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# EXPERIENCES WITH CHROMIUM PLATING ON MEDIUM SIZED DIESEL ENGINE CRANKSHAFTS

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The intention of this paper is to provide confidence in the use of chromium plating of crankshaft journals of medium sized diesel engines as a feature or reclamation process. The paper attempts to clarify the important features of chromium plate and makes comparison with other methods of surface treatment. Details of crankshaft preparation and machining operations are discussed together with a review of the desired standard of surface finish. The success of the technique is demonstrated by reference to the results of fatigue tests on full sized specimens and extensive experience with crankshafts in commercial service.

## INTRODUCTION

The electro-deposition of chromium in engineering applications is applied either (a) to increase the wear resistance, or alternatively (b) for the reclamation of worn, damaged or over machined surfaces. The chromium plating of diesel engine crankshafts has been practised for many years although on a relatively limited scale, and even today its use is still not widespread nor particularly well known. There is a precise division of opinion amongst design engineers associated with the process who either appreciate its attributes or who remember the problems experienced during the early history of chromium plated crankshafts, such as poor adhesion and the deleterious effect of chromium plating on the fatigue strength of the crankshaft material. In addition doubt is often expressed on the suitability of chromium plate when applied to a damaged journal for reclamation purposes.

It is the purpose of this paper to promote confidence in the use of chromium plating for crankshafts—for increased wear resistance, compatibility with hard bearing materials and for the reclamation of damaged bearing surfaces. The paper also attempts to clarify the important features of chromium plate and it reports on the extensive experience in commercial service of the performance of reclaimed damaged journals. Also demonstrated is the absence of any fatigue reducing effect of correctly applied chromium plate as evidenced by full scale fatigue tests and it is shown that the consistent research effort over the years, by the platers in particular, has resulted in solutions to the plating problems previously mentioned. It is appreciated that chromium plating is used for a wide variety of engineering applications but there is no doubt that one of its most exacting duties is when applied to crankshafts and therefore the standard of application and finish must be at the maximum level of current technology. The modern practice of anodic cleaning, detailed attention to surface finish, limiting the plating area and controlling the plating conditions can result in an adherent, stress-free chromium layer of excellent wear resistance with no effect on the fatigue strength of the crankshaft.

The content of the paper is generally based on information obtained from the authors' experience with diesel engine crankshafts of approximately 4m in length with journal diameters of 160 to 220mm in marine and railway service. The tensile strengths of the steels used are in the range of 750 to 1100 MN/m$^2$. No reference is made to the actual design of crankshafts as the procedures are well documented and outside the scope of this paper.

For both technical and economic reasons the paper emphasizes the close liaison that is essential between designers, manufacturers and platers of crankshafts in order to obtain a satisfactory chromium plated surface. Though the residual stress level can be measured, it is virtually impossible to non-destructively test the adhesion of the chromium layer to the substrate steel, and it follows that a high standard of integrity and workmanship is required at all stages of production from the various sub-contractors. Provided the correct plating technique is used, satisfactory adhesion and residual stress levels are always obtained in the chromium plate and therefore the use of nationally known concerns with adequate technical resources is considered advisable. Of equal importance are the subsequent machining and finishing operations as described later in the paper.

Costs are discussed under the next section but it is worth noting that the experience behind this paper is from engines operated and repaired in the UK. It is quite possible that handling, shipping and waiting costs will be greater for obtaining a new crankshaft for installation in a crippled engine in far distant locations. Nevertheless it could still be worthwhile saving a damaged crankshaft for reclamation on a non-urgent basis and the reclaimed shaft held as a spare.

For an original chromium plated design of crankshaft the use of plating permits the designer an increased freedom in that he can select the most suitable alloy steel for the particular application, based solely on the design stress criteria. Thereafter a hard chromium plate on the bearing areas enables the attainment of the optimum surface conditions for wear resistance and thus it is not necessary excessively to harden the base metal of the crankshaft in order to obtain a satisfactory level of wear resistance. This eases the problems of the base steel selection in several ways; for example the limiting ruling section for any particular alloy would be increased for quench and temper heat treatments if lower tensile strength steels were used. Secondly the possible use of a lower and hence cheaper alloy steel for the crankshaft gives the advantage of using the steel at a lower tensile level and hence decreased susceptibility to the notch fatigue reducing effect of inclusions and transverse grain flow. As a repair technique, chromium plating is especially acceptable on economic grounds in two areas. It can obviate the scrapping of a crankshaft, which is a particularly expensive part of a diesel engine, due to wear for damage of perhaps only one journal.

The engine down time is reduced to an acceptable level due to the speed of the process thus overcoming the problem

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of a long lead time for the manufacture of a new crankshaft, especially in the case of older engines, and the need to carry more than a nominal number of spares. The other economic area is the avoidance of having to run a crankshaft at non-standard sizes thus requiring special bearing shells for which one pays a price premium. This latter practice results in having to stock a large number of non-standard bearings and maintenance staff occasionally fitting an incorrect shell. In the case of reclamation, a simple yardstick is whether the reinstating of an otherwise scrap crankshaft, by virtue of building up journals to within available bearing diameters, will cost less than a new shaft. Generally speaking when a journal is ground down in preparation for plating, the resulting diameter cannot be more than 2 to 3mm less than the bottom undersize at the maximum since 1 to 1·5mm thickness of chromium plate is the limit of the authors' experience. As the journals of the shafts referred to in the paper are in the range of 160 to 220mm in diameter it may be considered that a reduction of 2 to 3mm will not bring about a significant increase in operational stress.

On crankshafts containing chromium plated journals as a design feature it is usual to plate a thickness of 0·125 to 0·3mm. Reclaimed shafts are plated to a maximum thickness of 1mm on the basis of this being the limit of fatigue testing of sample crankshafts. However, it is known that a small number of shafts are in service with a plating thickness of 1·5mm. There are also many shafts in service with a 'flash' chromium plated bearing surface of up to 0·05mm in thickness for increased wear resistance. The authors have only limited experience with this latter plating thickness.

### FOR AND AGAINST CHROMIUM PLATING

This section compares the merits of hard chromium plating relative to other forms of crankshaft journal coating or thermal treatments and in particular to the use of nickel either by itself or as an undercoat for the chromium. Whilst the authors have no experience of nickel plating some of the pros and cons can be extracted from a literature survey.

Chromium coatings are hard but brittle and crack easily producing stress concentrations which may reduce the fatigue strength of the underlying steel. Nevertheless the low coefficient of surface friction of chromium plate and its high hardness combine to make it an excellent bearing surface. The crankshafts reported on in this paper had a deposit hardness in the range 700 to 800 Hv compared to 250 to 290 Hv for an unplated Cr/Mo steel crankshaft, and as such have a high resistance to abrasion and hence a low wear rate. In common with other non-thermal processes chromium can be deposited without distortion or other thermal effects. Hard chromium plate can be deposited satisfactorily over a thickness range of 0·025 to 1·0mm, and although some authorities quote 0·5mm as an economic limit it is known that apparently successful deposits in excess of 1·0 mm thickness are in service. The normal effect of chromium plate on the base steel is a reduction of fatigue strength. This is discussed later in the paper. This effect has been shown by various workers ([2, 3] and [8]) to be largely independent of deposit thickness in the range 0·05mm. to 0·5mm. The full scale tests reported in this paper, are attempting to extend this knowledge to 1·0mm deposit thickness, when the plating is limited to the bearing surface of the crankshaft journals. Conversely the quality of nickel as a bearing surface is dubious as evidenced by some authorities. Conventional nickel deposits have hardnesses in the range 130 to 300 Hv and whilst hard nickel deposits can be obtained in the range 400 to 650 Hv such hardness levels are still at a disadvantage as regards abrasion resistance when compared with chromium plate. Nickel plating is generally cheaper than chromium plating and may be obtained in even greater thickness, although some hard nickel deposits have restrictions as regards thickness and cost. But perhaps the greatest disadvantage of nickel may be regarded as the reduction of fatigue strength with increasing deposit thickness. Various workers have reported on this phenomena ([2, 11, 12]) but perhaps the work reported by Williams and Hammond is best quoted. Increasing the thickness of nickel from 0·025 to 0·125mm caused a marked reduction of fatigue strength of the base steel. They reported for a steel of tensile strength 665 MN/m$^2$, a fatigue strength of 285 MN/m$^2$ for 0·025mm of nickel; when the thickness of nickel was increased to 0·125mm the fatigue strength of the steel was dropped to 225/185 MN/m$^2$. It is known that nickel has also been used as an underlay to chromium plate and some sources suggest this is preferable where coatings thicker than 0·25mm are required but it is considered that this practice can only meet with limited success. The problem is that the fatigue strength of nickel at a maximum of $\pm$225 MN/m$^2$ $\times$ 10$^7$ cycles is appreciably lower than chromium at $\pm$300 MN/m$^2$ $\times$ 10$^7$ cycles and a Cr/Mo base steel at say $\pm$ 335 MN/m$^2$ $\times$ 10$^7$ cycles.

Table I shows the comparative fatigue strengths of chromium and nickel plated specimens.

For deposits of the order of 1mm in thickness the use of a

TABLE I—FATIGUE STRENGTHS OF CHROMIUM AND NICKEL PLATED SPECIMENS

| *Material** | *Tensile strength MN/m²* | *Coating* | | *Bending fatigue strength* | | *Ratio B/A* |
|---|---|---|---|---|---|---|
| | | *Type* | *Thickness mm* | *A—Unplated MN/m²* | *B—Plated MN/m²* | |
| Armco Iron | 230 | Cr | 0·15 | 166 | 192 | 1·18 |
| 0,3C N | 510 | Cr | 0·15 | 246 | 254 | 1·03 |
| 0,5C N | 620 | Cr | 0·05 | 293 | 277 | 0·95 |
| 0,5C N | 620 | Cr | 0·15 | 293 | 284 | 0·97 |
| 0,5C H & T | 680 | Cr | 0·05 | 338 | 322 | 0·95 |
| 0,5C H & T | 680 | Cr | 0·15 | 338 | 310 | 0·92 |
| 0,5C H & T | 730 | Cr | 0·15 | 368 | 312 | 0·85 |
| En 25 H & T | 810 | Cr | 0·05 | 425 | 295 | 0·69 |
| En 25 H & T | 810 | Cr | 0·15 | 425 | 315 | 0·74 |
| En 25 H & T | 810 | Cr | 0·30 | 425 | 305 | 0·72 |
| SAE6130 N | 480 | Cr | 0·11 | 226 | 219 | 0·97 |
| Cr,Mo,V | 1100 | Cr | 0·20 | 564 | 330 | 0·59 |
| Ni,Cr | 1050 | Cr | 0·25 | 542 | 280 | 0·52 |
| 3%Ni | 665 | Ni | 0·025 | 377 | 302 | 0·80 |
| 3%Ni | 665 | Ni | 0·125 | 377 | 227 | 0·60 |
| Ni,Cr | 984 | Ni | 0·04 | 539 | 339 | 0·63 |
| Ni,Cr | 984 | Ni | 0·40 | 539 | 241 | 0·45 |

Conventional Chromium Plate at 2 000/3 000 amps/m$^2$ at 50 $\pm$ 5°C, Unbaked.
Nickel results refer to Watts Bath.
*N—normalized, H—hardened, T—tempered.

sprayed steel, plasma sprayed deposit or indeed of reclamation by weld deposit may be considered. Sprayed steel tends to give a rather laminated and porous deposit with hardness in the range of 150 to 250 Hv and with a poor adhesion to the base metal of circa 30 MN/m². The adhesion can be increased to 70 MN/m² by the use of a molybdenum undercoat but the undercoat has the effect of a marked reduction on the fatigue strength of the base metal. In turn this fatigue strength reduction can be largely eliminated by the use of shot peening to create residual compressive surface stress, before the molybdenum underspray. Sprayed steel deposits have been successfully used on small crankshafts with journals of approximately 50 to 75mm diameter and steels in the tensile strength range of 450 to 600 MN/m², but it is considered that its use on larger crankshafts at higher levels of tensile strength is not advisable. An extensive spectrum of plasma sprayed deposits is available in a wide range of hardness. No experience is available to the authors on such deposits but it is of note that spalling of thick deposits over 0·5mm has been reported, due to the laminated nature of the deposit. Finally the use of a weld metal build up by using a low heat input fine wire process could possibly be developed for cast steel or mild steel crankshafts, but not for the higher tensile strength steels used for crankshafts reported on in this paper.

Alternative methods of obtaining a hard wear resistant surface comparable with hard chromium plate might be induction hardening, case hardening or the use of flame detonation coatings such as a tungsten carbide aggregate in a cobalt matrix (WC-Co). Hardness levels of 700 Hv can be obtained with induction hardening over the bearing surface and to a depth of 5 to 7mm in the steels commonly used for crankshafts. Service experience has shown that if a bearing seizure occurs, with the high level of internal stress associated with 700 Hv induction hardened surfaces the seizure can result in such extensive cracking beneath the hardened surface as to make the crankshaft irreparable. Conversely, if induction hardening of circa 350 Hv is used, although such hardness levels show resistance to extensive cracking, when seizure occurs they offer no appreciable advantage over an untreated crankshaft as regards wear resistance. Nitriding or case hardening steels are the most obvious solution to the problem of wear but they are most expensive alloys to process. For use in engines associated with the crankshafts reported in this paper the use of case hardening steels would result in gross overdesign as regards fatigue strength. Many crankshafts, smaller than those considered here, are successfully nitrided in volume production but an attempt to make a large scale crankshaft (circa 4m in length) in the UK met with failure due to distortion. However, provided sufficient work is undertaken in developing a technique for nitriding large scale crankshafts it is the authors' opinion that success could be achieved and that the distortion considered acceptable would be dependent on the crankshaft design and bearing technology. Finally, WC-Co flame detonation coatings have a high hardness of approximately 1000 Hv and an excellent adhesion to the base metal of circa 350 MN/m². But the thickness of such deposits is limited to 0·15mm and they require finish grinding by a most expensive diamond wheel process.

In these days of considerable rises in price it is considered impossible to compare the cost of various techniques directly in money terms. Realistic production costs are also often difficult to obtain since the authors are primarily involved with development. It is perhaps therefore more appropriate that the manufacturing processes applied to large crankshafts should be based primarily on technical requirements. However, from experience it is considered that the cost of reclaiming one journal of a crankshaft would be of the order of some 10 to 15 per cent of the cost of a new crankshaft. For reclaiming four journals the cost would be expected to rise to some 30 per cent of a new crankshaft and subsequently to 40 to 50 per cent for reclaiming all journals. For a design incorporating chromium plated bearing surfaces an increase in price of approximately 20 to 25 per cent over the price of an unplated shaft of the same steel might be expected. This would compare favourably with an equivalent increase of cost of some 40 per cent if a nitrided crankshaft could be developed. It should perhaps be noted that the actual cost of the plating process is quite low and for a single journal reclamation would be only some 1 or 2 per cent of a new crankshaft cost. Most of the reclamation cost is usually absorbed in preparation, non-destructive testing and post plating machining.

### SELECTION FOR PLATING

Before chromium plating a new or damaged crankshaft the effect of the plating on the mechanical properties of the shaft must be carefully assessed and data is given in later sections. It was stated earlier that the use of chromium permits the designer more freedom in the selection of materials: however, it is known that in certain conditions the chromium plating causes a reduction in fatigue strength of the substrate steel. In general the adverse effects become more pronounced as the tensile strength of the base metal increases and therefore designers should avoid selecting materials of unnecessarily high tensile strength.

The metallurgical condition of a new crankshaft presents no problems, for the plating is applied as an integrated part of the manufacture. The microstructure of the base steel is normally a tempered martensite matrix which provides a satisfactory surface to obtain a sound bond for the electro deposit.

In the case of plating as a repair technique it may be utilized in two reclamation fields; either for worn or damaged journals. Crankshafts are normally designed to permit regrinding to a fixed number of standard undersizes and if the worn shaft is at the bottom undersize before reclamation is undertaken, it is necessary to verify that, after preparatory grinding the "in service" stress level in the shaft is still acceptable. At the same time due allowance must be made for the effect of the overlying chromium for the thickness and disposition of the chromium plate are such that it must be considered to have a negligible effect on the load/web deflexions, etc., of the crankshaft. A worn crankshaft will normally require plating of all journals and the determination of the chromium thickness to be applied will be dependent on the standard bearing sizes, the required remaining life of the shaft, the negligible wear rate of the chromium and the cost. An important factor here is the logistics of the spares supply and which is of particular significance in countries with lower technological standards. A normally worn shaft will be in a similar metallurgical condition to a new shaft and therefore requires no additional inspection before plating, other than magnetic particle crack detection after preparatory grinding.

The economic case for reclamation of a crankshaft with damaged journals (often it is only one journal) is obvious and usually the design and inspection aspects are sufficient to determine whether or not a particular shaft is recoverable. The usual cause of journal damage is partial or total bearing seizure and the extent of surface damage experienced by the shaft is largely a matter of luck, i.e. the speed with which operating staff detect the onset of the bearing failure. Unfortunately though, the damage is often extensive by the time the engine has stopped rotating and is characterized by deep circumferential scores and tears. Once out of the engine, the shaft receives a preliminary inspection to determine if any cracks are present and whether the damage can be removed with a reasonable amount of grinding. Magnetic particle crack detection of the journal is used throughout as the damage is removed, whilst of course the minimum undersize as permitted by the designer must be borne in mind. Once any cracks or other physical defects have been removed the journal is degreased and etched with a 5 per cent Nital solution (solution by volume of nitric acid in alcohol). The ferritic areas of the journal darken after a few seconds whilst any untempered martensitic hard spots, caused by abnormal local heating during the seizure (greater than 720°C), remain light, perhaps surrounded by a dark ring. This etching also permits a detection of copper diffusion from the bearing, appearing as small bright yellow spots. The grinding and etching must be continued until the surface is in a uniform condition. Hardness may also be checked by using a recoil device—Sclerographé. The removal of untempered martensite and copper is especially important since both are the source of possible fatigue cracks and the chromium does not cover up defects but actually amplifies them. The new shafts and those to be reclaimed would then have reached a common stage in the chromium plating process.

TYPES OF PLATING

This paper refers entirely to crankshaft journals (mains, pins and also gear or chain wheel seatings) plated with dense, non-porous, 100 per cent engineering chromium which is substantially stress-free. The definition of "substantially stress-free" means that the residual stress level does not exceed $+75\ MN/m^2$. The residual stress level in the chromium is of vital importance and is entirely within the control of the plater, being dependent on the electrolyte concentration and temperature, plating voltage and current. Typical deposition rates to produce the chromium layer in the optimum condition vary between 0·015 and 0·075 mm/h, with substantially stress-free deposits generally being obtained at the lower levels of the range. This means that building up the chromium layer to give a finished thickness of, say, 1mm is a slow and expensive operation but nevertheless it is absolutely essential that every care is taken to ensure the success of the plating. All too often the plater attempts to hasten the operation, usually with disastrous results. Among the faults that can be encountered are unsatisfactory adhesion of the chromium to the base steel, blow holes, nodulation of the surface and high residual stress level. The residual stress in the chromium can be determined by use of a "spiral contractor meter" or by simultaneous plating one side of a flat steel strip, measuring the resultant deflexion, calculating the bending stress and thus the residual stress.

With optimum plating conditions an entirely satisfactory deposit of stress-free chromium can be laid down as shown in Fig. 1. The journal shown is actually coated with developer after dye penetrant crack detection. Depending on the plating and grinding conditions, the chromium layer often contains a connected network of fine cracks described as craze cracking. This feature does not become readily apparent until the grinding has been commenced and usually takes one of two forms —separate plates 1 to 2mm across, or 4 to 5mm across as shown in Figs. 2 and 3 respectively. Admittedly the latter illustration is rather severe with craze cracking extending right to the edge of the chromium at the oil hole. Craze

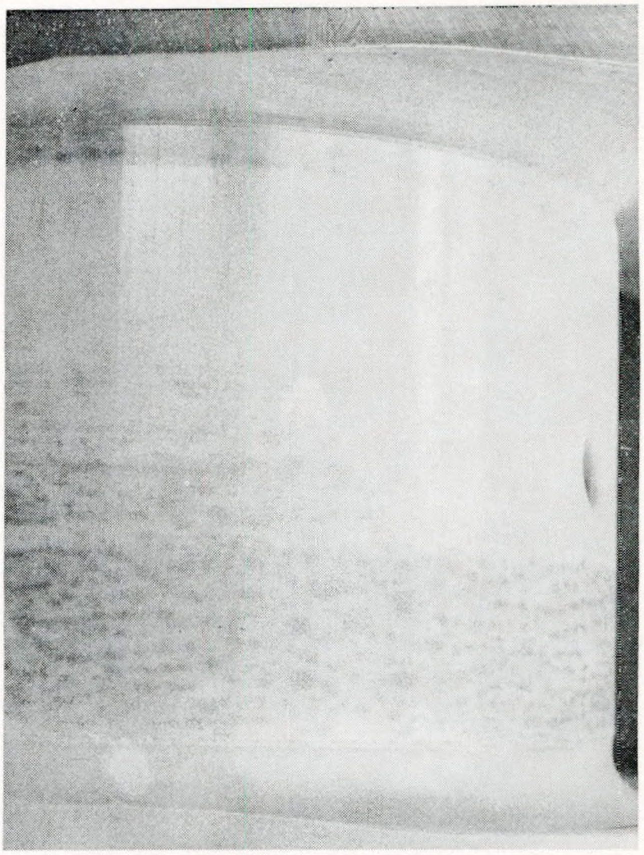

FIG. 2—*Craze Cracking – 1 to 2mm spacing (coated with dye penetrant developer)*

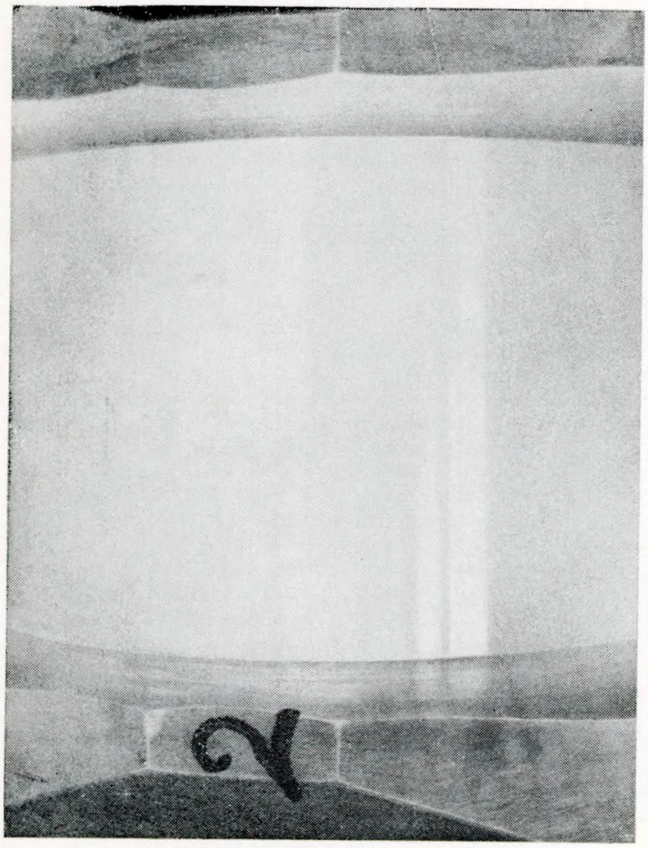

FIG. 1—*Stress free chromium plated journal (coated with dye penetrant developer)*

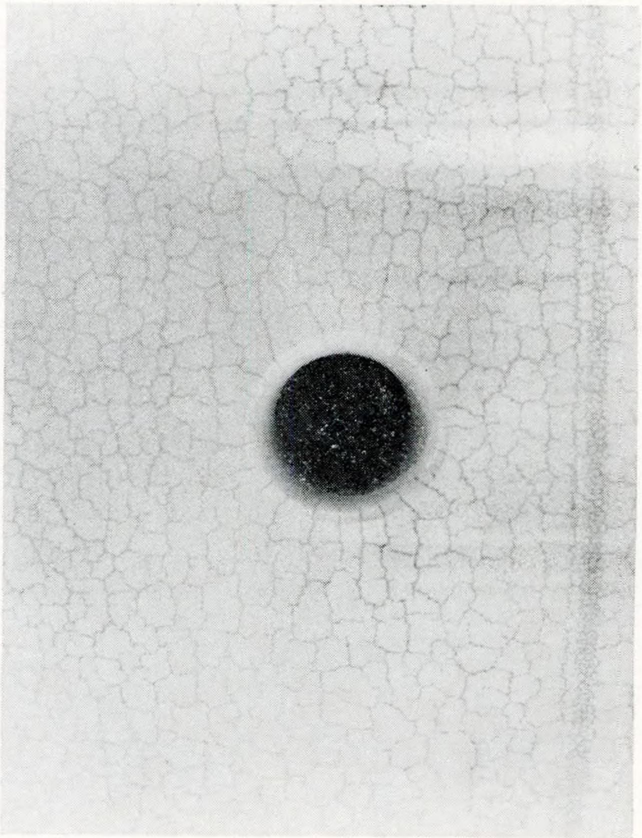

FIG. 3—*Craze Cracking – 4 to 5mm spacing (coated with dye penetrant developer)*

cracking of the type shown in Fig. 2 is accepted by many as the norm and consequently there must be a large number of shafts in service in this condition. One of the dangers of course is that the cracks may propagate through the chromium to the chromium/steel interface and then proceed to initiate a fatigue crack in the steel. Fine craze cracking can also be produced by incorrect grinding even in a stress-free chromium plate and is discussed in the section on Machining.

The authors have considered a more recent development known as micro-cracked chromium—not to be confused with craze cracking, In this technique an extremely fine network of cracks, circa 120/mm (3000/in) is deliberately created in the chromium during the plating process with the objective of providing stress relief (and presumably a higher deposition rate) and an oil retaining surface. A number of technical problems were encountered and the authors did not proceed with any assessment of this technique. Some concern was expressed over the deliberate creation of cracks due to the known possibility of fatigue crack initiation from this type of feature.

Other aspects of chromium are dealt with elsewhere in the paper but the plating used on the crankshafts in the authors' experience has received no post plating heat treatment; it is described as "unbaked".

The authors have looked into the techniques and art of electro-deposition and are agreed that there is little point in the designer becoming too deeply involved, if at all, in the details of the process. Of course the plater must be given all pertinent details of finished sizes and ultimate duty of the crankshaft, but it is considered that all other aspects should be left to the expertise of the plater. It goes without saying that the plater must be committed to eradicably underwrite his work and guarantees have been witnessed which indemnify the safety of the engine from damage due to defective plating.

As a guide to the three principal plating processes utilized throughout the world, basic details of each are given below, though of course each specialist company has its own particular modifications. It is particularly important to avoid plating or attempting to plate the oil hole and transition fillets because of the stress raising effect of the chromium and the associated difficulty of obtaining a consistently satisfactory deposit in these areas. The oil hole, transition fillets, webs and all other such areas must therefore be carefully masked before plating, the extent of masking being determined by the characteristics of the process utilized.

*Vat or Bath Plating*

The traditional bath of electrolyte is still employed by many platers with the work piece as the cathode and a stainless steel, lead or lead/antimony anode with all the deposit material coming from the electrolyte. The bath can be designed either to accommodate vertical or horizontal work pieces. Mechanical or air agitation of the hot electrolyte is used to remove gas bubbles from the surface being plated, although this is not always successful. The main disadvantage of this process is that the entire crankshaft is immersed in the electrolyte and thus the whole of the shaft has to be masked except the journals to be plated. The plant heating and post plating cleaning costs are also high in this process. Crankshaft designers hold certain views on the method of support of shafts and they should be consulted to ensure that the shaft weight is not allowed to cause excessive strain or deflexions due to the method of suspension in the vat.

*Spray Box*

A split box which carries a cylindrical anode surrounds each journal to be plated by this process. The electrolyte is copiously sprayed onto the cathodic journal to flush off the gas bubbles and is retained in the box by seals running on the transition fillet which is masked to limit the area being plated. This method is particularly useful for reclamation of crankshafts if only one or two journals are to be plated, and is relatively cheap. The process becomes more expensive if all journals are to be plated due to the appreciable setting up time for boxes, electrolyte and electrical connexions. The simplest version is with the work stationary but alternatives involve rotating the shaft whilst the box remains stationary.

*Swab Plating*

A development of the spray concept is to have the work piece continually wiped by swabs, to remove plating gas bubbles. This process inevitably involves sprays or piped electrolyte and boxes are demanded also. There are known examples of hand applied plating methods using anodic backed swabs that must utilize a special electrolyte. The skill required with this process to achieve consistently good results is such that it is doubtful whether it has any commercial or technical value on crankshafts.

Each of the above processes has its own particular technical merits and it is probable that the final selection will depend on the cost and service offered by a particular company.

## MACHINING

This section deals with pre and post plating machining of the crankshaft journals. Generally, original manufacture and reclaimed crankshafts follow the same procedures with the exception of additional inspection stages in the latter case.

*Pre-machining inspection*

This operation presents few problems with a new crankshaft as the preparation for chromium plating is an integrated part of the manufacture. The required surface finish is identical to that for crankshafts being reclaimed and the choice of the deposit receiving surface profile is dependent on the finished chromium thickness. A crankshaft for reclamation due either to wear or damage to a journal(s) must first be crack detected all over by a magnetic particle process with particular attention being paid to transition radii and oil holes. An initial careful examination must also be made of any scored journals to determine the extent of damage and possibility of reclamation. De-magnetization is essential after any electric or magnetic testing.

One of the main differences between an original manufacture crankshaft and one for reclamation is that the original machinist has plenty of safety margin in the relatively large tolerances on a forging, whereas a repairer must hit targets only fractions of a millimetre wide to keep within diameter, parallelism, stroke and crank angle. In broad terms therefore an accurate geometric picture must be obtained to enable the shaft to be installed and adjusted in the grinding machine so that the journal(s) to be recovered run on correct axes of rotation. Inspection measurement involves a robust accurate surface table and equipment suitable for 0·025mm TIR support or better and 0·015mm measurement of heights and diameter. For this work the shaft must be thoroughly clean as also must the vee blocks used as support for the main journals. Roller blocks are deprecated because foreign matter could damage journal surfaces. On this precision support, at as many points as possible, journal diameters are measured at several planes (see Fig. 4) and a record is made. Secondly, using dial or vernier height gauges, the shaft is progressively stepped around the positions of the four diameters employed above and shown in Fig. 4. At each step, the top or bottom height of every journal in each of the three planes is measured and recorded. By relating the resulting figures to the previously recorded diameters, it is possible to build up a full picture of the shaft, even taking into account of discovering twist, bend or out-of-roundness of both bad or otherwise good surfaces.

*Pre-plating machining*

The machining depends on the amount of stock to be removed. On new shafts it is the practice to use a pinning machine—a specialized tooling unit employing a form tool and which is especially useful on those crankshaft designs which incorporate a recessed transition radius. This is followed by a single grinding operation to produce a surface finish of $14\mu''$ to $20\mu''$ CLA, for plating. A similar pre-plating surface finish is required on crankshafts being reclaimed, and grinding is the usual method of stock removal. The extent of course depends on the desired chromium thickness and finished size of the journal in relation to standard bearing sizes. Transition radius profile tooling attachments for grinding machines are known but changeover times and finishing of this area are costly. In the case of recessed transition radii there is no alternative to the use of attachments of either tooling or

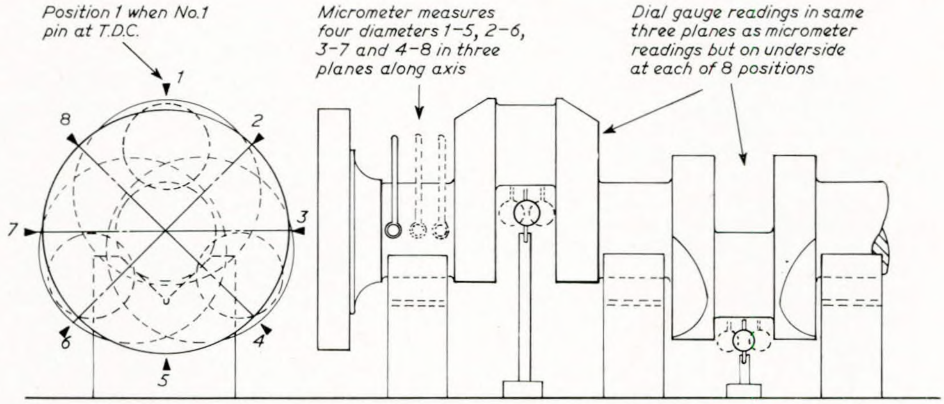


FIG. 4—*Measurement of crankshaft journals and alignment*

grinding type. The crankshaft with a damaged journal requires more attention than one with worn journals which are ground to fixed dimensions. The damage must be removed and the journal proved free from defects by the non-destructive testing methods described in the section on Selection for Plating.

*Profiles*

The profile of the deposit receiving surface and the extent of chromium on the journal has undergone considerable investigation and is also referred to in the section on the Effect of Chromium Plate on Fatigue Strength. From development work the two alternative profiles advocated by the authors are shown in Fig. 5A and B, together with the extent of the chromium layer. In the authors' experience profile A is recommended for thin deposits up to approximately 0·4mm whilst profile B should be used for all thick deposits. Profile A does present the platers with some problems of obtaining a satisfactory "unshielded" deposit at the chrome/steel boundary, although considerable service success is currently being achieved with this profile with thin deposits. "Shielding" or "shading" of the plating, caused by the proximity of geometrical changes and masking, does occur, but experience has shown that it is not a problem with profile B. Most platers agree that the majority of defects and problems occur with the thicker deposits. Other considerations of the choice of preparation profile are grinding wheel widths and profiles. A plain or radiused wheel will suffice for finishing the chromium of either A or B but B requires additional wheels to cope with finish grinding of the chromium edge or fall off, whereas A requires a radiused corner wheel for preparation grinding. Again with profile B, since the deposit edge will never be straight and perpendicular to the journal surface, but rather a fall off inwards and upwards towards the centre of the journal it will be seen that bearing width will be lost. To date this has not caused any problems, possibly because the finished, hard, precision journal surface presents a consistently greater area of intimate contact between journal and bearing material than does a softer steel journal whose effective contact area must inevitably reduce due to uneven wear, bruising, etc., during its service life. With the superior contact of the chromium, the bearing pressure must stay at its lowest value for longer than steel. Nevertheless the majority of crankshafts referred to in this paper were ground to profile B for the following reasons:

a) Preparation grinding does not always necessitate chromium reclamation if a suitable undersize is arrived at in the preparation process, therefore a finished profile can be left at just that stage.
b) Preference is felt for the plain profile to avoid complications of watching and controlling the annular ridge between the stepped radii of profile A, during preparation grinding.
c) After plating, the exact position of the base steel surface is known from the register at the bottom of the transition radius (see Fig. 5).

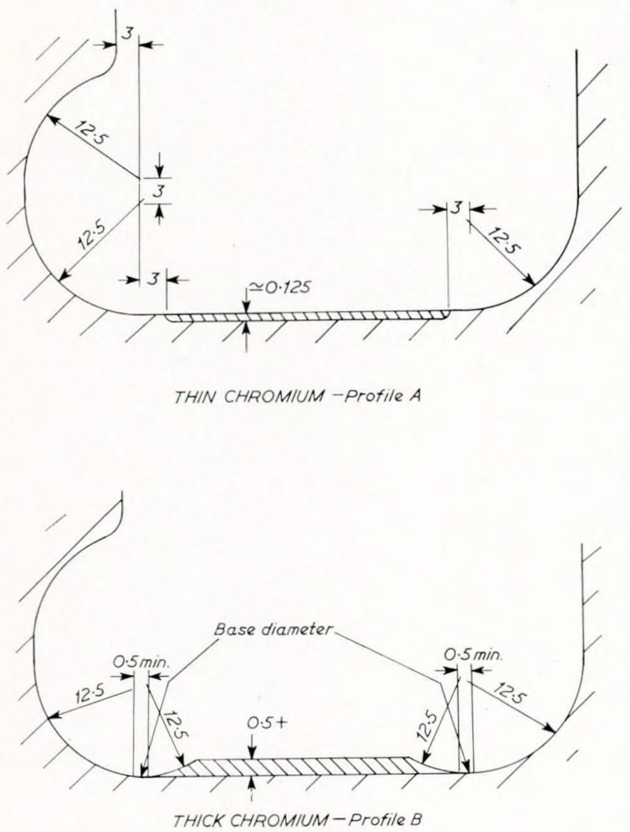


FIG. 5—*Profile of deposit receiving surface and transition or fillet radii (typical dimensions)*

*Chromium Plating*

After preparation grinding the journals are cleaned with a petroleum solvent, followed by acid etch or grit blasting. The plating processes were referred to in the section on Types of Plating and it is assumed that a substantially stress-free deposit has been achieved. The chromium fall off is difficult for the plater to perfect but experience shows that profile B is easier to finish than A on the basis that local polishing is often possible to remove minor defects. In the case of profile A, if there are any defects at the edge of the chromium, a grinding groove must be made down into the otherwise flush surface, thereby reducing the bearing area and creating an undesirable stress concentration.

Defective plating can usually be detected after the first few grinding cuts and must be removed chemically or by grinding, and the journal replated.

*Post-Plating Machining*

The grinding of the chromium is as vital to the success of the use of chromium plating as the plating itself, and it is imperative that cuts should not exceed 0·013mm and preferably 0·010mm. Excessive feeds rates are readily detectable by dye penetrants since, even in stress-free chromium, incorrect grinding results in fine craze cracking of the type shown in Fig. 2. The plater's skill is necessary to ensure that over-plating above the desired finished thickness is avoided, thereby removing the temptation of the machinist to take large initial cuts. The plater usually allows up to 0·25mm additional deposit on finished size for grinding allowance. The authors have experience of calling for extra allowance to enable eccentric grinding to take care of odd geometric errors discovered in shafts and those which could not be corrected entirely at pre-plating machining; this does not appear to have adversely affected the fatigue strength of the crankshaft.

A representative set of conditions to achieve a finish of, say, 14 to 20μ" CLA, free from fine craze cracking is:

1) Soft wheel of 60 grit; H hardness
2) Grinding wheel peripheral speed 20 to 30 m/s
   Workpiece peripheral speed 0·15 to 0·3 m/s
3) Light cut 0·010mm to 0·013mm
4) Liberal coolant—soluble oil
5) Heavy, substantial machine—free from self induced or external vibration.
6) Frequent wheel dressing—this has been found to be very important.

A finish of better than 14μ" CLA can be achieved under ideal grinding conditions but it is preferable to undertake a final polishing operation with wooden lap boxes and 240 grade emery to achieve a finish of 8 to 12μ" CLA.

*Finishing of Radii and Oil Hole*

The finish of the chromium/steel boundary is of equal importance and a similar standard of surface finish to the bearing area is required. At the transition radius of profile A, a flush surface is automatically obtained and no further grinding is necessary. Where profile B is used some 1·2m or 20m of transition radius requires to be finished on a single journal or all journals respectively of an eight throw crankshaft. It is considered that this finishing should be done by a machining process rather than a hand held bob grinder which cannot produce entirely satisfactory results. Detail of the transition radius is shown in Fig. 5 but evolution of a satisfactory grinding technique has still not been concluded. Development work in connexion with the grinding of chromium will also be applicable to pre-plating machining. Several problems present themselves, e.g.:

1) Sufficiently solid support of the work piece and of grinding tool.
2) Variations of profile dimensions due to non-production nature.
3) Extra precision requirements of blending radii, etc., and hitting datums.
4) Radii recessed into webs, i.e. recessed transition radii.

Nearly all the authors' experience is with a rotating workpiece. Post-plating machining of transition or fillet radii of profile B presents problems because a profiled wheel must be used, see Fig. 6. This is costly due to wasted stone lost at profile dressing and an alternative being actively pursued is the employment of a bob. A proposal is shown in Fig. 7, but to date a small enough pneumatic or electric tool to be accommodated between webs has not been found. Such a proposal appears practicable to the authors. It should be mentioned here that when a crankshaft is rotated in a machine, when set up for pins, it runs true only for a few pins, due to the lack of like rotation pins available for a support, e.g. with a 6 throw shaft, pins 1 and 6 are complementary but support at one, whilst the other is being machined, is of minimum assistance to stability. Hence, invariably when pins are being machined, there will be obvious whip or flopping that detracts from good machining finish. However, experience has shown that careful selection of shaft rotational speed can reduce this effect to a minimum depending on the shaft, speeds of between 10 and 30 rev/min being usual. The resulting out-of-roundness appears so far to be small enough to be tolerated in service. To overcome this problem, which should not appear in

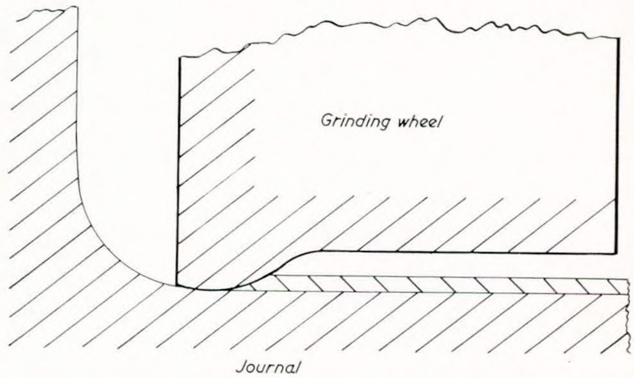


FIG. 6—*Shaped grinding wheel for transition radius - Profile B*

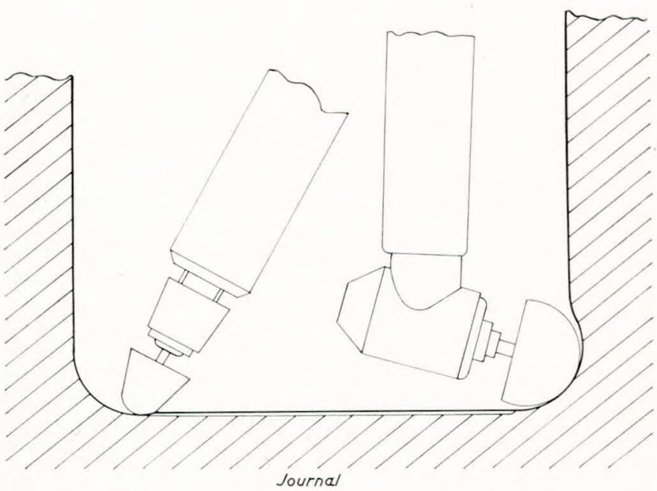


FIG. 7—*Proposal for grinding transition radius (open and recessed) - Profiles A or B*

connexion with main journal machining, another proposal is to investigate the use of a pinning machine, currently employed in new manufacture of shafts, suitably adapted to take a small bob-grinder in place of the full width tool usually employed. In such a case the shaft is held stationary.

There is no alternative at present to hand finishing of the oil hole, by means of bobs or emery cloth on rotating pads. The oil hole profile, which is shown in Fig. 8, will no doubt

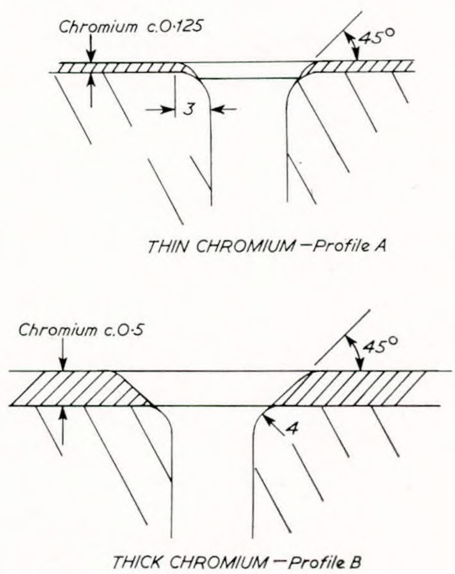


FIG. 8—*Oil hole profiles*

continue to present difficulties although by means of a shaped plastic plug as a mask during plating, the deposition phenomenon of shaded areas can be utilized to provide an approximate profile.

The transition radii should be wiped with a 2 per cent copper sulphate solution and the surface examined for any area of chromium which will stand out bright against the red-brown background. Careless plating can occasionally leave these small spots of chromium in this area and experience has shown that they can be the source of fatigue failure. The chromium can be removed by local dressing. The journal is finally examined for craze cracking of the chromium with dye penetrant.

### QUALITY OF SURFACE FINISH

As mentioned in the previous section, the surface finish of the steel and chromium is most important. Apart from the desirability of having an exceptionally good bearing surface it is also desirable that all highly stressed surfaces are super-finished to reduce the risk of propagation of fatigue cracks from notches in the surface finish. Such a super-finish is also of material help in detecting the presence of diffused material or previous seizure defects that might remain in the bearing surface during the pre-plating examination.

A number of workers have investigated the effect of surface finish on fatigue strength but generally have not utilized precise measurements of surface finish. Usually they have designated the surface finish by the method of preparation of test specimens. If the physical efficiency of an alloy is to be utilized to its fullest extent, the standard of surface finish must accordingly be at an acceptable level. However this does not mean that an especially fine polish is always to be applied but rather that the most suitable and economic standard of finish should be adopted. A survey of many designs of crankshaft show a requirement for finishes in the range of 12 to 32μ″ CLA. The authors in their work on new and reclaimed crankshafts have adopted a scale of surface finish of one grade higher, i.e. 8 to 24μ″ CLA. It is felt that since the machining of crankshafts is a costly business the additional cost in raising the standard of surface finish is worthwhile. It also ensures that a high standard is always aimed for in production.

The critical regions of the non-bearing surfaces of the crankshaft design with which we are concerned are the fillet radii and oil holes. Two measurements of fillet radii surface finish can be obtained: firstly, from a circumferential traverse of the measuring stylus which therefore measures the "longitudinal" surface, i.e. at right angles to the stylus traverse; secondly, from a longitudinal stylus traverse which measures the circumferential surface finish. It is this latter surface finish, which is at right angles to the direction of bending stress caused by web deflexion, which is of prime importance. This effect of direction of surface finish is amply illustrated by some fatigue results of Fluck [18] in which the insensitivity of the material to a 45μ″ CLA finish parallel to the stress is demonstrated in Table II. Siebel and Gaier [19] have found that there is a "critical surface roughness" beyond which there is no increase in fatigue strength with decrease in surface roughness. This critical roughness is independent of the type of fatigue stress but varies with the material and metallurgical structure. They used the maximum depth of surface groove as a criterion for classifying surface roughness rather than CLA values. For steels tempered to relatively high strength the "critical surface roughness" is 40 to 80μ″, whilst for annealed steels a range of 160 to 240μ″ pertains. These surface finish levels appear excessive for maximum fatigue strength but it should be remembered that they are not the general CLA surface finish but the maximum depth of a particular groove on the surface, and also that ground finishes generally contain at least one or two scratches in the range of 20 to 100μ″ even if the CLA finish is at a level of 4μ″, e.g. surface finish of ball and roller race tracks.

TABLE II—BENDING FATIGUE LIFE OF SAE 3130 STEEL

| Type of finish | Surface roughness μ″ CLA: Longitudinal traverse | Surface roughness μ″ CLA: Circumferential traverse | Mean fatigue life Cycles × 10³ |
|---|---|---|---|
| *Stress ±625 MN/m²* | | | |
| Lathe Formed | 105 | 15 | 24 |
| Partly Hand Polish | 6 | 4 | 91 |
| Hand Polish | 5 | 3 | 137 |
| Ground | 7 | 45 | 217 |
| Ground and Polished | 2 | 6 | 234 |
| *Stress ±610 MN/m²* | | | |
| Lathe Formed | 105 | 15 | 54 |
| Partly Hand Polish | 6 | 4 | 280 |
| Hand Polish | 5 | 3 | 311 |
| Ground | 7 | 45 | 368 |
| Ground and Polished | 2 | 6 | 690 |

from Siebel & Gaier [19]

In general it is found that the highest levels of fatigue strength are obtained with emery polishing in the direction parallel to the loading. If very gentle grinding is used, i.e. passes of approximately 0·01mm, then a similar fatigue strength to the emery polished surfaces can be obtained. Conversely if grinding passes are of the order of 0·05mm, this can result in tempering and the introduction of tensile stress into the surface which can severely reduce the fatigue strength. Such a reduction of fatigue strength generally cannot be redressed by subsequent emery polishing.

Machinery currently used for reclamation is generally not specifically made for superfinishing odd fillet radii. This process is usually coped with in the new manufacturing field by expertise rather than by any sophisticated production methods. Therefore reclamation will inevitably involve adaptation of lower precision machines by way of attachment, etc. Some ideas have been postulated in the section on Machinery.

The sequence and choice of machining operations depends on the target surface finish and the amount of material to be removed. Where large quantities of material are involved and particularly when a recessed fillet is associated with a seizure, turning is the obvious choice for economical stock removal. In the case of a crankshaft design with an open fillet then plunge grinding is often preferred. For smaller amounts of metal to be removed an alternative process is grinding. Lapping and polishing cannot really be regarded as a stock removal process. It has been found prohibitive in cost to improve a turned or ground finish of say 24μ″ CLA level by lapping or polishing so that serious thought should be given to the development of a grinding method to give a CLA finish of 12μ″ directly. This finish could be subsequently improved economically by lapping or polishing if desired.

In the case of oil holes the finishing process must remain a manual one, for very little machining or fixture holding of bobs is possible. Chromium must not extend down the oil hole more than half way down the bell mouth of the oil hole radius and it is recommended that a finish of 12μ″ CLA or better be adopted for this critical region. Where the crankshaft specification calls for reaming and ball draw peening care must be taken that the latter process does not result in cracking of the chromium plate.

### EFFECT OF CHROMIUM PLATE ON FATIGUE STRENGTH

The effect of different types of chromium plate on the fatigue strength of steels of various tensile strengths has been extensively investigated by many workers by the use of small size specimens (i.e. 7 to 12mm diameter). The papers by Stareck, Steys and Tulumello [9] and also by Williams and Hammond [2] give an excellent review of the subject and in Table I typical results are reported for substantially stress free unbaked chromium plated deposits.

Many factors were shown to influence the fatigue strength of electroplated specimens but two were shown to be dominant. Firstly, the intrinsic fatigue strength of substantially stress free chromium plate appears to be of the order of ±300 to ±375 MN/m². Chromium plating on materials of higher fatigue strength results therefore in a lowering of their fatigue strength; the higher the fatigue strength of the base metal the higher is the percentage reduction of fatigue strength. Secondly, residual stress in the chromium plate reduces the fatigue strength still further. The level of residual stress has been shown to be largely a function of plating conditions and in particular of the plating temperature.

Williams and Hammond[9] published the following formula by which it is possible to estimate the reduction of fatigue strength due to chromium plating, *viz:*

$$L = 50 - T - 3S$$

where L = per cent change in fatigue strength
T = Tensile Strength in ton f/in²
S = residual Stress in ton f/in².

In order to use this formula it is necessary to have a residual stress measurement made concurrent with the plating, as referred to in the section on Types of Plating.

Where a residual stress figure is not available a similar expression by Stareck[9] may be used in which the fatigue strength of the chromium plated specimen is related to the density of craze cracks in the chromium plate. The higher the density of the craze cracks in the chromium plate was taken as evidence of the relief of residual stress and hence the lower the reduction of fatigue strength would be. Craze cracking of this type is either discrete cracks or alternatively incomplete craze cracking. Any craze cracking introduced into the chromium plate by incorrect grinding can interfere with the accuracy of the formula.

$$F_p = F_s + 1 \cdot 3\,C - 85$$

$F_p$ = Fatigue limit of plated specimen in 70 kgf/cm² (1000 lbf/in²)
$F_s$ = Fatigue limit of unplated steel in 70 kgf/cm² (1000 lbf/in²)
C = number of cracks per inch.

Both these formulæ relate to unbaked deposits without shot peening beneath the deposits.

In order to retain a high base metal fatigue strength and hardness in the chromium plate it has been found necessary by various workers [6, 7, 8] to shot peen the base metal before plating. Such a technique has a most beneficial effect on the fatigue strength and in addition a subsequent low temperature heat treatment to eliminate any hydrogen embrittlement has no detrimental effect on the fatigue strength [6]. Shot peening has not been practised on the crankshafts in the authors' experience.

As stated the crankshafts referred to in this paper are in tensile strength range of 700 to 1000 MN/m² and such are not normally considered to be susceptible to hydrogen embrittlement. Consequently post plating heat treatments which is usually used to relieve hydrogen embrittlement, has not been practised on the crankshafts referred to in this paper. It is however considered necessary to detail the danger, associated with post-plating heat treatment. For steels of 1200 MN/m² and over various authorities suggest a post-plating heat treatment of two to six hours at 200°C. However Wiegand and Scheinost [1] and others [2, 3, 4] have shown that post-plating heat treatments in the range if 150 to 300°C can significantly reduce the fatigue strengths of high tensile steels still further. Logan [3] and subsequently others [2,4] have shown that heat treatment *circa* 450°C after plating can restore the loss of fatigue strength. However such high temperatures can result in loss of base metal strength and softening of the chromium plate from a plated hardness of 800 to 900 Hv to approximately 650 Hv[5]. If these reductions in properties are acceptable then post-plating heat treatments can be practised.

Information on the effect of chromium plating on the fatigue strength of full size crankshafts is sparse, although Williams and Brown [15] carried out tests on full size crankshafts of 525 MN/m² Tensile Strength and obtained a fatigue strength of 170 MN/m² for the unplated specimen (i.e. 0·32 of the Tensile Strength) and 100 MN/m² for the plated crankshaft (i.e. 0·19 of the Tensile Strength). Their results were obtained on crankshaft specimens with the radii and oil holes plated and represented a considerable reduction in fatigue strength.

From the proceeding two reasons testing full size chromium plated crankshaft specimens emerged. In addition it was questioned whether commercial platers and crankshaft manufacturers could handle a crankshaft of some 4m in length, and deposit and machine the chromium plate satisfactorily on a production basis. The detailed nature of the most satisfactory method for limiting the extent of the chromium on the bearing surface became the matter of some controversy. The opportunity was therefore taken of testing in plane bending and torsion, full size crankshaft elements (an element consists of two journals, two webs and one crankpin) as they became available, and comparing the effects of various techniques and design details on the fatigue strength. It was considered desirable that the chromium plate should have no effect on the fatigue strength of the crankshaft as to be evidenced by initiation of fatigue cracks entirely outside the chromium plated area, i.e. the product of stress concentration effect of the chromium layer and associated working stress to be less than the similar product at other geometrical features of the crankshaft design. As well as different thicknesses of chromium plate, various design alternatives were tested. Fig. 5 details the two alternative designs proved to be most successful in delineating the end of the chromium plate on the bearing surface at the transition radius and oil hole. The machining techniques discussed in the section on Machining were used on all the crankshafts tested in this programme.

The tests were undertaken on one of two, purpose built, resonant fatigue rigs as described by Cox [16]. One rig was for testing specimens in the bending mode and the other for testing in the torsional mode. The specimen was stressed in the required mode by making it the elastic element in a spring resonant system. In this system a rod was driven axially at a controlled amplitude and frequency by an electric motor and eccentric, and was coupled to the resonant system by means of a slipping clutch. The frequency of oscillation of the exciter rod was increased till it reached the resonant frequency of the mass-spring system at which point the clutch ceased to slip and the amplitude of oscillation was controlled by excursions of the exciter rod. The crankshaft elements were first stress analysed by determining the position of maximum stress in the transition radii by means of brittle lacquer followed by actual measurements with a series of electrical resistance strain gauges. The relationship was then obtained between the maximum stress and web deflexions. Crankshafts elements were stepwise tested at ±30 MN/m² intervals for $10 \times 10^6$ reversals at each step. For example, ±100 MN/m² for $10 \times 10^6$ cycles; ±130 MN/m² for $10 \times 10^6$ cycles and so on. The second specimen was then tested at intervals of stress of say ±115, ±145, and ±160 MN/m² and this permitted the fatigue srength of the crankshaft to be determined within a ± 15 MN/m² accuracy. The ± 30 MN/m² steps were chosen to be sufficiently coarse so as not to promote the coaxing phenomena.

Work on the fatigue strengths of unplated shafts showed that they had fatigue strengths of 0·27 to 0·35 of the tensile strength of the relevant material. This is in general agreement with the work of Williams and Brown[15] who showed that a 0·32 ratio of the tensile strength could be obtained. Normally on 10mm diameter longitudinal specimens of hardened and tempered steels a ratio of 0·5 of the tensile strength would be expected.

On these large diameters and with the influence of transverse properties, the lower ratios are to be expected. Tests on ten plated crankshaft specimens have shown that with the finishing techniques detailed in Figs 5 and 8 and provided that substantially stress free chromium plate is also used, then the specimens always break outside the chromium plated area and therefore have fatigue strengths similar to the unplated specimens. However if small areas of chromium plate are left in the highly stressed transition radii due to inadequate inspection, a substantial reduction in the fatigue strength of the crankshaft can result to as low as 0·17 of its tensile strength. A number of specimens with craze cracking similar to that illustrated in Fig. 2 cracked in the chromium plated area with fatigue strengths of 0·18 of the Tensile Strength. A single torsional fatigue test has been made with chromium plate down the oil hole and this resulted in a reduction of the torsional fatigue strength by some 40 per cent over that obtained for an unplated control specimen. Table III details the steels used and typical results.

TABLE III—FATIGUE TEST RESULTS

| *Engine type* | 6 in line | 12 *Vee* | 16 *Vee* | 16 *Vee* |
|---|---|---|---|---|
| Chemical Composition | | | | |
| Carbon | 0·50 | 0·31 | 0·32 | 0·56 |
| Silicon | 0·23 | 0·19 | 0·22 | 0·25 |
| Manganese | 0·80 | 0·56 | 0·51 | 0·77 |
| Nickel | 0·09 | 0·19 | 0·07 | 0·10 |
| Chromium | 0·74 | 2·52 | 2·66 | 0·73 |
| Molybdenum | 0·46 | 0·24 | 0·21 | 0·40 |
| Vanadium | | | 0·13 | |
| Properties | | | | |
| Proof Stress MN/m² | 585 | 655 | 905 | 620 |
| Tensile Strength MN/m² | 790 | 880 | 1080 | 875 |
| Elongation, per cent | 21 | 24 | 17 | 28 |
| Hardness Hv | 245 | 293 | 335 | 275 |
| Bending Fatigue Strength ±MN/m² | 230(1) | 325(2) | 305(1) | 305(1) |
| Bending Fatigue Strength per cent of T.S. | 30(1) | 37(2) | 28(1) | 35(1) |
| Bending Fatigue Strength ±MN/m² | + | + | 226(3) | 148(4) 157(5) |
| Bending Fatigue Strength per cent of T.S. | + | + | 21(3) | 17(4) 18(5) |

1) Typical results for plated or unplated specimens which broke outside the chrome plated area. (0·125 to 1·0mm chrome).
2) Result for unplated specimen.
3) Plated specimen (0·3mm chrome) failure occurred at chrome plate/steel junction.
4) Plated specimen (0·125mm chrome) failed in radius at 1mm dia spot of chrome.
5) Plated specimens (0·50 and 0·525mm chrome) failed in plated area which was craze cracked.

\+ Tests continuing—no failures influenced by chromium plating to date.

The criteria for no reduction of fatigue strength from chromium plating of the bearing surfaces both in bending and torsional modes are therefore:

1) Substantially stress free chromium plate.
2) Finishing design, as illustrated in Figs. 5 and 8
3) No chromium plate left in the highly stressed transition radii or permitted down the oil hole.
4) No craze cracking of chromium detectable by dye penetrant methods after finishing grinding.

## PRACTICAL EXPERIENCE

The practical experience of the authors with chromium plated crankshafts extends over a continuous period of about eight years and with the exception of development work the association has been with two particular designs of crankshafts in commercial service. In retrospect it is freely admitted that much knowledge has been acquired during this period and not only from the results of development work. One of the particular difficulties has been educating staff, new to the technique, of the critical nature of many of the varied operations in the plating and grinding process. This observation can be made equally of management, design and production staff. The first named group have been most difficult in context probably because of their obsession with cost and production rates. It will have now become apparent from the paper that the subject is exacting from production aspects but always well worth that "bit of extra effort" and to this end co-operation at all levels enables satisfactory results to be obtained. It can be said with confidence that the experience gained has enabled the standard of plating and finishing to be raised to a level which gives a chromium plated crankshaft an adequate fatigue life and one which is at least equal to that of the rest of the diesel engine.

The number of chromium plated crankshafts in service to the two designs mentioned above are 5 of a vee 12 cylinder 1200kW engine and 100 of a straight 6 cylinder 935kW engine. The failure rates are 0 and 3 per cent respectively. The failure statistics for the vee 16 crankshaft, which are chromium plated to 0·125mm thickness as a design feature, are such that no conclusions may be drawn except to say that to date they are performing entirely to satisfaction and on the basis of extensive development work there is no reason to believe that they should not continue to do so. At present each of these crankshafts has completed an appreciable number of engine hours. It is of significance that chromium plating of 0·125mm thickness has been specified for all future replacement and new build engine crankshafts of this design.

On the surface the failure rate for the straight six chromium plated crankshafts, the majority of which were reclaimed for one reason or another, does not appear particularly impressive and perhaps is the one aspect that certain sceptics have seized upon to condemn the technique. It is considered much more realistic to state that already a success rate of 97 per cent has been achieved with this particular design of crankshaft, and that this alone is sufficiently encouraging to extend the use of this method of bearing surface treatment. In consequence it is felt desirable to refer to these three failures in more detailed notes, to put the statistics into perspective and to further illustrate the standards of workmanship and inspection required throughout the reclamation process. On the other hand the required standards are not considered excessively high on an expensive and highly stressed dynamically loaded component. The chromium plated crankshafts of this particular design have seen a widely varying service of up to 30 000 engine hours each and have plating thicknesses generally in the range of 0·5 to 1·0mm.

### *Failure A—Reclaimed Crankshaft*

The fracture face characteristics were typical of a multi-point initiation reversed bending fatigue failure, with a 0·9mm chromium thickness. There was also evidence of a longitudinal crack probably associated with torsional stresses, although as is usual there was some mechanical damage to the fracture faces in the initiation area which had destroyed much of the evidence regarding the failure. The substrate steel was metallurgically satisfactory. The chromium plate was covered with both types of craze cracks as shown earlier in Figs 2 and 3. Many of the large craze cracks, thought to be due to high residual stress during plating, had penetrated through the chromium to the steel. The failure had initiated in the bearing area of the journal, approximately 10mm from the chrome fall off and away from the fillet radius, which is a common initiation area for a bending mode fatigue failure. Despite extensive investigation the precise cause of failure was obscure and can only be assumed to have initiated from a defect which was probably incurred during the reclamation process, for example untempered martensitic hard spot, surface score on the steel prior to plating, hydrogen embrittlement, blow hole in chromium or weld repair of same during plating, propagation of one of the craze cracks in the chromium into the steel or misalignment of the crankshaft in the engine. It is significant that all but one of the above possible causes of failure could have been avoided by the correct plating and/or grinding procedures.

*Failure B – Reclaimed Crankshaft*

The fracture face is shown in Fig. 9. The failure, in a crank pin, was of almost identical characteristics to that of failure A. The chromium thickness was 1·0mm and again the bearing surface was covered with the larger craze cracks which had penetrated through to the steel. In practically every aspect this incident was a repeat of failure A and the same conclusions were drawn. However, during the investigation, a section was taken transverse to the crack at the initiation point and at the edge of the bearing area at the chromium fall-off to the fillet radius, a number of the craze cracks had propagated into the steel. These are shown in Fig. 10, together with a deep score filled with chromium. The cracks in the steel, thought to be fatigue, were approximately 0·04mm long. This was the only occasion that such cracks have been found by the authors, propagating from the base of craze cracks in the chromium. Whilst this discovery was disturbing it was not totally unexpected. Although these cracks in the steel were close to the initiation area of the fracture it could not be stated categorically that the failure of the crankshaft was from a similar crack and equally since their presence could not be ignored it had to be finally concluded that in fact both these crankshafts had probably failed due to propagation of one or more of the craze cracks. It is the authors' opinion that both crankshafts were the victims of unsatisfactory preparation or plating which would have been evident after grinding and which should have been identified by the finished work inspectors.

*Failure C – Reclaimed Crankshaft*

This crankshaft failed in a torsional mode through a main journal and the web. It is significant that the crack did not originate at the oil hole as in most torsional failures, immediately pointing to a fault with the chromium plate of greater effective stress concentration. The failure is shown in Fig. 11 and as with the previous two failures the extent of damage to the bearing shell was such that it could not have been the cause of failure. The chromium plate on the broken

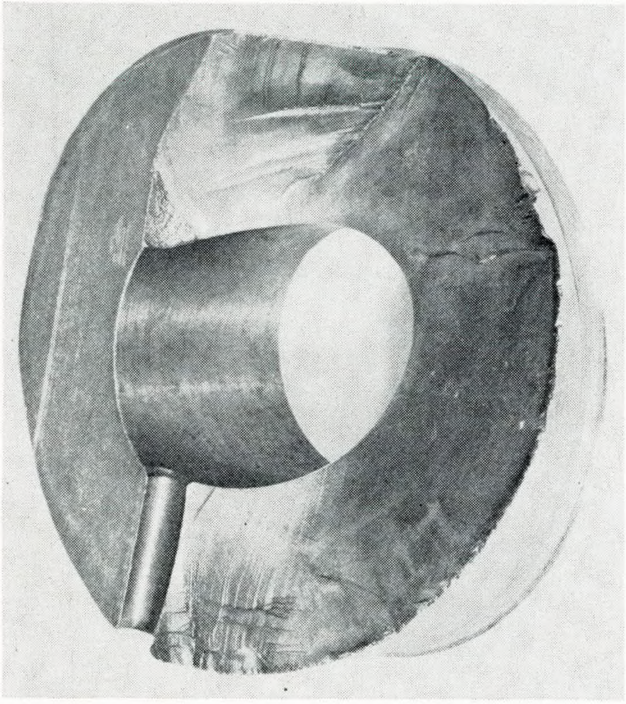

FIG. 9—*Failure B – Fracture Face in Journal*

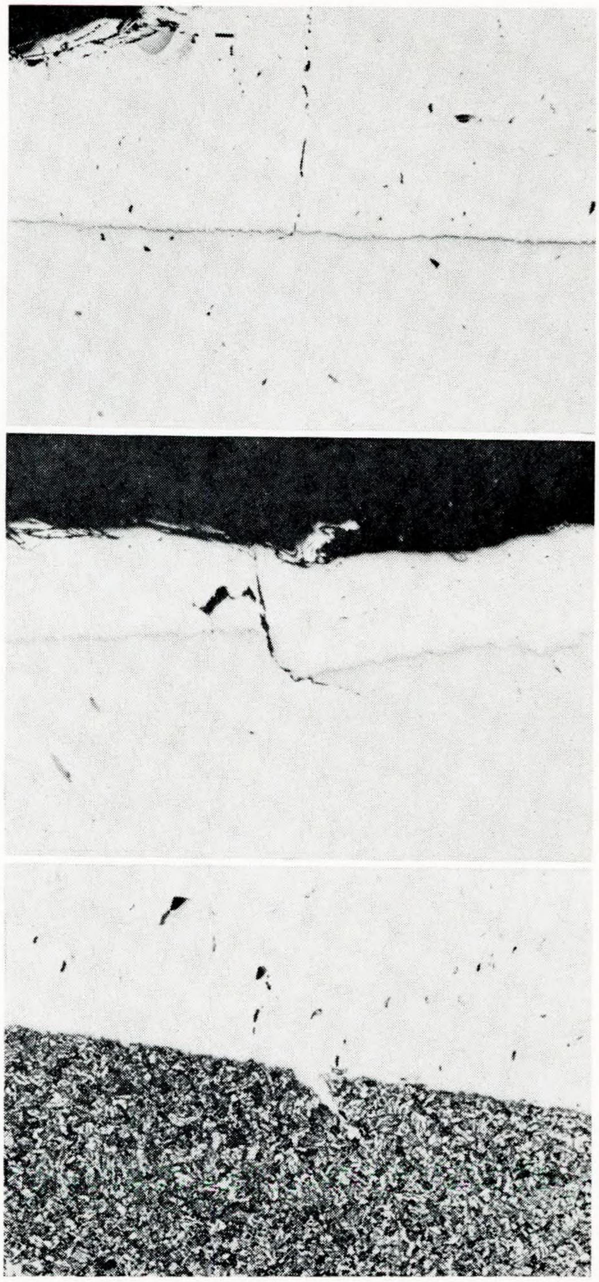

FIG. 10—*Failure B – craze cracks penetrating into steel from chromium (chromium is top layer in each illustration)*

journal was again covered with large craze cracks but of greater severity than seen previously, to the extent of distinct open voids around each plate of chromium. Sections were taken through the journal and the result is shown in Fig. 12 with the chromium falling away from the base steel at the saw cut. The plating was obviously unsatisfactory and in fact it is difficult to imagine how the crankshaft passed inspection.

There was appreciable damage to the fracture face as the crankshaft had severed in the engine and it was not possible to identify the exact cause of failure. On the other hand the evidence available enabled it to be concluded that again unsatisfactorily plating was a primary factor in the incident.

It may be concluded beyond reasonable doubt that the three failures which have been experienced to date are insufficient evidence to condemn chromium plating of crankshafts, serving to illustrate the importance of quality control in the plating process. Certainly this aspect appears more critical to the success of the technique than the subsequent grinding operations, though of course mistakes can be made

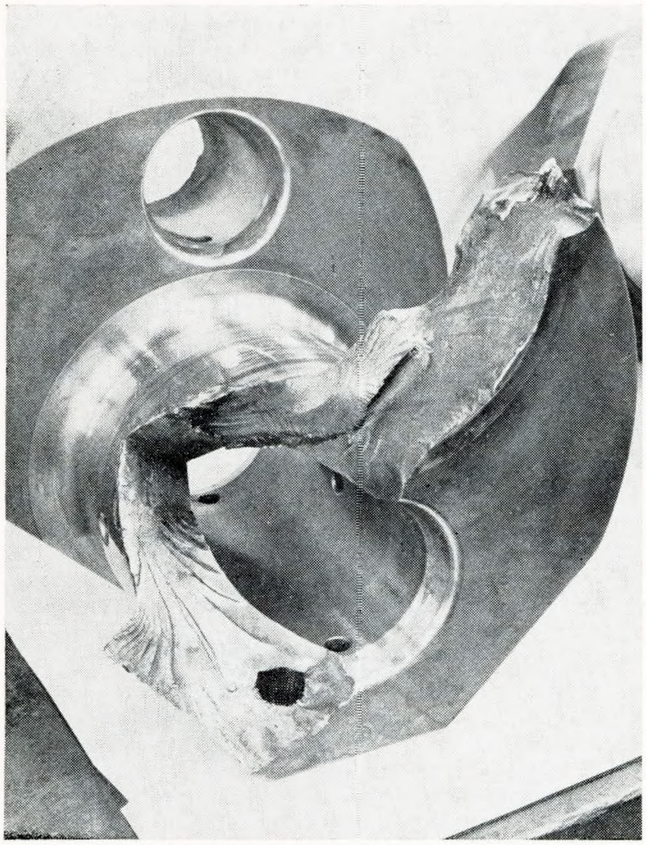

FIG. 11—*Failure C – Fracture face in journal*

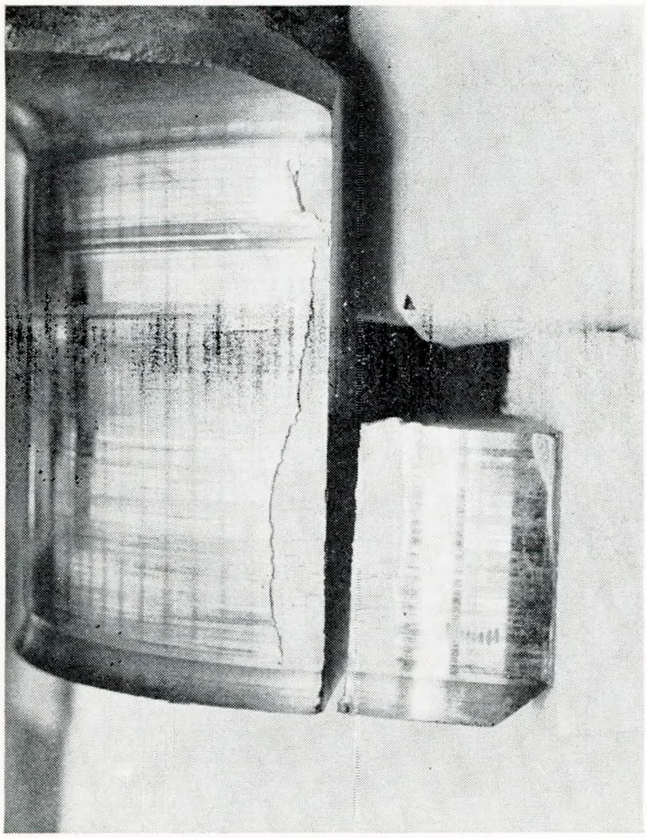

FIG. 12—*Failure C – Defective plating*

in this area also. If these three failures are regarded as a part of the overall development programme then the associated costs of repairing the subsequent engine damage was not especially excessive. In fact there was only minor damage to the three engines in the incidents described above. The service performance of the remaining chromium plated crankshafts is considered entirely satisfactory and represents a substantial saving in the capital costs of new shafts.

It is not possible to give accurate statistics of the wear rate for these crankshafts basically because today they are negligible and none have required regrinding. At present the indications are that the wear rate is appreciably lower than the standard crankshaft. The introduction made reference to a number of "flash" chromium plated crankshafts, which are in rail traction[13] but slightly shorter in length than those referred to in the paper. As far as is known they too are performing entirely to satisfaction and some have already been in service so long that they have been replated.

The authors have, from time to time, been involved in discussion on the level of craze cracking that is acceptable for commercial service. Unfortunately, it would appear that due to lack of knowledge, a certain amount of craze cracking has been considered the norm and the responsibility of acceptance of an individual journal appears to have been left to the discretion of the inspectors. Any cracking of the chromium will not become evident until the final grinding and quite understandably the inspector, having found a not entirely satisfactory deposit, would be under extreme pressure from senior staff to accept the shaft because of the expense and time involved in rectifying the defects. A recent exercise has demonstrated that with a thick (1·0mm) deposit which is craze cracked, in this sort of situation it is well worth attempting carefully to reduce the journal to the next standard undersize for it may be possible to remove the defective area. Nevertheless Fig. 1 shows that a crack-free deposit can be obtained and the onus is thus placed on the plater and grinder to ensure that their manufacturing conditions are correct. It can thus be simply stated that craze cracked deposits are not acceptable for optimum service, this further reinforcing the statements made in the section on Effect of Chromium Plate on Fatigue Strength.

## CONCLUSIONS

In the authors' experience the chromium plating of large crankshafts is both an economic and technically successful process which can be applied with confidence to diesel engines and reciprocating compressors. Provided the crankshafts closely follow all the non-destructive testing, machining and plating procedures detailed in the paper then it can be assumed that either an increased working life will be obtained with original plated crankshafts or an adequate economic extension of working life will be obtained with a reclaimed crankshaft. The fatigue tests have demonstrated that there is a negligible increase in probability of fatigue failure with a correctly chromium plated and machined crankshaft, and this is confirmed by service experience.

## ACKNOWLEDGEMENT

Acknowledgement is made to the Ministry of Defence (Navy) and the British Railways Board for permission to publish this paper, but it is emphasized that all opinions expressed in the paper are solely those of the authors and do not necessarily represent any official policy.

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## Discussion

MR. G. P. SMEDLEY said there was a growing interest in engineering in surface treatments which could be applied to reduce the wear of principal machinery parts, or to reclaim them after a breakdown involving surface damage. Although most of the techniques had been available for some years, there was a dearth of reported data on service experience on which to judge the limitations and reliability of each method. The ordinary engineer was often faced with the alternative of delay to the plant pending delivery of replacement parts or uncertainty of the reliability of reclaimed parts. Moreover, he was also faced with the problem of specifying a method of reclamation appropriate to the duty. The paper was most welcome because it dealt fully with the problems, indicated clearly the essentials necessary to a good sound job, and reported considerable service experience. These data must increase confidence in the chromium plating of new crankshafts and for rebuilding the surfaces of worn pins and journals by the deposition of up to 1 mm of chromium.

From his experience the contributor supported all the views expressed by the authors, and providing their recommendations were followed the job should be sound and reliable. Like the authors, his experience of chromium plated crankshafts was that failures in the affected zones could be prevented by following a proven procedure and efficient quality control. However, proper operation and maintenance was of equal importance. Overheating was likely to cause craze cracking in addition to the causes quoted in the paper by the authors.

He had seen one or two failures from this cause where the cracks had propagated into the base metal by thermal fatigue and afterwards they had propagated to sizeable fatigue cracks under the normal cyclic torsional and bending loadings on either the pin or the journal. Clearly, if one could crack chromium plating in grinding, which was entirely a thermal process, one could crack it if one got bearing troubles and starvation of oil. Failures which he had seen went back a fair number of years now and were very similar in nature to Failure C described by the paper.

Fig. 5 showed the recommended preparations and finishes for deposits on journals having recessed fillets. These were also satisfactory for journals with external fillets providing the minimum distance between the runout of the plating and the junction of the pin fillet radius to the surface of the pin or journal was maintained as shown in the diagram. However, there was one problem, which was not dealt with in the paper, although the presenter had raised it in introducing the paper. This was the loss of bearing area. In some cases where bearing loadings were high, engine builders were not prepared to accept the loss of bearing area beyond the run outs of the deposits. It was advisable, therefore, to consult engine builders about repair procedures where bearing loadings were high.

As stated in the paper, post deposit heat treatment at 150°C to 300°C could reduce significantly the fatigue strength. Lloyd's Register of Shipping considered that such temperatures could be attained at the surface of a pin or journal during operation. For this reason they restricted the tensile strength of the crankshafts that were reclaimed by a plating process.

He asked the authors whether they agreed with this view, and if so what restrictions they placed on the strength in this respect? Some years ago Lloyd's Register of Shipping had conducted a series of tests on 75 mm diameter shafts with chromium plating and also with chromium on nickel. The results of the tests with the latter deposit had been poor in comparison, and they had not gone into it thoroughly because they felt that as they had advised the plater of the purpose of the shafts he knew what he was up against. Since that time they had not favoured chromium on nickel as much as a plain chromium deposit. He asked for the authors' views on this.

Turning to Fig. 5, and in particular Profile A, he asked the authors what sort of run out was preferred here. His Society had considered a variety. The plating manufacturers seemed to prefer a small shoulder with a fillet. It appeared to be successful, but it had always been a worry that if there was not complete adhesion at the run out where one had got the shoulder, failure of the shaft was likely to occur. He asked the authors whether they considered that this was the type of run out to use or whether a shallower type of taper was of any value.

Finally, when one had done a wealth of work such as the authors had done, and reported, it must be quite clear that British Rail and the Navy Department must have pretty good specifications for these repairs. It would be appreciated if these could be included in the discussion for the benefit of marine engineers, or lodged in the Institute library. He would appreciate information on the method of approval of the firms that plated their crankshafts. Did both organizations employ the same system, and were these based on audits of fully detailed quality control and assurance systems?

PROFESSOR F. T. BARWELL said that when he read the paper his reactions had been very much those of Mr. Smedley. Firstly, he had felt that it represented a very thorough investigation and a considerable measure of achievement which must have involved a certain amount of perseverance under discouraging circumstances. His second reaction had been how exactly was it possible to ensure that the important precautions specified so clearly in the paper were, in fact, carried out by the plater and, indeed, by the subsequent machiner. The implication was that the plating process was somewhat exotic and difficult to specify. One knew that there were certain mysteries about chromium plating from experience with cylinder bores. Some designers specified porous bores: others specified a dense plating but with etching; others got away with simply plating the piston ring surfaces. He assumed that a combination of density, porosity and surface finish had been available in this case. He was not sure that they had been investigated.

He noted that the authors specified dense surface plating and a good finish as it came rather than a special super-finish. The problem of ensuring that the plater knew his job might be easily solvable in the UK, but what if the marine engineer wanted to have the work carried out in some foreign port? He imagined that he would have a certain amount of difficulty in trying to find good platers all around the world. British Rail probably had an easier task in that they did not serve the whole world and therefore could have a limited number of platers. Was it not possible to have specifications which could be adhered to checked so that the range of platers could be extended internationally?

Another disturbing thing was the statement that one was dependent entirely on the integrity of the people in the plating shop, because a very simple little score could actually cause severe risk of fatigue failure and it could be covered up by the plating. This seemed to be a very grave risk, and he wondered how the authors really safeguarded themselves against it. It did not seem to him to be quite good enough just to rely on the plater knowing that such an apparently trivial defect could have such serious consequences.

One knew that the engine was a tribological system, and when one altered one part other consequences sometimes occurred in other parts of the engine. As had already been mentioned, as one went away from whitemetal as a bearing material one had to specify hardness of shaft and, in fact, as the authors had pointed out, one had to use a steel which was really too good for most of its functions in order to have a hard shaft surface. It was stated in the paper that there was a low coefficient of surface friction associated with chromium plating. He would like to know under what circumstances this had been measured and what, if any, were the repercussions on the bearing against which one was rubbing? The chromium oxide film must be rather different from the ferrous oxides which were normally in contact with the bearing. Did the bearing pick up these oxides? Did they become embedded? Did they get into the lubricant? Were they circulated to any other parts of the engine? Was there any evidence of any other part of the engine being affected by chromium plating?

He said that to some extent the criticisms of the system were actually commendations of the authors. In the well controlled systems of British Rail and the Admiralty they were able to employ quite sophisticated techniques, relying on the good inspection and the good discipline in their organizations. He thought, however, that the paper must leave many maintenance engineers with a question mark, because however much they might like to use this they had to ask themselves if they could really be sure that they could supervise and ensure that the plater and the subsequent machiner were doing a good job.

Mr. W. Richardson congratulated the authors on their paper. He said his contribution formed a question in respect of the fillet radii finishing and the means used for finishing these fillet radii. Did the authors consider that it was more important to have dimensional accuracy, as given in Fig. 5, or was a high degree of surface finish more important?

Also, looking at the proposal for grinding these fillet radii, did the authors consider that grinding them in the direction shown might give rise to circumferential scores, especially at the transmission from the chromium plate to the parent material which would be more difficult to get rid of in subsequent polishing operations? If the grinding were done in a direction more in the axial plane of the pin this would be easier to control in respect of scoring, especially bearing in mind the direction of the stress in the fillet radii.

Dr. H. Fessler also raised a question about the fillet radii and the dimensions which the authors had decided to use. He asked whether the authors had merely accepted established practice, or whether they had actually done some tests in order to decide how far they could take the chromium plating, because, as had been mentioned, it would be of advantage if the chromium plating could extend further so that there would be no loss of bearing surface. It seemed from the work he had done on a number of different shapes of crankshaft fillets that it was extremely unlikely that the stresses at the run out of the fillet at the junction of the fillet to the crank pin were going to be significant compared to the peak stresses in the fillet. Therefore, his question was: would it not be possible to extend the undercutting for the repair or the build up of the chromium plating rather further and not have this disadvantage? He then illustrated this point by showing some slides.*

With regard to Mr. Richardson's comments, he said that one had got to be careful when considering optimum grinding directions because there were significant torsional stresses so the directions of the principal stresses varied around the fillet and along the fillet.

Mr. G. McNee, F.I.Mar.E., the Chairman, said he would like to ask one or two questions mainly on the economics of the exercise. One of the things found with generators was that the part that gave the most trouble was the crank pin. In the paper the authors spent their time talking about the journals. He said that he had found very little trouble with journals. Crank pin trouble was mostly damage due to bearings running out and one got scoring of the journals. The experience of his company over many years was that the crankshaft of the generator more or less lasted out the life of the ship. They might have to have it out part way through the life of the ship and machine up the journals, but he did not think there was any particular case for going to chromium plating for that sort of thing. He would not think of taking a crankshaft out of a ship because one journal was under sized. The economics was such that taking the crankshaft out was a very large part of the cost and one could not afford to do that because one journal had failed.

* Fessler, H., and Good, V. K. 1971. "Stress Distributions in some Diesel Engine Crankshafts." *A.S.M.E.*, paper No. 71-DGD-1, pp. 3, 4. Figs. 1 and 3.

## Correspondence

Mr. J. W. Oswald* wrote that one of the main difficulties of finishing plating on crankshafts was that of producing a smooth change of section between journal and web. The few failures seen personally were due to poor finishing technique, leaving a notch in the radius from which the fatigue failure started. These shafts were used on earth moving equipment. Fig. 13 indicated a suggested method of preparation from plating which ensured satisfactory finishing. This procedure was, however, only suitable for new shafts and could not be used for salvage.

Mr. Oswald was not too happy with some of the thicknesses of chromium suggested in the paper. Chromium was a hard, brittle metal and as such was susceptible to shock loading which could cause it to splinter and break away from itself. Whilst thicknesses of 1·0 to 1·5 mm might be satisfactory on main journals, he felt pins of diesel crankshafts were subjected to hammering and this could cause breakdown of the plate. However, the authors appeared to have practical experience of such deposits and it was possible the contributor was being over-cautious.

On the subject of thickness, Mr. Oswald had been given to understand that the Admiralty were specifying 0·15 mm as a maximum thickness of chromium to be applied to crankshaft journals.

He agreed with the authors' comments on the necessity for depth of cut to be taken on grinding chromium.

* Now deceased.

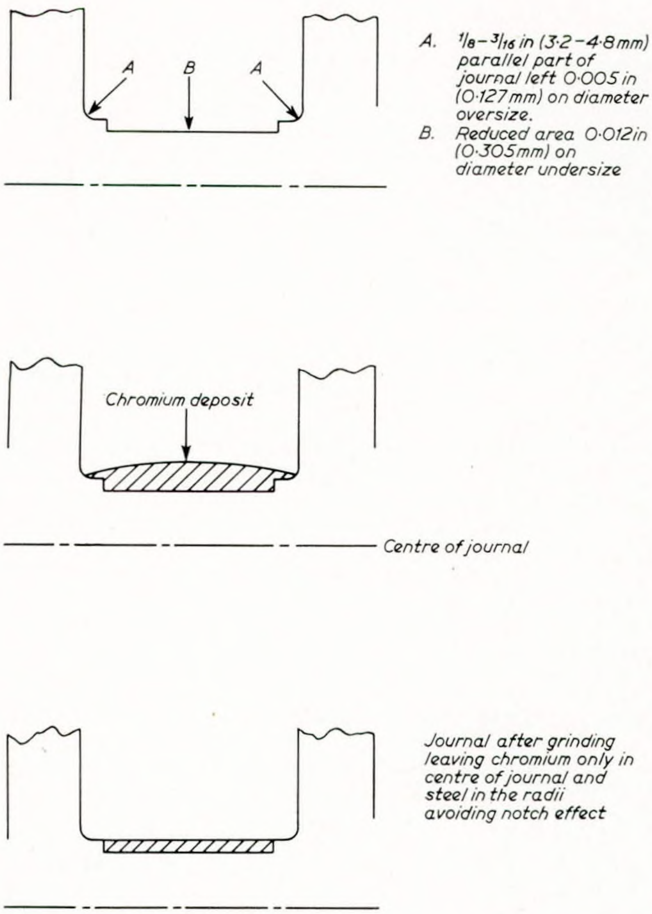


FIG. 13—*Suggested method of preparation*

In fact, the contributor felt that the maximum depth should no exceed 0·007 mm. Such cuts should be used from the beginning as a heavy initial cut could cause cracks that were not eliminated by subsequent careful grinding.

Mr. Oswald believed that one of the difficulties on regrinding crankshaft pins was ensuring that the final ground deposit was concentric with the underlying steel. For example, if the increase in diameter was 0·3 mm, there was no guarantee that the radial increase was 0·15 mm, but it could be 0·2 mm on one side and 0·1 mm on the other.

The authors made no suggestions in regard to bearing materials for use in contact with chromium. Mr. Oswald considered that copper-lead was probably the best material. Lead-bronze and whitemetal also gave excellent results. It was essential, however, in all cases to ensure adequate lubrication.

In order that the user could specify the type of chromium required, it was suggested reference should be made to British Standard 4641: 1970—Electroplated Coatings of Chromium for Engineering Purposes, or Defence Specification DEF 160—Chromium Plating for Engineering Purposes.

Mr. J. F. WARRINER in his written contribution said: following the presentation and verbal discussion of the paper, he was left unsure as to the authors' recommendation on the finished surface roughness of crankpin or journal running surfaces. The paper suggested a range of 8 to 24 $\mu''$CLA, whilst in the discussion reference was made to achieving values at the bottom (8 to 12$\mu''$ CLA) of this range. He wondered what values were generally achieved on repaired crankshafts which were then put into service. From the viewpoint of a bearing designer, Mr. Warriner would have thought it was important to achieve a low figure for surface roughness on a chromium plated surface, and to achieve this by final polishing rather than finish grinding. Any ground finish would leave sharp asperities on the surface, and under marginal lubrication conditions these could cause scoring and overheating of the bearing surface, or might be polished off and become embedded in the bearing surface. If the latter occurred, the embedded particles could then cause scoring and overheating of the shaft surface. As explained in the presentation of the paper, overheating of the chrome surface would cause craze cracking and could initiate fatigue damage to the shaft.

Regarding reduction of bearing length due to the run out of the chromium plated surface, although Mr. Byer in reply to one question stated this made a difference of only 1 mm to the length of bearings on the engines the authors had been associated with, reference to Fig. 5 would show that for Profile A there was a potential for approximately 6 mm extra bearing land length, and for Profile B, 8 mm. On some bearing designs, it was critical that all available length be used to achieve satisfactory oil film thickness. This point must be seriously considered when contemplating such a surface treatment for other engine types.

Mr. Warriner stressed that wherever the chromium plated surface terminated, the bearing length should not be greater than the extent of the hardened zone. The edge of the bearing must not overlap the chromium plated surface. Mr. Byer stated that in the engines with which the authors were concerned, the bearing length had been reduced. Mr. Warriner only wanted to re-emphasize the point.

# Authors' Reply

Regarding Mr. Smedley's point that overheating could cause craze cracking, the authors agreed that this could occur under seizure or near-seizure conditions. Where the internal stress in the deposit was high this would be algebraically additive to the normal service stresses and could easily have resulted in an overstressed deposit and hence craze cracking. But using the criterion of 75 $MN/m^2$ maximum internal tensile stress, deposits of this nature have undergone, in a test rig, seizure trials promoted by oil starvation. The results were rewarding in that craze cracking was not promoted by seizure even though extensive bearing metal damage occurred. Provided the internal stress was low it would appear that there was an increased resistance to craze cracking. Of course if the seizure reached the point where the steel backing of the bearing was involved, extensive damage could be expected as would also be the case if unplated surfaces were involved in seizure under these conditions.

As far as thermal fatigue was concerned the authors had not experienced this phenomenon and would generally consider that the fatigue damage due to dynamic loadings would be greater than any fatigue damage due to thermal loads and consequently the former would be of greater importance.

The importance of not increasing the bearing pressure was appreciated; however, the reduction of bearing area on crankshafts when they are chromium plated to Profile B was of the order of 5 per cent. It was considered that reductions of this order should be acceptable and experience on BR engines had confirmed this. In MoD (N) the use of Profile A did not involve any loss of bearing area.

As Mr. Smedley noted, all the authors' work had been restricted to chromium plate without any post-plating heat treatment in view of the reduction of fatigue strength that could occur with post-plating heat treatment. It was agreed that thermodynamic temperatures of 150 to 300° C could be calculated for the crankshaft journal surface but the authors had not practical experience that this had occurred to the extent to cause reduction of fatigue strength or craze cracking.

The present use of chromium plate within the authors' experience was limited to steels of 1100 $MN/m^2$ maximum tensile strength which obviated the problems of hydrogen embrittlement. Higher tensile strength steels could be satisfactorily chromium plated provided shot peening and post-plating heat treatment was practised; however, this technique was quite complicated and expensive. Alternative methods rather than the use of higher strength steels were available where an increase of fatigue strength of a crankshaft was desirable. The use of chromium plate permitted the two requirements of fatigue strength and hardness of journal surface to be tackled separately. The recent use of greater overlap between the main and pin diameters such as was practised in the Valenta crankshaft highlighted the possibility of improved crankshaft design in greatly reducing fatigue stresses. It would be appreciated that steels of tensile strength greater than about 1100 $MN/m^2$ in the heat treatment sections used in the type of crankshafts considered here (i.e. approximately 200 mm diameter) were extremely expensive and of limited availability.

The authors would agree that the use of nickel plate beneath the chromium plate was undesirable in view of the thickness sensitivity effect of nickel on fatigue strength reduction, and had not used such dual plating.

Finally, the type of run out used for Profile A has been a small radius. The authors had not experienced a shallower runout, but it might be noted that the small radii used had proved satisfactory in service and fatigue tests up to a thickness of 0·25 mm (finish deposit). The authors agreed that for thicker deposits the use of a shallower run out or of Profile B would be desirable to obviate any lack of adhesion or porosity at the run out. However, it should be noted that a shallower run out was more expensive and difficult to prepare.

In reply to Professor Barwell the authors agreed that the integrity of the plater and the machinist were vital. In this respect it was hoped that the prototype specification included in the reply would be of help. The specification provided quality targets for the repair and plating concerns to follow and, in addition, opportunities for the customer to check the work at various vital stages. The etching and crack detections, etc, could be witnessed by the customer whilst the plater could be called upon to supply a permanent record of the stress level in the form of a test strip as detailed in the specification. Development of plating concerns was proceeding internationally with European firms of repute setting up branches overseas to which they would provide technical quality control and expertise and it was hoped that this would eventually provide a satisfactory world-wide service.

The authors had used dense, low stress chromium plate, and the use of porous chromium, for oil retention, as practised on cylinder liners, had been avoided, as this latter type of plate frequently contained high stresses used as an aid to the formation of the correct type of porosity pattern during subsequent back etching. However, some experience of microcracked chromium plate was available in full scale fatigue tests, at a thickness of 0·125 mm and a crack density of 120 cracks per millimetre. This plate was made under conditions of low temperature plating, etc, so as to give compressive stress in the deposit. Full scale fatigue tests were satisfactory but the process was not used in an engine crankshaft in view of its extra cost over that of more conventional plating.

Within the authors' experience they had found a wide variety of metals in the lubricating oil using the spectrographic and atomic absorption techniques available, but they had never found chromium. This was perhaps to be expected when the almost insignificant wear of chromium plated journals was considered combined with the high throughput of lubricating oil in modern engines.

The authors agreed with Mr. Richardson that grinding in the axial plane was most desirable. In the authors' practise most of the grinding finish in the radii of Profile B chromium plated crankshafts was done by hand at an angle (not a right angle) and the subsequent axial finish was obtained in the final polishing operation. It would be preferable if all radii grinding and finishing could be done by a machining operation instead of by hand. It might be noted that the use of Profile A where gentle plunge grinding of the journal/radii transition could be made was a help in obtaining an economical finish. In general it was agreed that the radii surface finish was more important than perhaps a high precision in dimensional finish of the radii in the steel crankshaft. The rule adopted was that the radii of reclaimed shafts should be equal to or greater than the radii in the original crankshaft design.

The authors agreed with Dr. Fessler that the stress gradient in large radii (e.g. 12·5 mm R) was low but experience with plating that had been allowed to enter the radii had shown in full scale fatigue test a reduction of fatigue strength of the crankshaft of some 20 per cent. It was therefore considered essential to avoid chromium plating in the radii entirely.

In reply to the Chairman, the authors elucidated the point about journals in that the term was used for both mains and pins, and the authors' experience agreed with him in that trouble was mainly on the pins in the form of wear, scoring, etc. Repair *in situ*, especially of crankshafts larger than the authors had experience of, was of course most desirable on ground of cost and rapid repair. This *in situ* repair technique was only practised to a limited extent by BR and MoD (N) and in crankshafts up to 4 m in length were mainly repaired by refit or replacement with a reground or chromium plated crankshaft.

In reply to Mr. Warriner the authors had taken plastic replicas of the typical standard which was not accepted, and it was found 10 to $14\mu''$ CLA was easily obtained, hence there was a tendency to talk about the finer end of the range advocated.

It would appear that the authors had caused some confusion over bearing length and have given the impression that special length bearings were used. In fact the standard length bearing in both BR and MoD (N) was used. It was appreciated that bearing width was an important parameter in maintaining oil film thickness but at most only 1 to 2 per cent of bearing width capacity on bearings ranging from 130 to 150 mm in width was lost, and such a reduction should be acceptable. It would be appreciated that bearings were shorter than the theoretical maximum bearing length and the 6 to 8 mm of length lost by the finish the authors advocated, came down to 1 to 3 mm loss of bearing width in practice. With Profile B, of course, the full effective bearing width was maintained whilst with Profile A the loss of bearing width was acceptable. It might be noted that many hundreds of bearings that slightly overlap the chrome plating had been run without any trouble.

In reply to Mr. Oswald the authors agreed with many of the opinions expressed by Mr. Oswald in his contribution, and in particular would like to endorse his confirmation of the vital importance of care in grinding throughout, the importance of the blend between parallel length and radii and the necessity for the absence of chromium in the radii.

With reference to Mr. Oswald's proposed preparation method for new crankshafts, this was similar to Profile B preparation. But the authors deprecated the plating in the radii even if subsequently removed by grinding and would, of course, like to see a radii or taper at the corners of the insert chromium.

Finally, the authors thanked the Institute and the questioners for their interest in the subject of the paper and trusted that the repair and plating specification which followed would be of use to them.

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*Process Sequence and Specification for the Chromium Plating (Unbaked) of Crankshaft Journals Made of Steels With Up to 1100 MN/m² Tensile Strength.*

For reclamation use steps (1) to (16) inclusive.
For new manufacture use steps (6) to (16) inclusive.

1) General visual and dimensional examination of the crankshaft to determine whether the crankshaft was suitable for reclamation.

2) Remove damaged surface from journal(s) by a suitable grinding technique.

3) Check the damaged and ground journal(s) for thermal damage and copper penetration by etching with five per cent nitric acid in alcohol (nital). A light etching area surrounded by a darker etching material was indicative of thermal damage whilst copper penetration from a bearing seizure was shown by its copper colour.

4) Repeat sequence 2) and 3) until no thermal damage or copper penetration is present.

5) Crack detect by dye penetrant.

6) Provide a pre-plating finish of 12 to 24 CLA ground surface on the journal(s) at a suitable diameter and Profile finish. Use Profile A for new manufacture with up to 0·25 mm deposits. For reclamation use Profile B for deposits of up to 1·0 mm radial thickness.

7) Deposit chromium plate up to the thickness required; for thicknesses up to 0·25 mm overplate by 0·125 mm to allow for post-plating machining; for thicknesses in excess of 0·25 mm allow a 0·25 mm overplate.

8) The chromium plate to be dense chromium. The plater might use any pre-plate cleaning, anodic etching, bath composition, temperature, current density and plating fixtures he considered suitable—provided that the result was that the stress in the chromium plate does not exceed 75 MN/m² tensile with the plate in the unbaked condition.

9) The plater should guarantee, in writing, his plating method as providing a stress level of less than 75 MN/m² tensile in the chromium plate. He should provide evidence obtained at the time of plating the crankshaft and under the same conditions, if so required, that the stress criterion had been met; for this purpose a spiral stress meter or the bent strip method may be used. (See Note 1).

10) As plated the deposits should be free from holidays, porosity and excessive nodule formation especially at the edges of the plating; no repair of plating defects or post-plating heat treatment (i.e. baking) should be permitted.

11) If the plating was rejected under criterion 10) the deposit should be stripped and the journal replated.

12) The plated journal should be grounded under the following conditions; it was vital that at no time during grinding the maximum depth of cut be exceeded. Indeed a smaller depth of cut might be used if found desirable.

- i) soft wheel of 60 grit, H hardness;
- ii) grinding wheel peripheral speed of 20 to 30 m/s. Workpiece peripheral speed of 0·15 to 0·3 m/s;
- iii) light cut of 0·010 mm to 0·013 mm;
- iv) liberal coolant—soluble oil.

13) Crack detect the ground surface for craze cracking using dye penetrant; the presence of continuous craze cracking should result in rejection of the plated shaft.

14) Finish ends of the chromium plating at the radii and oil holes as detailed in Figs. 5 and 8; for the radii use a surface finish at right angles to the direction of bending stress, during all stages of edge finishing if possible, but at least for the final polish.

15) Etch radii and oil holes with a two per cent water solution of copper sulphate to detect traces of chromium left in radii or oil holes; remove if necessary and recheck for removal.

16) Finish the chromium plate on the journal by lapping to a surface finish of 8 to 12 CLA.

*Note 1*

*Bent strip method for stress determination.*

A flat strip of stress relieved spring steel was mounted in a non-magnetic jig so that both ends were held down, except for the stress gauge length the jig and strip were blocked off with plating wax. The test piece so prepared was plated at the same time as the crankshaft and under the same plating conditions. Subsequently one end of the strip was released and the deflexion of the strip was measured. The stress in the chromium plate was calculated by the use of the following formula. A suitable strip size was: Overall length 180 mm. Gauge length (i.e. plated length) 130 mm. Width 5 mm. Thickness 0·4 to 1·0 mm, depending on the thickness of chromium deposited.

Formula:

$$S \text{ equals } \frac{E\, d^2\, A}{3\, L^2\, t\, [\, 1 - \frac{t}{d}\, ]}$$

where $S$ was stress (internal) in deposit.
$E$ was Young's modulus of the spring steel.
$d$ was thickness of steel strip.
$A$ was deplacement of end of steel strip.
$L$ was length of deposit.
$t$ was thickness of deposit.