PISTON RING SCUFFING

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Conference sponsored by
The Tribology Group, The Combustion Engines Group,
and the Automobile Division of the
Institution of Mechanical Engineers
The Department of Industry
The Diesel Engineers and Users' Association
The British Compressed Air Society

London, 13-14 May 1975

Published by
Mechanical Engineering Publications Limited for
The Institution of Mechanical Engineers
LONDON AND NEW YORK

CP5-1975

CONTENTS

C63/75

PISTON RING SCUFFING – GENERAL REVIEW

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SYNOPSIS Satisfactory operation of piston rings in a modern engine is a miracle, which is only possible if there is a separating oil film between the rubbing surfaces. Scuffing is a consequence of contact pressures getting higher than the momentary local lubricating conditions can bear. The peculiarities of ring lubrication and ways to improve it are discussed. Hot blow-by gases will destroy the lubricating oil film. The mechanism of piston ring sealing is discussed and the scuffing process analysed. A certain stable wear rate for piston rings running under severe conditions has to be allowed in order to stabilize their operation. Too low a wear rate may lead to scuffing.

INTRODUCTION

1. The limiting factor for the output which may be delivered by an internal combustion engine is often set by the running behaviour of piston rings. Their troubles, like wear, breaking etc. often pass through a first stage of scuffing. Apparently this happens so often, as to warrant the assembly of a conference of this importance in order to discuss and hopefully assist in solving this problem.

FRICTION AND LUBRICATION OF PISTON RINGS

Friction

2. The friction conditions of piston rings are very different from those of other engine elements like bearings.

3. They are characterized by:

- variations of velocity from zero in the dead centres to a maxium of 10 to 20 m/sec in mid-stroke (about 50 km or 30 miles per hour) compared to constant speeds in most bearings,
- variable contact pressures,
- peculiar lubrication conditions.

4. The speeds and loads valid for piston rings are dictated by commercial competition. Their mean values are not so much different from those of the bearings, but their lubrication is usually several levels lower than the one with which bearings are pampered. Thus for anyone closely familiar with piston rings it appears like a miracle that they even run at all! We must not forget that such a poor piston ring in a marine diesel engine has to skid for about 100'000 miles under miserable conditions before it is exchanged against a spare after a year's service!

5. The difference between success and failure of piston ring operation is given by the lubricating conditions. With moderate loads, speeds, decent design and generous lubrication a full fluid film may be established, in mid-stroke by a hydrodynamic wedge, in the dead-centres by squeeze action. With still higher pressure concentrations, the material resilience of the running partners may assist matters in order to establish an elasto-hydrodynamic film still fully separating the surface asperities. These conditions may be computed (e.g. Ref. 1), as will also be shown in some of the papers of this conference.

6. If the loads are still higher or if there is not enough oil - on account of insufficient supply, irregular distribution or burning away by the torch-like blow-by gases - even a boundary film of a tenth of a micron will suffice to separate the rubbing contacts and prevent high wear. But if even this last bit of oil is absent, scuffing will be the inevitable result.

7. The behaviour after the onset of scuffing depends very much on how much energy is available to overcome friction. In a watch e.g. the few Microwatts supplied by the driving spring are not sufficient to continue the motion, a poorly lubricated watch simply stops, a small engine will slow down, but the ten and more Megawatts available in a large engine will burn and destroy pistons, rings and liners, if misled from the propeller or generator to be transformed into heat by friction.

8. The great variations of speeds and loads during an engine cycle help the rings to support without, or with only minor trouble, very high peaks of loading even under poor lubricating conditions as these occur only during short periods, leaving time in between for cooling-off and healing.

9. Here lies a fundamental difference between piston rings on one hand and continuously loaded bearings on the other. Such a bearing will usually be burned out completely after an initial scuff. A ring however, which has occasionally run through short periods of scuffing will only show scuff marks on its surface and maybe a somewhat higher wear, but otherwise will still have been performing satisfactorily. This explains why sometimes scuffing marks are visible on dismantled rings. This always indicates that - whilst having

still fullfilled their duty - they nevertheless have sometimes run within the limits of trouble.

10. There is also a fundamental difference in friction behaviour between ring and cylinder. Under poor running conditions the ring is always heated on the same spot, whereas the same friction energy is dissipated over a much greater surface of the liner. Thus the bulk temperature at the rubbing spot is higher on the ring than on the liner, and this may have a decisive influence on the friction mechanism, particularly if the temperature rises to levels where chemical or metallurgical reactions take place. Then decisive differences in wear and influence of additives may result. A similar difference exists between pin and disc in a wear rig.

11. It is thus very important to define in which region of lubrication we are working:

- with a stable hydrodynamic film,
- under boundary conditons at the limits of trouble or,
- in the unstable scuffing region.

Furthemore it is just as important how long we stay within these regions - particularly the last one - and how long are the less severe periods inbetween, which allow healing.

12. The wide variations of all these influences make it very difficult to predict the behaviour of a particular piston ring set-up in operation.

Lubrication

13. The best way - and often the only one available - for a better operation of rings is the improvement of their lubrication. If lubrication is perfect, even the rubbing materials are of no importance, as they never touch each other.

14. We may improve lubrication by a more generous supply of lubricant and its better distribution. Every spot of the cylinder liner and ring surfaces has to be covered by at least the necessary minimum layer of lubricant.

15. With the splash lubrication usual in small engines, the amount of oil left on the running surface is the difference between a great quantity splashed on it from the crankcase and an almost equally great amount scraped off. To establish a stable equilibrium with a minute constant difference of two much greater quantities requires great practical experience, and much test work is needed in order to spread this trace of remaining oil evenly. Consequently in most cases a higher overall oil consumption is to be allowed for in order to keep a minimum oil film thickness even on the driest spot.

16. Separate cylinder lubrication guarantees equal distribution of oil to every cylinder and even to every sector of its circumference. Even here there is room for improvement by better utilisation of the few drops of oil supplied. This may be achieved e.g. by the appropriate locating of the lubricating feed holes and grooves. Also cyclic timing of the lubricant feed may help - be it by timed delivery or by application of the accumulator principle.

17. One of the most efficent ways to spread the oil evenly and to scrape off excess lubricant efficiently is the application of a revolving piston as it is done in Sulzer Medium Speed Engines. It applies the old principle "never twice over the same spot in the same direction" - which has been used for ages in lapping, honing, polishing lenses and mirrors etc. - to piston operation and has improved their running behaviour decisively. (Fig. 1) Eventual hot spots on the rings are continously transferred to new, cool and well lubricated regions of the liner, and the scuffing mechanism described in detail later is efficently interrupted. Furthermore, streaks of excess oil leading to high oil consumption are avoided.

18. The spreading of oil in axial and circumferential direction may be influenced by the design of piston rings and scrapers, also appropriate structures of the rubbing surfaces are beneficial for lubrication. Both aspects will be treated later.

SEALING MECHANISM OF PISTON RINGS

19. The other way to improve lubrication is the protection of an existing oil film against its destruction by blow-by. The action of blow-by gases in an diesel engine is more severe than that of an acetylene blow-torch! It may be greatly reduced by appropriate design and decent operating conditions of a piston ring set.

20. A good-running piston ring operates as shown in Fig. 2 sealing well against the lubricated surfaces of groove and cylinder. If it always behaves like this, no trouble will arise.

Leakage Areas

21. Ways for blow-by past a ring are:

- through the joint,
- between ring flank and groove bottom,
- between ring face and cylinder.

The size of the leakage areas of all these three paths may vary within wide limits and may even change during a cycle.

22. For sharp edged rings the leakage through the joint is very small (Fig. 3), the leakage area consists of the minute rectangle, long as the tangential ring gap and wide as the clearance between piston land and cylinder. It is increased many times when the ends are chamfered as it is sometimes done in order to protect them from being caught in liner ports (Fig. 4). In this case the length of the rectangle is increased to the length of both chamfers, and the decisive minimum section is constituted by the same rectangle as in the case with sharp edges and the triangles leading into the chamfers. (F6 is ten times larger than F5).

23. The leakage between groove and ring flank depends on the correct machining of the flat surfaces to begin with and the retention of this flatness in service. Here groove-flank protection on both sides by smoothly ground chromium plate is the best we know, with unprotected cast iron, steel and aluminum being poorer in this order.

24. The most important leakage occurs between ring face and cylinder. A well manufactured ring will hug the cool liner like in figure 2 around its whole circumference and will seal well. But

temperature differences will alter its shape and will raise it from the liner forming gaps, which - if they are not sealed by the action of gas-pressure or thermal deformation - will let the hot gases pass by, destroying the oil film and distorting the ring. Some forms of thermal deformation will correct gaps, others will open them up. These latter are particularly dangerous. The author has described these mechanisms in a paper in 1973, (Ref.2).

Correction by Pressure

25. Pressure may correct axial and radial gaps by squeezing them flat. In order to do it the ring must have a sufficient pressure difference across it and have an appropriate profile to utilize it. This means that each ring must take a sufficient portion out of the total pressure drop to be sealed, and to achieve this, it has to seal well in relation to the other rings.

26. The distribution of the total pressure drop onto the individual rings depends on the relation of their leakage areas to the volumes in between them and on the time available during the cycle to fill these volumes with pressure. This relation determines how deep a pressure peak penetrates into the ring set and how each ring is loaded during the cycle.

27. The leakage area of the individual ring depends in turn on distortion and correction mechanisms caused by the temperature differences and pressures acting on it, and as the pressures in turn are determined by the leakage areas and the temperatures by blow-by conditions, another very wide set of self energizing cycles is introduced as variables.

28. The pressures between the rings vary during each cycle. It may occur that the pressure is higher below a ring than above it. Then the ring will jump to the top flank of the groove, possibly assisted by friction or inertia, (Ref.3). During the jump the leakage area is much greater than during normal operation.

29. The pressure difference across an individual ring forces it against the cylinder and the groove flank. For the ideal ring of Fig. 2 one half of it is effective. Actual rings have never such correct profiles. On account of wear and distortion they may only touch on the top or bottom edges of the face and inner or outer edge of the flank (Fig.5). This raises the effective gas force acting on the ring up to its full value or balances it out. In reality the contact surfaces are not even rectilinear but curved resulting in compromises between loading and balancing. A slightly curved face profile is beneficial for the development of a hydrodynamic film during motion but detrimental for resistance against squeeze in the dead-centres. Any concentration of high load on a narrow carrying zone will increase the contact pressure and may lead to scuffing if lubrication is not able to carry the load. A sufficiently high wear rate will stabilize matters by widening the contact zone and reduce hard-bearing spots. This is accomplished by a thorough running-in process and has to be continued throughout the whole life of the rings in order to accommodate changes due to distortion and wear.

30. Nowadays ring profiles are often manufactured with barrelled faces to protect the rings against the dangerous concentration of pressure on the top edge and to establish a narrow contact zone for rapid running in. Taper-face rings are relieved of radial gas forces. Rings with an inside edge cut away and other unsymmetical profiles distort and do not touch the lower groove flank if not forced down by gas pressure (Fig.6)(Ref. 4.) Both types of rings are benefical in certain applications, but under difficult conditions may lead to instability like poor sealing or radial collapse by the pressure acting on the outside face. The profiles of piston ring faces are very important for the transport of oil in up - or down - direction (Ref. 1).

31. The possible variations of the forces acting on an individual ring introduce another widely spread set of operating conditions complicating matters still more. This influence our main subject <u>ring scuffing</u> directly by possibly creating high contact pressures and indirectly by affecting lubrication by poor sealing and blow-by.

MATERIALS

If lubrication fails, the properties of the rubbing materials get into action.

Scuffing Mechanism

33. First let us look a little closer at the scuffing mechanism: (Fig.7, left). If a body B slides over a body A (the speed v is directed away from the reader) under boundary conditions of lubrication, the heat produced by friction

$q = v.p.\mu$ (speed x pressure x friction coefficient)

is dissipated into both bodies resulting in linear heat-flows q through them. If in a particular spot more heat is developed by higher friction, due e.g. to a momentary lack of lubrication or a tiny speck of dirt, this spot gets warmer, expands on account of its higher temperature and will produce a "thermal bump" which in turn rubs harder, becomes hotter, grows higher, and so on in a vicious circle (Fig.7, right). If the wear rate is high enough to level the bump out as fast as it grows, conditions remain stable, and when the dirt speck is removed or the lubrication reinstated by passing during the course of the stroke over an oily patch, the "thermal bump" cools and shrinks, leaving behind a minute scar. The sum of these scars in addition to scratches by foreign bodies and, eventually, corrosion constitutes the total wear rate.

34. If, however, the wear rate is not high enough to wear the bump off, the process develops exponentially until the temperature rises so high as to alter the friction conditions, usually destroying lubrication. This destruction of the oil film in turn raises the friction coefficient and thus the exponent of the scuffing equation until micro-welding, that is initial scuffing, develops. If the process is stopped at this stage by improved lubrication, a scuffing mark will be the result. First it involves - still on a micro level - a change of the surface structure with formation of "white spots" or "white layers". Here martensite will be formed by temporary rapid

heating and immediate cooling by the cold surroundings. In a further stage visible scuffing marks will by produced, and if the heating action continues, severe scoring will result.

35. Attempts to calculate the contact temperatures have been made by Blok (Ref.5), Archard (Ref.6), Uetz (Ref.7) and others, and the expression "thermal bump" has originated with NASA. An attempt for a very simplified calculation of the scuffing progress has been published by the author in the Appendix to his CIMAC 1973 paper (Ref.2).

36. Under the assumption of linearity made in that work, the thermal conductivity of the material is of no influence - in reality, however, it plays a very important role as it determines the temperature of the rubbing point and thus the type of friction mechanism.
The danger of scuffing may be expressed by a value "D" standing in the exponent. "D" is the product of two values:

$$D = Sv. Sc$$

One of them is "Sv" characterising the severity of the friction setup.

$$Sv = \frac{v.p.\mu}{l}$$

It depends on the product of rubbing speed v, load (initial unit pressure p) and the friction coefficient μ. This product is divided by a value "l" characterizing the resilience of the material or its support, "l" reduces the force increase in case of growth of a "thermal bump".

37. The other factor is a pure material constant, the scuffing index "Sc". It has the form:

$$Sc = \frac{E\ \varepsilon}{c.\rho.}$$

(E: Young's modulus, ε: coefficient of thermal expansion, c: specific heat and ρ: density).
The scuffing index Sc of cast iron - in effect a carbon steel polluted by graphite and other foreign crystals - is the lowest (best) of all metals. Cast iron has a low modulus of elasticity E because the metal structure is well broken up by a graphite net work, and is more resilient than e.g. spheroidal iron. Its thermal conductivity is high on account of the well distributed graphite content. Furthermore graphite may act as an emergency lubricant and anti-weld-agent preventing the catastrophic rise of friction. This confirms the choice made by practice more than a century ago!

Surface Structure

38. An appropriate surface of the rubbing materials is important - too smooth is not good. A surface with plateaus to support the load and shallow depressions inbetween to supply lubricant and to hold wear products is very favourable. Such a surface has to be maintained throughout operation. Here again a good cast iron with a wear resisting phosphide or carbide grid in a pearlitic structure with pockets full of graphite and oil stands out. Its unhomogeneous structure does not allow a scuffing furrow to develop far as it is stopped by changes of material. The scuff-prone ferrite is present only in minute layers within the pearlite, and the graphite flakes interrupt the rubbing surface every few tenths of a mm.

Porosity

39. Porous materials will retain a certain reserve of oil for emergencies which is very favourable under boundary conditions. On the other hand under elasto-hydrodynamic conditions ring prosity will drain away the load carrying oil film.

Material testing rigs

40. Attempts to classify materials by test rigs according to their wearing and anti-scuffing properites have been made many times. The scatter of the results contained in the literature is overwhelming and does not allow any clear separation between the very many factors affecting scuffing, lubrication and wear. The author is of the opinion that for every reference showing a benefical influence of an individual factor like e.g. relative hardness, there is at least another-one showing the same factor to be detrimental! Very often the special rigs designed to clear up one problem end up in elucidating quite another-one, still contributing, however, to our knowledge.
A recent attempt for such tests made in this country is the rig designed by MIRA and described at the Montreux conference of the Institute of Petroleum in 1973, let's hope it will produce useful results in due time.

BENEFICIAL WEAR

41. If we get into the scuffing region, the wear rate at the beginning of a "thermal bump" is decisive. If it is high enough the process will stablize, if it is not exponential growth of the bump will result with disastrous consequences. We thus arrive at the very important law "wear prevents scuffing" or in other words, a certain stable wear rate appropriate to the severity of the friction setup is beneficial for practical operation as it will help to avoid high unstable wear due to scuffing.

42. Wear is particularly important during running-in of new piston rings and liners. Here rapid wear is necessary in order to establish sealing and to create the correct rubbing surfaces. Any influence reducing wear will prolong the running-in process and possibly lead to scuffing. Thus running-in with wear-reducing HD-oils renders the process more difficult than with plain mineral oils. Mild EP-additives, graphite or molybdenum-disulfide also prevent wear and should not generally be used, their use is only justified in an emergency to heal a beginning scuff. Also a slight lacquer formation on the cylinder which separates the metallic surfaces may be favourable.

43. The machined surfaces have to have an appropriate roughness "as smooth as possible, but as rough as necessary", as, "a sharp file never scuffs".

44. Surface treatments against scuffing

- prevent incipient welding by fragile porous layers which at the same time improve lubrication (like phosphates, unfortunately they are so thin as to be effective only in small engines and then only for a short period)

- promote sealing by their rapid wear (tin and in particular thick copper layers)
- provide wear-increasing abrasives (iron-

oxides, varnishes containing abrasives).

Wear may also be increased by additives to fuels and lubricants producing abrasives which have proved their worth in difficult cases.

45. Even after running-in has been accomplished a certain small wear rate is beneficial, as changes in operating conditions e.g. temperatures may require minor adaptations of shape by wear. In old engines with liners and pistons rings already polished by moderate service to a very smooth surface with no oil pockets the oil scrapers may work too well and reduce oil consumption locally too much leading to "old-age scuffing."

46. Wear might well be zero, if lubrication conditions would always remain perfect. But as nothing is perfect on this Earth, accidents (minor local contacts with higher friction) will occasionally occur and - as we have seen - must be stabilized and healed by wear. If the wear rate is too low they may develop into scuffing. In the author's opinion such extremely low wear rates may be the cause for the high wear due to scuffing when operating with high alkaline lubricants and low-sulphur fuel. As a cure for this problem Multi-Purpose lubricants, which in case of incipient oil film failure will increase wear artificially - be it abrasively or chemically - and never let the wear rate fall too low - would be desirable.

CONCLUSIONS

47. Concluding we may state:

Piston ring scuffing is the consequence of contact pressures getting higher than those which the momentary local lubrication conditions can bear. This happens accidentally, and, as in all accidents, a number of influences must turn adverse at the same time. If one of these influences - even an apparently minor one - is not adverse, then the rings run unexplainably well even under otherwise extremely poor conditions!

48. The reason why scuffing occurs today more often may be on the one hand

- the higher speeds and mechanical and thermal loads common nowadays, (high Sv!) and on the other hand
- lubrication becoming too scanty. Exaggerated trends for a low overall oil consumption may reduce it locally below the necessary level,
- the thermal loading is now so high as to require HD-oils for running-in which renders it less effective.

49. Possibly our endeavours to reduce wear are too successful. Of course we want to reduce wear - but who asks for a large diesel liner to last for 50 years or a car engine to run for a million miles? By that time the ship will have been scrapped and the car will have rusted through anyway.

50. Some possible cures against scuffing are:

1) in engineering

   a) logical designs with adequate cooling, avoiding machanical and thermal deformation,

   b) appropriate choice of materials,

   c) high quality manufacturing and correct surface structures and

2) in operation

   a) decent running-in procedure,

   b) very important, adequate lubrication in every spot of the running surface, this means a sufficient oil supply and its even distribution,

   c) and just as decisive, allowing an adequate stabilizing wear rate, if required.

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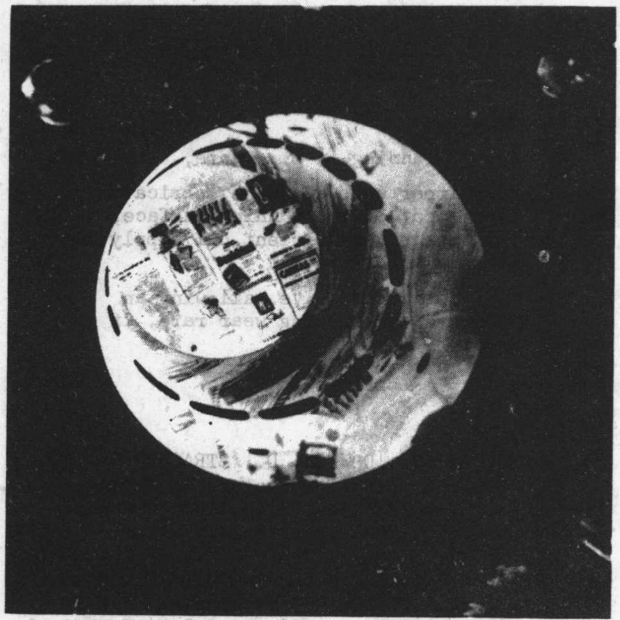

Fig. 1. Cylinder liner after 1000 hours of running with a revolving piston (1947)

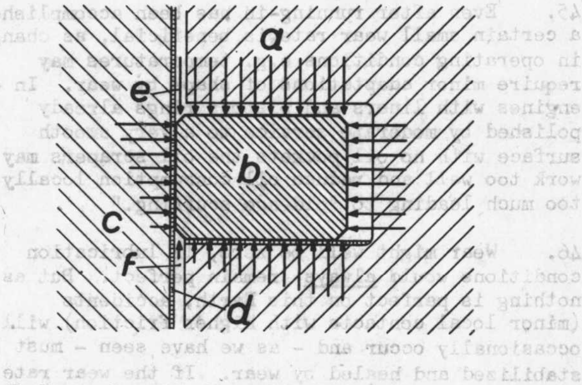

Fig. 2. Piston ring operating under ideal conditions (a) Piston, (b) Piston ring, (c) Cylinder liner, (d) Oil film, (e) upper gas pressure, (f) lower gas pressure

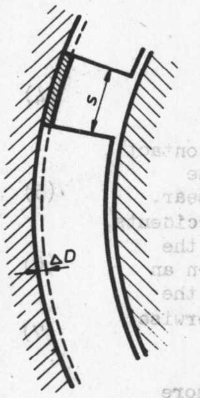

Fig. 3. Leakage area of a sharp edged ring joint

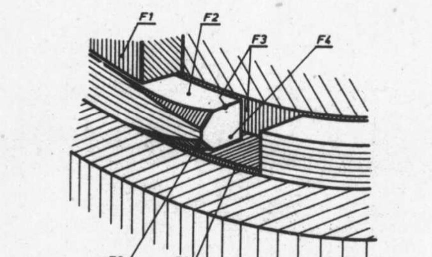

Fig. 4. Leakage areas of sharp edged and chamfered ring joints

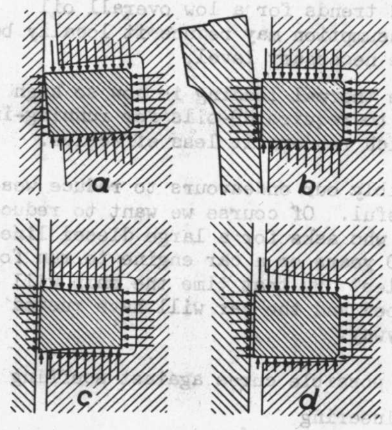

Fig. 5. Typical gas pressure distribution around piston ring profiles (a) radially loaded, (b) radially balanced, (c) axially balanced, (d) axially loaded

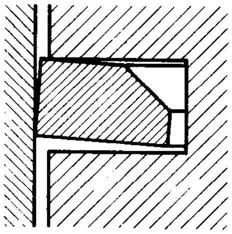

Fig. 6. Piston ring with inside chamfer without gas pressure

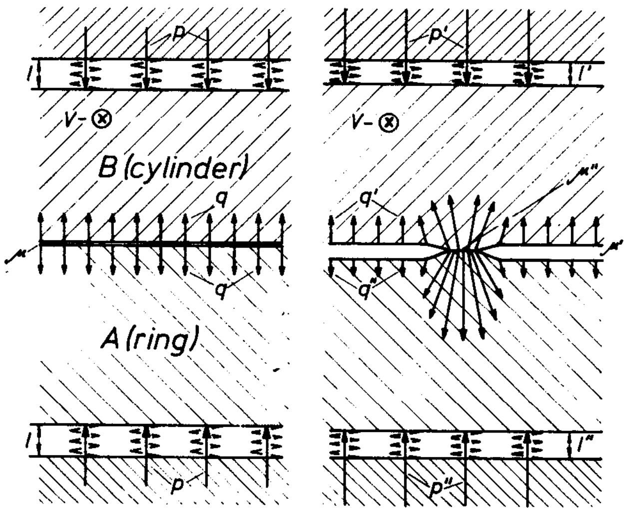

Fig. 7. Scuffing mechanism

C64/75

DIESEL ENGINE RING SCUFF – IS THERE A MAJOR PROBLEM?

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ABSTRACT The paper is mainly of the discussion type and does not present new data from research work. The nature of ring scuff in diesel engines is briefly summarised, and its status as a major field and development problem is discussed. It is concluded that in the last five years the action taken by industry has produced a marked reduction in scuff incidence, and the current major problem is that of piston top groove carbon. The most important factors leading to the change of ring scuff status are presented, and the continued need for research to establish a better understanding of ring behaviour is emphasised.

INTRODUCTION

1. Some 5 years ago the author in collaboration with a colleague presented a paper to the Diesel Engineers & Users Association which included a description of the problem of ring/liner scuffing in diesel engines and some of the principal factors affecting it. (Ref.1) The paper used such expressions as "its (scuff) incidence has increased markedly in line with the increases in specific power output, speed and performance standards" and "the technical margins are only being won by a more scientific and fundamental approach, and nowhere is this more true than in the solution of the problem of ring/liner scuffing". At that time it was obviously widely felt that diesel engine ring scuffing represented a serious problem which was the source of many service failures, limiting the rate of engine development, and costing the industry considerable sums of money. Today, however, it is felt there has been a significant change in this position.

2. This paper presents the case for the existence of such a change and describes the factors which have been responsible for it, while at the same time commenting on the continued wide interest in the subject of scuff. The paper is mainly of the discussion type aimed to stimulate an exchange of views. It does not present any new facts from research programmes, but draws fully on material from the previous publication mentioned.

THE NATURE OF SCUFF

3. The recognition and definition of scuffing particularly that of piston rings are not subjects of much general disagreement. The breakdown of lubricant film allowing metal to metal contact leading to "gross damage characterised by the formation of local welds between sliding surfaces" as described by Barwell (Ref.2) is typically shown in minor and severe forms in the rings of Fig.1. The streaky wear patterns on the rings also normally appear on the bore surface, and detailed examination of them shows conditions of local high temperatures, and in the case of cast iron the formation of a hard white phase layer, probably a high carbon compound, which is known to spall and give a high wear rate condition. (Ref.3) (Ref.4).

4. While ring scuff can occur at any time in the life of an engine it is most commonly encountered during running in, and generally commences at the top compression ring and spreads down the pack. The early outward signs of scuff in an engine are rapid increase in oil consumption and blowby which, if unnoticed and allowed to become severe, can cause damage to the piston with the possibility of complete seizure.

5. It is not difficult to list over 70 factors which have a direct or indirect influence on ring/liner scuff performance. These fall broadly into the categories of ring, liner, piston and engine design, lubrication, combustion, build and operating conditions.

6. While scuff can arise as a result of one deficiency, say bore finish, it is more usual that it occurs as a result of the combined effect of several. This raises the idea of a critical scuff level represented by the integration of several adverse features which, when exceeded by an engine, will result in major scuff problems. Continuing such thinking it is easy to see why some engines have the reputation of being "scuffers" while others never or seldom fail due to ring problems. It is well known that a cure for scuffing is not normally effected by the correction of one fault, but more by a wide attention to many details. Conversely it is interesting to note how difficult it can be to make an engine scuff to order. Anyone who has ever tried to develop an engine test rig for scuffing will bear out this point and it is not unusual for several engine features to require modification to produce a scuff condition.

DISCUSSION – IS THERE A MAJOR SCUFF PROBLEM?

7. Recent surveys of the high speed engine field apparently suggest that ring scuff is still considered a major cause of failure, in service and during development testing, but particularly the latter. This conclusion, however, is not substantiated by the technical reports coming into

the author's company from a wide range of diesel engine customers. While severe scuff problems still seem to exist in petrol engines, the incidence in diesel engines, although still present, is now of a minor order.

8. A possible reason for this difference of view would seem to lie in the interpretation of ring scuff as the principal failure. Close examination of many engines with obvious signs of ring scuff shows the primary cause of failure to be ring stick or carbon packing. Fig.2 shows a typical case of ring stick where carbon has reduced the ring side clearance and prevented normal piston/ring relative motion. The ring in this condition acts as a carrier of piston side thrust with resultant high pressures and scuffing. Alternatively carbon packing, and early signs of it are shown in Fig.2, occurs where carbon fills up the groove space behind the ring, again stopping relative piston/ring motion and producing scuff.

9. It is not within the scope of this paper to examine the causes of such carbon problems, but it is clear that there are many cases where a prognosis of ring scuff should have been ring stick or carbon packing. At the same time over the last year there has been a marked increase in carbon problems which are largely unaccountable. Several cases are known where engines, having been developed without problems and trouble free in service for many years, suddenly reveal carbon formation in the top ring groove at very early stages of running - as low as 10 hours. The extent of the failure due to carbon is such as to suggest that this is the major problem currently being met in piston and ring development today.

10. The recognition of an industrial problem and the subsequent definition of the research programme and its funding to help solve it, tend by the very nature of things, to be "high inertia" features and consequently slow to get moving. Continuing the analogy, however, once set in motion they are not easily diverted or stopped.

11. A pattern along these lines would seem to apply to ring scuffing. In the course of approximately 10 years it has moved through the various stages of service/development problem, measurement of size of problem and setting up of research programmes, until at the present time there is a well developed enthusiasm for the subject in industry and academic institutes alike.

12. The inclusion of a paper on scuffing at a meeting or conference would seem to guarantee good attendance, animated discussion and the expression of strong views. The word 'scuff' is both descriptive and onomatopaeic, while at the same time having strong emotive connotations. This may well have contributed a little to the fact that the subject is one which has caught the imagination of investigators in both applied and theoretical fronts.

13. The achievement of such enthusiasm at a time when there is little enough of it about is to be commended. There is some danger, however, that the extant situation is not fully recognised and more significant problem areas are being overlooked.

14. Competition and commercial pressures can be closely likened to the "necessity" which "mothers" invention. A severe technical problem which is affecting company markets and profitability cannot generally wait for answers from the total research approach, and solutions are found in the short term. In some cases these solutions are not economic and can be considered more as improvisations. The correct or more elegant answer must indeed await the full research and development investigation.

15. In the case of diesel engine ring scuffing, in the last five years essential non-compromising practical solutions have been found which represent the integration of many improvement factors as will be shown later.

16. This does not imply that the research programmes set up to study the subject have become superfluous to the engine industry's needs. There is still an important requirement to achieve a better overall understanding of the behaviour of the ring as a gas and oil sealing element in a ring pack combination. Further, there is a vital need to be able to design and predict precisely the performance of a ring pack, say in terms of life and oil consumption, for a given set of conditions before it has run in an engine. Much of the current research work on rings is making valuable contributions to such an aim. The examination of the dynamic film conditions which exist between ring and liner obviously have a direct bearing on such performance factors as oil consumption, blowby and ring and bore wear. It should be clearly recognised, however, that the work, at least as it is associated with the diesel engine, is not directed towards a major ring/liner scuff problem. Lack of recognition of this fact, it is suggested, does no service to the diesel engine industry as a whole.

17. If, indeed, in the last five years the status of the scuff problem has changed, what are the steps which have been taken to effect this change? A recent survey by Neale & Creese (Ref.5) provides an excellent summary of published information on rings and bores, giving many details of current engine design and operational practice, particularly in relation to wear and scuff performance. This survey clearly demonstrates the considerable depth of know-how available in, and being supplied by, the industry to overcome scuff problems.

18. A full presentation of all the corrective measures now being regularly adopted would be a lengthy document. A few of the more important, however, are now high-lighted in summary form.

IMPROVEMENT FACTORS

Cylinder bore finish

19. The advent some 15-20 years ago of the diamond honing stick with its higher production efficiency unfortunately had an adverse effect on bore scuff resistance. Diamond honing produces a highly "peaky", torn and folded surface character which can cause metal to metal contact and particle detachment. Examination of run-in bores and the knowledge that rings seldom scuff after run-in, showed the extreme importance of developing a surface characteristic of flat topped peaks. This recognition - that surface finish and peak form and character must be closely and consistently controlled, has perhaps contributed more than any other factor to the reduction in ring/liner scuff incidence. (Ref.6).

20. In the late 1960's production techniques were developed using rubber bonded or cork impregnated silicon carbide stones applied after diamond honing to give a clean, burr free, plateau type surface finish. The effect of the cork stone process in comparison with the straight diamond honing technique is illustrated in the surface finish measurements and corresponding Stereoscan photographs of Fig.3. The surface cleanliness and flat top peaks produced by the cork stones can be clearly seen as can the peaky and flaky surface of the diamond honed finish. It is not difficult to understand the interesting practical point that the cork stone surface feels smooth to the touch and will not pick off material when rubbed with a soft cloth as will the diamond honed surface (Ref.7)

21. The factors required of a bore surface for optimum anti-scuff performance and which are now widely achieved by engine and liner manufacturers can be summarised as follows :

(a) dimensional accuracy
(b) finish consistency
(c) oil spreading and retention grooves/pockets to last over a long engine life
(d) cleanliness, freedom from embedded particles and burrs
(e) contact characteristics to limit point pressure loading and maintain good heat transfer

22. While some sources recommend the use of smooth bore finishes down to 5 micro inch CLA, particularly with barrelled rings, a wide experience of high and medium speed diesel engines shows that a finish of 25-40 micro inch CLA with a plateau characteristic is to be preferred. This surface gives good oil retention properties, long life and good scuff resistance.

Bore distortion

23. The ideal bore is one which remains round but not necessarily parallel, after engine build and during running conditions.

24. The non-parallel feature at the top dead centre position is associated with the development of the optimum ring profile in good hydrodynamic and squeeze film conditions (Ref.5) and is a refinement which is not yet known to be deliberately produced in practice. A certain degree of preferred bore profiling takes place naturally due to top deck restraint. While the very nature of the problem suggests that the achievement of the ideal bore is extremely unlikely, marked advances have been made in recent years.

25. Rings are designed to seal in a round bore, and while they can conform to certain minor bore variations, the consequence is a combination more susceptible to scuff. Bore distortion results in high pressure conditions, normally at the ring gap, causing oil film breakdown and potential scuffing. In addition an out-of-round bore tends to resist ring rotation. It is a well established fact that fixed rings, say by pegging, are much more prone to scuffing than those free to rotate. This arises presumably from contact conditions being repeated continuously at the same point on the ring and bore surface.

26. Fig.4 shows a ring horn scuffing condition which is typical of that experienced due to bore distortion.

27. The degree of distortion in any engine can readily vary from bore to bore. It is a common feature to find only one bore giving a problem. However, the avoidance of siamesing, better cooling level and distribution of heat and block, improved structural rigidity and head bolting arrangements, and better control of head tightening and material heat treatment, are just some of the features which have led to more consistent, rounder bores, and a more satisfactory ring environment.

Ring/bore materials and coatings

28. The metallurgy of ring and liner materials to achieve optimum scuff resistance is a well established science which continues to be developed. More recently the wider appreciation of the importance of such factors as ferrite levels, the use of medium phosphorous irons, and the achievement of "A" type graphite structures close to the bore surface, have helped the general scene. In addition there has been an overall tightening up of material specifications, and closer control of quality.

29. Electroplated chromium is still regarded as the best overall surface coating for ring and liner wear and scuff resistance. Its wider use, particularly for top compression rings and high load conformable oil control rings has been a significant factor in reducing scuff. In addition better manufacturing control of the plating process giving less "beading" and improved edge condition has provided further gains.

30. Sprayed molybdenum has been shown to offer the best scuff resistance of any coating, and is typically applied to the top compression ring of particularly difficult cases. In certain applications molybdenum coatings have resulted in higher bore wear and it has a tendency to oxidise and break down at temperatures in excess of 250°C. Nevertheless some very successful engines are running with molybdenum coated top rings.

31. Other composite and pseudo alloy sprayed coatings have been developed which have excellent resistance to scuff, and also good wear properties. There is, however, as with molybdenum, a tendency for such coatings to give increased bore wear.

32. Copper plate applied to both chromium and iron surfaces has been shown in many cases to improve scuff resistance during running-in, and is currently specified for several engines.

33. While sintered rings have made significant inroads into petrol engine practice, to date there has been no appreciable application to the diesel field. While development work has shown that they suffer from limitations as a diesel top ring material, they do have excellent scuff resistance and could well find useful application for rings below the top ring position.

34. Apart from the use of chromium plated liners, soft nitriding and phosphate and sulphur based coatings are being used with considerable success as running-in, anti-scuff bore treatments.

Piston/bore temperatures

35. The importance of improved block cooling on liner distortion has already been covered. It is also extremely important that the temperature of the surface over which the ring travels is not allowed to rise to too high a level, say about 180°C. Improved water circulation at the top of the liner and keeping total ring travel within the water space are widely accepted design features which have helped the ring environment at its most susceptible position - the top of the stroke. The control of piston top groove temperatures to a value not exceeding 225°C is now generally acknowledged as important in helping to limit carbon formation in this region. In highly rated engines the application of more advanced oil cooling techniques, including the use of galleries behind the top ring groove have enabled this temperature criterion to be achieved. At the same time the level of heat flow through the top ring has been controlled with beneficial effects in terms of ring distortion and surface temperature.

Running-in procedures

36. Running-in is the most critical period of an engine's life in relation to scuff. On production engine pass-off there is a strong pressure on economic grounds to reduce run-in times and the importance of this, coupled with the avoidance of ring scuff, has resulted in manufacturers studying this feature very closely and developing more effective running-in procedures. It is evident that there is no one running-in procedure which suits every engine although there is an increasing tendency to include early light load high speed running in the procedure.

37. It is anticipated that further advances will be made on this subject as instrumentation becomes available to measure externally when ring and bore surfaces have reached full compatability.

Ring/Ring Pack design

38. At the same time as there has been a requirement to reduce scuff, more stringent targets on ring and bore life and oil consumption have set up conflicting technical demands on ring pack design.

39. While there is no sign that a standard ring pack design applicable to all engines is a short or medium term prospect. the number of ring types found in diesel engine practice today is certainly reducing. Some typical three and four ring packs are shown in Fig.5.

40. It is noticeable that none of these packs contain a skirt ring which is now generally, wherever possible, avoided to permit maximum lubrication of the skirt.

41. A fact which is now more clearly understood and has had a significant influence on ring scuff is that control of oil has to be shared by the whole pack. Sufficient oil must be available at the top ring to lubricate it and remove carbon without allowing too much to pass by and be burnt. There perhaps has been a tendency in the past to over-scrape by means of the lower rings, particularly the oil control or conformable ring, resulting in starvation of the top ring and high wear or scuff.

42. The barrelled profile chrome compression ring is now widely used as a top ring, giving a neutral oil control action, good hydrodynamic film generation and quick and scuff-resistant bed-in. Where oil control has been found particularly difficult, a chromium plated taper faced or inlaid chromium top ring usually provide an answer. In general there has been an increasing trend towards the greater use of chromium and the all chromium ring pack is commonly encountered.

CONCLUSIONS

43. While ring scuff still does occur, particularly during development, in the diesel engine at least it no longer justifies the status of a major problem. Overall attention to detail, the better control of manufacturing processes and quality, and a wider appreciation in design and operation of the factors which are important has produced a marked reduction in scuff incidence.

44. There is, however, no room for complacency and much has still to be learned about individual ring and ring pack behaviour and related performance. In this respect it is encouraging to see the many papers of excellent quality covering both theoretical and practical investigations which are currently being produced.

45. Ring stick due to carbon and carbon packing is considered the major ring problem in diesel engine development and service today, and would seem to justify wider detailed investigation in current engine research programmes.

46. The original meaning of the word 'scuff' was 'to drag one's heels'. Reverting to this meaning it is clear that the industry and research centres alike are not 'scuffing' on the subject of rings.

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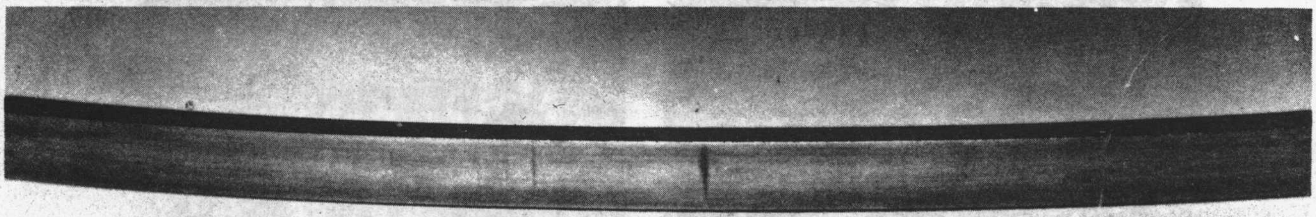


(a) Minor Scuffing

(b) Severe Scuffing

Fig. 1. Typical examples of ring scuffing.

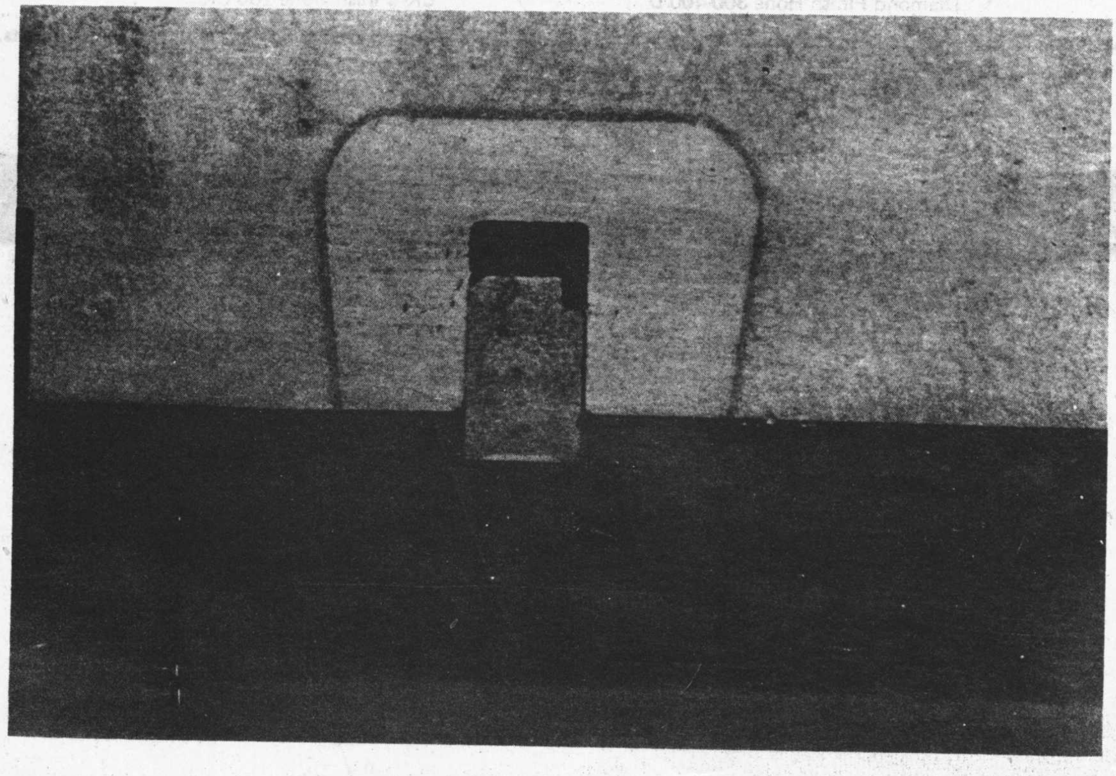
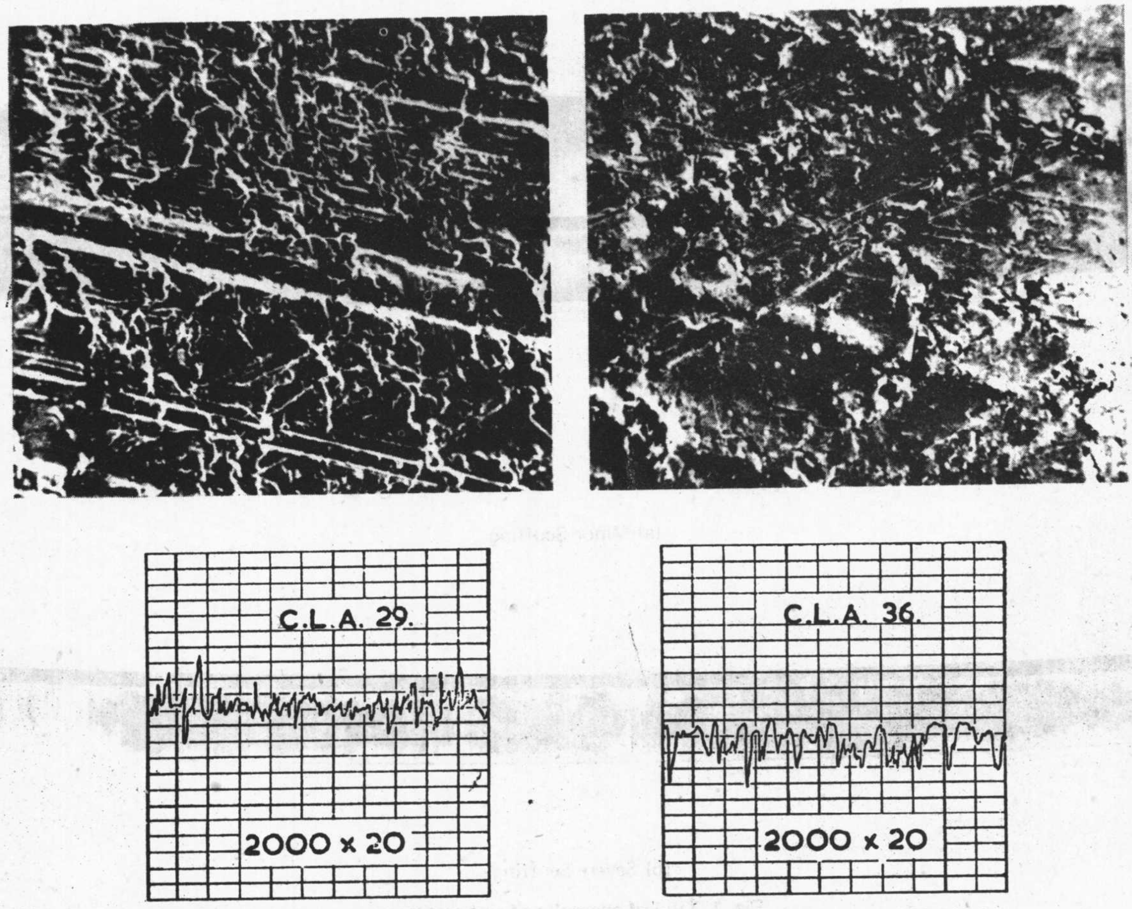


Fig. 2. Ring stick due to carbon.



(a) Diamond Base Hone 120-140 D
Diamond Finish Hone 300-400 D

(b) Diamond Base Hone 120-140 D
'CK' Finish Hone 200 CK

Fig. 3. Stereoscan photographs of diamond honed and cork honed bores with corresponding surface finish measurements.

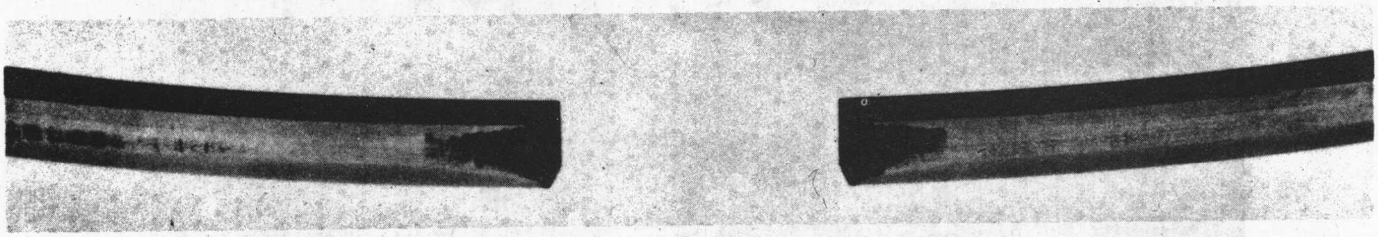
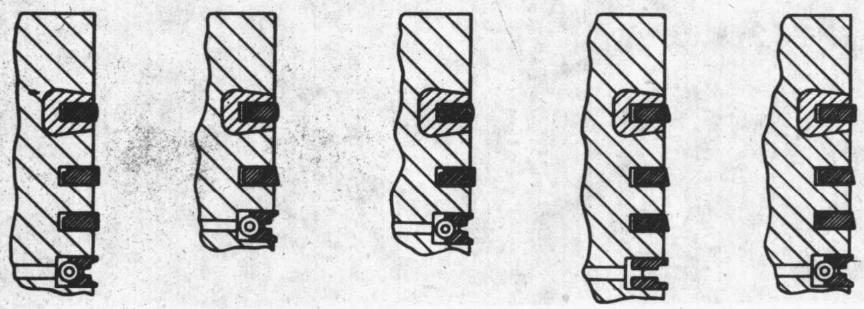


Fig. 4. Typical horn scuffing.



(a) (b) (c) (d) (e)

Fig. 5. Typical High and Medium speed diesel engine ring pack.