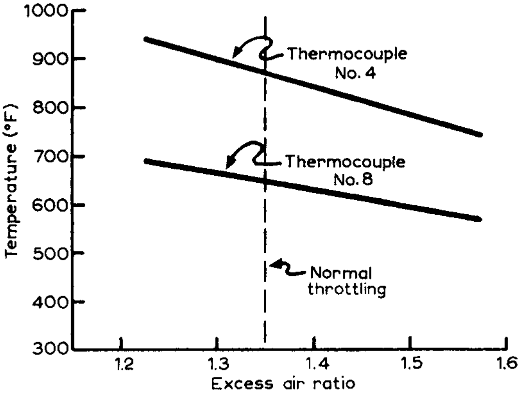


Fig. 6. Valve and insert temperatures as a function of excess air ratio.

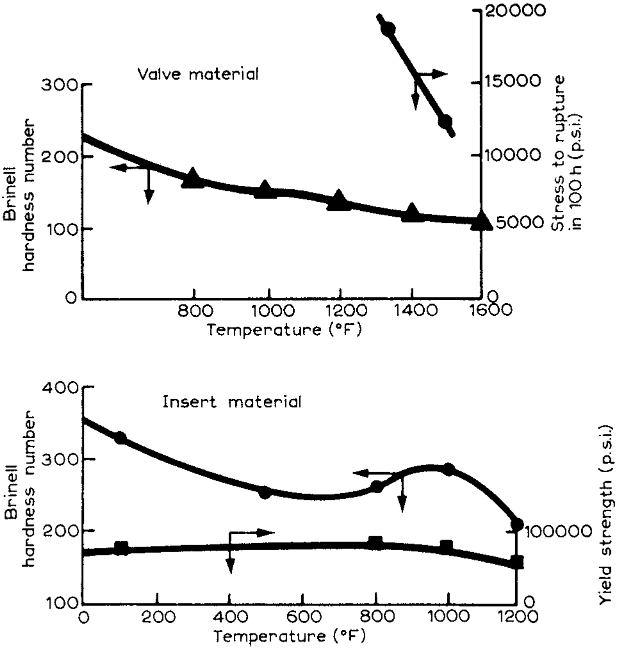


Fig. 7. Temperature-stress characteristics for valve and insert material.

Valve dynamics

Valve dynamics were studied on a specially built test facility consisting of a cylinder head with the complete valve actuation mechanism.

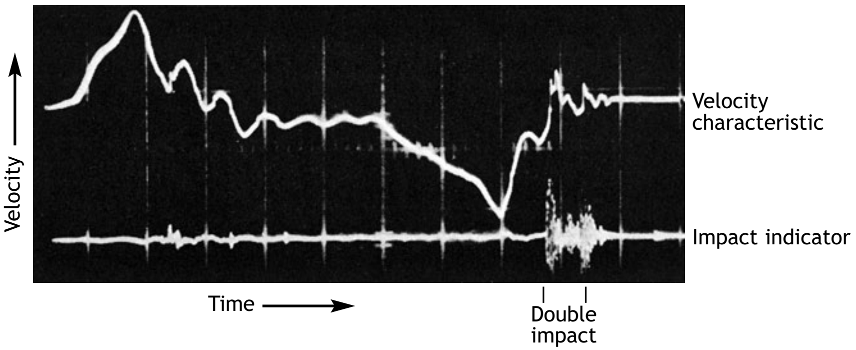


Fig. 8. Multiple seating of exhaust valve. (Horizontal) time scale 1 cm = 30 crank degrees; engine turns at 425 rev./min. (Vertical) velocity scale (upper trace) 1 cm = 2.8 ft./sec.

Early measurements revealed that the valve and linkage oscillated with a rather large amplitude. This oscillation resulted in multiple seatings of the valve as shown in Fig. 8*. A rough calculation of the system's natural frequency, 140 c/sec, agreed well enough with the measured frequency, 120 c/sec, indicating that the cam with the rapid-opening characteristic produced resonance in the system. Rapid-opening cams incidentally, are considered necessary to obtain a maximum pulse effect in the exhaust system for efficient supercharging.

Efforts to change the natural frequency of the system by stiffening and lightening it failed to produce results. It was, therefore, concluded that the cam contour had to be changed. Two approaches were followed. The first was to design a cam with a slow-opening characteristic by using conventional design methods. This was considered acceptable for gas engines which require less air than diesel engines. However, since the basic engine can be built either as a gas or a diesel engine, a second approach was to realize a rapid-opening characteristic using the polydyne design method[2]. This method avoids abrupt changes in the acceleration of the valve making the lift and its important derivatives a continuous function of an independent time variable. The coefficients of this polynomial equation are selected to obtain the best fit to the selected lift curve. In order to calculate the

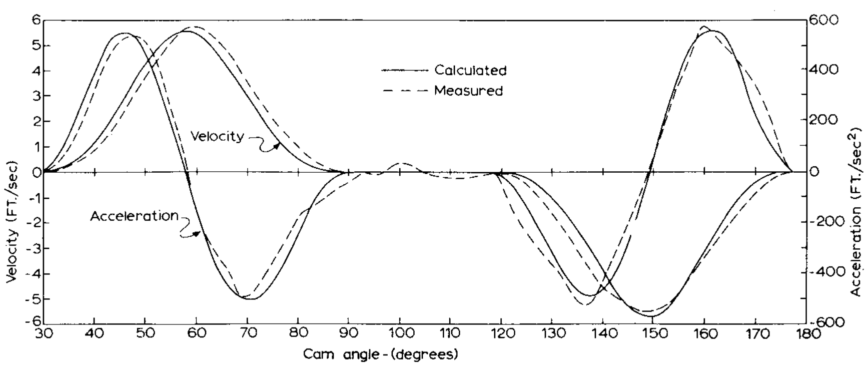


Fig. 9. Comparison of calculated and measured valve dynamics.

* In the early stages of the study, an accelerometer was used. Poor frequency matching resulted in a poor acceleration trace but the multiple seating effect is clearly visible.

required cam contour, the method takes into account the static and dynamic deflection of the valve gear train.

Figure 9 shows how closely the measured valve velocity and acceleration match the calculated values. Beside these convincing measurements, it was also the complete absence of valve train and impact noise that proved the superiority of the polydyne cam.

Thus, one can easily imagine the disappointment when after a few months of field testing it turned out that the improved cam design did not solve the valve wear problem.

Metallurgical investigation

Worn valves and inserts from the spark-ignited gas engine were compared with valves and inserts from a dual fuel engine* which had operated for 16000 h experiencing virtually no wear. The comparison was based on metallography and surface microscopy of the worn areas.

Metallography

Microstructure analyses were made in the areas indicated in Fig. 10. Since the insert is the part that suffers virtually all the wear, two areas were examined for reasons

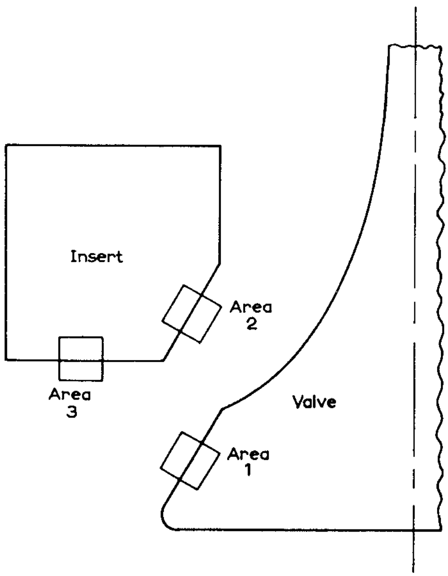


Fig. 10. Areas selected for microstructure analysis.

explained later. Figure 11(a) and (b) show the microstructures of the spark-ignited and dual fuel engine inserts. It will be noticed immediately that on the spark ignition insert, the two-phase surface layer evident in Fig. 11(b) is totally absent. The insert material is a cast tool steel with a composition as shown in Table 1. Using microprobe analysis, the inner darker surface layer in Fig. 11(b) was identified as an iron oxide, most likely Fe_3O_4, while the

* A dual fuel engine is a compression ignition engine which burns natural gas but ignition is provided by a small quantity of diesel oil.

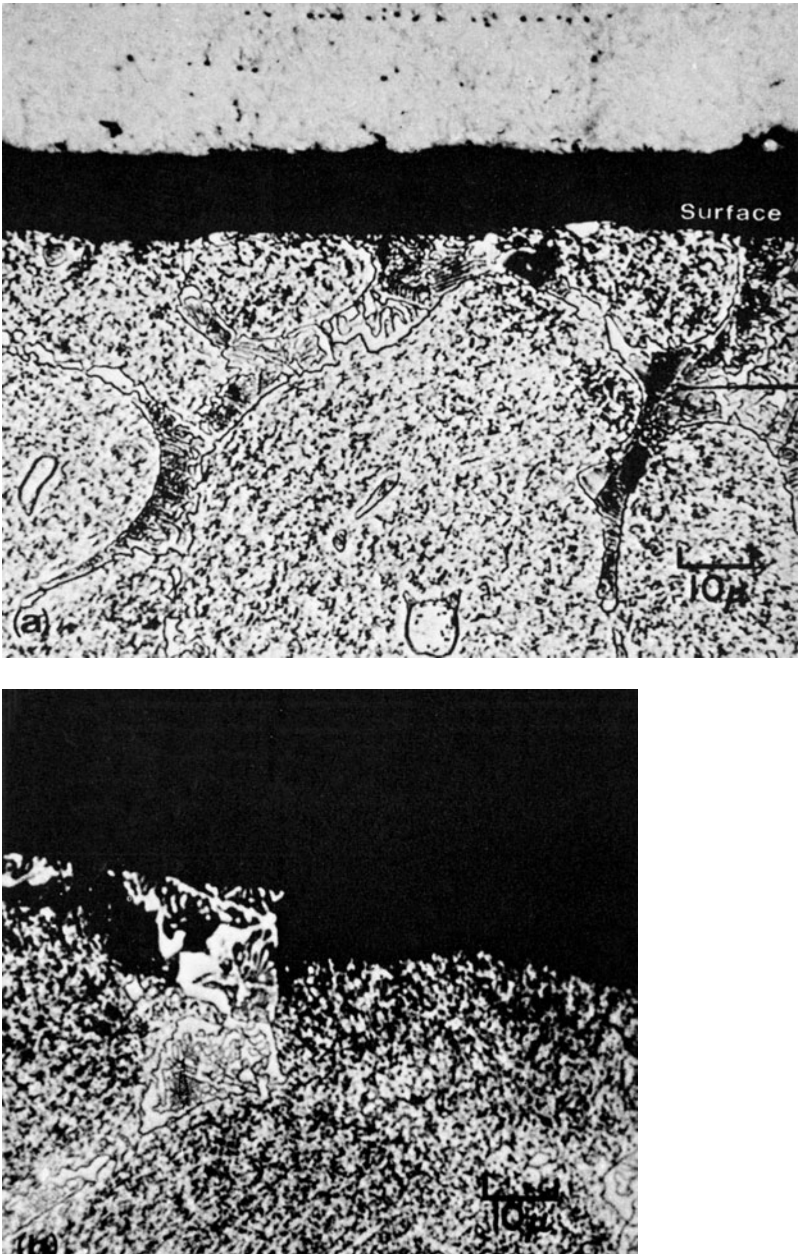


Fig. 11. (a) Photomicrograph of spark-ignited tool steel insert, indicating that no oxide film has formed on the seating area surface (area 2). (b) Photomicrograph of dual fuel tool steel insert, showing very clearly the protective two phase oxide film found on the seating area surface (area 2).

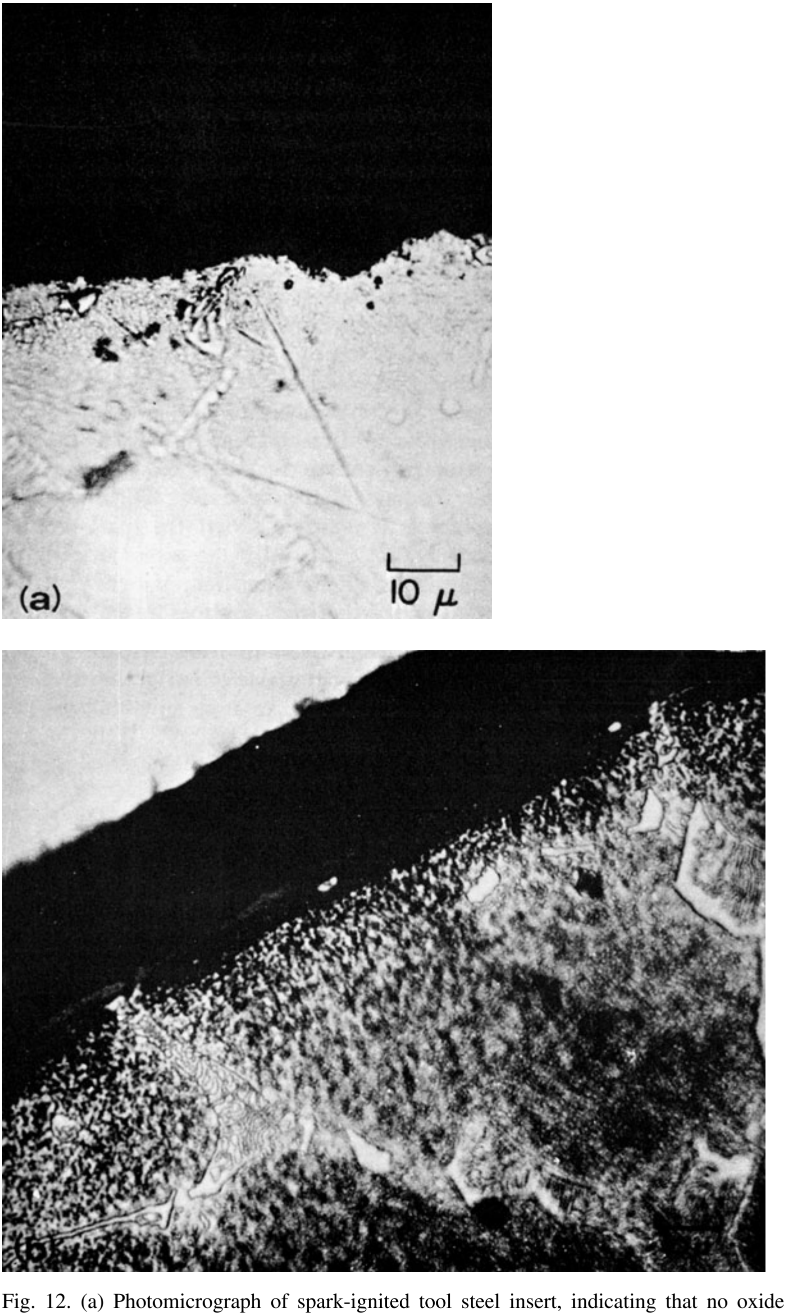


Fig. 12. (a) Photomicrograph of spark-ignited tool steel insert, indicating that no oxide film has formed on the surface not exposed to mechanical abrasion (area 3). (b) Photomicrograph of dual fuel tool steel insert, showing that the two phase oxide film has formed on surface not exposed to mechanical abrasion (area 3).

outer layer was most likely a double oxide $FeO \cdot Cr_2O_3$. The mechanism for the formation of this two-phase oxide film was visualized as follows. At the surface an oxygen-rich spinel forms first. Due to the preferential oxidation of the chromium, this double oxide has the structure $FeO \cdot Cr_2O_3$.With the continued supply of oxygen, chromium and iron diffuse through the film to be oxidized and thus contribute to the growth of the film. Some oxygen manages to penetrate to the interface where it attacks the matrix preferentially along the carbide grain boundaries. The carbide network can be seen sticking up into the oxide film (see Figs. 11(b) and 12(b)). This process continues until the outer spinel layer is apparently able to halt further oxygen penetration[3].

Very little doubt existed that the presence of the film on the dual fuel insert was associated with the low wear rate of the insert. Why, then was not this protective oxide found on the inserts from the spark-ignition engine? Was it abraded away or did it never form? To find the answer, metallographic sections were made of area 3 which is exposed to the attack of corrosive gases but not subject to mechanical abrasions (see Fig. 12(a) and (b)). Again the absence of oxide film on the spark-ignition insert is demonstrated very clearly. It was apparent, therefore, that the protective film did not form in the spark-ignition engine. To explain this behavior, the combustion processes of the two engines were analyzed. It was found that the spark-ignition engines generally operated at an excess air ratio of 1.35 while the excess air ratio for dual fuel engines was approximately 1.6*. Thus, after combustion, more oxygen was available for high temperature oxidation of the tool steel surfaces in the dual fuel engine.

Since operating conditions could not be changed, a solution for the spark-ignition engine valve wear problem had to be found in a better material selection for the valve seat insert. And indeed, in this way wear rates were reduced to an acceptable level (see Fig. 13). The material adopted for the inserts was made by the Martin-Wells Co. and the composition of the material is shown in Table 1. After 8500 h of operation, the insert was

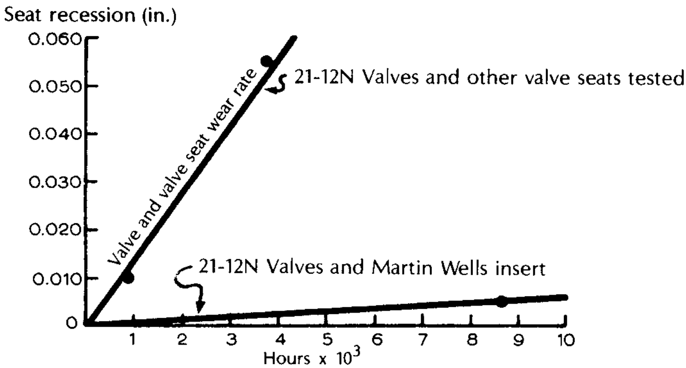


Fig. 13. Wear rates with Martin-Wells insert material.

removed for metallurgical examination. Figure 14 shows a photomicrograph of a tapered section made in the seating area. The clearly-visible oxide film is very thin, so thin that taper sectioning was necessary to detect it. Still it was unmistakably present. (Taper sectioning did not reveal any oxidation on the inserts shown in Figs. 11(a) and 12(a)). It is suspected that the chromium, being present in a larger quantity in this alloy than in tool

* Excess air ratio is the ratio of the mass of air actually available and the quantity theoretically required for complete combustion.

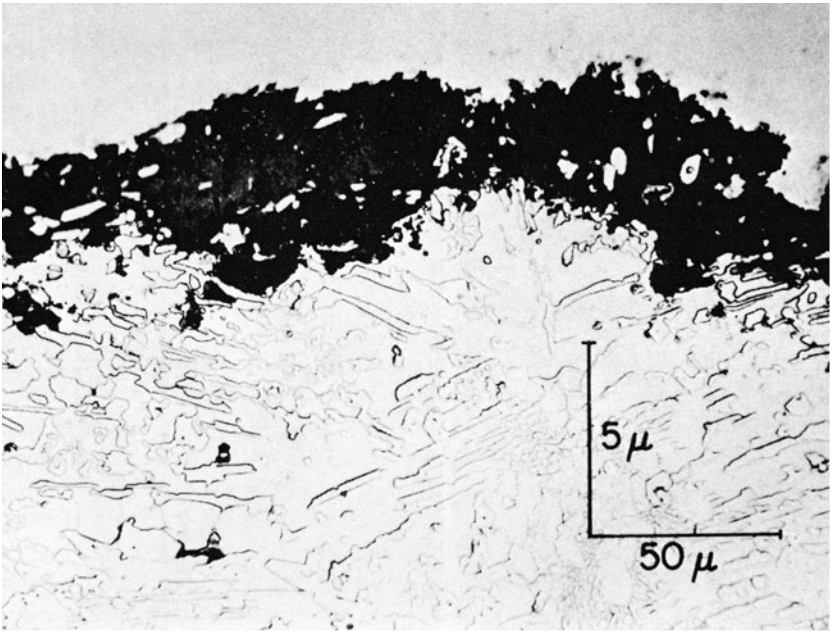


Fig. 14. Photomicrograph of taper section Martin-Wells material (area 2), showing clearly the oxide film.

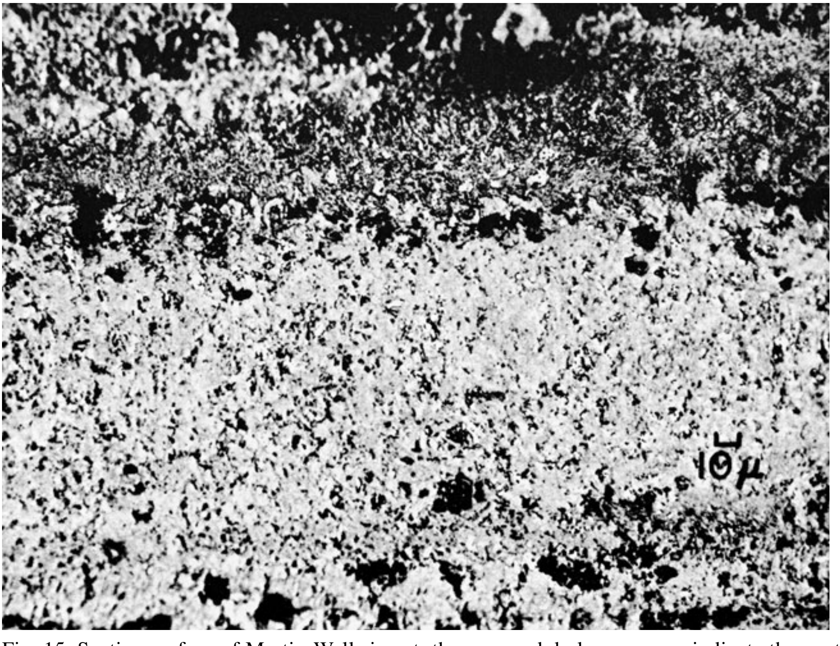


Fig. 15. Seating surface of Martin-Wells insert; the gray and dark gray areas indicate the continuous oxide film.

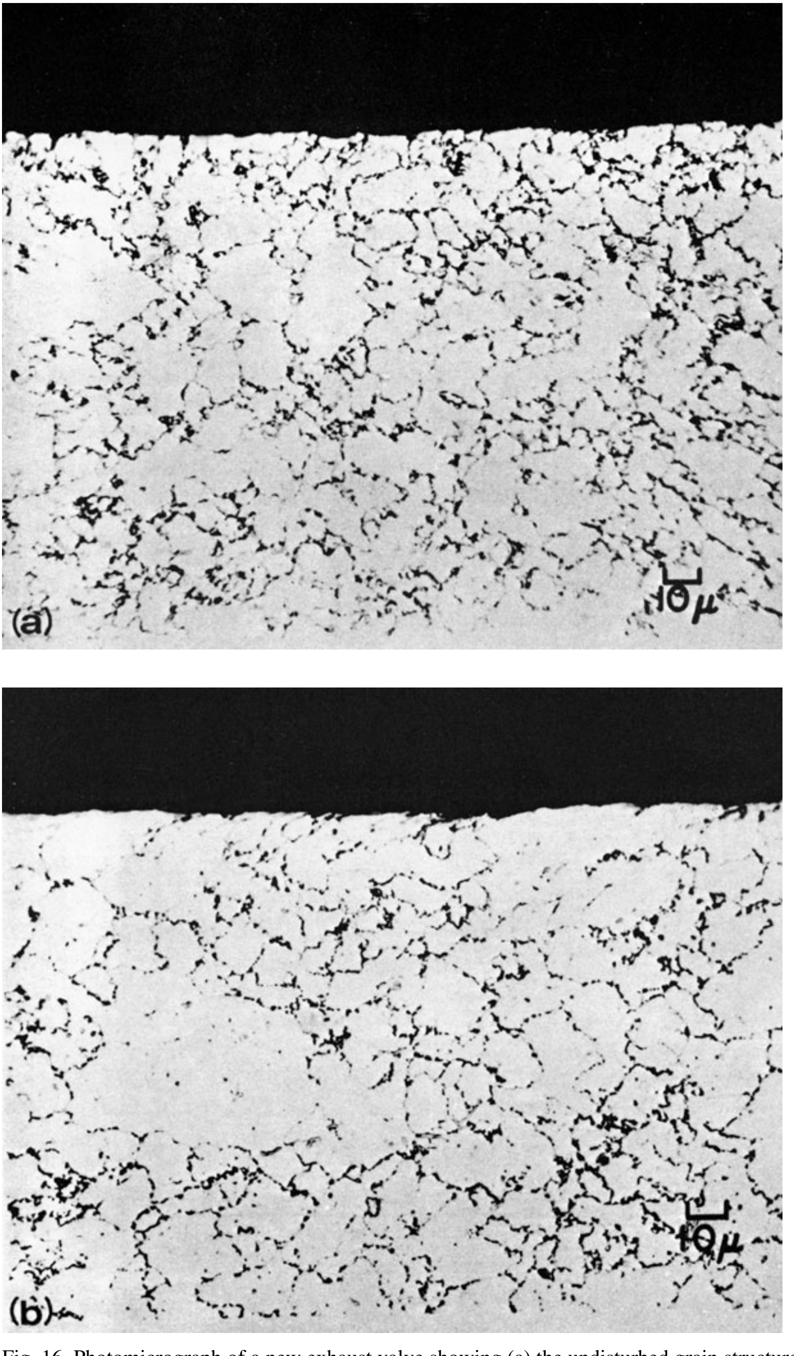


Fig. 16. Photomicrograph of a new exhaust valve showing (a) the undisturbed grain structure in seating area 1, and (b) the plastic deformation of the surface grain in the seating area 1.

steel, was an important factor in promoting growth of an abrasion-resistant oxide with the limited supply of oxygen. Again this would be a complex iron-chromium oxide which inhibits further diffusion of oxygen and forms a tight tenacious film. The carbide structure provides the necessary support under contact pressure while the tough matrix due to the high nickel content is capable of absorbing considerable mechanical energy by work-hardening.

Surface microscopy

Surface microscopy confirmed the presence of an almost continuous oxide film on the Martin-Wells insert. In Fig. 15 the oxide can be seen as the gray and dark gray areas, while the small white areas scattered throughout the surface are bare metal.

On all examined seating surfaces, of both inserts and valves, surface microscopy showed evidence of plastic flow. This plastic flow was in the radial direction, and is believed to cause the typical ridging which is quite often observed as concentric rings on the seating surfaces. A ridge can be seen in the upper part of Fig. 15.

Plastic flow, in the case of the tool steel inserts results in high wear rates, while it does not seem to affect the valves which virtually do not wear. In addition to the surface microscopy, a microstructure analysis was also performed. The material composition is given in Table 1 and photomicrographs of a new and a used valve are shown in Fig. 16(a) and (b). Clearly visible is the plastic deformation of the surface grains and it is obvious that the austenitic valve material has been able to absorb the deformation energy without fracture and microfragmentation.

CAUSE OF WEAR

After having examined the wear problem from several angles, which ultimately resulted in the finding of a remedy, it still remained to formulate a wear theory. By process of elimination one must conclude that the wear mechanism must be of a mechanical nature. More precisely, material is removed on a microscopic scale due to very small relative motion between the two contacting areas. Since good valve dynamics virtually eliminate excessive impact loading, the relative motion must be generated during combustion, when the valve face is exposed to the full force of the combustion pressure. At least two other sources confirm this concept[4, 5]. POPE has developed a wear factor as a function of the coefficient of friction μ, maximum cylinder pressure P, engine speed, material properties and valve geometry. It is clear that all these influences are known with sufficient accuracy except μ and it is this factor that will determine the wear rate of valve and insert.

From our investigation it appears to be very likely that the friction coefficient of the system $FeO–Cr_2O_3$ on austenitic steel is sufficiently low to give acceptable wear rates. It may very well be that the oxide film acts as a solid lubricant.

One may also speculate about the role of the oxide film in retaining the deposits from lube oil additives. Earlier experiments, before the insert material was changed, included introduction of lube oil specifically for the purpose of lubricating the seats and also changing to a lube oil specifically for the purpose of lubricating the seats and also changing to a lube oil of a higher detergency level, which contained more ash-forming additives, but this proved futile. Other investigators have reported success in using this approach[4, 6].

CONCLUSION

When designing valve gear for an internal combustion engine, it is well within designer's reach to attain low temperatures for valves and seats. The present state of the art also permits designing for favorable dynamic characteristics of the system. Yet, if excessive wear does occur, it is the result of very small relative motion between contacting surfaces of the valve face and valve seat. It is then necessary to reduce the coefficient of friction by adopting the proper material combination for the prevailing operating condition in the engine.

Valve wear has been found to be a very complex problem and, when encountered, requires thorough investigation to arrive at an acceptable solution.

ACKNOWLEDGEMENT

The metallography, which was a major factor in gaining an understanding of this wear problem, was carried out by the Battelle Memorial Institute, Columbus, Ohio.

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