THE DEVELOPEMENT OF A PROCESS FOR THE RADIUS HARDENING OF DIESEL ENGINE CRANKSHAFT JOURNALS

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DECLARATION

This is to confirm that the contents of this dissertation are the result of my own work and investigations.

The opinions contained herein are my own and are not necessarily those of the Cape Technikon.

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ABSTRACT

Radius hardening on journals of forged steel Diesel
engine crankshafts is performed in order to increase
fatigue life characteristics. This requirement may
be necessary if the demands for engine power are to
be increased, but where the existing crankshaft
design is close to its fatigue limit, such that an
increase in loading will cause it to fail.

Induction hardening of journal radii changes the
make-up of the material from a coarse to a fine
crystalline structure which alters the features of
crack propagation. As a consequence of this higher
loads can be applied onto the crankshaft without
ultimately resulting in catastrophic material
failure. Extending the induction hardened zone from
the bearing surfaces into the radii of journals,
culminates in process difficulties which are not
experienced in non-radius hardened crankshafts.
Hardening of journal radii induces as well as
releases stresses in the crankshaft webs. This
results in a deformation of the crankshaft which can
be measured in the form of journal runout. Such a
problem cannot be overcome by straightening the
crankshafts in order to reduce runout, since this
will cause the radii to crack once hardened.
Straightening in the unhardened state on the other
hand induces stresses which will be released again
after hardening. This results in an increase in
runout. High runout indicates that stresses have
been induced into the crankshaft material. This is
undesirable since this will make critical
manufacturing processes such as grinding, governing
of journal lengths, uncontrollable. It can

furthermore result in creep of the crankshaft long after the manufacturing date. This results in crankshaft deformation, noticeable through an increase in runout. Since the crankshaft cannot be straightened after hardening, the consequence is that it will be unusable. The process must therefore be developed in such a manner, that all variables which can contribute towards stress induction resulting in journal runout, must be investigated and resolved.

In this dissertation all variables which can cause the induction of stresses, from the forging process, through hardening and journal grinding are investigated. In addition, techniques of component testing which are vital to confirm the success of the process development are explored and discussed. This is achieved by means of probing the theoretical background of the factors which affect radius hardening, and then applying this theory into practice. In many instances empirical evaluations are performed during development of the process in order to achieve satisfactory results.

The intention of this dissertation is to demonstrate a universal methodology of process development. Although one particular type of crankshaft, namely the ADE 366 model, was used for developing this process, the theory and method of process development is applicable to any type of Diesel engine crankshaft. As demonstrated in this dissertation, a workable process for radius hardening of Diesel engine crankshaft journals was developed. The final result being a manufacturing process which produces crankshafts which can be employed in engines with higher power outputs.

OPSOMMING

Radiusverharding van smeeyster krukaslaers, vir dieselenjin-krukasse, word gedoen om die vermoeidheids-eienskappe van die krukas te verhoog. Hierdie verhoging in die vermoeidheidseienskappe mag nodig word, waar die bestaande krukasontwerp naby sy vermoeidheidsgrens is, en die enjindrywing verhoog word. So 'n verhoging in enjindrywing kan krukasbreuke veroorsaak.

Induksieverharding van die laer radiusse, verander die samestelling van die materiaal, van 'n growwe na 'n fyn kristallyn struktuur, wat die verskynsel van kraak propagasie verander. Hoër ladings kan dus op die krukas geplaas word sonder dat dit uiteindelik in materiaalbreuk ontaard.

Die uitbreiding van die induksieverharde sone, vanaf die laer oppervlakte tot by die radiusse, kulmineer in vervaardigingsprobleme wat gewoonlik nie in radius onverharde krukasse voorkom nie. Die verharding van die radiusse veroorsaak dat daar spannings in die krukasweb opgewek, asook vrygelaat word. As gevolg hiervan word die krukas vervorm. Die vervorming kan as 'n verandering in die slaglengte gemeet word. Die probleem kan nie reggemaak word deur die krukas reguit te druk nie, aangesien die verharde radiusse sal kraak, wat weereens krukasbreuke sal veroorsaak.

Die regbuig van 'n onverharde krukas, aan die anderkant, plaas spannings in die materiaal wat, na verharding, weer vrygestel word en weer 'n verhoogde slag tot gevolg sal hê. 'n Verhoogde slag beteken dat spannings in die krukasmateriaal opgewek word, en is ongewens omdat dit kritiese vervaardigingsprosesse soos slyp, beheer oor

laerlengtes onkontroleerbaar sal maak. Dit kan verder ook
lank na die vervaardigingsdatum, tot die rek van die krukas
lei, wat 'n verdere vervorming van die krukas veroorsaak.
Dit sal gesien word in 'n verhoging van die laer slag.
Omdat die krukas nie na verharding reggemaak kan word nie,
sal die krukas onbruikbaar wees. Die proses moet derhalwe
in so 'n mate ontwikkel word dat alle veranderlikes wat
spanningsinduksie kan veroorsaak, nie deel van die proses
mag wees nie.

In hierdie verhandeling word alle veranderlikes wat
spanningsinduksie kan veroorsaak, vanaf die smeeproses tot
by verharding en slyp van die laers, ondersoek. Verder
word die metodes waarop die krukas getoets word, bespreek,
omdat dit uiteindelik bepaal of die prosesontwikkelingsfase
doeltreffend was of nie. Dit word gedoen deur die teorie
met die praktyk te vergelyk. In baie gevalle word
empiriese afleidings gemaak ten einde bevredigende
resultate te verkry.

Die doel van hierdie verhandeling is om 'n universele
metodologie van prosesontwikkeling te demonstreer.
Alhoewel die ADE 366 krukas gebruik is om hierdie proses te
ontwikkel, kan die teorie en metode van prosesontwikkeling
op enige ander tipe dieselenjin-krukas toegepas word.

Soos in hierdie verhandeling aangetoon, is 'n bruikbare
proses vir die radiusverharding van dieselenjin-krukaslaers
ontwikkel. Die eindresultaat is 'n vervaardigingsproses
waar krukasse geproduseer word wat in enjines met hoër
kraglewering gebruik kan word.

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CHAPTER 1

PROBLEM AND OBJECT FORMULATION

1.1   Introduction

1.1.1   Factors Initiating the Study

It is a common phenomenon in any engineering field
to continuously strive for component improvement.
The reasons for this are manifold, but a very common
reason is commercial pressure from competitors.
Diesel engines used in commercial vehicles are a
good example of an engineering product being prone
to such factors. Typically, power rating is one of
the crucial areas where any competitor would like to
have the competitive edge. Increasing the power
output of a Diesel engine is fairly simple to
achieve, but often the mechanical elements of the
engine have not been designed to support such
increase in loading. One of these components is the
crankshaft, which is one of the most highly loaded
members of a Diesel engine. Failure from higher
loading will not happen instantly, but will occur as
a result of fatigue after a certain period of time.
Fatigue failure in a crankshaft occurs primarily in
the region of the radii blending the journals of the
pin and main journals into the collar faces.

1.1.2   Problem Definition

The problem can be stated as follows:

What can be done to improve the fatigue resistance

of the crankshaft in the region of the radii when
the loading of the pin journals from the pistons is
increased ?

1.1.3   Problem Analysis

Conventionally the bearing surfaces of high power
Diesel engine crankshafts are induction hardened
only on the running surface of both the main and pin
journals (see fig 1.1).
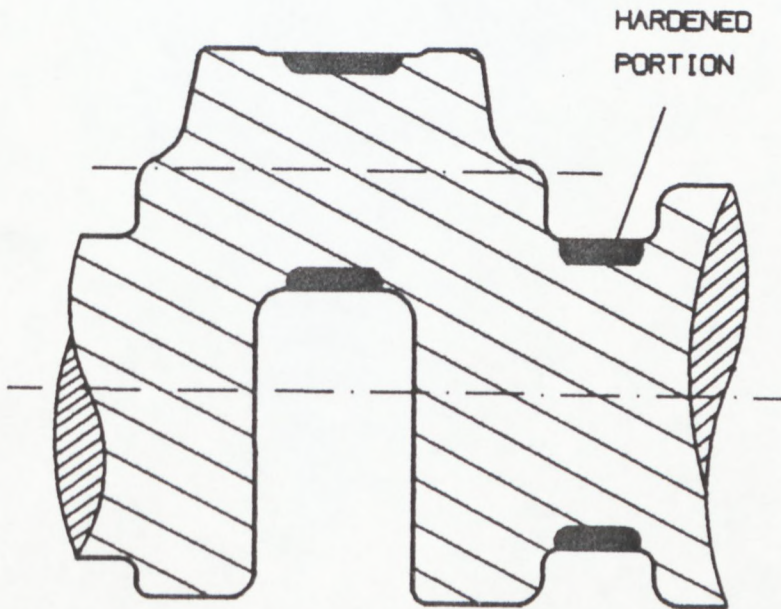
Fig.1.1- Section through conventionally hardened
        main and pin crankshaft journals. The
        black areas indicate the hardened portion.

The need for having to increase engine power even
further, leave the designer with three choices:

(i)   To physically strengthen the crankshafts by
       changing the actual shape of the forging, for

instance by designing a new forging.

(ii) To use a higher grade steel capable of higher
      loading, without changing the physical shape
      of the crankshaft. This is not always
      possible, since the toughest steel available
      might already be in use on the existing
      design. It might also be possible that the
      use of a different steel could increase the
      price to such an extent that cost will become
      the governing factor.
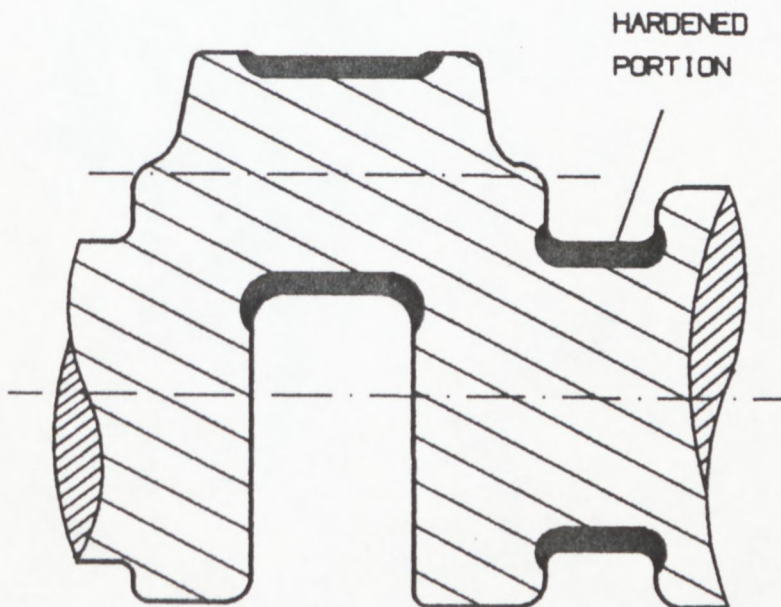
Fig.1.2- Section through radius hardened main and
         pin crankshaft journals. The black areas
         indicate the hardened portion.

(iii) To change the physical properties in the
      radius such that the fatigue characteristics
      are improved. This could be achieved by not
      only hardening the bearing surface, but also
      by hardening the radii of the side faces (see
      fig. 1.2 above).

As a result of this the crankshaft can withstand higher stresses without premature failure. This means that the same infinite fatigue life can be obtained with higher loading.

The complexity of radius hardening lies mainly in developing a manufacturing process, which is suitable for commercial implementation.

1.1.4 Aims and Objectives

1.1.4.1 Aim

The aim of this dissertation is to obtain a methodology of approach when developing a process for radius hardening. Even though one particular crankshaft type (ADE 366, 6 cylinder) is used as the basis for research, the results, conclusions and recommendations arrived at, should be universally applicable for any other type of crankshaft which requires to be radius hardened.

1.1.4.2 Objectives

The main objectives for the purpose of this project are stated below:

(i)   Research into the reasons why radius hardening of crankshaft journals improves fatigue life, permits higher stresses and thus the application of higher forces on pin journals.

(ii) Investigation into the most suitable types of steel for the radius hardening process.

Emphasis here will be directed on cost, machinability and fatigue resistance.

(iii) The development of a suitable manufacturing process taking into account variances to the conventional process of non-radius hardening. Such variances include:

- The inability to straighten shafts after hardening as cracks will occur in the radii. Runout (cf. 1.4.1.1) of the journals must therefore be controlled differently.

- As a result of hardening in the radii, it is expected that more severe deformation after hardening will occur. This could result in either shrinkage or elongation of the shaft. The method of compensating for this will have to be determined.

- Investigations into the most suitable induction hardening method and process. Types of inductors to be used, hardening sequence, quenching medium, quenching temperature, settings.

- Method of stroke control of crankshaft pin journal. It is expected that radius hardening induces residual stresses, which are mostly released during the final machining (grinding) stages. These will have a tendency to distort the pin journals relative to the main journals.

- Methods of hardness checking.

(iv) Long term durability testing of crankshaft. This consists of various fatigue testing methods available, such as testing of a component in an engine, or loading the crankshaft in a fatigue test rig.

1.1.5 Comprehension and Elucidation

Fatigue is termed as the progressive localised structural change that occurs in a material subjected to repeated or fluctuating strains at stresses having a maximum value much smaller than the tensile strength of the material (A.S.M.-Vol.10, 1975:95). Fatigue may culminate in cracks or fracture after a sufficient number of fluctuations or cycles. Fatigue fractures are caused by simultaneous action of cyclic stress, tensile stress and plastic strain. If any one of these three is not present fatigue cracking will not initiate and propagate. The cyclic stress starts the crack and the tensile stress produces crack growth (propagation).

Although compressive stress will not cause fatigue, compressive loads as exist in a crankshaft, may do so.

The process of fatigue may be considered as consisting of three stages:

(i) Initial fatigue damage leading to crack initiation
(ii) Crack propagation until the remaining uncracked cross section of a part becomes too weak to carry the loads

(iii) Final sudden fracture of the remaining cross
      section.

One of the areas where fatigue will occur first is
the radii of the crankshaft pin and main journals
since this is the region through which all the load
is transmitted (Dubbel Vol.1, 1974:800). In a
fatigue fracture localised plastic deformation is
responsible for crack formation. (A.S.M.-Vol.10,
1975:110). The microstructure of the material can
influence this crack growth by inhibiting or
modifying the plastic deformation process.
Sometimes the nature of the cracking process is
changed from ductile to brittle. Transition of the
cracking process from one involving plastic
deformation to another one involving coming apart,
is largely determined by the microstructure of the
material.

Since a Diesel engine crankshaft should be designed
for high cycle fatigue, the grain size of the
material plays an important role. Low cyclic strain
in other words high cycle fatigue, favours metals
with reduced grain size.

Heat treatment used to increase tensile strength,
generally increases fatigue strength (A.S.M.-Vol.10,
1975:111; Dieter, 1981:442-446; Bargel/Schulze
1988:382). This is one of the reasons why
crankshaft steels are normally hardened and tempered
after the forging process. In steels a tempered or
stress relieved martensitic structure has the best
fatigue properties. The lower fatigue resistance of
mixed structures is generally the result of
metallurgical notches which are typically formed in

structures containing coarse pearlite, free ferrite, retained austenite and carbide segregation. Hardening of the radius therefore will increase fatigue resistance in the critical region, since the hardened radius will consist of a fine grained martensitic structure.

1.1.6 Structure

1.1.6.1 Work Plan

Based on theoretical considerations and investigations the development of the process was instituted. The process development took all stages into consideration, from the raw stage of the crankshaft, right along all relevant machining operations up to the completed product. Verification of the process was carried out through component testing.

1.1.6.2 Framework

The framework of this research project consists of five chapters.

In Chapter 1 the Problem Definition and Object Formulation is stated. Here an overview of aims and objectives is given, as well as an analysis of the problem and the approach to it.

Chapter 2 encompasses a study of relevant literature in order to present a theoretical and more detailed background to the problem and its solutions.

The actual carrying out of the investigation is done

in Chapter 3. Methods of investigation are discussed and how they are performed and analysed.

Results obtained during the investigation are discussed in Chapter 4.

In Chapter 5 a synthesis of the relevant facts is presented, together with conclusions and recommendations.

1.2 Crankshaft Radius Hardening

1.2.1 Fatigue Failures in Crankshafts

There are various causes for fatigue failure in crankshafts. Design related as well as metallurgical problems are the prevalent factors. Fractures which occur on a crankshaft of a Diesel engine are almost always of the low range/high cycle type, which are brought about by millions of cycles of stress variation at a comparatively low level of stress, which is near the fatigue limit for the type of stress fluctuation in question, and with a maximum stress below half the tensile strength of the material. Since fatigue failures occur at one critical spot, the problem of stress elimination consists of finding the critical point and calculating the variation of stress at this point, taking into account any stress concentration there may be due to the local geometrical shape of the crank (Purday, 1962:Chapter 7).

One of these areas is the fillet or radius of a crankpin (Purday, 1962:147). For the purpose of this research project only this form of fatigue failure

is being considered. Torsional vibrations may cause this failure to occur. As the whole shaft system has elasticity and locally concentrated inertias it will have a certain number of torsional vibration frequencies (Lilly, 1986:8/3). Depending on these frequencies, it is possible for certain harmonic orders to apply their torques in phase with the natural frequency of the shaft at certain speeds. When this occurs the amplitude of resonance can build up on resonance to many times those due to the slow application of the same torques. This phenomenon is known as torsional vibration, which in severe cases, can lead to shaft failure as the result of torsional stress fatigue. Since the region on the underside of the crankpin, where the radius joins a crankweb, is common to the crankpin as well as the crankweb stresses have to be taken into account together (Purday, 1962:156).

1.2.2   Why Harden Crankshaft Journals?

In industrial Diesel Engines high loads are subjected onto journal surfaces, which if not hardened will cause plastic deformation as well as fatigue during early stages of the component life.

Hardening a journal brings the benefit that higher journal loading can be achieved without any plastic deformation (ductility of metal reduced), as well as greatly improving torsional and bending fatigue strength (Shigley, 1986:141).

1.2.3   The Benefit of Radius Hardening

From the above discussion it becomes apparent that the fillet or radius of a crankshaft is a critical

design feature when analysing component failure. The incorporation of a martensitic zone, which has a fine crystalline structure, in the radius is beneficial to the fatigue life of the crankshaft, by altering the characteristics of crack propagation.

If the load on a crank is increased the same fatigue life can be obtained without changing the external design of the crank. Only the process of hardening the journals has to be modified.

Research performed for the purpose of this dissertation deals with the development of such a process and the resulting changes when compared to a regular hardening process.

1.2.4 Types of Hardening Methods

Journal surfaces can be hardened by different methods. There are two distinct different principles available. Those involving phase transformation of a steel, by change in crystalline structure to a martensitic form, or those where the general structure of the core material is unimpaired, because this causes a change in the boundary layer of the material by means of fusion with other materials.

Hardening methods used to fulfill the above mentioned requirements are inter alia nitriding and induction hardening.

In terms of general fatigue life improvement, nitriding provides an acceptable all round solution, which is cheap to implement. When taking into

account that loads on crankshafts are forever increasing in order to achieve a better engine power to mass ratio, this solution no longer seems to be the most acceptable. As loads increase mean effective pressures per cylinder increase, thus imparting more load onto the crank. Nitriding is not suitable when impact loads, or loads which are moving towards impact type nature, are being applied (Thelnig, 1975:377-389; Bargel/Schulze, 1988:181). Assuming that the crankshaft is intended for heavy industrial Diesel application, nitriding no longer represent a viable manufacturing proposition when intending to obtain a similar fatigue life as on a lower stressed crankshaft.

In addition it is standard practice in the heavy industrial Diesel engine market that crankshaft journals have re-grind stages to smaller diameters incorporated. This is mainly in order to save cost as a worn crank can be re-ground to a smaller diameter, instead of having to be replaced. A shaft which has been hardened through nitriding cannot be re-ground, since it only has a hardened layer of approximately 0,02 mm thick. Induction hardened shafts on the other hand have hardened zones in the region of 2-6mm thick.

Induction hardening on both journal diameters and radii appearsto be the obvious choice when aiming at the heavy industrial Diesel crankshaft application.

1.3   Steel Selection

Modern technology has developed at such a pace that the designer has an abundance of different steels

which he can select for a particular application. In this particular case of radius-hardening the following basic considerations should be looked at:

(i)   The steel has to be hardenable (i.e. medium to high carbon).
(ii)   The steel must have a high tensile strength, which means that the total crankshaft is normally hardened and tempered, in addition to subsequently hardening the journals.
(iii) The cost of the steel.
(iv)   The machinability of steel.
(v)   The expansion and or contraction of steel during hardening.

When analysing the above requirements, research will have to be performed in particular on alloy steels, since alloying elements will have particular influences on certain aspects required in the manufacturing process. This will be discussed in more detail in Chapter 2.

1.4   Manufacturing Process

A manufacturing process is the actual trial-ground, where all theoretical aspirations have to be transformed into reality. From the theory and possible previous experience gained a basis for a new manufacturing process has to be established. Any new process has to be confirmed by means of trials. Any trial results will have to display such a pattern, that it can be believed that they are of a representative nature. It is therefore important that sufficient confidence exists in the trial results before a permanent process can be drawn up.

Any misinterpretations could be a costly mistake when taking into account that a revised process has to be developed and implemented.

In developing the manufacturing process particular emphasis will be placed on the areas discussed in the following subsections.

1.4.1   Hardening Process

In many instances there are no hard and fast formulas for defining the hardening process, instead data has to be collated in order to establish the hardening process most suitable for a particular need and circumstance.

1.4.1.1 Runout Control

Runout of a crankshaft is defined as follows:

- Runout is the deviation from a straight line through the centre of the shaft. It is easily measured on a journal by applying a dial indicator clock onto a journal and rotating it around its own centre (shaft supported between two centres). The range of the reading obtained (difference between maximum and minimum reading) is defined as the runout. Runout of a crankshaft mostly follows a bow like shape, where the highest runout is normally found on the centre journal of the shaft.

A too high runout after hardening, will induce stresses which will not be fully released during the grinding process (Dieter, 1981:430). Residual

stresses arise when plastic deformation is not uniform throughout the entire cross section of the part being deformed. Runout of a shaft which was straight prior to hardening, confirms that plastic deformation has taken place.

1.4.1.2 Hardening Sequence and Support of Shaft

On multiple inductor machines hardening is mostly completed in one single operation, or at the most in two operations. For instance pin and main journals can be hardened separately in one go. For the purpose of this investigation, a single inductor (universal type) hardening machine was available, so that all conclusions and recommendations drawn will be restricted to this type of machine.

Multiple inductor machines are more suitable since deformation of the shaft can be better controlled through a more uniform heating throughout the shaft, but such machines are extremely costly (± R 6 million) and are normally used only in high volume production set ups.

On single inductor machines the problem of deformation of the shaft could also be overcome by the use of supports or steadies, which have to be manually placed in position as determined during the process development phase.

1.4.1.3 Quenching Temperature

Quenching temperature could have an influence on the way the shaft deforms. Cooling curves of the quenchant will have to be analysed in order to

ensure that minor variations in quenching
temperature will not induce deformation of the shaft
(A.S.M.-Vol.4 , 1981:32).

1.4.1.4 Hardness Pattern

Hardness patterns are prescribed by the design of
the crankshaft. It is important to be able to
analyse the hardness pattern correctly. For the
purpose of this, suitable laboratory equipment such
as Vickers or Rockwell hardness testers are
required. Sectioning equipment is also needed in
order to take samples of the hardened portions of
the crankshaft journals. The sections are etched in
a suitable solution (such as Nital) which will
highlight the hardened portion.

As with all such processes hardening depths will be
subjected to a manufacturing tolerance. Since
hardening causes deformation of the shaft, it will
have to be established whether it is sensible to
make full use of the tolerance (which can be up to
1,5 mm big), or restrict this to an in-process
dimension which will yield more acceptable results.

1.4.1.5 Shrinkage of Shaft Whilst Hardening Radii

The crankshaft displays a shrinkage in length
direction after hardening. The reason for this can
be attributed to the fact that the radii of the
crank journals, once hardened, are transformed from
a coarse grain structure consisting of ferrite and
pearlite, to a fine martensitic structure. The
change to a finer structure causes the material to

shrink around the collar faces of the crankshaft journals. This induces a hoop stress around the journals as well as causing the crank to shrink in overall length after hardening (Thelnig, 1975:169-175).

The stress induced causes the crank to buckle and twist. The shrinkage in length causes problems when trying to establish exact journal length positions and collar face depths. This cannot be ignored should the shrinkage be larger than the tolerance of the journal length positions. Typical tolerances on the length of journals are in the region of 0,1 - 0,2 mm. If the shrinkage amount is ignored, it will affect the position of oil holes, the position of which is often critical for correct lubrication of bearing shells. The other effect is that journal collar faces will be ground unevenly, resulting in possible non-clean up on one side, and grinding into the web of the crank at the other end.

When establishing a process for radius hardening the amount of shrinkage which occurs after hardening must be known, since this must be added as additional length in the soft machining stage. The amount of shrinkage is also dependant on the depth of the hardened radius. Before establishing the shrinkage amount it is therefore imperative that the hardening process and parameters have been finalised.

1.4.2   Machining

As during the hardening process it is desirable not to induce any residual stresses in the soft

(unhardened) machining stage; (cf. 1.4.1.1 for definition).

As discussed under 1.4.1.1, runout on the main journals has to be limited to certain values in order to prevent undesirable problems such as non clean up on journals after grinding and residual stresses released during grinding which result in possible creep of the component (Dieter, 1981:297). The only method to overcome this is by ensuring that the machining process in the "soft" stage is such that very little stresses are induced into the shaft and that runout before hardening is kept to a minimum.

1.4.2.1 Elimination of Stress (Soft Stage)

Stresses can only be eliminated if they are not induced into the component in the first stage. When looking at a typical "soft" machining process, there are certain machining operations which induce higher

TYPICAL SOFT STAGE MACHINING PROCESS FOR THE MANUFACTURE OF CRANKSHAFTS		
	MACHINING OPERATION	STRESS LEVEL
1.	End milling (length of crankshaft)	low
2.	Centering of crankshaft	low
3.	Milling of main journals	very high
4.	Straightening of shaft through press	very high
5.	Fine turning of journals	low
6.	Milling of pin journals	very high
7.	Straightening of shaft through press	very high
8.	Milling of counterweight mounting face	medium
9.	Drilling and tapping of c/wt. bolt holes	low
10.	Gun-drilling of oilways in crankshaft	low

Table 1.1- Material stress levels for typical soft stage crankshaft machining operations. Stress level established from journal runout after machining - Source ADE.

stresses than others. Table 1.1 presents a listing
of conventional sequential machining operations and
the extent of the machining stress level.

From the above table it can be noted that there are
some operations which can induce high stresses into
the component. As a result of this one of the aims
in developing the process is to try and eliminate
the straightening process which follows after main
and pin-milling. This is achievable through
optimization of machining feeds of the milling
operations, as well as establishing tool change
frequencies which ensure that the runouts remain
within the prescribed process parameters.

1.4.2.2   Elimination of Stress (Hard Stage)

Non-radius hardened shafts are normally ground to
the finished dimension in one stage. The journals
are not pre-ground after hardening, but finish
ground straight away.

During the process development stage (refer section
3.4) it was found that problems were experienced in
holding the stroke tolerance of the pin journals
(in the case of the ADE 366 crankshaft ± 0,05 mm).
This normally arose once the pin journals were being
ground. The main journal was used for the location
from which the offset for the stroke was taken
from. Upon measurement of the stroke after grinding
it was found that the runout was excessively high
(out of tolerance) as well as the strokes being out
of specification. Very often this was accompanied
by a non clean up on the pin journal collar faces of

the crankshaft.

The reason for these phenomena is again the release of stresses from the radii of the journals. The release of stresses allows the shaft to buckle or warp resulting in a widening between sections of the webs on each side of the pin journal. As a result of this it is no longer possible to control the stroke tolerance. The problem with the non clean up of the collar faces could be solved by adding additional grinding stock in the pin journal milling operation, but this has distinct disadvantages. One of them is an increase of cycle time on the grinder, as well as increased wear on the grinding wheels. Since grinding wheels are very costly this factor has to be taken into account.

In the case of non radius hardened journals no stresses from hardening are released which explains why no problems of this nature were experienced. In addition the non-radius hardened shaft may still be straightened after grinding if necessary (although this is also undesirable since shafts could also creep while being stored).

1.5   Component Testing

The success of any improvements made to any machining process, which affects the life expectancy or durability of a component, is generally proven through extensive component testing.

In the case of a crankshaft which has been radius hardened, two type of tests would have to be

performed in order to validate the gain in durability and strength. These tests consist of an engine durability run at varied load cycles, as well as a fatigue test (destructive test) on the crankshaft pin journals in order to prove the retention or increase in fatigue life at higher loads.

Both tests are highly cost intensive requiring specialist equipment and personnel. These test are deemed necessary though in order to prove beyond reasonable doubt that the crankshaft will not fail at higher loads. Bearing in mind that crankshaft failure can cause serious and costly damage to an engine, with the added risk of human injury, such expense is unquestionably justifiable.

In the case of this dissertation only the engine durability test could be performed. Because of a lack of facilities for fatigue testing, by means of applying reoccurring bending moments across the web between the pin and main journals, this could only be completed at an overseas company. Nevertheless the theoretical aspects of fatigue testing will be discussed in-depth in section 2.5.

* * *

CHAPTER 2

LITERATURE STUDY

2.1 Introduction

The problem of Radius Hardening has its firm roots in the metallurgical sphere. It is therefore important to understand the theoretical metallurgical background in order to be able to translate this into a working manufacturing process. It is for this purpose that all aspects relating directly and indirectly to the manufacturing process are researched in order to provide a better understanding of the interrelation between manufacturing and theory.

There is a variety of literary material available covering a range of metallurgical topics. Radius Hardening, as a specific topic is not discussed, but the necessary deductions can be made by combining various aspects of literary information together.

2.2 Crankshaft Radius Hardening

2.2.1 Material Fatigue in a Crankshaft

Machine component failures are in 90% of all cases due to fatigue (Thelnig, 1975:58). By fatigue is meant crack formation caused by fluctuating loads, where the maximum stress being applied is always less than the ultimate tensile strength of the material. The blend from the journal to the collar

face of a crankshaft is normally executed in the
form of a radius. This radius is critical when
considering the fatigue life cycle of the crankshaft
(Purday, 1962:156; Dubbel Vol.1, 1974:800). Fig.
2.1 below illustrates a section through the web,
main and pin journals of a crankshaft. The region
where failure will occur is indicated.

REGION OF
FATIQUE
CRACKING
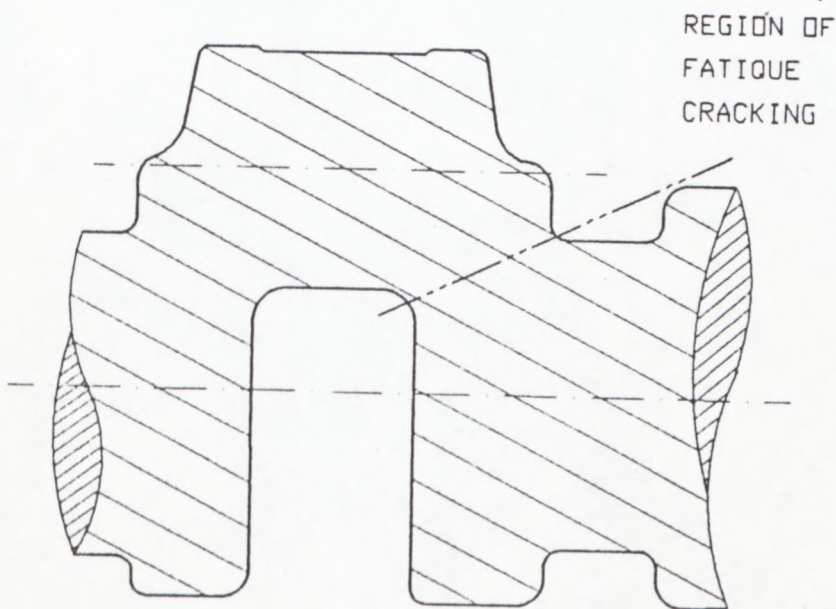
Fig.2.1- Section through main and pin crankshaft
journals, showing region of fatigue
which will commence with cracking
(Purday, 1962:156).

For the purpose of this research project only this
form of fatigue failure in a crankshaft is being
considered. Torsional vibrations can also cause
this failure to occur (Lilly, 1986:8/3-9). Since
the region on the underside of the crankpin, where
the fillet or radius joins a crankweb, is common to
the crankpin and the web, the crankpin as well as
crankweb stresses have to be taken into account
together. It is therefore important to understand
the mechanisms which cause fatigue.

2.2.2 Prediction of Fatigue Life

Fatigue life can be expected to depend on the following (A.S.M.-Vol.10, 1977:95) :

(i)   Type of loading (Uniaxial, bending, torsional)

(ii)   Shape of loading curve

(iii) Frequency of load cycling

(iv)   Load pattern (periodic loading at constant or variable amplitude, programmed loading or random loading)

(v)   Magnitude of stresses

(vi)   Physical size of component

(vii) Fabrication method and surface roughness

(viii) Operating temperature

(ix)   Operating atmosphere.

For the purpose of this dissertation only aspects (ii) and (v) will be considered, based on the assumption that all other influences remain unchanged with an increase in loading. This is not strictly correct since the frequency of load cycling could change with an increase or decrease in engine revolutions. This is linked to a higher power (in the case of the ADE engine revolutions were decreased from 2800 r/min to 2600 r/min) as well as an increase in operating oil temperature due to the higher power output. Both factors are considered negligible since,

(i)   there is a reduction in engine revolutions and

(ii)   oil temperature is limited to 120°C.

Referring to fig. 2.1 one type of failure from

material fatigue will occur in the region indicated
(A.S.M.-Vol.10,1977:97). By hardening the radius as
shown in fig. 1.2 it is intended to change the
fatigue characteristics in that region.
Traditionally fatigue life has been expressed as the
total number of stress cycles for a fatigue crack to
be initiated and then to grow large enough to
produce catastrophic failure by separation of the
specimen involved into two pieces (A.S.M.-Vol.10,
1977:95). Fatigue life can thus be expressed in
terms of total life or in terms of crack growth
rate. It was more recently discovered that cracks
develop early in the fatigue life of the material
and grow continuously until catastrophic failure
occurs. This has also led to the use of crack
growth rates for the prediction of fatigue life.

To determine the strength of materials under actions
of fatigue loads, specimens are subjected to
repeating or varying forces of specified magnitudes,
whilst the cycles or stress reversals are counted to
destruction. The results of this are plotted on an
S-N diagram (also called Wöhler diagram) as
depicted in fig. 2.2 (Shigley, 1986:227-234). In
the case of ferrous metals and alloys the graph
becomes horizontal after the material has been
stressed for a certain number of cycles. The
ordinate of the S-N diagram is called the fatigue
strength S_f; a statement of this strength must
always be accompanied by a statement of the Number
of cycles N to which it corresponds. In the case of
steels a knee occurs in the graph and beyond this
knee, failure will not occur, no matter how great
the number of cycles. The strength corresponding to
the knee is called the endurance limit S_e or the

fatigue limit. Fatigue failure in the region of 0,5 ≤ N ≤ 1000 is classified as low cycle fatigue. High cycle fatigue is for values of N ≥ 1000. A finite life and infinite life region also exists. The boundary between these two regions cannot be clearly defined except for a specific material, but it lies somewhere between 10^6 and 10^7 cycles for steels, as shown in fig. 1.3. In designing critical components such as crankshafts, where failure can cause danger to life, the designer always works on the assumption that infinite life occurs after 10^7 number of cycles.
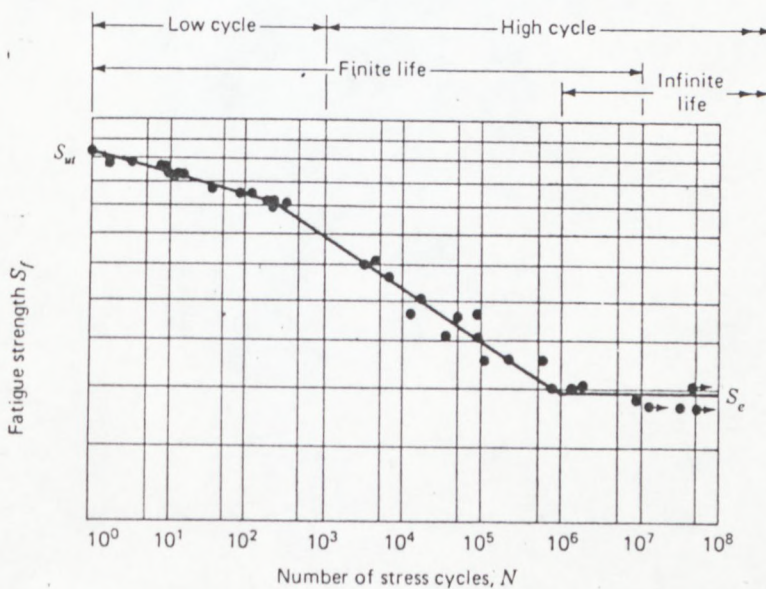
Fig.2.2- An S-N diagram plotted from the results of completely reversed axial fatigue tests, using CrMo steel which has been normalised; (Shigley, 1986:230)

2.2.3   Designing for Fatigue Life

In order to analyse fatigue failures, graphs are available which give the designer the possibility of

geometrically laying out his shaft in such a manner
that it will meet the required criteria. The
following abbreviations are used in the graphs and a
brief explanation of each follows (Purday,
1962:146):

(i)   FSRF (or K_f) = Fatigue Strength Reduction
      Factor. This is the factor by which the
      fatigue strength is reduced by a stress
      raising feature such as a fillet radius, as
      compared with the the fatigue strength of a
      specimen of the same basic shape and size,
      without a stress raiser.

(ii) SCF (or K_t) = Stress Concentration Factor,
      the factor by which the maximum value of the
      relevant stress criterion at the stress
      raising feature exceeds that in the above
      specimen in which the stress raiser is absent.

Fig. 2.3 shows theoretical data on the Stress
Concentration Factor (SCF, or K_t as designated in
fig. 2.4) of a stepped shaft in torsion and bending
with various ratios of step and various ratios of
fillet ratios to the smaller shaft diameter. For a
ratio of D/d = 2 and r/d = 0.06 (which is a very
usual ratio for crankshaft fillet radii, and also
the ratio used on the ADE 366 crankshaft), the SCF
is about 1.6 for torsion and 1.8 for bending. These
values must be compared with those obtained from the
graph shown in fig.2.4, which shows the Fatigue
Strength Reduction Factor for fillet radii on a
shaft made out of mild steel.

The value of the two graphs which reduces the stress
the most is the critical value which has to be used

by the designer. The characteristics of graphs are dependant on the type of material used.

FILLETS : TORSION, $D/d = 2$.
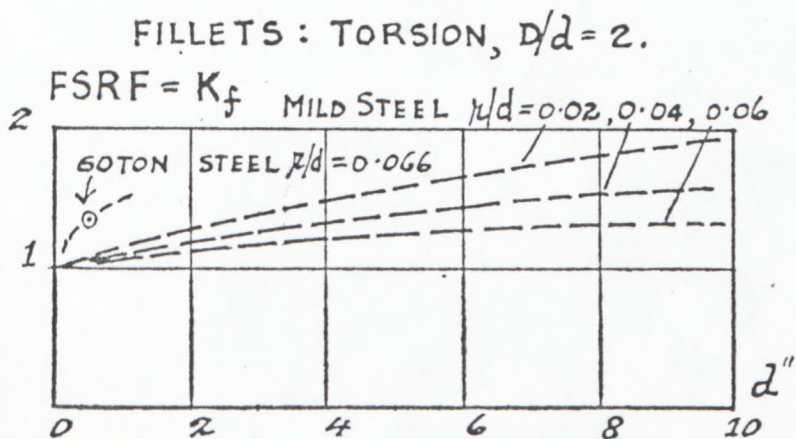
Fig.2.3- Fatigue strength reduction factors (for steel) for fillets in stepped shafts subject to torsion. (Purday, 1962:158)
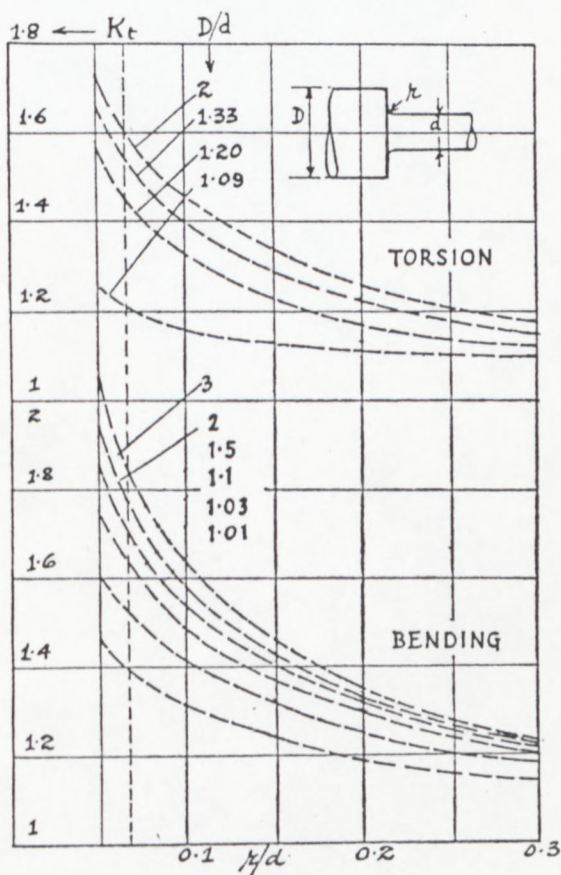
Fig.2.4- Stress concentration factors (for steel) for fillets in stepped shafts subject to torsion and bending (Purday, 1962:157)

2.2.4   Improvement of Fatigue Life

For a given material the increase of stress may cause it to change from an infinite to a finite life cycle (cf. 2.2.2. & 2.2.3). Once this situation has been reached there are two basic options left to the designer:

(i)   Use an alternative material (steel)
(ii) Modify the material fatigue strength in the radius by use of hardening techniques.

In the instance where an existing hardening plant is in operation, the use of an alternative steel may often be more costly in the long run (depending on manufacturing volume), as opposed to modifying inductors to accommodate the hardening of the radius. In actual fact hardening the radius might result in the use of a lower grade steel which is cheaper than the current steel being used (refer also to section 2.3).

The incorporation of a martensitic zone,.which has a fine crystalline structure in the radius is beneficial to the fatigue life of the crankshaft, since the characteristic of crack propagation is altered (A.S.M.-Vol.10, 1975:111). Fatigue strength generally is increased by any heat treatment that increases tensile strength. Mixed structures, which are non-martensitic in this instance, show lower fatigue resistance which is the result of metallurgical notches such as formed by coarse pearlite, free ferrite, retained austenite and carbide segregation.

The following subsections serve to provide a background of basic metallurgical processes which are relevant to radius hardening.

2.2.4.1 Behavioural Characteristics of Steel Upon Heating

In fig. 2.5 the heat treatment ranges of steel are
shown.
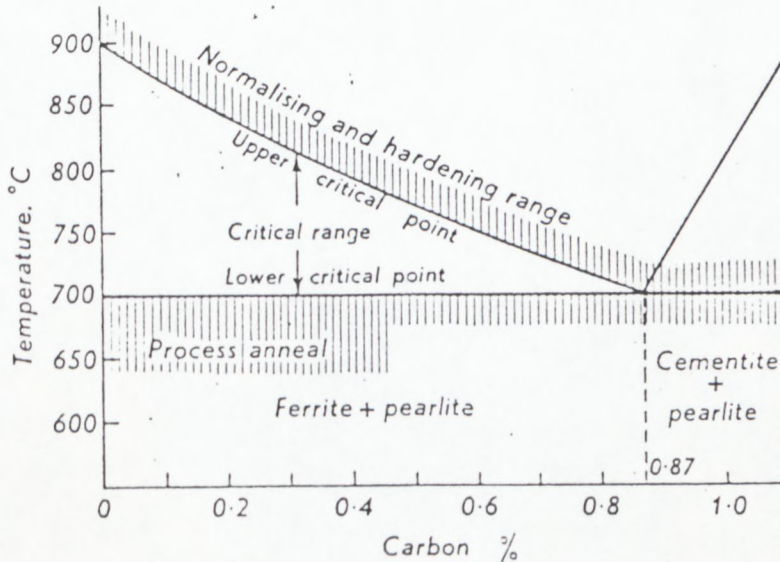
Fig.2.5- Heat treatment ranges of steel.
       (Chapman,1972-part 1:37)

When a steel is heated its structure remains stable
up to a temperature of 333°C (Bargel/ Schulze,
1988,137-142).   Beyond this point the carbon in the
pearlite commences to dissolve in the iron. This
change of state continues until the whole structure
of the metal consists of a solid solution of carbon
in iron which is called austenite. On cooling the
reverse takes place, where at 723°C the austenite
changes back to pearlite again. This phenomenon is
very important in the study of steel.   The
temperature points at which the change starts and
ends are called the critical points and the

range including them the critical range. The
temperature at which the change starts (lower
critical point) is the same for all steels and is
about 700°C, but the finishing point of the
transformation (the upper critical point) varies
according to the steel carbon content.
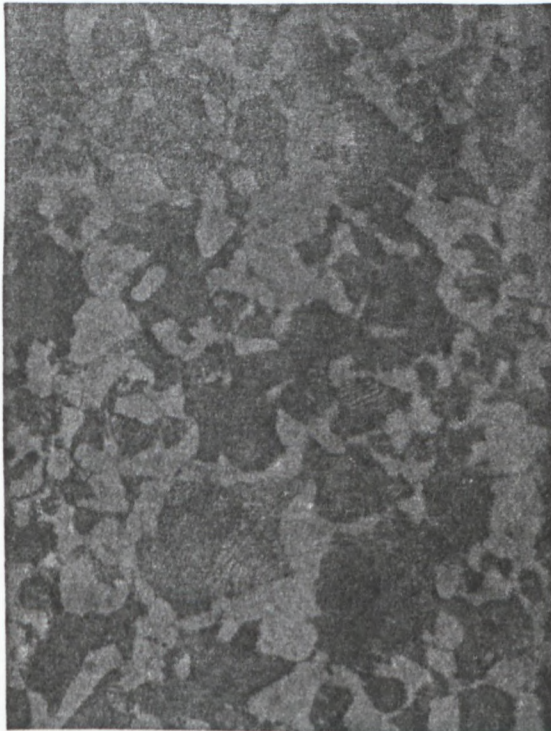
Fig.2.6- Normal structure of ferrite and pearlite
        (Magnification X 500); (ADE laboratory).

In fig. 2.6 and 2.7 the change which occurs to the
microstructure of steel when the carbon goes into
solution is shown. Fig. 2.6 displays the normal
structure of ferrite and pearlite and fig 2.7 shows
the austenite at the end of the change. Austenite
is a solid solution of carbon in iron, and all
ordinary steels above the critical range are in this
condition. Other changes which occur to steel
during the critical range are:

(i)   Austenite is a non-magnetic material so that when it forms the steel loses its magnetic quality.   A change which is useful for establishing the upper point on the critical range.

(ii)   When being heated a considerable contraction occurs at the critical range. When cooling, there is a corresponding instantaneous expansion.

(iii) The metal becomes extremely plastic at this point.
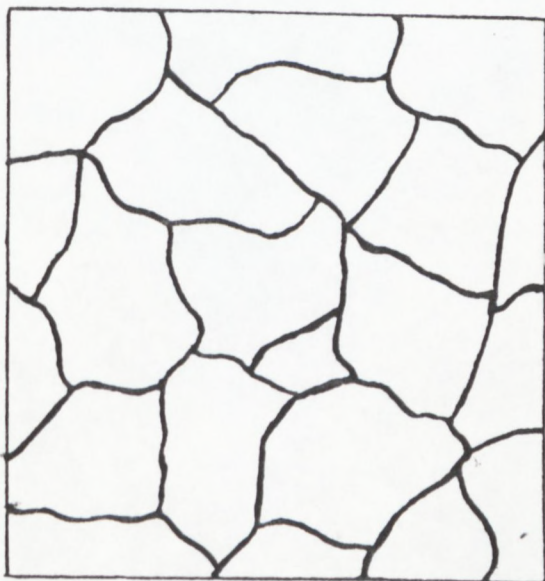
Fig.2.7- Austenitic structure of the steel when carbon has gone into solution (Magnification X 500); (Chapman 1972).

2.2.4.2 Hardening of Steel

As discussed in section 2.2.4.1, the critical range

is in the interval between two temperatures, the lower of which is about 700°, and that when steel cools normally through this range it is transformed from austenite to pearlite plus a free constituent (Bargel/Schulze, 1988:137-142). If by some means the temperature of transformation of austenite can be lowered to 300°C instead of 700° it will not revert back into pearlite, but will instead be transformed into a constituent called martensite. This temperature of transformation can be lowered to say, 300°C by cooling the metal suddenly so that the change does not have time to take place at the normal point, but is forced to occur at a lower temperature. The sudden cooling is usually made to take place by quenching the steel in water or some other liquid. The efficiency with which the quenching occurs determines how much of the austenite is transferred into martensite and determines the hardness of the steel.

Martensite is a very hard substance capable of resisting extreme wear and of cutting other metals. It has a needle-like structure as shown in fig. 2.8. It must be noted that martensite cannot be formed (and the steel hardened) until the steel is in the austenitic condition.

When steel contains less than 0,3% carbon, and this includes all mild steels, the solution of carbon in iron which forms the austenite is naturally a much weaker solution and contains more iron than for the higher carbon steels. When steel of this class is quenched, some of this extra iron is set free in the structure and this, together with the fact that the smaller amount of carbon results in a smaller amount

of martensite, makes it impossible to harden mild
steel. A mild steel will be somewhat harder after
hardening, but it will not be hard in the generally
accepted engineering sense. In table 2.1 quenched
steel (based on 95% martensite) is illustrated.

Carbon %	0,1	0,3	0,5	0,7	0,9	1,2
Vickers Hardness (HV1)	160	480	670	790	810	820

Table 2.1- Hardness of steel in relation to carbon
content (Chapman,1972-part 1:46)
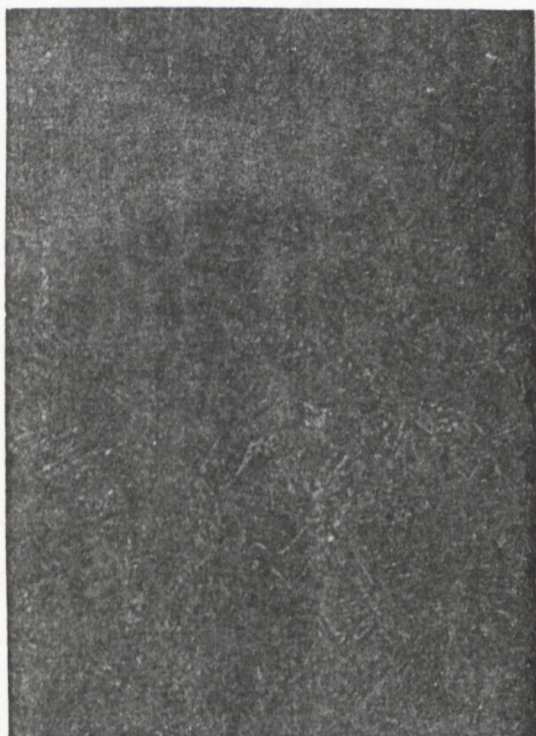
Fig.2.8- Martensitic structure in a hardened steel
(Magnification X 500); (ADE laboratory).

2.2.5   Types of Hardening Methods

Two of the most commonly used hardening methods in the manufacture of crankshafts are nitriding and induction hardening. Although the decision for the purpose of this dissertation is to use the induction hardening approach (cf. Section 1.2.4), it is still worthwhile to present a brief theoretical background on nitriding since lower powered industrial Diesel engines could utilise the nitriding route if an improvement in fatigue strength becomes necessary.

2.2.5.1 Nitriding

The process of nitriding is a ferritic thermochemical treatment and usually involves the introduction of atomic Nitrogen into the ferrite phase in the temperature range of 500-590°C, and consequently no phase transformation occurs on cooling to room temperature. The method was first used in the 1920's and since then its application has continuously spread. Steels which have been tempered are suitable for such treatment (Thelnig, 1975:377-389; Bargel/Schulze, 1988:181).

The properties imparted to steel by nitriding can be summarised as follows:

(i)   Higher surface hardness and wear strength
(ii)   High fatigue strength and low fatigue notch sensitivity
(iii) Improved corrosion resistance for non stainless steels
(iv)   High dimensional stability
(v)   Hardness values of up to 1200 HV are attainable

(vi)   Case depths of up to 0,4mm are achievable

(vii)   Risk of crack formation is highly reduced

(viii) Impact type loading, as typical from connecting rods of Diesel Engines, can cause fracture of the thin hardened layer if loading is too high. In this sense the thickness of the hardened case determines the limit of application.

Three main types of Nitriding processes exist. These are gas nitriding with ammonia, salt bath nitriding and a more recent development of salt bath nitriding called tufftriding. This method was developed by the German company DEGUSSA in the early 1970's.

The depth of case in nitriding is directly determined by time. A case depth of 0,4mm typically takes 1 - 2 hours to achieve.

2.2.5.2 Induction Hardening

Induction hardening consists of heating the workpiece by means of electromagnetic induction using an alternating current (Bargel/Schulze, 1988:178). Electromagnetic induction heats the steel from the inner core outwards. Hardness is obtained by quenching the steel from its austenitic stage.

Typical case depths for such applications are in the region of 1,5 - 6,5mm. To obtain these case depths a frequency range of 1-10 kHz is recommended.

The principal metallurgical advantages that may be obtained by surface hardening with induction include

increased wear resistance and improved fatigue
strength. Other advantages of induction hardening
are:

(i) Short heating up cycle prevents deformation
and crack formation
(ii) Suitable for automation since the process can
be precisely controlled.

The major disadvantage of induction hardening is
that capital equipment required is costly so that it
is only worthwhile for production purposes if high
volumes are obtainable.

2.3   Steel Selection

2.3.1   Constitution of Steel

A steel by definition is a mixture of iron or
ferrite and carbon (Bargel/Schulze, 1988:137-142).
The percentage of carbon in a steel will determine
the type of steel , as well as its properties when
subjected to heat treatment.

Carbon Content (%)	Type of Steel
≤ 0,12	Dead mild
0,12 - 0,25	Mild steel
0,30 - 0,50	Medium carbon steel
0,50 - 0,90	High carbon steel
0,90 - 1,30	Tool steel

Table 2.2- Classification of steel in relation to
carbon content (Chapman,1972-part 1:44)

In table 2.2 different types of steel in relation to carbon content are shown.

The microstructure of pure iron (fig. 2.9) shows clear crystals of ferrite with their grain boundaries. Normal iron is very soft and ductile with an ultimate tensile strength of only 300 MPa.
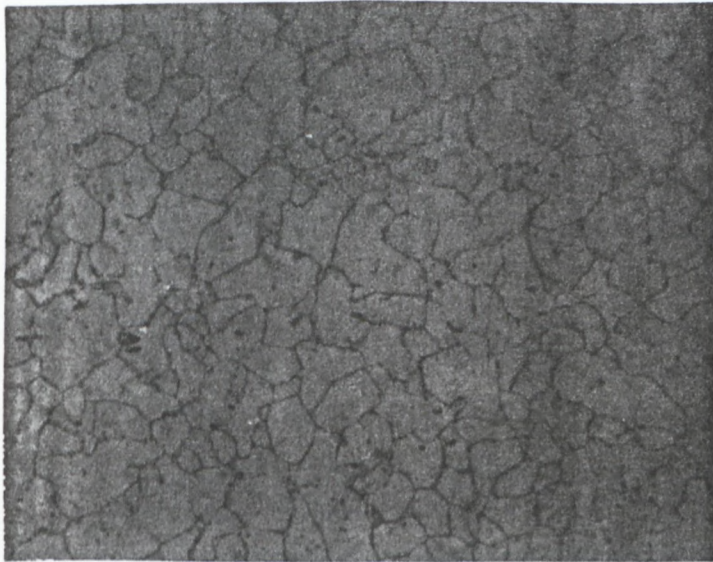
Fig.2.9- Structure of pure iron, showing ferrite crystals. (Magnification X 500); (ADE laboratory).

As soon as carbon is added to iron a change occurs in its structure and properties. Fig.2.10 shows the microstructure of a typical mild steel containing 0,25 - 0,3 % carbon. The white constituent is ferrite, whilst the dark patches represent that part of the structure containing carbon. This dark structure is called pearlite which consists of parts of ferrite and iron carbide (also called cementite). As the carbon content in a steel is

increased the proportion of pearlite is increased. Once it contains 0.87% of Carbon the structure of steel consists entirely of pearlite. If the carbon content is increased even further, there will be some cementite left over and this will appear in the structure as a free constituent in the same way as free ferrite appears in the low carbon steels.
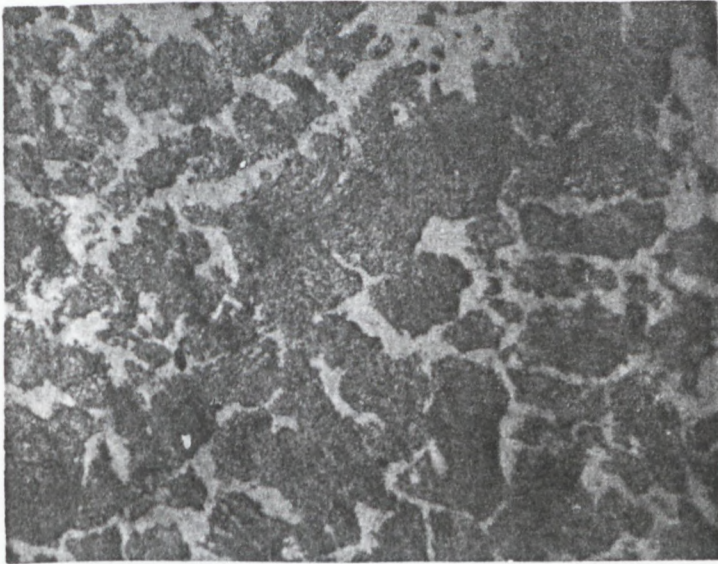
Fig.2.10- Structure of medium carbon steel (0,4 % C) showing ferrite and pearlite. (Magn. X500); (ADE laboratory).

Ferrite on its own is relatively soft while cementite is hard and brittle without much strength. As the carbon (and pearlite) is increased, the steel will become harder and stronger up to the point when it contains 0,9% of carbon. Beyond this point the percentage of cementite increases whereas pearlite decreases so that the hardness of the steel will increase, but its strength will decrease.

This is illustrated in fig. 2.11 where the effect of carbon content on structure, strength, hardness and ductility is shown.
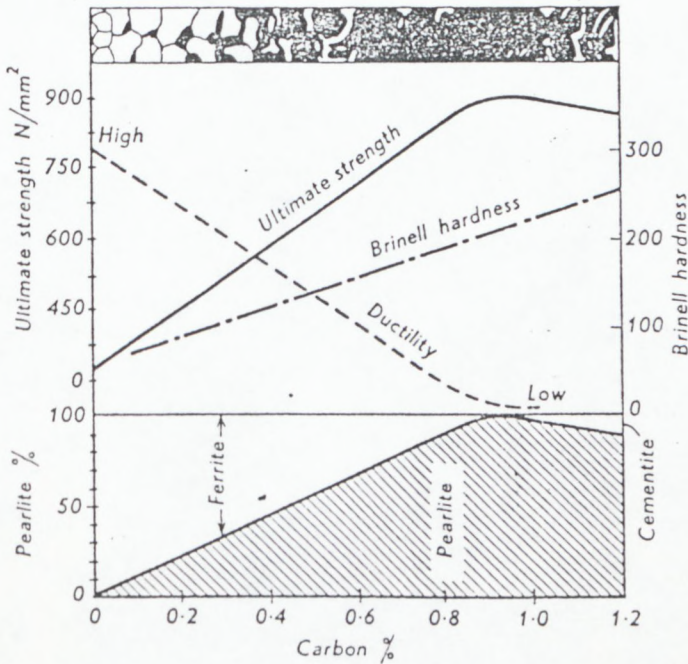
Fig.2.11- Relation between carbon content, structure, strength, hardness and ductility for steel. (Chapmann, 1972 part-1:35)

2.3.2   Alloying of Steel

Apart from iron and carbon, steel can contain a variety of alloying elements (Bargel/Schulze, 1988:182). Because of this the change in characteristic can only be described in a general manner. Exact prognosis on the change is also not possible since the addition of alloying elements in a steel does not have an additive effect.

Alloying elements are added to a steel in exact quantities in order to achieve specific

characteristics, in order to improve, remove unwanted characteristics or allay them.

Alloyed steels are classified into two different categories, such as highly alloyed steels (sum of alloying elements > 5%) and low alloy steels (sum of alloying elements < 5%). Low alloy steels principally have the same characteristics as unalloyed steels, but the technically most important improvement is the considerably improved hardenability. Other improvements of low alloy steels are:

(i)   Improved thermal strength. The addition of Molybdenum to the steel, enables it to retain its strength, even at higher temperatures.

(ii) Improved stress relieving and/or tempering characteristics are achieved as a result of the thermal and chemical properties of Carbides of the alloying elements.

Typical alloying elements are Aluminium, Bismuth, Boron, Chromium, Cobalt, Copper, Lanthanum, Lead, Manganese, Molybdenum, Nickel, Niobium, Selenium, Silicon, Tellurium, Titanium, Tungsten, Vanadium and Zirconium. Whilst all steels will contain some traces of these elements the minimum weight percentage of added elements is laid down before they are classified as alloyed steels (cf. EURO-NORM 20-74).

2.3.3   Tempering of Steels

Because of the high stresses applied onto a Diesel

engine crankshaft, the steel used for the forging is
normally hardened and tempered after the forging
process.   The   reason   for   this   is   that   pure
martensite is generally so hard and brittle that it
cannot   be   used   in   this   form   (Bargel/Schulze,
1988:173). This is overcome by tempering and/or
stress relieving the steel at a temperature below
the critical temperature of the steel. As a result
of this the microstructure of martensite is brought
into a more stable condition.

Depending on the temperature of the heat treatment
various types of temper are achieved. The different
temper levels are briefly described below:

(i)   Temperature 100-200°C:
       Low reduction in hardness. The elimination of
       "glass type hardness" is achieved, which makes
       the steel machinable. Residual stresses from
       the hardening process are also removed, which
       is why tempering at this temperature range
       often also is termed stress relieving.

(ii)   Temperature 200-350°C:
       Ultimate tensile strength and hardness drop
       considerably, yet yield strength remains
       unchanged.   Overall, when compared to
       unhardened steel, tempering at this
       temperature still produces a steel with
       considerably improved strength properties

(iii) Temperature 350°C up to critical temperature:
       Ultimate tensile strength and hardness further
       reduced, yet fatigue resistance improved as a
       result of higher notch toughness. Most temper

steels in this category are heated to a temperature between 550°C and 650°C. From a design point of view an important combination of characteristics is achieved. A still acceptable yield limit combined with an astonishingly high notch toughness.

2.3.3.1 Selection of Temper Steels

Temper steels, in general, have a carbon content of between 0,2% - 0,65%. Generally temper steels are tempered at fairly high temperatures (≥ 500°C). They have high strength combined with good toughness characteristics, depending on their chemical composition. Toughness in a steel is the way the material reacts to stress concentrations such as sharp cracks (Dieter, 1981:275). Temper steels are usually used for dynamically loaded components which require high strength, such as Diesel engine crankshafts.

Because of the required purity and small tolerances of the alloy element addition, temper steels are also known as Quality Steels. Temper steels can be used in environments where temperatures of up to 350°C are experienced. Guidelines for the selection of the application of temper steels are given by various standards associations such as ISO, DIN, BS, ASM etc. Noticeable are the multitude of recommended steels for which there are various technical as well as economical reasons.

Steels which have been alloyed with chromium generally have a high degree of toughness. The addition of Molybdenum will also further improve

tensile strength. In case of the ADE engine a 42CrMo(S)4 steel was used. With the increase in power and torque when introducing the ADE 366 model, the tensile strength of this steel no longer sufficed. Referring back to DIN 17200 this steel has minimum tensile strength of 650 MPa when used for shafts in the diameter range of 41 - 100 mm. The non-turbocharged version of this engine uses a 37Cr(S)4 steel, which only has a minimum tensile strength of 520 MPa (which is reduced because of the omission of Molybdenum). DIN 17200 also specifies that both steels are suitable for use in crankshaft applications. For the nomenclature of steels refer also to DIN 17200. In case of the 37Cr(S)4 steel this contains 0,37% of carbon, 1% of chromium and 0,04% of sulphur.

The tensile properties in the critical fatigue sensitive areas of the crankshaft are raised by radius hardening the 37Cr(S)4 steel. This steel, not being alloyed with Molybdenum, will therefore be cheaper than the 42CrMo(S)4 steel (which, in any case, would no longer suffice due to the power increase of the engine requiring an even higher alloyed steel which has Vanadium of Nickel added to it). Testing the component (refer to component testing in Chapters 1-5) will be prove whether the lower tensile steel in the radius hardened form is adequate.

2.3.3.2 Machinability of Temper Steels

Machining processes produce the required shape by removal of selected areas of the workpiece through a machining process. Most machining is accomplished

by straining a local region of the workpiece by the relative motion of the tool and the workpiece (Dieter, 1981:701).

The addition of sulphur as an alloying element is one method to improve machinability of a steel.

2.4   Manufacturing Process

In a manufacturing process such as radius hardening, most of the problems are concentrated around the hardening process.   It is therefore pertinent that this section should investigate the theoretical background of induction hardening.

2.4.1   Induction Hardening

Electromagnetic Induction is one method of generating heat within a part for hardening or tempering steel (A.S.M.-Vol.4, 1981:451).   Any electrical conductor can be heated by electromagnetic induction.   As alternating current flows through the inductor, or work coil, a highly concentrated, rapidly alternating magnetic field is established within the coil. The strength of this field depends primarily on the magnitude of the current flowing in the coil.   The magnetic field thus established, induces an electric potential in the part to be heated, and because the part represents a closed circuit, the induced voltage causes the flow of current. The resistance of the part to the flow of the induced current causes heating.   Most induction surface-hardening applications require comparatively high power densities and short heating cycles in

order to restrict heating to the surface area. The
power required to cause heating can be calculated
by:

$$P = I^2R \quad (W)$$

where: I = current in Ampere
         R = Resistance in Ohm

From experience it has been established that 85% of
the heat induced is useful in transforming the
metal, resulting in a power loss equal to 15%.

The pattern of heating obtained by induction is
determined by:

(i)   The shape of the induction coil producing the
       magnetic field
(ii)   The number of turns in the coil
(iii) The operating frequency
(iv)   The alternating current power input
(v)   The nature of the workpiece.

The rate of heating obtained with induction coils
depends on the strength of the magnetic field to
which the part is exposed. In the workpiece, this
becomes a function of the induced current and of the
resistance to their flow. The depth of current
penetration depends on workpiece permeability,
resistivity and the alternating current frequency
(Bargel/ Schulze, 1988:178). Since permeability and
resistivity vary comparatively little, the greatest
variable is frequency. Depth of current penetration
decreases as frequency increases. High frequency
current is generally used when shallow heating (thin

case) is desired and intermediate to low frequencies are used in applications requiring deeper heating. The following formula shows their relationship to hardening depth (d)

$$d = \sqrt{(R/fu)} \quad (m)$$

where: R = specific electric resistance
           f = frequency of alternating current
           u = magnetic permeability

2.4.1.1 Inductor Design

The selection of any induction hardening application, is related to the selection and design of the proper work coil or inductor (A.S.M.-Vol.4, 1981:458-460). This design is influenced by a number of factors, including the dimensions and configuration of the part to be heated, the heat pattern desired, whether the part heated is heated throughout its length at the same time or progressively, the number of parts to be heated at one time and the amount of power available.

The strength of the magnetic field within the inductor is the basic factor that determines the rate of heating. For most rapid heating rates, therefore, inductors are designed to provide the maximum flow of current in the inductor, and the closest coupling (distance between inductor inside diameter and the part) permissible , after consideration of work handling features and arcing between the work and the coil. In practice considerable variation exists in the design of coils

for different type of induction generating units,
such as tube, spark-gap, solid state, static
frequency converters and line frequencies. At all
frequencies however the coils are generally of
copper because of its high conductivity and wide
availability at moderate cost. The copper may be in
the form of tubing, solid busbar or a combination of
both if required.

For the purpose of hardening cylindrical shapes, or
specifically crankshaft journals, the inductor
consists of a single-turn coil for scanning a
rotating surface. This will provide a heating
pattern as required on conventionally hardened
crankshaft journals. For the purpose of hardening
the radius or fillet additional coils are required
for side heating, which also consist of a
single-turn coil but positioned perpendicular to the
axis of rotation of the journal axis (see fig. 2.12)
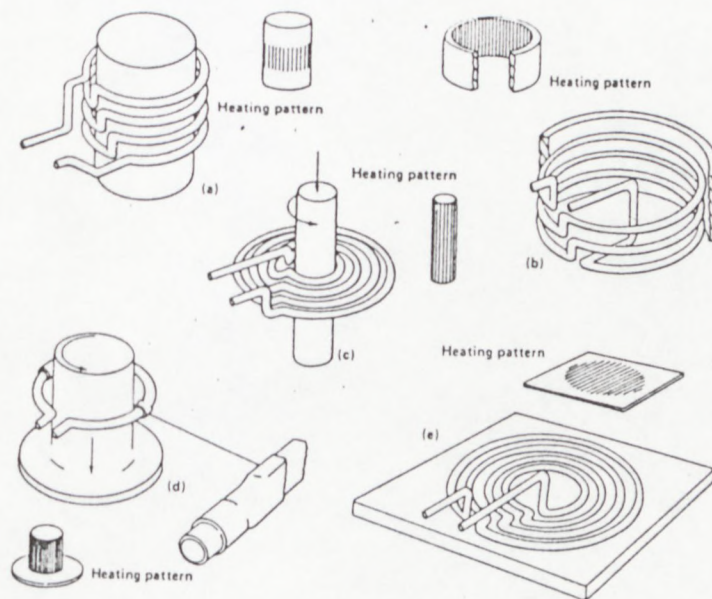
Fig.2.12-Typical work coils for medium - high
frequency units; (A.S.M.-Vol.4, 1981:459)

These two coils are combined into a single inductor housing, so that the heating of the journal and radii is performed in one single operation. The coupling of the inductor is normally in the region of 1.6 - 3 mm between the workpiece and the coil. Considerable adjustment in the heat pattern is possible by varying either the spacing between the inductor coils or the coupling for individual turns.

The thickness of the copper conductor used with medium frequency units is important. For efficient operation the following minimum thicknesses of wall may be used as a guide in constructing multiturn coils:

Minimum Wall Thickness (mm)	Frequency (Hz)
3,0	1000
1,8	3000
1,0	10000

Table 2.3- Wall thickness of medium frequency
            copper inductor coils
            (A.S.M.-Vol.4, 1981:458)

Whenever possible in the construction of single-turn coils, with which the current densities may be considerably higher, these minimums should be increased three or four times.

Since inductors used for heating crankshaft journals are normally of the single coil type cooling of the coil becomes necessary. Because of the high current

densities and the extremely thin cross section in
which the current confines itself artificial cooling
is required. This is usually accomplished by
circulating water through channels in the inductor
provided for this purpose. These channels may be
made by drilling connecting holes or milling out a
path to make a completed loop around the bore of the
inductor, and then plugging the exposed ends of the
holes or brazing a copper sheet over the milled
passage to make a continuous watertight cooling
channel. Cross sectional areas of the passages of
30 to 80 mm² provide adequate cooling at water
pressures of 275 to 345 kPa for power inputs ranging
from 30 to 150 kW.

Dependent on the type of induction hardening plant
used, the quenching of the heated component will
take place either in a quenching bath in which the
component is submerged immediately after hardening,
or this can be integrated into the inductor. In the
single turn inductor this will consist of an
additional water chamber with a suitable pattern or
series of orifices directed for spray quenching the
heated area. Such a spray quenching is effective
for single-shot hardening of work.

Inductor coil design in itself is a highly
specialised field. Where existing units are to be
modified it is best to consult the original
equipment manufacturer before performing major
design modifications on inductor units.

2.4.1.2 Quenching

In order to harden a steel, austenite must be

transformed to martensite efficiently. This can only be achieved through rapid cooling which brings about troubles with distortion and cracking. There are two factors which cause a metal to warp and crack when quenched (A.S.M.-Vol.4, 1981:31; Thelnig, 1975:129-131) :

(i)   When a metal is cooled it undergoes a general contraction which is not uniform, but first occurs at the outside surfaces and in the thin sections of the component being quenched.

(ii)   When a steel cools through the critical range an expansion takes place. This results in the outer layer of the metal expanding first. As further heat transfer takes place the critical inner layer also starts to expand as it passes through the critical range. The stresses induced as a result of this process can result in cracking of the outer layer.

In order to overcome the problem of cracking, commercially developed quenchants based on polymer solutions are used (A.S.M.-Vol.4, 1981:54). Their effect is to retard the quenching time of the metal in order to achieve a controlled rate of cooling through the material.

In the past the principal quenchants were water, perhaps modified by some special additive such as inorganic salts and naturally occurring oils. With the discovery of petroleum oil, hydrocarbon products became a major medium for quenching. It has been established that certain water soluble organic polymers are useful in modifying the cooling characteristics of water. In general it has been

the objective of polymer quenchants to provide
cooling characteristics intermediate between water
alone and petroleum oils.

Various commercially manufactured polymers are
available consisting of Polyvinyl Alcohol (PVA),
Polyalkylene Glycols (PAG), Polyvinylpyrrolidone
(PVP) and Polyacrylates. Fig. 2.13 below depicts a
typical cooling curve for a metal, showing the
influence of polymer concentration on the quenching
rate of a steel. The cooling power of quenchants is
not critically affected by small variations in
operating temperature, but just as water exhibits a
marked decrease in cooling capability as its
temperature is elevated, this same loss is
translated to the aqueous solutions of polymer
quenchants (A.S.M. - Vol.4, 1981:35 & 55).
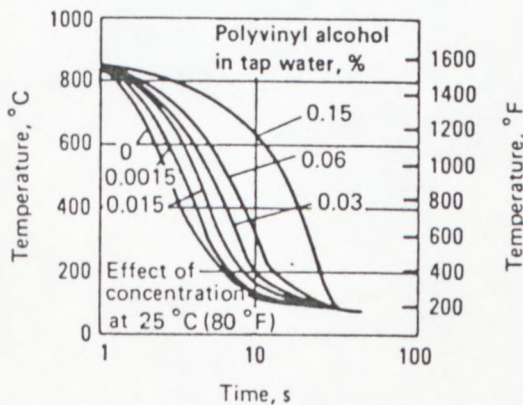
Fig.2.13- Typical cooling curve for polyvinyl
          alcohol solutions;
          (A.S.M. - Vol.4, 1981:55).

2.4.1.3 Hardness Depth Evaluation

Checking of hardness depth based on etch pattern

alone is unsatisfactory (Thelnig, 1975:128). The etch pattern of a hardened portion does not visually reveal the actual hardness of the heat treated part of the metal. The etch pattern merely reveals that the microstructure of the metal is different from the base metal once it has been heat treated.

From a design point of view the actual hardness of the material is important. The designer will specify the hardness required and at what depth. This must be taken into account when analysing heat treatment parameters.

For the purpose of evaluating the hardness depth it is common to take a section through the hardened component (destructive testing) and etch it with Nital in order to reveal the hardened portion. The etch pattern will reveal whether the actual pattern and proportions of the hardened component are correct. The hardness is checked at the surface as well as at fixed depths from the surface.

The two common methods of prescribing hardness are:

(i)   By specifying the surface hardness only accompanied by a depth, without specifying the hardness at that depth.

(ii) By specifying the surface hardness as well as the hardness at a certain depth.

In the case of (i) where the hardness at the specified depth is not stipulated, DIN 17 014 prescribes that 80% of the specified hardness at the prescribed depth must be achieved. E.g. a component hardened 3mm deep with a surface hardness of HRC 60,

must still have a minimum hardness of HRC 48 at a depth of 3mm.

In fig. 2.14 typical hardness depth curves are shown (Thelnig, 1975:129). Hardness in this instance is specified in Rockwell-C, but this can also be represented by any other type of hardness check. The shape of the curves is typical for steel.
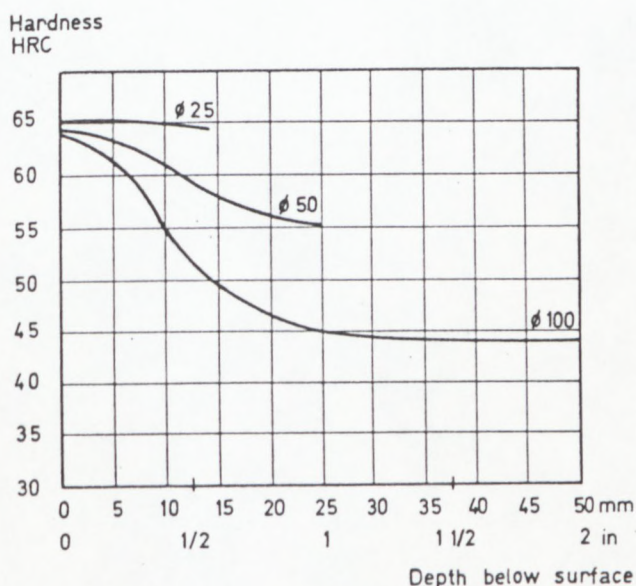
Fig.2.14- Depth in hardening in different dimensions after oil quenching. Test pieces quenched from 800°C, 820°C and 840°C for diameters 25mm, 50mm and 100mm respectively; (Thelnig, 1975:129).

Surface hardness is usually measured according to the Rockwell-C method (HRC); (Bargel/Schulze, 1988:112-115). Hardness across a section in order to evaluate the hardness at a depth is normally measured in Vickers using a 1 kg load (HV1). The Vickers measuring method is more accurate, but more time consuming, when compared to the Rockwell-C

method. Once parameters for the process have been set up successfully it is no longer practical nor cost effective to check hardness on a section. The loss in accuracy by checking with the Rockwell method on the journal surface is therefore acceptable.

2.4.2   Stress Elimination

There are three main sources of stress which are imparted onto a crankshaft during the manufacturing process, namely during the forging, machining and hardening operations. These stresses cause deformation of the component, which can be subsequently released, resulting in runout of the crankshaft journals as well as buckling.

There are many sources of residual stress which can occur anywhere between the processing of the material from ingot to final product form (A.S.M.-Vol.4, 1981/3-4). Residual stresses can also be generated during forging and forming operations (i.e. machining operations including grinding). Residual stresses are present whenever a component is tressed beyond its elastic limit and plastic flow occurs. Bending a crankshaft in order to straighten it at a temperature where recovery cannot occur, will result in one surface location containing residual tensile stresses, whereas a location opposite it will contain residual compressive stresses. Quenching of thick sections (such as crankshaft journals) results in high residual compressive stresses on the surface of the material. These high compressive stresses are balanced by residual tensile stresses in the internal areas of the section. Grinding a hardened

section will release stresses if it protrudes into the inner areas (i.e. high stock removal). Grinding stock removal should therefore be limited to a minimum. Deformation of the shaft after hardening should consequently be kept to a minimum and should be determined through a hardening sequence etc. during the process development stage.

Stress relieving after hardening at temperatures between 100°C and 200°C will cause some release of internal stresses, but primarily this is done to prevent the release of stresses upon machining (c.f. 2.3.3).

2.4.3   Changes in Dimension When Hardening - Shrinkage

One of the most difficult problems involved in the heat treatment of steel, is the dimensional changes that occur in the steel during hardening (Thelnig, 1975:466).

One of the main causes of dimensional changes is the stresses which occur as a consequence of the contraction of the material during cooling The other main cause is the transformation stresses which occur as a result of martensite transformation. In a crankshaft which is being radius hardened it is difficult to predict the exact effect of deformation which will be experienced after hardening, since a crankshaft consists of a complex geometric shape. In more regular shapes such changes in form and dimension can be more accurately predicted (Thelnig, 1975:467-475). The change to a finer structure causes the material to shrink around the collar faces of the crankshaft

journals.   This induces a hoop stress around the
journals as well as causes the crank to shrink in
overall length after hardening.

Cognisance must therefore be taken of the fact that
dimensional changes will occur which will result in
runout and shrinkage of the crankshaft. The process
employed will be determined through empirical
evaluation of the hardening and machining processes.

2.5   Component Testing

In practice, prediction of the fatigue life of a
material is complicated because, except for a few
relatively brittle materials, the fatigue life of a
material is very sensitive to small changes in
loading conditions, local stresses and local
characteristics of the material (A.S.M.-Vol.10,
1975:95).   Because it is difficult to account for
these minor changes in either the dynamic stress
prediction techniques or in fatigue failure criteria
there is a large uncertainty inherent in analytical
predictions of fatigue life. Thus the designer is
also required to rely on experience with similar
parts and eventually on qualification testing of
prototypes or production parts.   It is for this
reason that laboratory fatigue testing is
supplemented with actual dynamic functional tests,
in this instance testing of the crankshaft in the
engine.

2.5.1   Fatigue Testing

In a fatigue test the fatiguestress may be regarded
as resolved into a constant static and fluctuating

stress which varies with time (Thelnig, 1975:60).
Hence the applied stress varies between an upper and
a lower limit, σ_{max} and σ_{min}, respectively. The
constant stress is called the mean fatigue stress
(σ_m) and is defined as :

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$
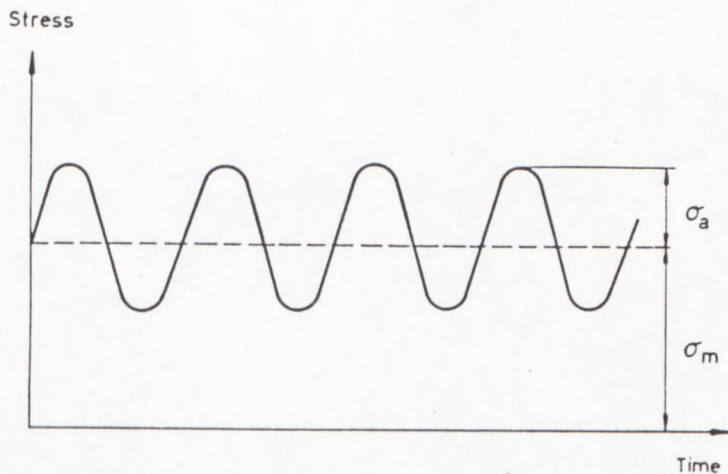
Fig.2.15- Mean fatigue stress σ_m and stress
amplitude σ_a; (Thelnig, 1975:60).

The fluctuating stress may be defined by its
amplitude σ_a, (see fig. 2.15) as follows :

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

In the case of a crankshaft σ_{min} and σ_{max} have
opposite signs during each load cycle and are
referred to as alternating stresses (see fig. 2.16).
The results of fatigue tests are usually plotted on

S-N or Wöhler diagrams (c.f. 2.2.2). In these diagrams the amplitude of the stress is plotted as a function of the number of load cycles to fracture.
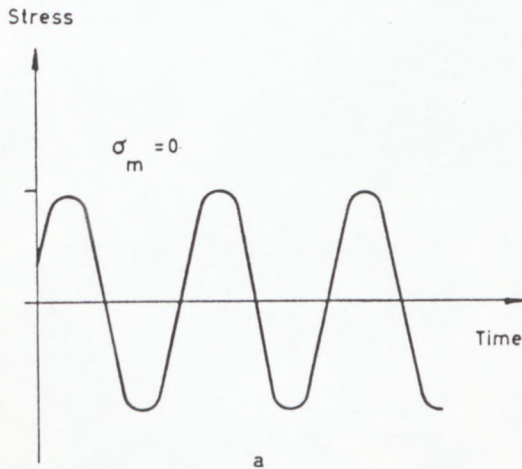
Fig.2.16- Alternating stress; (Thelnig, 1975:60).

2.5.2   Engine Testing

All test procedures require power measurement (Lilly, 1986:30.2). This involves the measuring of rotational speed and torque. Speed measurement has become very simple and precise with the development of electronic pulse systems. The other quantity needed in power measurement is torque. Torque is measured on a dynamometer. The power (P) can be calculated using the following formula:

$$P = \frac{2 \pi N T}{60} \quad (W)$$

where: N = rotational speed of engine in r/min
       T = torque in Nm

Most dynamometers are of the absorption type where the engine power is converted into heat or electrical energy. Dynamometers should preferably be of a programmable type since engine testing consists of repetitive cycles, which otherwise would have to be manually controlled.

With the engine coupled to the dynamometer the torque (specified by the engine designer) which the engine should deliver at a specific rotational speed is measured. Using the above formula the power can be calculated.

In durability testing an engine is specially assembled incorporating the components to be checked The engine is then run over a specific period of time at varying load cycles. Such types of test programs have been established by engine designers and are largely based on experience. They will therefore differ from one engine manufacturer to another. In the case of the ADE engine, a test program consisting of a 200 hour engine run was utilised.

This program consists of the following features:

(i)   An 80 minute run-in program
(ii)   A 21 hour oil consumption test after which piston and crankshaft bearing inspection is performed
(iii) A 50 minute run-in program after re-assembly of the engine
(iv)   A 200 hour validation program consisting of:
       - 25 hour load program between maximum torque and maximum power speed range

- 60 minutes at maximum power
- 30 minutes at maximum torque
- 30 minutes at 1000 r/min
- 25 hours at 50% of maximum power at rated speed
- 13 hour oil consumption program

Note: All the above tests performed use a standard fuel injection pump fuel delivery setting.

After completion of such a test program crankshaft end float, timing gear play, connecting rod axial end float, piston protrusion, blow-by and oil consumption are checked against established maximum permissible values. In addition, a visual inspection of bearings and crankshaft journals is performed in order to compare this to established norms.

Finally the crankshaft is crack detected in order to determine whether fatigue cracks have originated during the test run.

* * *

CHAPTER 3

CARRYING OUT

THE INVESTIGATION

3.1   Introduction

An existing crankshaft machining line, with an established manufacturing process for the manufacture of non-radius hardened crankshafts, had to be converted to manufacture radius hardened crankshafts. This meant that where possible existing manufacturing equipment had to be used, but this could be modified to suit. Furthermore the intention was to confine capital expenditure where possible. In addition, because of time constraint, trials were limited to smaller batches of components from which production processes were directly formulated. Process development will therefore concentrate around hardening and processes affected by the change in hardening. The intention of this investigation is to adopt a methodical approach in developing a process by using one particular crankshaft (ADE 366) which could then be applied to similar crankshafts. In fig. 3.1 a drawing of the ADE 366 crankshaft with its basic dimensions is depicted, including a nomenclature of commonly used crankshaft terms.

3.2   Crankshaft Radius Hardening

3.2.1   Cracking of Radii Upon Straightening

The process of conventional non-radius induction

hardening of journals is relatively simple. The fact
that the radii are not being hardened means that no
stresses from the hardening process, from heating up
and quenching, are induced into the webs of the
crankshaft. In addition, shafts can be straightened
after hardening in order to achieve main journal
runout limits as specified by the process.
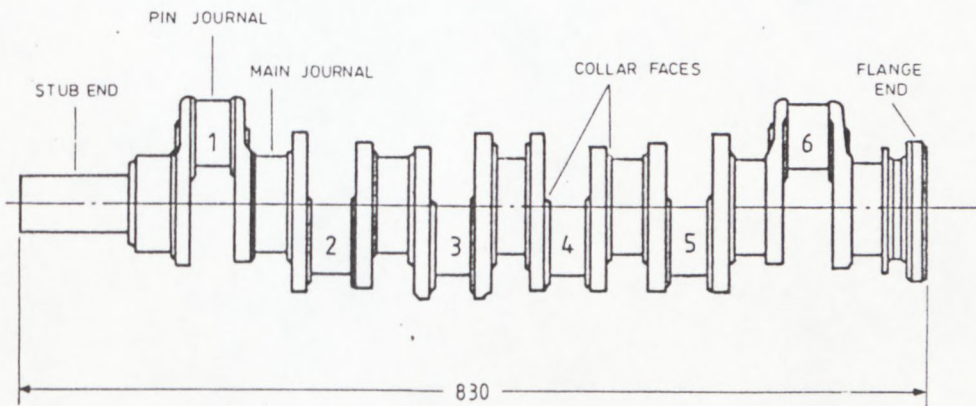
Fig.3.1- ADE 366 Crankshaft - Basic dimensions and
        nomenclature of crankshaft terms

Radius hardened shafts, on the other hand, cannot be
straightened after hardening. The reason for this
is that the martensitic zone of the radius, whilst
assisting in improving fatigue life, is also brittle
caused by change in Young's Modulus. The deflection
produced in the radius when straightening a journal
will exceed the ultimate tensile strength of the
material causing it to rupture. Tests performed on
crankshafts made from 37Cr(S)4 steel, which had a
runout in excess of 2,5 mm after hardening, showed
signs of cracking after being straightened. The

cracks became visible using a magnetic flux crack detector which reveals externally visible cracks. Internal cracks which might already be present on lower runout levels can therefore not be seen. Table 3.1 below shows results of tests performed.

Max. Runout of Shaft (mm)	Crack Present YES	NO
0,5 - 2,0		X
2,1		X
2,2		X
2,3		X
2,4		X
2,5	X	
2,5		X
2,6	X	
2,7	X	

Table 3.1- Determination of crack formation in journal radii. Crankshaft material 37Cr(S)4. Runout simulated by deflecting crankshaft with hydraulic press prior to hardening.

The fact that one shaft displays cracking at a runout of 2,5 mm as opposed to the other one, can be explained by this being the borderline between the crack being internal as opposed to externally visible.

3.3   Steel Selection

The lower powered ADE engine already used the 37Cr(S)4 steel in the non-radius hardened form. Since this steel in theory (c.f. 2.3.3.1) would be suitable for radius hardening, it was decided to continue using this steel for manufacturing trials.

This also meant that if trials proved successful, stock holding in the forge could be limited to one type of steel, whereas previously two types were required.

While carrying out the investigation into runout after hardening (c.f. Chapter 1.4 - Process Development) it was noticed that some crankshafts forged out of 37Cr(S)4 steel displayed higher runout results after hardening than others although all shafts were subjected to the identical manufacturing process. It was therefore assumed that some influence could come from the forging process.

3.3.1   Forging Process

In the forging process, all crankshaft forgings are checked for runout. All forgings which had a runout in excess of 3,2 mm were straightened to a maximum runout of 2,6mm (this process had been established previously for non-radius hardened crankshafts used for this type of engine). These forgings were not stress relieved by reheating after straightening. In addition, straightened forgings were intermixed with non-straightened ones, so that no distinction could be made on the production line.

Trials were then performed by separating and identifying straightened forgings from non-straightened ones. In addition the straightened forgings were also stress relieved in the forge at a temperature slightly below the original tempering temperature. The following two types of batches were then hardened:

(i)   Straightened and stress relieved (222 off),

referred to as "S" in table 3.2 below

(ii) Not straightened (95 off), referred to as "NS" in table 3.2 below

<u>Note</u>: Hardening process utilised with supports, and sequence of hardening of pin journals followed by main journals (c.f. 3.4.2.1)

The results of runout on centre journals, measured after induction hardening and stress relieving at 200°C for 2 hours are listed in table 3.2 below:

FORGE BATCH CODE NUMBER	RUNOUT		AVERAGE RUNOUT (mm)
	S (mm)	NS (mm)	
CDT	0,770	0,997	0,884
CDV	0,818	0,923	0,871
CDBL	0,648	1,020	0,834
AVERAGE RUNOUT	0,746	0,980	0,863
TOTAL SHAFTS	222	95	317

Table 3.2- Crankshaft main journal runout after hardening and stress relieving (measured on centre journal) compared to straightened/stress relieved and non straightened forging condition. Material 37Cr(S)4. Quench BP Quendila at 14% concentration.

From the above results it can be seen that shafts which have been straightened and stress relieved by reheating to below the tempering temperature exhibit lower (better) runout results.

3.4   Manufacturing Process

3.4.1   Runout Control (Soft Stage)

Runout on the main journals has to be kept as low as possible before hardening. A high runout indicates that the shaft has been deformed during the machining operation, which induces stresses into the material (c.f. 1.4.2.1). Low runouts can be achieved by optimising the machining process in terms of feeds and speeds and tooling. The evidence of low stress induction can be measured in terms of a low runout on the main journals.

Since the final component drawing permits a maximum runout of 0,15mm on the centre journal, it was decided that a lower maximum average value should be strived for, as an in-process dimension. The reason for this decision was that hardening and grinding will induce further stresses which could then aggravate the situation such that the final tolerance of 0,15 mm could not be kept.

3.4.1.1 Machining Sequence

In terms of existing facilities, the machining sequence tabulated in table 3.3 yielded the lowest runout result before hardening. The aim of achieving a lower average runout than the maximum final drawing tolerance of 0,15 mm, could not be achieved. An average runout of 0,18 mm was achieved. Most stresses were induced after the pin milling operation which caused plastic deformation resulting in runout. The possibility of straightening shafts before hardening in order to

reduce runout was debated, but it was decided to abandon this idea for the following reasons:

(i)   New stresses being induced into the shaft which could be released upon hardening and grinding, especially since no fixed position of runout could be established.

(ii) If a press is left on the machining line the danger of hardened shafts being straightened could exist. This would be catastrophic as such shafts would have cracks in them and would eventually fail in an engine.

MACHINING SEQUENCE - SOFT STAGE	
MACHINING OPERATION	AVERAGE RUNOUT (mm)
End milling (length), geometric balancing, pre-turning of stub ends and flange faces, milling of centre main journals	0,25
Fine turning of main journals	0,11
Milling of pin journals	0,18
Milling and drilling of counter weight faces and bolt holes, gun drilling of oilways in main and pin journals	0,18

Table 3.3-   Soft stage machining sequence of crankshaft compared against average runout on centre journal. Material 37Cr(S)4

It was decided to rather continue developing this process with the runout results achieved. Should these prove unacceptable, straightening of shafts could be considered and investigated at a later stage.

3.4.2   Runout Control (Hard Stage)

Hardening trials were initially conducted using the same method as on non-radius hardened shafts. All main journals (except thrust journal which is the centre journal) were hardened sequentially, all pin journals hardened sequentially and finally the centre journal.   Employing this method resulted in unacceptably high runouts in excess of 2,5 mm. The aim was to achieve runouts in the region of 0,5 mm - 0,8 mm for the following reasons:

(i)   The collar (or side) faces of both pin and main journals tended to suffer from non-clean up conditions if the runout was too high. The position of the highest runout was always in line with the non-clean up. This problem can be overcome by adding more grinding stock onto the collar faces, but this in turn is again more time consuming when manufacturing the shaft and also results in higher wear down of grinding wheels, which are expensive.

(ii)   On non-radius hardened crankshafts a radial grinding stock of 0,5 mm was utilised. This had resulted in acceptable grinding wheel wear and was sufficient to clean up journals from any surface irregularities from machining and hardening stages. If a shaft has a runout of 1 mm this means that grinding stock of 0,5 mm would just be sufficient for cleaning up the shaft (zero condition). Any surface irregularities though would not be catered for and result in a non-clean up on the shaft surface.   This would not be acceptable since

crankshaft journals typically have surface
finishes in the region of Rz = 2-3 micron
(before polishing), and roundness tolerances
of 5-10 micron. (Rz = average surface profile
as defined by ISO standards)

The following subsections investigate areas which
were believed to have an influence on runout of the
shaft.

3.4.2.1 Hardening Sequence and Support of Shaft

A variety of induction hardening machines are
available. The most common type, used for a medium
volume production of 8-10 medium sized Diesel engine
crankshafts per hour, is the single inductor
machine. In this machine the shaft is supported
between the ends on centres. Underneath the shaft
is a tank containing the quenchant. Each journal is
individually heated with the inductor (whilst the
shaft is rotating) and then dipped into the
quenchant for hardening. The geometry of the
crankshaft will determine what hardening sequence to
follow in order to obtain the lowest runout.

The following hardening sequences were evaluated
during hardening trials and collated against
runout. For each hardening trial one crankshaft was
used. Runout before hardening as listed in table
3.4 was measured in each case to ensure that this
was within the 0,18 mm process dimension (c.f.
section 3.4.1.1:

(i)   Pins - 6,1,5,2,4 and 3
       Mains - 7,1,6,2,5,3 and 4
       No support utilised

(ii)   Thrust - 4
Pins - 6,1,5,2,4 and 3
Mains - 1,7,2,6,3,5 and 4
No support utilised

(iii) As (i) but with supports on mains 3 and 5 when hardening thrust (main 4); and support on main 4 whilst hardening remaining main journals

(iv) As (ii) but with supports on main 3 while hardening thrust.
(This trial had to be aborted since mains 3 and 5 were still unhardened, which resulted in heavy score marks from the support rollers on the journal surfaces, due to the runout generated by the shaft whilst being hardened).

(v)   Mains - 7,1,6,2,5,3, and 4
Pins - 6,1,5,2,4 and 3
Supports on mains 3 and 5 whilst hardening thrust (centre journal - main 4) and support on main 4 whilst hardening remaining main journals

(vi) Mains - 4,5,3,6,2,7 and 1
Pins - 3,4,2,5,1 and 6
No support utilised.

NOTE:

a) Pin journal No.6 and main journal No.7 are on the flywheel end of the engine

b) Supports used for hardening consist of spring loaded rollers which support the shaft on the main journal

In table 3.4 the maximum runouts are listed, using hardening sequences described above.

| SEQUENCE | RUNOUT (mm) | | | LOCATION OF HIGHEST RUNOUT ON MAIN JOURNAL |
	BEFORE HARDENING	AFTER HARDENING	AFTER STRESS RELIEVING	
(i)	-	-	1,30	Main 4
(ii)	0,13	0,82	0.75	Main 4
(iii)	0,11	0,60	0,52	Main 4
(iii)	0,08	0,49	0,41	Main 4
(iii)	0,10	0,35	0,36	Main 4
(iv)	TRIAL ABORTED			
(v)	0,06	0,55	0,45	Main 4
(vi)	0,05	1,25	1,10	Main 4

Table 3.4- Hardening sequence compared to runout on crankshaft centre main journal. Material 37Cr(S)4.

Sequence (iii) appeared to be the most successful hardening method. For this reason three trial shafts were hardened to confirm that the runout was indeed lower. This sequence was utilised for further process development trials in order to determine hardness depth, grinding sequence and shrinkage.

3.4.2.2 Hardening Pattern Depth and Runout

Trials were performed on 40 shafts of which 20 were

hardened on the bottom end of the hardness depth tolerance and 20 were hardened on the upper hardness depth tolerance. Refer to fig. 3.2 for hardness pattern dimensions and tolerances.
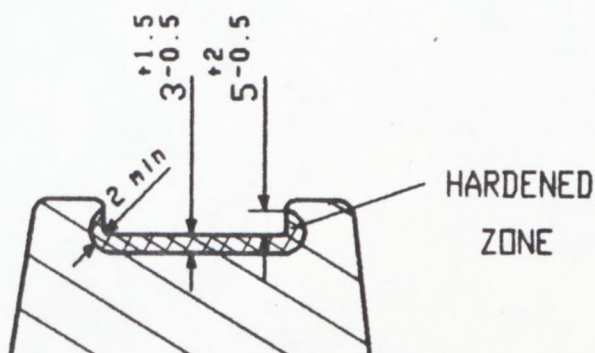
NOTE:

1) All hardened depth at HV 450 minimum.

2) Surface hardness HRC 56^{+3}_{-}.

Fig.3.2- Typical hardness pattern, dimensions and
tolerances of radius hardened journal

Runouts were measured after hardening and stress relieving, but no significant difference could be established between the two trials. The shafts with the lower hardening depth showed on average a slightly lower runout of 0,01mm. Based on this it was decided to harden the journals at mid tolerance of the hardening depth. This would allow for sufficient safety in the hardening process in order to maintain the radius above minimum specification. At the same time a mid tolerance hardening depth would result in an average increase of runout of only 0,005 mm, which can be considered as being

negligible (assuming a linear runout relationship
between minimum and maximum hardening depths).
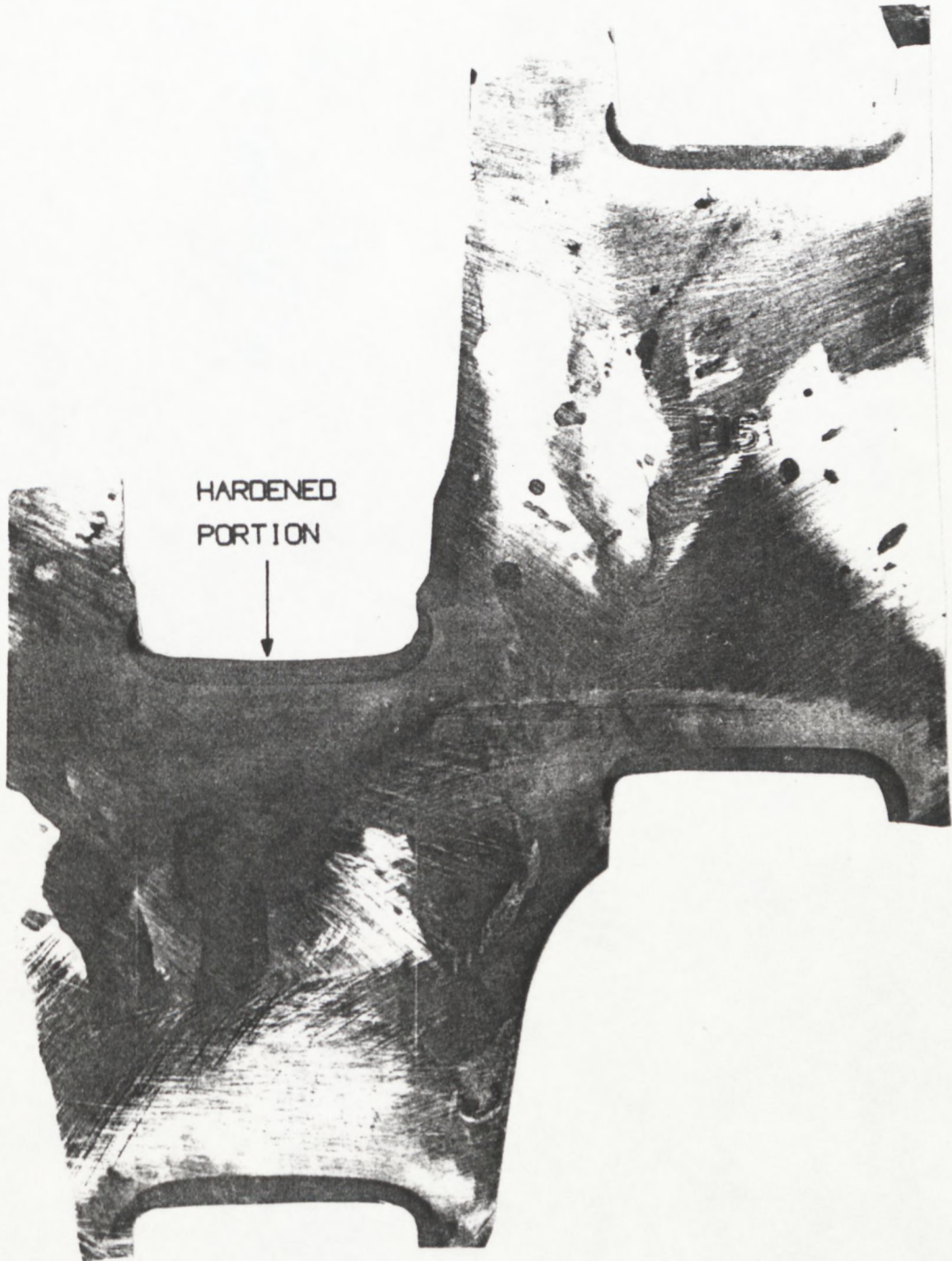
Fig.3.3- Section through main and pin journals of an
ADE 366 crankshaft. The hardened portion
is highlighted in black.

New inductors were purpose made by the manufacturer of the existing induction hardening machine. Verification of hardness depth and pattern was done by analysing sectioned portions of main and pin journals to the specifications mentioned above. Fig. 3.3 below shows a photograph of such a sectioned crankshaft portion. The hardened areas were polished and etched with nital in order to highlight the hardening pattern.

3.4.2.3 Quench Concentration and Runout

The quenchant utilised for the development of this process was BP Quendila which is a PAG type polymer (c.f. Section 2.4.1.2). A concentration of 10% - 15% in an aqueous solution is recommended by the manufacturer to obtain proper martensitic transformation for steels such as 37Cr(S)4.

Trials were done on 32 shafts with the concentration fixed at 10% and 30 shafts at 14%. These shafts had all been subjected to normal heat treatment in the forge without further straightening and re-stress relieving. The reason for choosing 14% as a limit was that hardness values began to drop off considerably beyond this concentration so that the hardness specification of RHT 450 (Vickers) could not be held. Results are shown in table 3.5 below:

QUENCH CONCENTRATION	QTY. SHAFTS	AVERAGE RUNOUT
10 %	32	1,4 mm
14 %	30	0,89 mm

Table 3.5- Quench concentration compared to runout on crankshaft centre main journal. Quench BP Quendila, material 37Cr(S)4.

Based on these results all further process trials
were conducted utilising a 14% quench solution.

3.4.2.4   Quench Temperature and Runout

The influence of quench temperature on runout of the
shaft was investigated.   The quench tank used for
the trials was thermostatically controllable to
regulate the maximum temperature.   Concern was
expressed that higher temperatures could cause
higher deflections.   Trials done using 80 shafts
over a temperature range of 32°C - 47°C revealed
that this had minor influence.   The results
obtained are plotted in fig. 3.4 below.
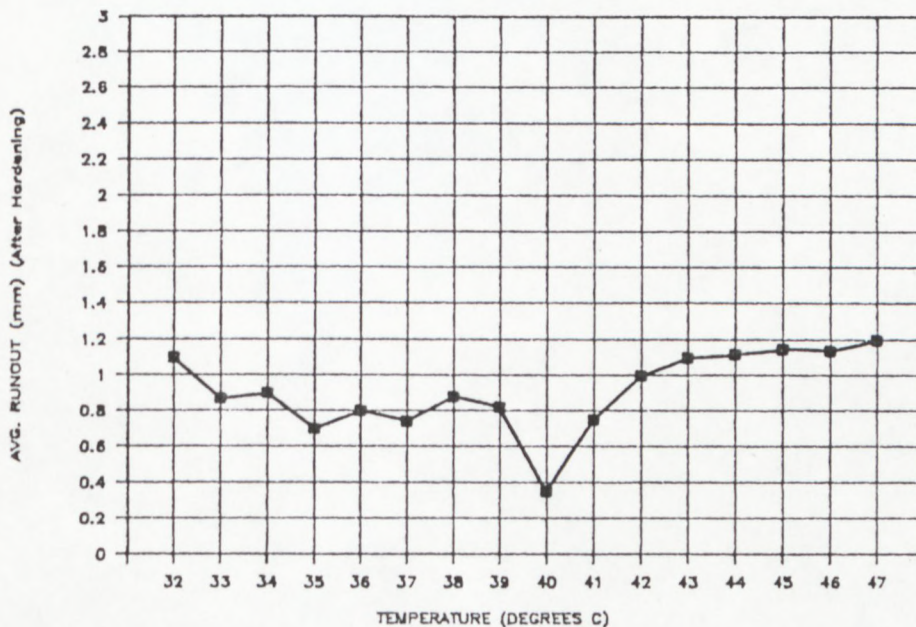
Fig.3.4- Quench temperature compared to crankshaft
         runout on centre main journal. Quench BP
         Quendila at 12% concentration, material
         37Cr(S)4.

Temperatures in excess of 40°C caused a marginal increase in runout of 0,04mm/°C. Manufacturers recommendations were that the quench temperature be kept above 28°C in order to achieve acceptable results to maintain a stable solution. It was then decided to regulate the tank temperature between 35°C and 40°C.

3.4.2.5 Stress Relieving and Runout

After induction hardening the crank is required to be stress relieved/tempered at a temperature of 200°C for a minimum period of 2 hours. This is done in order to slightly temper the steel to make it machinable by removing the "glass type" hardness (c.f. 2.3.3) and to release internal stresses which were induced during hardening. On non-radius hardened shafts the minimum period of 2 hours proved to be sufficient to provide acceptable results.

Trials were performed on 50 radius hardened shafts of which 25 were stress relieved for 4 hours and the other 25 for 2 hours. Runouts were measured after hardening on the centre journal. No significant difference could be established (average difference recorded 0,01 mm).

3.4.2.6 Grinding Sequence and Runout/Stroke

On non-radius hardened crankshaft journals, shafts were straightened down to 0,05 mm prior to grinding. The grinding sequence then was to grind to the final dimensions the main journals followed by the pin journals. In both grinding operations the shaft was located from centres at both ends of

the shaft so that a common datum was obtained. When applying the above method to radius hardened shafts it was discovered that the runout tolerance of 0,15 mm could not be maintained. In addition the stroke (or eccentricity) of the crankshaft pin journal, which is toleranced at ± 0,05 mm, could not be maintained. It was then proposed to undertake the following five trials in order to attempt to solve the problem:

TRIAL 1
- Pre-grind main journals
- Finish grind pin journals
- Finish grind main journals

TRIAL 2
- Pre-grind main journals
- Finish grind pin journals
- Re-centre centres at ends of crankshaft using main journals No. 1 & 7 as location (datum)
- Finish grind main journals

TRIAL 3
- Pre-grind main journals
- Pre-grind pin journals
- Re-centre centres at ends of crankshaft using main journals No. 1 & 7 as location (datum)
- Finish grind main journals
- Finish grind pin journals

TRIAL 4
 As trial 2 but without re-centering shaft

TRIAL 5
 As trial 3 but without re-centering shaft

NOTE:

The term pre-grinding means that the shaft is ground in the same way as finish grinding by removal of stock on collar faces, radii as well as diameter, but allowing a stock all round of approximately 0,1 - 0,2 mm for finish grinding.

RESULTS:

a) Trials 1,2, and 4 which all excluded pre-grinding of the pins, whilst being successful in achieving results below the maximum runout tolerance of 0,15 mm, were abortive in terms of not always achieving the stroke tolerance. Furthermore it was discovered after a period of 7 months that these shafts displayed tendencies to creep, whereas shafts which had been pre-ground remained entirely stable. Measurements taken on 36 shafts (not pre-ground on pin journals) are shown in table 3.6. It is interesting to note that the worst runout, as a result of creep occurs on journal No. 5 which is not the centre journal.

RUNOUT OF CRANKSHAFTS AFTER 7 MONTHS OF STORAGE (mm)	JOURNAL NO.				
	2	3	4	5	6
MAX. RECORDED RUNOUT	0,050	0,120	0,165	0,170	0,070
AVERAGE RUNOUT	0.026	0,076	0,122	0,141	0,057
MAX. RUNOUT SPEC.	0.070	0,110	0,150	0,110	0,070

Table 3.6- Creep of crankshafts not pre-ground on pin journals, after period of 7 months. Average runout taken from sample of 36 crankshafts. Material 37Cr(S)4.

b) For the purpose of trials 3 and 5, it was decided to take a batch of 100 shafts. Half of the shafts were to be centre-ground (trial 3) and the other half not centre-ground (trial 5). Tests commenced with trial 5, but it was discovered after only 18 components that the centre grinding operation is essential in terms of controlling the stroke of the crankshaft. Shafts which had not been centre ground displayed extreme variances in stroke across the 6 pin journals. Ranges of up to 0,24 mm per shaft were measured between the two extremes after final main grinding. The maximum permitted is 0,1 mm when making full use of the ± 0,05 mm stroke tolerance. On shafts which were centre ground, the maximum range per shaft measured was 0,10 mm. It was then decided to continue with trial 3 only, on the remaining shafts. Results achieved using this method are shown in table 3.7 below:

MACHINING OPERATION	AV. RUNOUT (mm) MAIN No. 4	AV. STROKE RANGE (mm)
After hardening and stress relieving	0,75	xxxx
After final pin journal grinding	0,11	0,105
After final main journal grinding	0,09	0,081

Table 3.7- Average runout and average stroke range obtained when pre-grinding main and pin journals, and re-centering before final pin and main journal grinding. Material 37Cr(S)4.

When perusing the individual readings, no relationship could be found between runout and stroke.

Table No. 3.8 shows the results of the average strokes recorded across the 6 pins when using the grinding sequence for trial 3.

PIN NO.	NOMINAL STROKE DIMENSION (mm)	ACTUAL AVERAGE (mm)
1		-0,045
2		-0,059
3	96,25	-0.002
4	±0,05	0,037
5		-0,062*
6		-0,059*

Note: * = out of tolerance

Table 3.8 - Average strokes after pre-grinding pin
           and main journals

As can be seen the strokes on journals 5 and 6 are out of tolerance. This can be corrected through adjustment of the grinding centres by shifting them 0,012 mm into the positive direction. This will imply that the stroke of pin No. 4 will still be in specification, by making full use of the plus tolerance.

In fig. 3.5 the relationship between the orientation of the pin strokes on the shaft and

their direction within the tolerance band is shown. Pin strokes based on average are recorded in table 3.8.
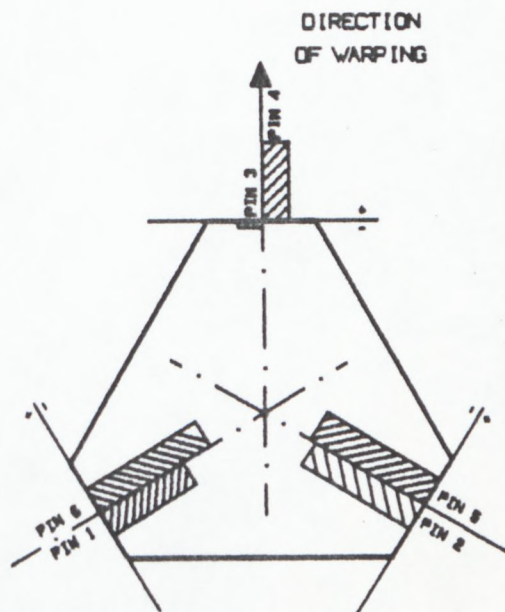
Fig.3.5- Orientation of pin strokes (after hardening and stress relieving), viewed from flange end of crankshaft. Material 37Cr(S)4.

3.4.3 Shrinkage of Crankshaft After Hardening

Preliminary trials confirmed that shrinkage of the crankshaft occurs after hardening At the same time the shafts displayed a high runout. Since a high runout can be mistakenly construed for shrinkage (depending on which position length measurements are taken), it was decided to determine the shrinkage allowance only once hardening and grinding parameters had been successfully completed (c.f. 3.4.2). The method employed to establish the shrinkage amount was to measure the difference in length of each main journal at the collar face, from

a common datum point, before and after hardening. In the case of the ADE 366 shaft, the common datum used was main journal No. 4 at the centre of the shaft. This also being the thrust journal from which all drawing dimensions originate. In order to compensate for runout after hardening the lengths were taken at three points 120° apart on the perimeter of the journal collar faces. The average of these three readings were then used for the determination of shrinkage. In figs. 3.5 and 3.6 the results obtained by taking average readings off 10 crankshafts were plotted. Shrinkages were measured directly after pre-grinding of the main journals (fig. 3.6) and after final pin journal grinding (fig. 3.7) This was done in order to establish whether the release of residual stresses after grinding have an influence on the shrinkage of the shaft.

HARDENING SHRINKAGE vs SHAFT LENGTH
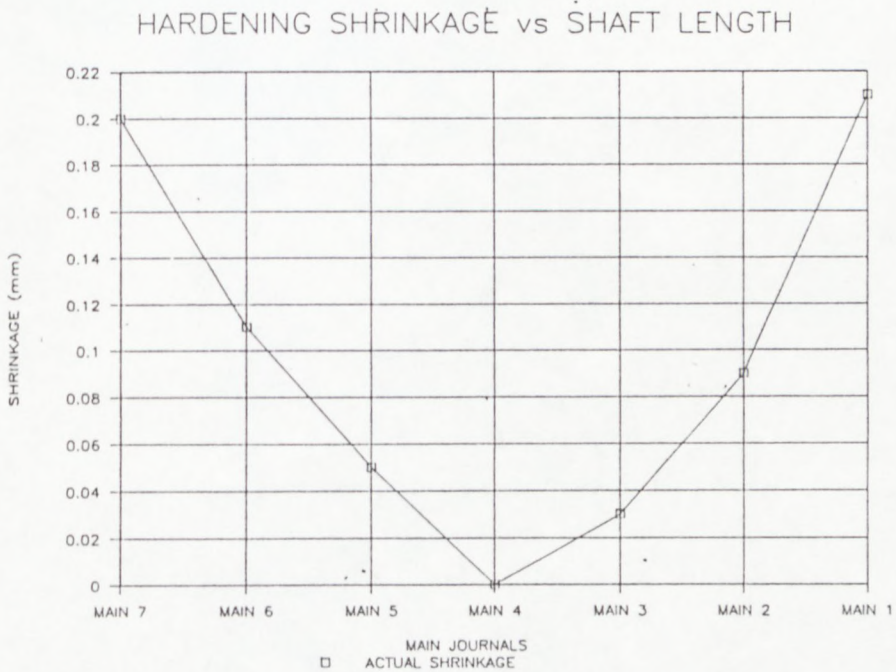
Fig.3.6- Shrinkage of crankshaft after hardening and pre-grinding of main journals. Material 37Cr(S)4.

No further shrinkage was detected after final main journal grinding. Adding the shrinkages, obtained towards each end, together, an overall shrinkage of 0,53 mm after completion of all grinding operations was obtained.

PIN GRINDING SHRINKAGE vs SHAFT LENGTH
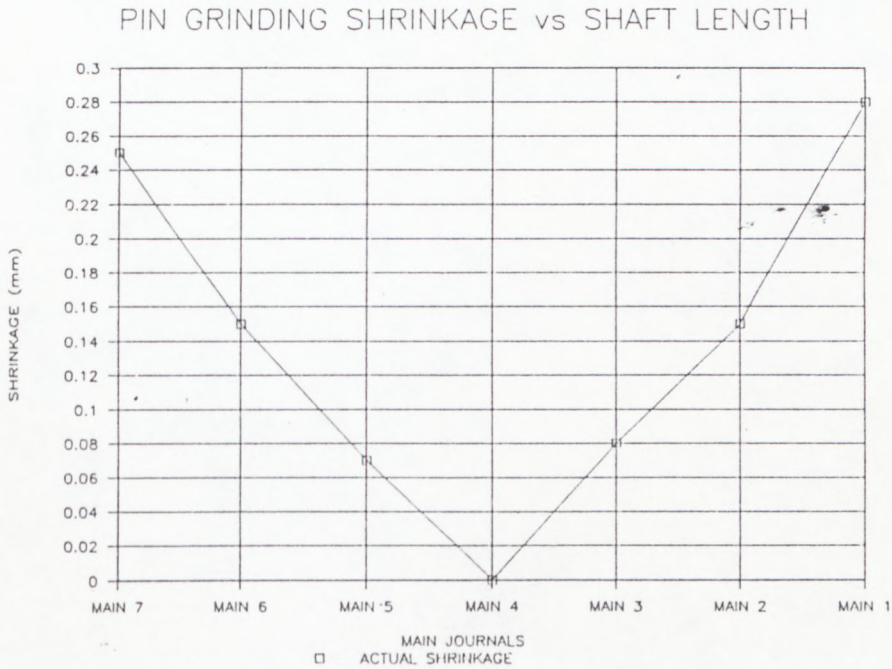
Fig.3.7- Shrinkage of crankshaft after hardening and
final grinding of pin journals. Material
37Cr(S)4.

3.4.4 Pin Journal Lengths

During the trials it was noted that problems were experienced with holding the length positions of the pin journals. The lengths of the pin journals are specified from the centre (thrust) main journal, and tolerances are larger for the extreme pin journals, being No.s 1 & 6.

An analysis was performed on 50 shafts (measured after final main journal grinding), based on the process specified so far. The results achieved are displayed in table 3.9 .

PIN JOURNAL LENGTHS (from thrust)						
	JOURNAL No.					
	1	2	3	4	5	6
TOLERANCE (mm)	± 0,15	± 0,10	± 0,10	± 0,10	± 0,10	± 0,15
MAX. READING (mm)	0,37	0,49	0,39	0,34	0,22	0,35
MIN. READING (mm)	-0,72	-0,56	-0,68	-0,70	-0,46	-0,60
RANGE (mm)	1,09	1,05	1,07	1,04	0,68	0,95

Table 3.9 - Length of pin journals after final
            main journal grinding

The machining tolerances stipulated were the same as specified on non-radius hardened shafts. From the results achieved it is evident that the above tolerances cannot be met. On the other hand play between the piston and the conrod small-end is in excess of 2 mm per side such that the overstepping of tolerances by the amounts demonstrated would not cause any problems. The one concern is that the loading onto the piston from the conrod would be non central and cause a bending moment onto the shank of the conrod. This in turn would result in abnormal piston wear during running of the engine. This area is to be given attention during testing of the engine (refer section 3.5.2).

3.4.5   Counterweight Thread Distortion

After hardening the main journals it was discovered that threads for the bolting on of counterweights

had also been hardened. This was attributed to the threads being adjacent to the journal radii and receiving sufficient heat for them to become hardened after quenching of the crankshaft. Such a characteristic is unacceptable since it causes the thread to become brittle, resulting in failure once a torque is applied to it.

A method had to be developed which would successfully divert the heat away form the threaded portion so that the steel would not transform to austenite and become hardenable. For this purpose bolts were made out of brass and inserted into the threads for the duration of the hardening process. The theory being that brass has a high heat absorption capacity. This method proved to be successful, without any hardening nor shrinkage of the threads taking place.

During the trials it was noted that a few shafts exhibited thread distortion. This was detected by means of a thread plug gauge. Investigation showed that this was due to some brass bolts being worn, where the crest of the thread had become rounded resulting in a reduction of heat transfer from the crankshaft thread to the bolt.

3.5   Component Testing

3.5.1   Fatigue Testing

As mentioned in section 1.5, fatigue testing by means of applying reoccurring bending moments (or stress cycles) across the webs joining pin and main journals, could not be performed locally because of

the lack of suitable testing equipment. Two radius hardened ADE 366 shafts were subsequently sent to a German company which performed fatigue tests. Both shafts were tested and achieved the infinite life rating necessary for crankshafts, by achieving 10^7 stress cycles without any signs of failure.

3.5.2 Engine Testing

For the purpose of the test an ADE 366 engine was built fitted with the radius hardened crankshaft. Crankshaft bearing oil clearances, timing gear backlash and crankshaft end-float were checked and found to be within specification.

ENGINE ASSEMBLY - DIMENSIONAL DATA			
FEATURE BEING EVALUATED	DIMENSIONAL SPECIFICATION	RESULTS AFTER RUNNING 0 HOURS	200 HOURS
Crankshaft end-float	0,19-0,32 mm	0,23 mm	0,25 mm
Timing gear free-play	0,07-0,18 mm	0,14 mm	0,15 mm
Conrod No.1-Axial end-float	0,10-0,40 mm	0,25 mm	0,29 mm
Conrod No.2-Axial end-float		0,23 mm	0,26 mm
Conrod No.3-Axial end-float		0,24 mm	0,30 mm
Conrod No.4-Axial end-float		0,27 mm	0,33 mm
Conrod No.5-Axial end-float		0,21 mm	0,30 mm
Conrod No.6-Axial end-float		0,24 mm	0,25 mm
Piston No.1 - Protrusion	-0,088-0,3 mm	0,285 mm	0,267 mm
Piston No.2 - Protrusion		0,246 mm	0,238 mm
Piston No.3 - Protrusion		0,283 mm	0,269 mm
Piston No.4 - Protrusion		0,261 mm	0,240 mm
Piston No.5 - Protrusion		0,254 mm	0,223 mm
Piston No.6 - Protrusion		0,241 mm	0,210 mm

Table 3.10-Engine assembly dimensional data, taken off
critical features, before and after test run

The engine test program consisted of a 200 hour run as detailed under section 2.5.2. Results obtained from the test run are tabulated in tables 3.10 and 3.11. After the test run, the engine was disassembled and visually inspected for wear and defects. Special emphasis was given to piston wear as a result of out of tolerance pin-journal spacing (c.f. 3.4.4). No abnormal wear pattern on the cylinder bores nor pistons could be found.

The crankshaft was also crack detected and was found to be free of any defects indicating fatigue.

ENGINE PERFORMANCE DATA DURING TEST						
ENGINE SPEED (r/min)	POWER (kW) AFTER			BLOW-BY (l/min) AFTER		
	0 HRS.	100 HRS.	200 HRS.	0 HRS.	100 HRS.	200 HRS.
2800	142	138	138	85	83	85
1400	85	85	86	59	54	-
1000	43	41	41	40	38	-
OIL CONSUMPTION						
AFTER 100 HOURS		AFTER 200 HOURS		OVERALL		
45 gram/hour		65 gram/hour		54 gram/hour		

Table 3.11-Engine performance data, recorded before
        and during test run.

* * *

CHAPTER 4

DISCUSSION OF RESULTS

4.1 Introduction

A large scale investigation was undertaken covering all main aspects related to radius hardening. As mentioned previously this process was developed making use of a single inductor hardening machine. The results obtained are thus to be seen in this context. The principle of approach used in the preceding sections can therefore be applied for multi- inductor units, but results obtained will not necessarily be the same. From the results obtained it is possible to draw conclusions with regard to process formulation and implementation.

4.2 Crankshaft Radius Hardening

It was shown that cracking occurs in the hardened radii if the shaft is straightened. Runout as a result of hardening will therefore have to be kept to a minimum since shafts cannot be straightened because of the danger of crack formation. Crack formation in the radii is fully unacceptable since this this will lead to premature failure, which is similar in nature to fatigue failure.

4.3 Steel Selection

The 37Cr(S)4 steel selected proved to be suitable for the process. In terms of fatigue characteristics it also proved to be suitable for

crankshaft applications, provided that the radii are hardened (c.f. section 4.5).

4.3.1   Forging Process

During the development phase it was discovered that shafts which are subject to radius hardening are more sensitive to residual stresses stemming from the forging process. The hot forging operation induced residual stresses which were not fully released during the cooling down and tempering stages of the forging process. Straightening of the forging after tempering releases some of the internal stresses. This coupled with stress relieving at a temperature slightly below the tempering temperature produced a more stable shaft suitable for a manufacturing process.

4.4   Manufacturing Process

4.4.1   Runout Control (Soft Stage)

Runout of the finished centre main journal of the crankshaft is not allowed to exceed 0,15 mm (drawing specification). It was thus the aim to remain within this tolerance whilst machining the shaft through the soft stages. The reason for this was to keep deformation of the component in the soft stages to a minimum, as a high distortion indicates stress induction which could become uncontrollable during the hardening phase.

Although average runouts below 0,15 mm could not be achieved, with an average runout of 0,18 mm being obtained, acceptable results were gained once the

crankshaft was hardened and finish ground. The soft stage machining sequence utilised (c.f. table 3.3) was therefore acceptable.

Considering the favourable results achieved during the hardening and grinding stages, straightening of the shaft prior to hardening (in order to reduce runout) was not required and warranted no further investigation.

4.4.2   Runout Control (Hard Stage)

Runout of the crankshaft had to be kept low since straightening after hardening was not possible (c.f. 4.2). In addition it was desirable to keep runout to a minimum, since this amounts to less stock removal during the grinding stage. These requirements were achieved by making use of the measures discussed in the following subsections.

4.4.2.1 Hardening Sequence and Support of Shaft

Trials performed (refer table 3.4) showed that for this particular type of crankshaft the ideal hardening sequence was firstly to harden the pins and then the mains. Lowest runout results are achieved when supports, consisting of rollers, are used on mains 3 and 5 when hardening centre main No. 4 (thrust journal). For both pins and mains the hardening was performed from the outer ends of the shaft towards the inside, as listed below:

Pins - 6,1,5,2,4 and 3
Mains - 7,1,6,2,5,3 and 4

Note: Main No.7 is the one closest to the flywheel

end of engine

This data will vary depending on the type of crankshaft to be hardened. Also in a high volume environment where multiple inductors are used different types of supports will be used.

4.4.2.2 Hardening Pattern Depth and Runout

No notable reduction in runout was evident when reducing hardness depth. An average runout reduction of only 0,01 mm was recorded when comparing results obtained between the maximum and minimum hardness depths specified. Based on this it was considered ideal to harden shafts at mid tolerance depth (c.f. fig. 3.2 for tolerances).

4.4.2.3 Quench Concentration and Runout

The recommended quench concentration specified for the BP Quendila quenchant is 10% - 15%. Results of the trials performed showed that lower runouts are obtained with an increase in quench concentration. At the same time it was also noted that there was a drop off in hardness once the concentration was increased beyond 14%. Based on a concentration of 14% an average runout of 0,89 mm was obtained. this could be further reduced when using shafts which had been manufactured out of forgings which had been straightened and re-stress relieved prior to machining. On these shafts the average runout was reduced to 0,75 mm (c.f. section 3.3.1 & table 3.2).

4.4.2.4 Quench Temperature and Runout

Trials performed using BP Quendila as a quenchant,

resulted in the necessity to thermostatically regulate the quench temperature between 35°C and 40°C. From the results obtained (c.f. fig. 3.4) it is evident that best results are obtained in this band width.

4.4.2.5 Stress Relieving and Runout

No benefit is gained from stress relieving for a period of longer than two hours at 200 °C. Trials showed that stress relieving for longer than two hours resulted in no change in behavioural characteristics, or a reduction in runout. Since stress relieving longer is also more costly it was decided that stress relieving for 2 hours, which is also the same period used for non radius hardened shafts, was the ideal time scale needed.

4.4.2.6 Grinding Sequence and Runout/Stroke

The grinding sequence adopted to obtain acceptable results is as follows:

- Pre-grind main journals
- Pre-grind pin journals
- Recentre centres at ends of crankshaft using main journals No. 1 & 7 as location (datum)
- Finish grind main journals
- Finish grind pin journals

The fact that re-centering of the shaft is necessary in order to control the strokes proves that the shaft is so distorted after hardening, that the centres of the shaft no longer run true to the journals. This can be seen as the cones of the

centres lying at an angle to the journals. This
will induce an up and down motion while the shaft is
being ground. Because of this the stroke of the pin
journal cannot be controlled unless the centres are
realigned to the main journals by means of
re-centering after pre-grinding of the main
journals. This fact was proved when grinding shafts
which had not been re-centred. On these shafts the
stroke tolerance could not be maintained since the
position of the centres were not central to the
shaft.

Pre-grinding of both main and pin journals proved to
be a necessity in terms of releasing stresses
(caused by hardening of the radii) evenly. As was
demonstrated shafts which had not been pre-ground on
the pin-journals tended to creep up to 7 months
after grinding. This resulted in runouts being out
of specification. The motion of using 4 grinding
sequences instead of 2 (additional 2 pre-grinding
sequences) resulted in an even manner of disposing
of internal stresses in the shaft. One negative
connotation of this aspect is the fact that the
output capacity of the grinders is reduced by more
than half (when also taking into account the
additional handling time). This reflects a major
production on-cost when taking into account that the
current day cost of an automatic CNC controlled
grinder is in excess of R 4 million. One alternative
of overcoming this problem is by operating the
grinders on a 7 day 24 hour shift system. This will
still offset the cost of purchasing additional
grinders, or developing a new engine which does not
require radius hardened crankshafts.

4.4.3   Shrinkage of Crankshaft after Hardening

Shrinkage of the crankshaft occurs after hardening, after pre- and finish grinding of the main journals as well as after pre-grinding of the pin journals. No further shrinkage was detected after final main grinding (c.f. section 4.4.2.6 for grinding sequence). This in effect confirms that internal stresses induced during hardening are released during the grinding process. This releasing of stresses results in the shaft shrinking even more than after hardening only. It is a very important feature which must be realised in order to ensure correct machining lengths in the soft stage to allow for even grinding stock removal after hardening. From the graphs plotted in figures 3.6 & 3.7, it can be seen that shrinkage from the centre thrust journal is almost symmetrical when compared to opposite ends, between main journals 1 and 7.

4.4.4   Pin Journal Lengths

From the trials performed it was established that the tolerances stipulating the length positions from the centre main thrust journal could not be kept. This indicates that distortion emanating from the hardening process offsets the position of the pin journals. Since pin journal grinders are positioned by means of an even spark split (even stock removal on both sides of grinding wheel), this resulted in collar face steps between the journals and web faces remaining even. Apart from the length positions being out of tolerance by up to 0,57mm on a tolerance of ±0,15mm, the pin journal finishing in itself was kept within specification. Results from

the engine test showed that no negative influences from the out of tolerance pin journal length position were detected (c.f. section 3.5.2).

4.4.5   Counterweight Thread Distortion

Heat is conducted from the crankshaft journal radii into the region of the threads. This was evident when inspecting counterweight threads of radius hardened shafts since they displayed a blueish-brown discolouration. Excessive heat in the thread will cause it to deform and also be hardened. The acceptable solution to this was the use of brass bolts inserted into the threads during the hardening cycle. These provided sufficient heat transfer away from the thread into the bolt. It is important to note that bolts have to be inspected for wear, especially since brass is a soft material. Bolts which were worn on the thread crests had reduced heat transferring abilities resulting in thread distortion.

4.5   Component Testing

Testing of the components was done using destructive (fatigue cycle testing) and non destructive (engine testing) methods.

Fatigue testing confirmed that the increase in loading on the crankshaft could be achieved through radius hardening the journals.

Fatigue testing has to be supplemented by engine testing since this provides the actual dynamic conditions which the crankshaft is subjected to.

Aspects which have to be closely monitored are the wear characteristics on the journals as well as any visible signs of cracking in stressed areas on the crankshaft. In addition a problem was identified in the length position of the pin journals (c.f. 3.4.4). This meant that attention had to be given to the wear pattern on the pin journal and conrod small-end bushes.

All data analysed was comparable to that achieved on engines with lower loading using non-radius hardened crankshafts. Wear patterns on both pin and main journals, as well as conrod small-end bushes were fully acceptable. This was also confirmed by the acceptable oil consumption, oil temperature and oil pressure recorded, which are normally the first indicators when excessive wear problems are experienced. An increase in oil consumption could inter alia have been an indication of uneven piston wear due to uneven load distribution on the conrod small-end bush. Excessive or premature wear of the crankshaft journals would have resulted in a drop in oil pressure as well as an increase in oil temperature.

No signs of cracking were evident on the crankshaft after the test run, which indicated that there were no fatigue mechanisms in action.

* * *

CHAPTER 5

SYNTHESIS, CONCLUSIONS

AND RECOMMENDATIONS

5.1   Introduction

The aims of this dissertation was to develop a
method of radius hardening Diesel engine crankshaft
journals. This was seen in the light of having to
increase engine power output with the crankshaft, in
the non-radius hardened stage, being at it's fatigue
design limit. Two basic options were available,
(i) either change the physical properties of the
crankshaft such that its fatigue characteristics are
modified, or (ii) alternatively redesign the
engine. With the cost of redesigning an engine
being prohibitive, hardening of the journal radii in
order to improve fatigue characteristics was
investigated.

In analysing the objectives set it can be summarily
concluded that radius hardening of Diesel engine
crankshaft journals is a viable and cost-effective
alternative to enable increased loading on a
crankshaft. The process developed is immediately
workable and can be universally applied as a method
of process development for other crankshaft
designs. This does not preclude the fact that there
is room for continued improvement of any such
process developed. In almost all of the facets
investigated certain problems were encountered, some
of which could only be solved by reaching
compromises.

In all areas of manufacturing no process is static. Continuous development should be ongoing in order to improve a process, making it cheaper and more superior. This is the foundation of this investigation, which serves a stepping stone for the development of the process of radius hardening.

5.2   Crankshaft Radius Hardening

Hardening of crankshaft journal radii in theory and in practice is an acceptable form of improving the fatigue characteristics of a crankshaft. By hardening the journal radii, increased loading can be imparted onto the crankshaft.

In manufacturing setups where crankshafts require straightening for reducing journal runout as part of the process, changes have to be implemented since radius hardened crankshafts cannot be physically distorted. This was demonstrated by means of tests which revealed that straightening of a hardened shaft leads to cracks in the region of the radii, which subsequently will cause the shaft to suffer catastrophic failure. In the case of the ADE 366 shaft, no serious difficulties were encountered when modifying the process in order to eliminate straightening. The process could be developed in such a manner that the soft stage process was fine tuned in such a manner that it did not induce any stresses resulting in excessively high journal runouts before and after hardening. Other designs of crankshafts could possibly display runout characteristics which are more difficult to control. Here individual investigations have to be carried out to find the most suitable machining

process, which will induce the lowest stress. The
physical nature of the ADE 366 crankshaft is such
that it is not very rigid within itself. Larger,
more heavy type of crankshaft designs on the other
hand, will with a high degree of certainty display
more stable characteristics. This would reduce the
problem of not being able to be straightened.

5.3   Steel Selection

A suitable, medium cost steel (37CrS4) was selected
for the process. In the radius hardened form, this
steel displayed suitable characteristics in terms of
hardenability, machinability and fatigue resistance.

This steel requires a fairly stringent process
control in the forging and hardening and tempering
stages, since it requires to be straightened and
re-stress relieved after hardening and tempering.
Forgings made out of the same material when used for
non-radius hardened crankshafts did not require this
additional procedure. Forgings used for radius
hardened crankshafts required the extra
straightening and stress relieving operation in the
forge. Otherwise it acted very unstable,
displaying high runouts after hardening. This was
attributed to the fact that residual stresses are
induced during forging in the region of the radii
and are not sufficiently released in the tempering
phase. Only after additional straightening and
stress relieving, these stresses are sufficiently
liberated so as to not generate problems whilst
induction hardening the journal radii. Additional
research could therefore be done in the field of
micro-alloyed steels. These steels require no

hardening and tempering and are cooled down directly after the forging process, ready for use. New development is ongoing in this field and warrants further investigation in terms of possible better suitability for radius hardening applications, as well as being a cheaper steel since it does not require hardening and tempering after being forged.

5.4   Manufacturing Process

In developing the manufacturing process the presence of residual or internal stresses in the crankshaft became a very staunch issue which had to be addressed. As was demonstrated through all manufacturing phases, internal stresses from the soft machining stage, the forging process, induction hardening of journals,up to grinding, all influenced the stability of the shaft unless they were properly controlled.

For the purpose of inducing as little as possible stress into the material, deformation of the crankshaft, in the form of journal runout has to be kept to a minimum. The soft stage machining processes have to be controlled in such a manner that they induce only minimum amounts of stress into the crankshaft before hardening. Hardening in itself has to be controlled in such a manner that all influences such as support of shaft, quench concentration and temperature are such that the desired hardness and penetration is achieved but at the same time keeping runout to a minimum. Shrinkage of the shaft occurred after hardening and grinding, which resulted in having to adjust the process in the soft stage to compensate for changes

in length after hardening. Whilst this was controllable on main journals, pin journal lengths were very much out of control.

Ultimately all facets could be combined to form a functioning manufacturing process, albeit that some aspects such as crankshaft stroke and pin journal lengths require further investigation. Dependent on the crankshaft design more rigid crankshaft executions will be less susceptible to these type of process problems. The use of a multiple inductor hardening machine, instead of the single inductor machine used for developing this process, could also possibly reduce problem areas related to deformation and runout after hardening.

5.5   Component Testing

Component testing was performed in order to confirm that radius hardening of the journal radii increases fatigue resistance. Components were evaluated at the higher loading in two manners namely, a fatigue stress cycle test and an engine test. In terms of the fatigue test 10^7 cycles (infinite life) were simulated by means of applying a bending moment across the webs joining pin and main journals. In augmentation a crankshaft was also tested in an engine for a period of 200 hours after which the crankshaft had also completed well in excess of 10^7 load cycles. Both tests yielded successful results from which it could be concluded that radius hardening in itself as well as the manufacturing process proved acceptable.

Component testing is one of the most critical

aspects of the radius hardening process development. This is the only method to prove that all facets from theory to practice have come to fruition. Any new radius hardening process development involving other crankshaft types, must therefore be confirmed by means of component testing.

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Bibliography

AMERICAN SOCIETY FOR METALS (A.S.M.) 1981.
VOLUME 4, HEAT TREATING. METALS PARK OHIO,
AMERICAN SOCIETY FOR METALS.

AMERICAN SOCIETY FOR METALS (A.S.M.) 1975.
VOLUME 10, FATIGUE ANALYSIS AND PREVENTION.
METALS PARK OHIO, AMERICAN SOCIETY FOR METALS.

PURDAY, H.F.P. 1962. **DIESEL ENGINE DESIGNING.**
CONSTABLE & COMPANY LTD., LONDON

LILLY, L.R.C. 1984. **DIESEL ENGINE REFERENCE
BOOK.** BUTTERWORTH AND CO. (PUBLISHERS) LTD.,
LONDON.

SHIGLEY, J.E. 1986. **MECHANICAL ENGINEERING
DESIGN.** UNIVERSITY OF MICHIGAN - FIRST METRIC
EDITION. MC GRAW-HILL. BOOK COMPANY.

CHAPMAN, W.A.J. 1972. **WORKSHOP TECHNOLOGY.** PART
1 - AN INTRODUCTORY COURSE. EDWARD ARNOLD
(PUBLISHERS) LTD., LONDON.

DIETER, G.E. 1981. **MECHANICAL METALLURGY.** 2ND
EDITION - INTERNATIONAL STUDENT EDITION. MC
GRAW-HILL INCORPORATED.

THELNIG, K.E. 1975. **STEEL AND IT'S HEAT
TREATMENT.** BOFORS HANDBOOK. BUTTERWORTHS.

DUBBEL 1974. **TASCHENBUCH FÜR DEN MASCHINENBAU**. VOLUME 1, 13TH. EDITION. SPRINGER VERLAG, BERLIN / HEIDELBERG.

BARGEL, H.J. / SCHULZE, G. 1988. **WERKSTOFFKUNDE**. 5TH EDITION. VDI-VERLAG GmbH, DÜSSELDORF.

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