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PISTON RING PRESSURE DISTRIBUTION

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The discovery and introduction of the internal com-
bustion engine has resulted in a very rapid development
in machines utilizing the action of a piston. Design has
been limited by the internal components of the engine,
which has been subjected to ever increasing thermal and
mechanical stresses. Of these internal engine components,
the piston and piston rings are of particular importance
and the momentary position of engine development is not
seldom dependent upon the development of both of the com-
ponents.

The piston ring is a well-known component and has
been used in its present shape in the steam engine of the
last century. Corresponding to its importance, the piston
ring has been a rich field for creative activity and it
is noteworthy that in spite of this the ring has maintained
its shape through the many years. From the many and com-
plicated designs which have been suggested as a packing
between piston and cylinder wall hardly one suggestion
has remained which does not resemble the original design
of cast iron rectangular ring.

Material Development

From the metallurgical aspect it is known that the
graphite in the ring structure should be present in fine
filiform distribution, for only in this form of graphite
distribution maximum strength properties can be obtained.
The occurrence of eutectic graphite in the structure is
fundamentally undesirable because it is invariably asso-
ciated with the formation of ferrite pockets, which, from
the point of view of wear, are bad. The remaining carbon
is bound as pearlite in iron and its appearance is identi-
fied as fine lamella sorbite. The quantity of graphite
and structure formation, besides being dependent upon the
smelt charge and the composition of slag is dependent also
on the gas temperature, the mould material and the cooling

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speed of the cast. The speed of solubility of the iron
in the surface is dependent upon the alloying constituents,
as well as from the speed of heating. Manganese increases,
while silicon decreases, the speed of solubility.

This reaction of the alloying constituents necessitates
the uttermost care in their uses because silicon expedites
the precipitation of graphite in the structure while it
hinders the pearlite formation. A large addition of silicon
necessitates, therefore, an addition of manganese to pre-
vent excessive graphite formation.

Better carbide formation results in improved thermal
and strength properties while better graphite formation
results in improved running properties. The carbide form-
ing elements are chromium, molybdenum, vanadium, tungsten,
arsenic, antimony, while the graphite forming elements are
silicon, nickel, titanium, copper, and aluminium.

As has already been pointed out, the alloying of an
element of the first group usually necessitates the alloy-
ing of an element from the second group, if neither carbide
formation nor graphite precipitation is to predominate in
the structure and cause the ring to have either good running
properties and bad thermal and strength properties or the
opposite effects.

In addition, it is necessary that phosphorous be
alloyed to the ring. Although a phosphorous addition
affects unfavorably the strength properties of the ring,
the running properties are improved by its addition owing
to the possibility of the formation of uniform phosphide
pockets, thereby improving the adherence properties of the
oil film.

Manufacturing Processes

In general, the modern method of manufacturing piston
rings is the individually cast method, whereby the blanks
are moulded singularly and "heaped" cast. Cylindrical pot
casting was popular for a long time, but its use has declined
in spite of the fact that a very fine uniform structure was
obtained. The elastic properties of the cylindrical pot
cast rings were not sufficient to withstand the conditions
in the modern engine. The individually cast ring showed
in this respect promise, in that it was possible to stress
the ring to a high degree. In Germany, the centrifugal

method of casting rings is seldom employed, but in the
English-speaking countries the method is adopted.

Ring Stressing

Piston rings can be prestressed by three methods.
The first method is by hammering, a method which is
seldom used in Germany. By this method, the ring is
prestressed by stretching the inner fibres of the ring.
The process is applied by rolling or by notch-impact.
The second method of prestressing piston rings is the
heat formed method, which is being used extensively to-
day. In this method a ring which is entirely free of
stresses is split and the gap thereby resulting is forced
apart by a wedge. In this condition the ring is then
annealed whereby the stresses are nullified. An external
stress is then applied to the ring, and, in the closed
condition, is machined to finished size.

The third method of prestressing piston rings is the
out-of-round method. In this method ring blanks are used
which are not circular but formed according to an involute.
The ring is then cut by cutting away an appreciable piece
of the ring to form the gap. The ring is then pressed
together and finish turned to a circle. After machining,
the ring will maintain its natural casting stresses. A
heat treatment follows which prevents any subsequent loss
in stress due to the temperatures occurring under engine
operation conditions.

Heat formed rings result in a uniform ring pressure
distribution throughout the ring circumference, that is,
a round radial pressure pattern. Out-of-round rings can
be given any ring pressure pattern and it is possible to
make the rings with high radial point pressures especially
at the gap. It will be shown later that this is also
possible with heat formed rings.

The Stress Distribution or Ring Pressure Pattern

The question now arises as to what type of ring pres-
sure pattern is desirable. Originally, one had endeavored
to obtain a uniform ring pressure pattern; this type of
pressure pattern is very favorable, as, with it, the ring

is pressed at all points with uniform pressure against
the cylinder. It was found from experience, however,
that where the ring was subjected to maximum load, that
is, at the gap, ring collapse took place.

It is desirable not to have a uniform pressure pattern
when the ring is new, but after running the ring for some
time under operating conditions a uniform ring pressure
pattern should be attained. This means that when the ring
is new the gap should have higher radial or point pressure
than the rest of the circumference. In addition to this,
with the continuous increase in engine speed, towards the
higher speed range, certain processes occur, which cause
sudden increases in piston ring blow-by and oil consump-
tion. This process is termed piston ring flutter, a
phenomenon, which probably occurs when the ring is excited
by impulses in the range of its natural frequency. Reliable
data is, however, not yet available to analyse this con-
dition.

It can be shown experimentally, and the object of
this article is to show, that when the ring pressure at
the ring gap is high, the unfavorable condition of piston
ring flutter and its undesirable effects can be moved out-
side the range of actual engine operational speeds.

The mean specific ring pressure of the ring is con-
sidered as a most useful criterion. The mean specific
bearing pressure is calculated from the tangential force
acting at the gap which is necessary to close the ring to
the normal gap clearance. The measurement of the tangential
force is made by means of a "toledo" balance.

The following relation is obtained:

$$p_m = \frac{2 P_t}{h D} \text{ kilograms per squared centimeters}$$

in which

p_m mean specific ring pressure, kilograms per squared
         centimeter

p_t tangential force, kilograms

h ring width, centimeter

D ring diameter, centimeter

The results of stress obtained by means of the toledo
method will agree with the actual mean surface pressure
only when the ring pressure is evenly distributed over
the whole ring circumference, which means that the
radial pressure distribution pattern must be round.

The toledo stress and the stress obtained from the
calculated mean specific pressure are not in agreement
when the radial ring pressure is not evenly distributed
around the ring circumference. The ring with uneven
pressure patterns usually has high pressure points at
the ring gap and at other parts of the ring circumference.
The remaining sections of the ring may have low or even
very low surface pressures. The whole ring cannot be
considered stronger than that of its weakest section,
and this section cannot be determined from the radial
pressure distribution. It follows therefore, that for
out-of-round rings, which have been stressed, the radial
pressure distribution is important.

Measurement of Pressure Distribution

To obtain actual measurements of radial pressures
is not a simple matter and a method free of error does
not exist. Many references are to be found in the
literature relating to radial pressure distribution and
the results obtained are often represented in a compre-
hensive manner. It is, however, noteworthy that the manu-
facturers usually recede for one reason or another, di-
rectly measurements are asked for. Most of the measur-
ing methods give such unreliable data that they do not
lend themselves to criticism.

It may be worth mentioning that the radial pressure
distribution can be measured by the steel band method,
by means of which the ring is stressed to its normal size
by a thin steel band as shown in figure 1. With the aid
of calipers, the diameter of the ring is measured at vari-
ous position of its diameter. The out-of-roundness ob-
tained is ring ovality which can be as much as one percent
greater than the normal ring diameter. The positions of
low ring pressure cannot be determined by this method of
measuring ring pressures.

In spite of the fact that rings tested by this method
can give pressure distributions which appear to be entirely

satisfactory, they have failed when used in the engine. The failures were more frequent, the higher the loading of the combustion chamber. After very short operations in the engine, the faces of the rings at certain positions became discolored and there is an increase in blow-by and oil consumption. Ring examination for high duty engines should be carried out, therefore, by some other method.

The obvious solution of the problem lies apparently in the use of a ring gage, the inside surface of which has provision for a series of pressure gage sockets or nipples. It is fully realized that the difficulty of the solution may be the finding and mounting of such pressure gage sockets, which in the radial direction, permit the most accurate force indication with the smallest possible measurements, of the ring pressure. A relatively simple solution of the problem is described in the following arrangement and shown in figure 2.

The inner surface of a ring gage is arranged with a number of steel rollers. Each roller can be loaded externally through an orifice. A pattern of the radial ring pressure distribution is obtained by the resistance of the roller to turning by manual operation. The latter is very troublesome and, in addition, roller turning by hand only gives subjective measurements.

A measuring method developed by the Mahle Company of Germany is shown in figure 3. This method permits objective measurement to be made by means of pressure gages. The ring to be tested is inserted in a ring gage with a 0.02 millimeter greater diameter than the nominal ring diameter. The gage points of sixteen clock gages are in contact with points around the circumference of the ring. These pass through holes drilled radially through the ring gage. By suitable screw adjustment the gage points are pressed against the ring, so that all clock gages show identical readings and, therefore, similar stress. The gage points are then screwed further in against the ring, by means of a "minimeter" to an amount equal to 0.01 millimeter. The readings obtained from the clock gages present a pattern of the radial pressure distribution.

It has been found that this complicated apparatus cannot be used for practical purposes. The time required to take measurements is too lengthy, for when setting the

clock gages with equal pressure an alteration in the
setting of one clock necessitates variation and adjust-
ment of the other clocks. In addition, it is so com-
plicated that it is impossible to design an apparatus
suitable to test rings of different diameter.

A simpler apparatus for measuring pressure ring
distribution is that which has been introduced and de-
veloped by Messrs. Alfred Teves in conjunction with the
Zeiss Co. This apparatus operates on the piezo-electric
principle and is shown in figure 4. An inducement to use
the piezo-electric effect of a "quartz" is that the quartz
shows only a small tendency to deform in the direction of
the applied load or pressure. The movement of the measur-
ing point is practically zero. But it is a disadvantage
that the piezo-electric effect occurs not at constant
pressure but only during pressure changes.

The piston ring is inserted in a ring gage of the
apparatus. As the actual measuring procedure has been
described by C. Englisch, the author does not consider
it necessary to describe the apparatus at this stage.
As an essential component of the equipment is a loop or
carthode ray tube, it follows that a well equipped lab-
oratory is desirable.

Both the last two mentioned highly developed methods
of testing piston rings are so elaborate and lengthy in
time that they can only be used by specialist firms. The
engineer who uses piston rings and requires further know-
ledge concerning their characteristics is, therefore, forced
to use simpler methods of measurements such as the method
which is about to be described.

The apparatus again consists mainly of a ring gage,
the nominal diameter of which corresponds to that of the
piston ring to be tested. The ring gage has a shoulder
against which the piston ring is pressed. The gage points
of a clock gage, which is graduated in 1/100 or 1/1000
divisions, pass through a hole in the ring gage and rest
upon the circumference or bearing surface of the ring.
The apparatus is shown in figure 5. The front face of
the ring has a series of notches which are situated on
the right and left of the holes drilled for the gage
points. These notches are used to locate a hook, upon
which weights can be suspended in order to load the ring
bearing surface.

The procedure of measuring piston ring pressure
distribution is as follows: After inserting the piston
ring in the ring gage, the ring gage is adjusted to give
a zero reading. A simple turning of the ring gives an
indication of ring roundness, in the same way as is ob-
tained with the light method. Everywhere, where the ring
diameter does not correspond with the nominal diameter of
the ring gage, the clock indicates the occurring deviation.
A satisfactory ring will be within the limits of from 0.002
to 0.005 millimeter of its nominal dimension. It has been
found that many rings measured deviate from the nominal
diameter by as much as 0.03 millimeter. The weakest sec-
tion of the ring is in the neighborhood of the ring gap,
while the ring gap itself retains the dimension of the
nominal diameter.

Measurement of radial pressure distribution is carried
out in the simple manner of hanging weights on the suspen-
sion scale pan attached to the hook. The weight is increased
until the clock shows a deflection of 0.01 millimeter. The
reduction in clearance at the gap is given by the product
of π times the deflection and is of the order of 0.03
millimeter. This clearance reduction is unimportant, be-
cause even with rings of small dimensions the gap clear-
ance is 0.15 millimeter, or greater. In this way the ring
is measured at all sections and a pattern of the pressure
distribution is obtained of surprising impressiveness.
The suspended weight shows, in addition, the bearing or
surface pressure occurring at each point with some approx-
imation. By loading the ring until a reduction in diameter
of 0.01 millimeter occurs each point of the ring bearing
surface moves a small distance during the measurement in
the ring gage. The frictional force, thereby set up, varies
according to the position of the gap.

Should the point at which the measurement be made be
near the gap, then with a reduction in diameter of 0.01
millimeter the ring gap will not be reduced but the loaded
ring ends will yield towards the center of the ring. Hence,
no friction between the ring and the gage exists. Should
the point at which the measurement is made be on the side
opposite the gap, then a reduction in ring diameter can
only occur with a corresponding reduction in ring gap. The
friction which is set up between the ring and the gage will
be measured. It is for this reason, that the sum of all
the pressures measured on the gap half of the ring are al-
ways smaller than those occurring on the opposite or other
side of the ring. On the side opposite to the gap the

measured pressures are higher than the actual ones by an amount equal to the frictional forces which are of unknown magnitude.

The occurring error in measurement or experimental error is not small, but it can be easily estimated from the position of the center point to the pressure distribution curve, as the sum of the vectors of all the pressures must be zero.

Considered as a whole the accuracy of measurement is probably greater than that obtained with the other methods of measuring ring pressure, described in this article, because the latter only gives a pattern of the ring pressure distribution and not an actual value of the measurement.

With a certain amount of experience, measurements with the apparatus can be made quite quickly. The time required to measure the ring takes five minutes or less. The radial pressure curves are so characteristic for a ring, that from the curves it can not only be ascertained whether the type of stress in the ring was obtained by heat-forming or the out-of-round method, but also indicate the source from which the rings were obtained, as the tools used in the manufacture give the ring product certain characteristics.

Applications

Figure 6 shows the radial pressure distribution or pressure pattern of a heat formed ring, which had been used for some 8000 kilometers in an engine. The stress distribution is very uniform. The reduction of the surface pressure at the gap, that is, the collapse, is not apparent. The sum of all stresses on the side opposite the gap is somewhat greater than those occurring on the gap side of the ring. The cause of this is the error in measurement which has already been fully discussed. This error is a characteristic of the measuring method.

Figures 7 and 8 have been obtained from two rings both of which have been run for some 2000 kilometers. Both rings were heat formed. The first ring had a uniform pressure distribution while the second had a high pressure point at the gap. The stresses are partly typical. The toledo stress of both rings are in agreement.

It can be seen that high pressure points can be obtained with heat formed rings. It is interesting to note that, while with a ring having a uniform ring pressure distribution, the piston blow-by increased above 3800 rpm (fig. 9), the blow-by remained practically constant with a heat formed ring which had uneven pressure distribution. The opinion that the phenomenon of ring flutter can be overcome by the use of rings with high pressure points, is confirmed by the above measurements.

Attention should be paid by the manufacturers that high pressure points at the gap are not exaggerated, otherwise rings are produced having ring pressure characteristics as shown in figure 10. The high pressure at the gap is exaggerated and directly next to it a position of very low pressure is shown, so that the ring can hardly bear against the cylinder. The result is a break through of the hot combustion gases at the dangerous section and excessive heating of the rings, just at its weakest point. In an engine of low output the progressive running-in can remove at first the position of high pressure and eliminate the position of low pressure. In the high duty engine, the ring is often disturbed at the point of its minimum stress due to overloading of thermal stresses, before the running-in process can be of assistance.

This type of unsatisfactory stress distribution is especially found in out-of-round rings. Figure 11 shows a series of radial pressure distribution curves of piston rings, which have been picked out from a batch of rings.

A number of these out-of-round rings used in a high duty engine had to be replaced after short running periods, because at different parts of the circumference the rings showed burnt sections. The measurements of the rings showed ring pressure distribution curves as shown in figure 12. The position of the burnt sections occurring at the circumference of the ring are indicated and prove that the measurements of pressure distribution are correct. Further measurements obtained, with the steel band method, are shown in figure 12 by the pressure curve indicated by the broken line. This shows that the ring ovality is about 6 percent, but does not show the characteristic of minimum ring pressure which was apparent as indicated by the burnt or discolored ring sections. That out-of-round rings with satisfactory ring pressure distribution can be manufactured is shown by the curves in figure 13. This type of ring,

formed by turning, is especially of interest in that it
was manufactured from plain cast-iron. Its ackowledge-
able quality is not due to highly developed materials,
but apparently due to careful balancing of the ring
pressure distribution, which was very uniformly maintained
with all rings. The ring stress at the gap is not very
great, but the points of minimum pressure which occur
next to the gap are hardly noticeable.

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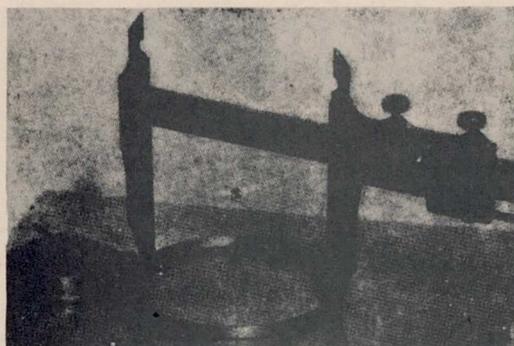
Fig. 1
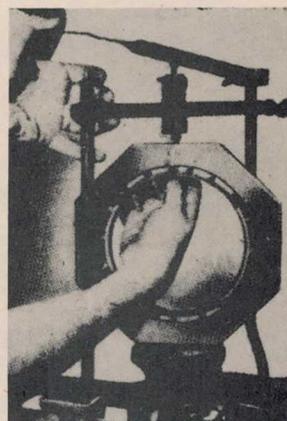
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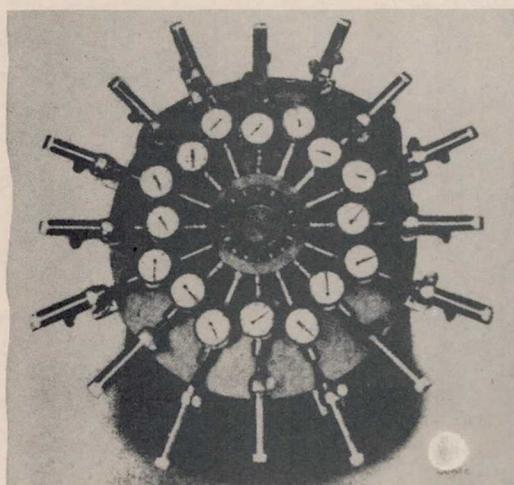
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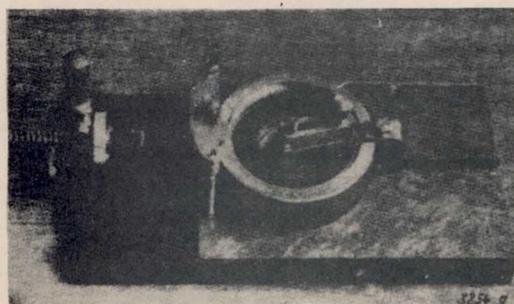
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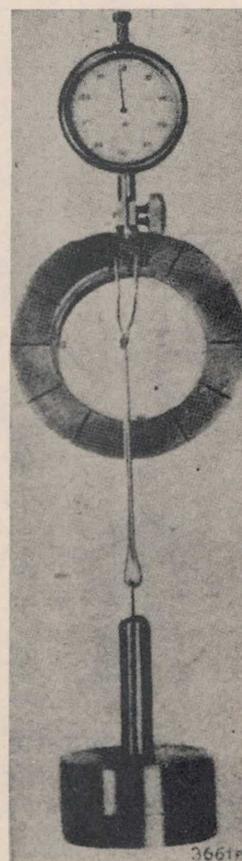
Fig. 5

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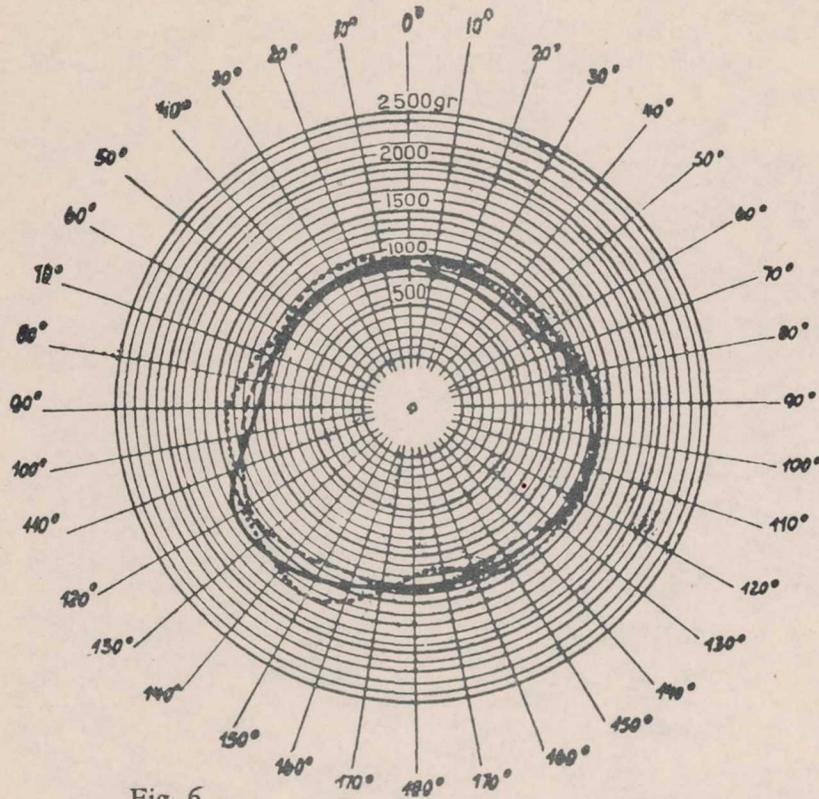
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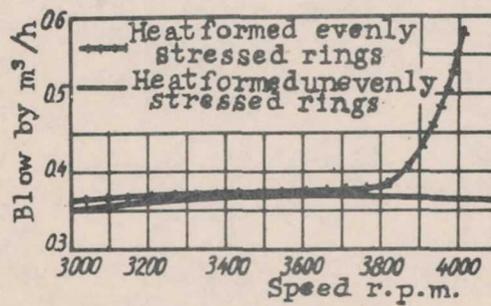
Fig. 9. Gas blow by with heat formed rings having uniform pressure
distribution and high pressure point or uneven pressure distribution.

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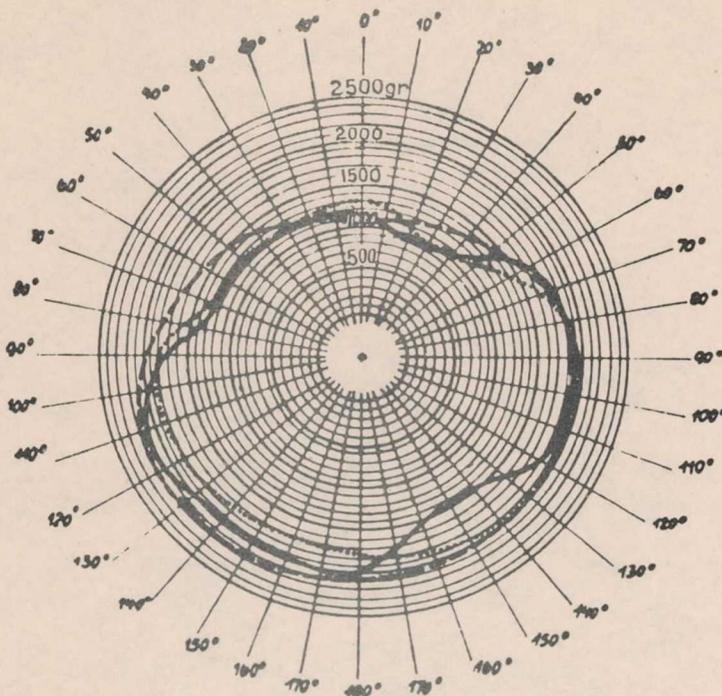
Fig. 7.   Heat formed rings from an Opel engine after 2,000 km., with evenly distributed pressure.   Mean specific pressure obtained from the tangential force to close the ring, pm = 1.28 kg/cm².
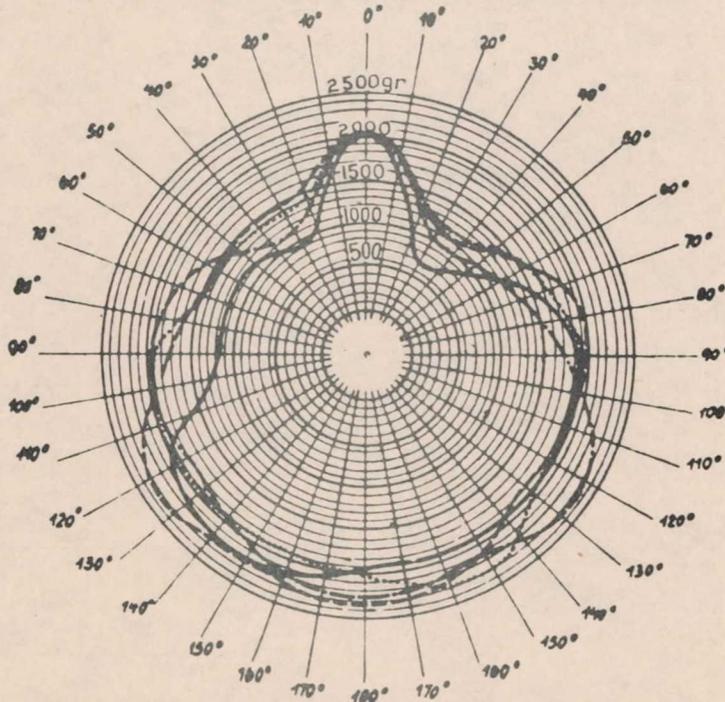
Fig. 8.   Heat formed rings from an Opel engine after 2,000 km., with high pressure point.   Mean specific pressure determined from the tangential force to close the ring, pm = 1.35 kg/cm².

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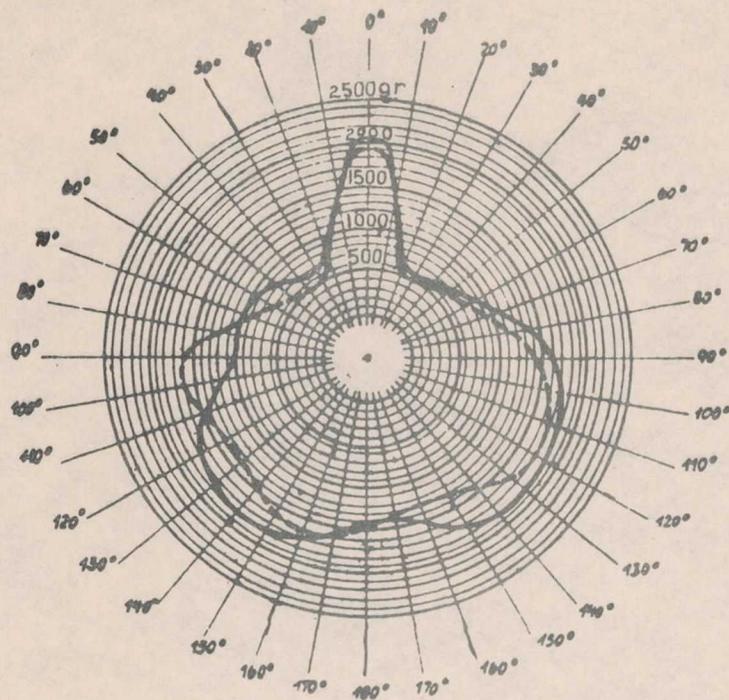
Fig. 10. Heat formed high pressure point ring with exaggerated high pressure point near the gap and sections of minimum pressure next to it. New rings.
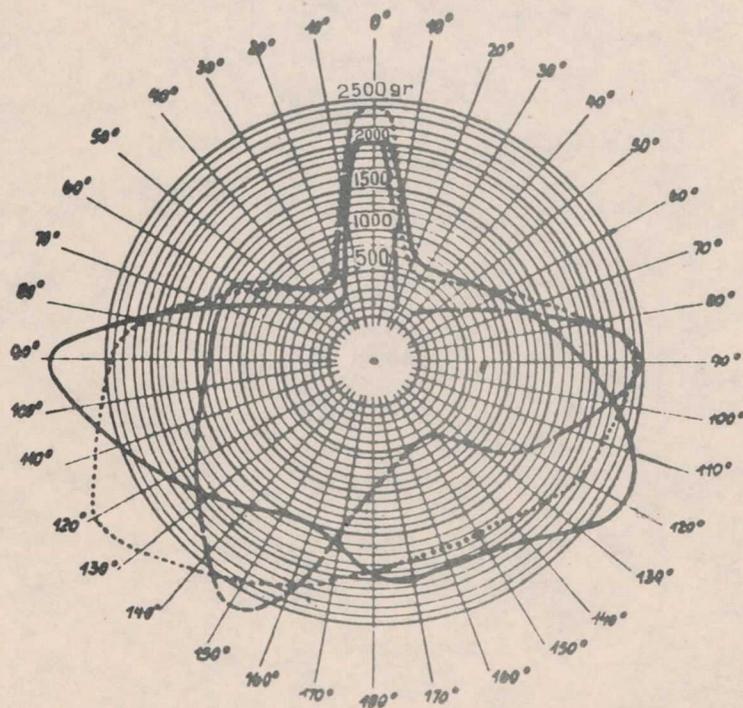

Fig. 11.   Turned ring with exaggerated pressure point at gap, followed by points of minimum pressure at other sections of the ring circumference.   Mean specific pressure determined from the tangential force to close the ring, pm = 1.42 kg/cm².
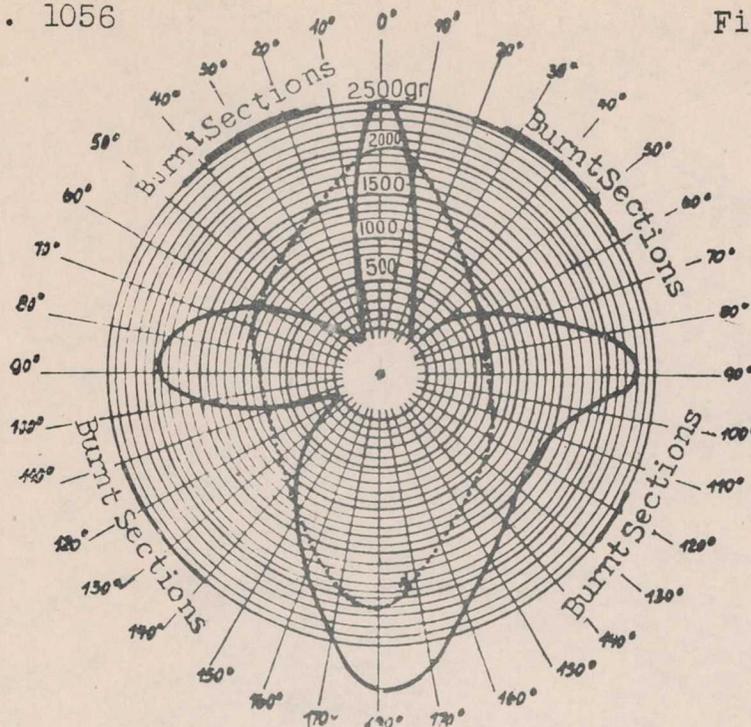
Fig. 12. Turned high pressure point ring with burnt sections. The radial pressure distribution is exaggerated at the gap and is useless. The stress determined by the steel band method is given by the broken line diagram. Time of running not known.
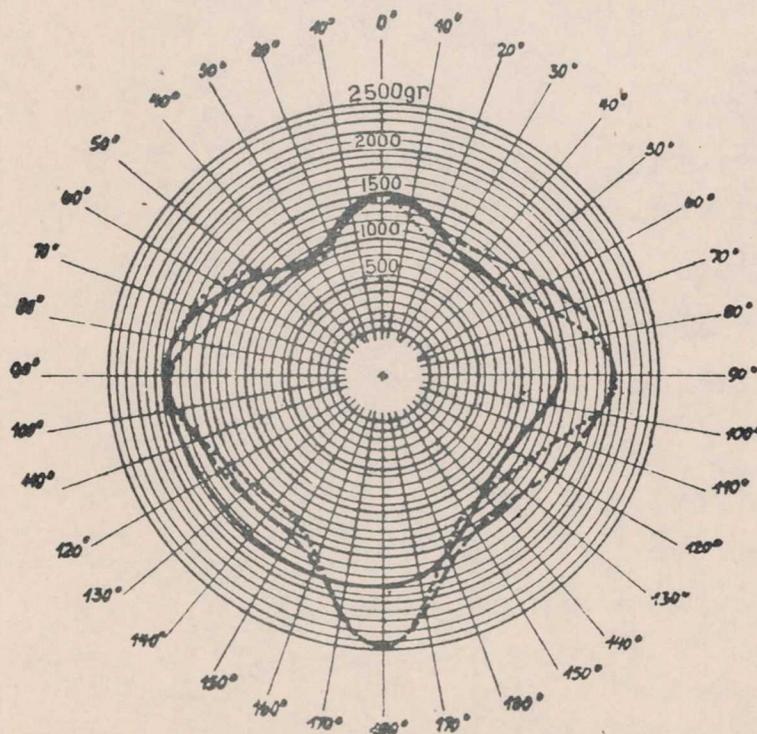

Fig. 13. Turned high pressure point ring with determined pressure distribution. No exaggerated high pressure point at gap and absence of low pressure points in the surface pressure. Mean specific pressure determined from the tangential force to close the ring, pm = 1.35 kg/cm². New rings.