SOME INTERESTING ENGINEERING FAILURES ENCOUNTERED IN AUSTRALIA

By

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INTRODUCTION

The place of Defence Research Laboratories in the field of applied secondary metallurgy in Australia is unique in that it is the only large independent laboratory engaged in this type of work and, as such, has gained much experience in this broad field, especially during and pinces World War II. This is particularly so in that aspect of the work dealing with investigation and elucidation of causes of service failure of engineering components, for it has long been recognised that only by thorough investigation and understanding of causes underlying failure can real progress be made in the related fields of design and engineering materials.

Many hundreds of engineering failures have been examined at the Laboratories and these have been drawn from a very wide field. The range has covered not only the Armed Services, but also the fields of transport, power generation, civil aviation and all types of manufacturing from light to heavy industry. The results of a high proportion of failure investigations have, naturally, been of interest only to the parties directly concerned, but in many cases general details and underlying causes are of wide interest. For this reason, a number of failures of special interest has been selected for description in this paper ; no strict criterion has been used for their selection, but those described have been included either for their showing unusual features or else being good examples of a mode of failure.

It is hoped that the cases described will be of general interest to engineers and metallurgists and that they may perhaps help in either solving cognate problems or preventing occurrence of similar failures.

1. FAILURE OF HIGH TENSILE STEEL BY INTERCRYSTALLINE PENETRATION OF LEAD

The phenomenon of intercrystalline penetration of stressed steels by certain non-ferrous metals and alloys has long been recognised and the literature contains many reports of failures due to penetration into steel of copper, tin, brazing alloys, solders and even mercury. So far as is known, however, no case of failure by lead penetration has yet been reported.

In the present instance, very extensive penetration by lead caused rapid failure in the lead holding cylinder of a 1000-ton capacity cable sheath extrusion press. In the cable making industry, experience has shown that this type of cylinder has an indefinitely long life ; wear in the bore is almost non-existent due to the practice of maintaining a 0.010 inch clearance between ram and bore surface, thus forcing a thin film of lead between the two during extrusion. The company which operated the press had never encountered a failure until this particular case which occurred 6 months after new installation of the press.

The cylinder was 27½ inch long, 14 inch outer diameter and 6¾ inch bore diameter ; it had been made from a medium carbon, nickel chromium molybdenum steel and had been hardened and tempered to an ultimate tensile stress level of approximately 75 tons/sq. inch. In operation, the cylinder served as a lead holding pot, molten lead being run into it from a central melting pot which feeds this and other presses. After filling, the lead is allowed to solidify and cool to 280° C before the load is applied and extrusion started. As mentioned above, failure of the

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cylinder occurred some 6 months after new installation, being detected when large steel chips were found incorporated in the extruded cable sheath.

The bore surface of the cylinder was found to be very extensively damaged, two wide longitudinal cracks 14 and 10 inch long respectively and lying about 2 inch apart being present in the upper half of Figure 1. Very extensive spalling of the steel adjacent to the cracks had occurred while, in addition, the bore surface showed a second system of cracks running circumferentially. Typical damage at the bore surface is shown in Fig. 1. Subsequent examination of sections from the cylinder showed the primary longitudinal cracks to extend radially to depths of $1\frac{1}{4}$ to $1\frac{1}{2}$ inch, while a third system of cracks, branching from the primary cracks and running parallel to the bore, was also seen. It was clear, then that spalling at the bore had occurred at intersections of the three crack systems. Microscopic examination of metallographic sections showed all the cracks to be intercrystalline in nature and to be lead filled along their entire lengths—a typical grain boundary network of lead is shown in Fig. 2.

It was thus established that extensive intergranular penetration of lead into the steel had taken place, a phenomenon which, so far as was known, had not been reported previously. It was necessary then to establish the mechanism by which lead had been enabled to " wet " the steel surface and to penetrate along intergranular paths. Two deep scores on the upper half of the bore, each corresponding with one of the deep longitudinal cracks, provided the answer to this question. The scores had been caused by contact of the leading edge of the ram with the cylinder bore during the first part of the ram travel. In normal press operation this should not occur because of the 0.010 inch clearance maintained between ram and cylinder ; in the present instance, however, trouble had been experienced with the press foundation at new installation and this had caused slight misalignment between ram and cylinder during the first half of the extrusion cycle. This allowed metal to metal contact which broke down the oxide film and allowed lead to wet the steel surface under local conditions of high pressure and temperature due to friction. It was clear from the metallographic evidence that lead penetration then occurred along grain boundaries, first along roughly radial paths and then at two directions normal to this primary direction to form secondary and tertiary crack systems. Subsequent extensive development of each system and eventual intersection of the systems had caused spalling of the bore surface and failure of the cylinder.

2. EXTREME BRITTLENESS IN HIGH SPEED TOOL STEEL.

The most usual causes of brittleness in 18 per cent tungsten, 4 per cent chromium, 1 per cent vanadium high speed tool are either (a) " burning " at elevated temperature before quenching, with formation of intercrystalline films of liquated eutectic or (b) presence of untempered martensite due to the steel not being cooled to a sufficiently low temperature before secondary hardening or between successive secondary hardening treatments. In the case to be described extreme brittleness was present but investigation showed that neither of the usual causes was responsible for this brittleness.

The component was a plain hollow cylinder, 9 inch long, 5 inch outer diameter and $3\frac{1}{2}$ inch bore diameter, which was to serve as a holding pot for extrusion of resin-cored solder. On first application of the extrusion load, however, the cylinder shattered into many pieces, each piece showing such brittleness that it could be broken further by light hammer blows.

On checking the history of the cylinder it was found that the purchaser had specified on his order that its hardness should be Rockwell C58 (instead of C58 minimum). The manufacturer had interpreted this literally. After quenching and one secondary hardening treatment at 570°C the hardness was C63 ; in an attempt to reduce hardness to C58, the heat treater raised the secondary hardening temperature to 630°C, giving the cylinder two periods of 1 hour at this temperature in an endeavour to achieve the specified hardness level. The hardness finally obtained was Rockwell C57.

Metallographic examination showed the steel to be very extensively cracked, and all cracks to be intercrystalline in nature. The grain size of the steel was medium coarse (A.S.T.M. No. 5

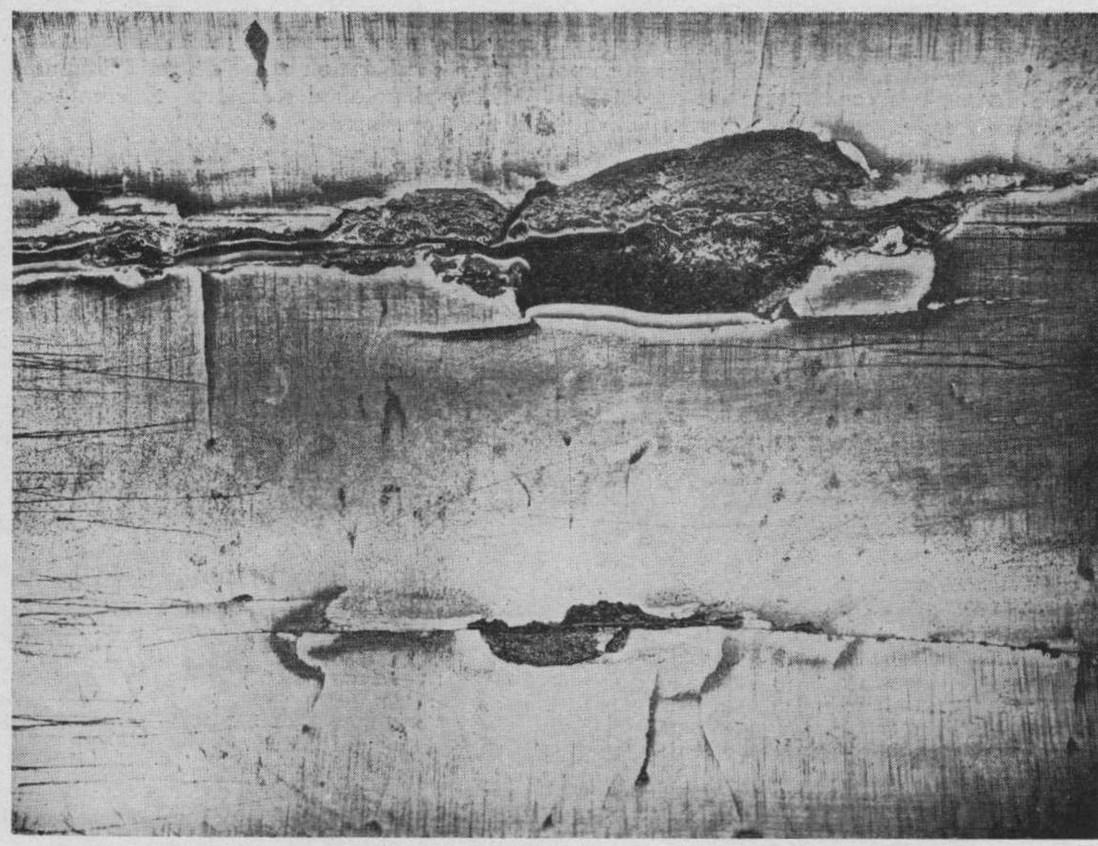

Fig. 1. Typical damage at bore surface, showing chipping around longitudinal cracks; note also the large number of crack running circumferentially. Mag. 1X

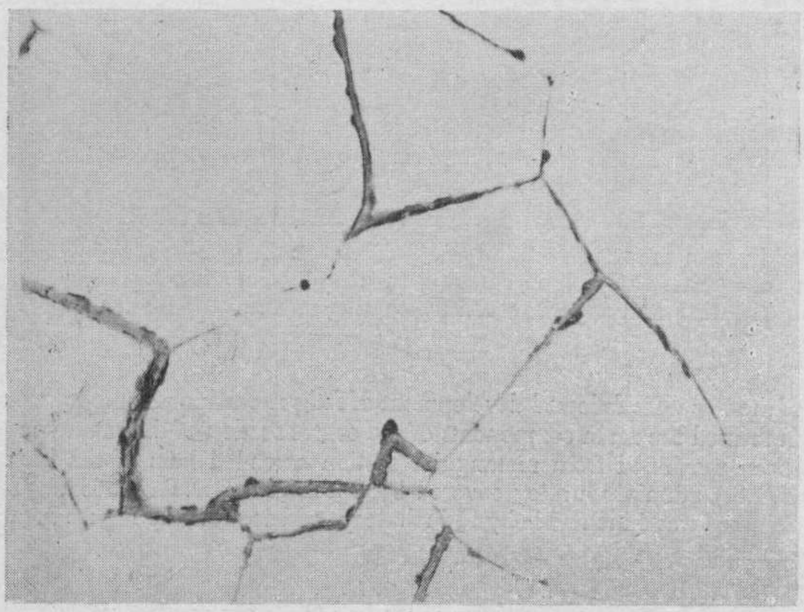

Fig. 2. Microsection from steel cylinder, unetched, showing intercrystalline network of lead. Mag- 75OX

to 6) while there was evidence of some massive carbide segregation. The grain boundaries were outlined by a dark etching constituent which was generally associated with the massive carbide segregates but which was also present at some positions in combination with fine grain boundary carbide films: this constituent had a somewhat diffuse spheroidised structure different in a appearance from that of liquated areas which result from overheating.

The dark intergranular constituent was clearly responsible for the extreme brittleness of the steel, but owing to its fine dispersion and diffuse appearance it could not be identified metallographically and its origin established. Experimental heat treatment was therefore undertaken using steel from the same bar as that used for the cylinder and also a similar steel from another source of supply. These were subject to the normal heat treatment cycle for 18:4:1 steel, to the treatment received by the cylinder and to experiments designed to show whether any isothermal transformation occurred on quenching the steel from 1290°C to 630°C and holding at that temperature. These experiments coupled with metallographic examinations showed that the dark etching, grain boundary constituent could be readily reproduced and that it was the product of isothermal transformation at 630°C of retained (untransformed) austenite. In the cylinder, there had been sufficient austenite remaining after one normal secondary hardening treatment at 570°C to allow development of the network during the two subsequent treatments at 630°C.

It is clear, therefore, that in applications where it may be desirable to reduce the hardness of hardened high speed tool steel by high temperature tempering, this should be done only after multiple secondary hardenings to ensure that no untransformed austenite remains.

3. FATIGUE FAILURE IN A SERRATED SHAFT.

A description of this particular failure has been included, not because it shows unusual features, but because it illustrates a " classical " case of fatigue cracking in a serrated shaft.

The failure occurred in the hollow propeller-drive end of a crankshaft from a radial aircraft engine. The shaft was made from a medium carbon nickel chromium steel hardened and tempered to an ultimate tensile stress level of approximately 60 tons/sq. inch. Experience had shown that the shaft had an indefinitely long life under normal operating conditions; in the present case the shaft had withstood a long service life without damage but, after the last engine overhaul, the driven female serrated component had been fitted to the shaft with excessive slackness. Fretting of the surfaces resulted and primary fatigue cracks developed at the roots of each of the thirty-five serrations and ran longitudinally along each root ; all of these cracks progressed radially, some extending through the full wall section. At a later stage, two secondary fatigues cracks running transversely across the shaft developed from each of the primary cracks with the result that the final fracture surface showed a total of thirty-five primary radial cracks and seventy secondary cracks ranging in size from " incipient " to " well developed ".

4. FATIGUE FAILURE IN A LIGHT ALLOY CHANNEL SECTION.

A recent failure in the centre section of an aircraft main spar boom provided an interesting example of the progression of fatigue cracking in a high strength aluminium alloy under the conditions of alternating and superimposed fluctuating stresses to which an aircraft structure is subjected.

Failure of the structure followed development of fatigue cracking in the lower of two channel members which formed the main components of the centre section of the main spar boom. Both channels had been machined from rectangular section extruded bars of the high strength (38 tons/sq. inch U.T.S.) aluminium alloy covered by Specification D.T.D. 363A. The channel in which failure occurred was 4 inch wide by $1\frac{3}{4}$ inch deep, and as shown in Figure 3, fatigue cracking had developed in one rib.

Figure 4 shows in greater detail the zone in which fatigue cracking developed and progressed before final failure of the structure. Cracking originated at the outer corner of the upper rivet

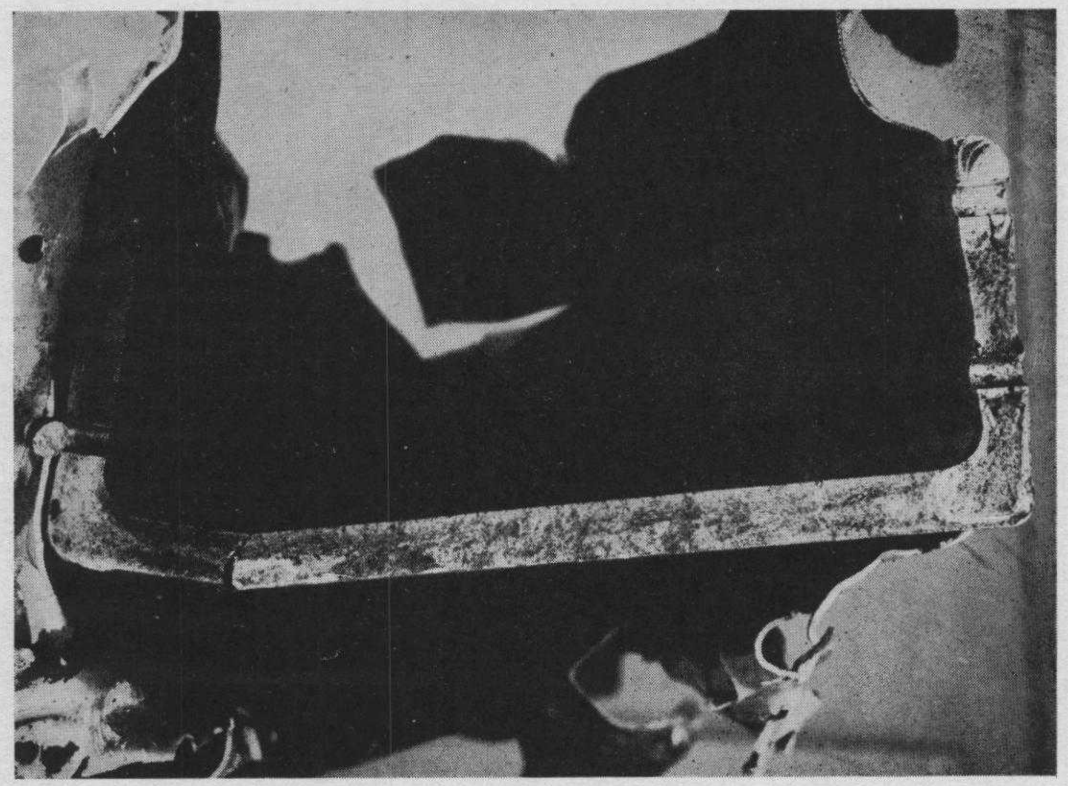

Fig. 3. Fracture in aluminium alloy channel section, showing fatigue cracking in right hand rib.

Mag. 1½X

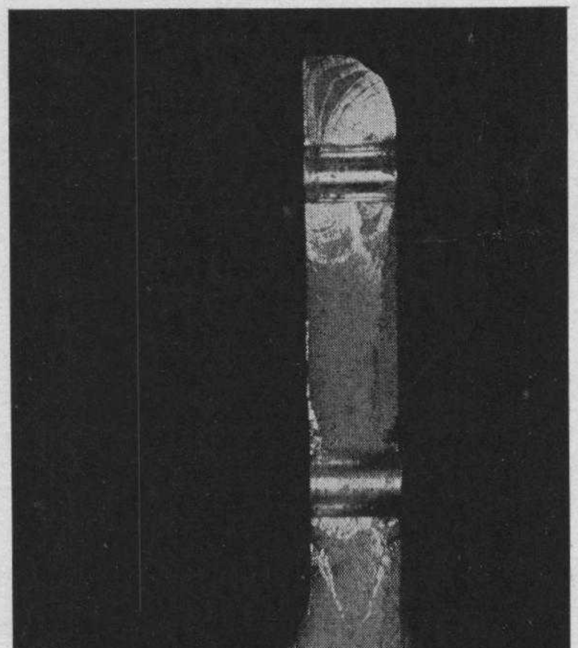

Fig. 4. Area affected by fatigue cracking in channel section, showing zones of alternate fatigue and rapid crack propagation.

Mag. 4X

hole and progressed through the section between this hole and the edge of the channel in a series of alternate stages of true fatigue progression and " rapid " jumps. These latter jumps are to be seen in Figure 4 as dark, curved bands of varying widths : in covering this portion of the section, some fifteen or sixteen stages of alternate fatigue and rapid crack propagation had been involved. Similarly two fatigue cracks originated at the bottom of the upper rivet hole, both developing again by a number of alternate steps of slow and rapid progression until the two systems amalgamated. A sudden heavy load application then caused a major " rapid " jump which covered the major portion of the section between the two rivet holes. Further fatigue cracking then commenced at the lower surface of the bottom rivet hole and again alternate slow and rapid crack propagation occurred until cracking had extended around the corner of the channel and about 5/8 inch along the base. Final rapid failure of the entire structure then occurred as a consequence of the next heavy load application.

The sequence of slow (fatigue) crack propagation alternating with rapid jumps can be readily followed by reference to Figure 4. The failure is of particular interest to the engineer in that it illustrates failure in a structural member of a design just below the safety borderline for normal service alternating stresses, and also shows the effect of intermittent heavy loading superimposed on normal vibration stresses by factors such as air-pockets. The mechanism of failure is also of interest to the metallurgist, for it provides information on the sensitivity of a high strength aluminium alloy to notches of extreme sharpness. It is clear in this instance that the alloy showed low notch sensitivity in an application where rapid failure could have been expected at a considerably earlier stage than actually occurred.

5. EFFECT OF REMOVING CARBURISED CASE ON TENDENCY TO FAILURE BY FATIGUE.

It is well known that certain surface treatments are capable, in appropriate instances, of greatly increasing endurance life of components. The present example illustrates the converse proposition that local removal of a favourable surface may have a disastrous effect on endurance.

The component was the camshaft of an in-line aircraft engine which has been subjected over a period of years to numerous modifications devised to increase power output well above the original. One of these modifications was increasing the size of an oil hole from $\frac{1}{8}$ to $\frac{1}{4}$ inch diameter near the driven end of the shaft to give improved lubrication at higher engine speeds. After this modification, however, numerous camshaft failures occurred after running for times as short as 6 to 7 hours ; in each instance failure was of the rapid fatigue type, cracks originating at the re-drilled oil hole and spreading rapidly along 45 degree helical paths in both directions along the shaft.

The shafts had been made from a 5 per cent nickel steel case hardened over all the external surfaces and down the sides of the oil holes. (The shaft was hollow, but the bore surfaces were not case hardened). In re-drilling the end oil hole, the case was removed and the comparatively soft core exposed. In subsequent service, fatigue cracks developed and progressed rapidly from the newly exposed low strength surface, thus providing a good example of the effect of removing the hard case from a critical part subject to high fatigue stressing.

6. A Serious Fatigue failure influenced by manufacturing practice

A serious aircraft failure, in which manufacturing practice played a role of primary importance, is described here to illustrate the importance of surface finish on highly stressed parts subject to fatigue stress conditions.

This particular failure occurred in the nose gear landing strut of a large civil aircraft. By good fortune, final failure took place during slow ground taxying of the plane after overhaul; it could have occurred equally readily, with very serious consequences, during landing with a full passenger load. Even so, the aircraft suffered very extensive structure damage.

The strut was of Y—shaped construction, the hydraulic leg and two inclined supporting arms being attached to the hollow centre section by flash butt welds. The centre component had been made as a forging from a low nickel chromium molybdenum steel containing 0·38 per cent carbon, 0·65 per cent nickel, 0·63 per cent chromium and 0·25 per cent molybdenum. After attachment of the leg and arms by welding the whole assembly had been hardened and tempered to a hardness of D.P.N. 460 in the centre section; this hardness level corresponds with an ultimate tensile stress of approximately 95 tons/sq. inch. After forging, the centre section had been machined internally; the only external machining had been that required to shape the two lugs. The remaining surface had been descaled by shot blasting and the whole unit cadmium plated.

Failure of the strut occurred by fracture through the full section of the central forging immediately below the bracing arm lugs. Failure had followed the development of two small fatigue cracks, one 5/8 inch long and 1/16 inch deep the other 5/8 inch long and 3/32 inch deep, at the external surface immediately below the two lugs. In addition to these two cracks, numerous other small fatigue cracks were present in the area surrounding each crack. Metallographic examination showed the surface at the critical position (and over the whole of the central forging) to be decarburised to a depth of 0·035 inch as a result of its not being machined after forging and heat treatment. Surface contour was rough while the shot blasting treatment used for descaling had caused slight peening in the ferritic surface layers only.

Initiation of fatigue cracking had been facilitated, if not actually promoted by, the deep surface decarburisation on a highly stressed part, the total wall section of which was 0·26 inch at the position of cracking; as such, this feature represented very poor aircraft practice. The strut would have been likely to fail at any time after initiation of fatigue cracks because of the notching effect of the cracks in a very brittle steel; this feature again represented poor practice, brittleness being due to use of a medium carbon low alloy steel at an ultimate tensile stress level far in excess of the safe limit for a part subject to impact bending stresses. In this regard, it was again fortunate that further complete failures did not occur, because, in a total of five other similar struts, four were found to show fatigue cracks at the critical position. In one of these, the cracks had progressed through the full wall section and had been detected by leakage of hydraulic fluid from the leg.

As a result of this experience and the occurrence of two serious crashes in other countries, due to the same causes, the strut was redesigned to reduce stressing at the critical position and steps were taken to ensure removal of decarburisation at positions where it could promote fatigue cracking.

7. A Simple example of creep failure

A simple example of failure of a metal component to continue to perform its intended function because of creep was investigated some three or four years ago.

The part involved was the lower portion of a sheet metal cannister used with a close fitting lid as a container for shoe polish. Due to tinplate shortage at the time, the polish manufacturer was forced to seek an alternative for the lower (container) part of the cannister and decided to use some zinc sheet (of slightly heavier gauge than the tinplate) for his purpose. A large number of containers was made and, in the usual way, these were filled with molten polish which was then allowed to solidify. The filled containers were then fitted with their tinplate lid which pushed over the rim of the zinc can with an interference fit of approximately 0·002 inch on the $2\frac{3}{4}$ inch can diameter. The cans were then allowed to stand for some time, usually overnight, before packing into large containers. On handling after this period, it was found that the lids had completely lost their interference fits, most lids being so loose that they fell off on inverting the cannister. This meant that the cannister was virtually useless because of the likelihood of losing lids during packing, transport, distribution etc.

It was clear that filling the container with hot liquid polish raised its temperature sufficiently to anneal the zinc. Then, in fitting the lid with its 0·002 inch interference, a compression stress was induced in the rim of the zinc container; simple calculation indicated that this stress was of the order of 5000 to 5500 lb./sq. inch, a stress well in excess of the limiting creep stress of zinc. As a result rapid creep took place, the interference fit between can and lid was substantially lost and lids became loose in a short time.

8. Failures in sporting weapons and ammunition

Experience has shown that whenever a mishap occurs in sporting firearms it is the unfortunate manufacturer of the weapon who gets the blame, rarely the maker of the ammunition—that is until an investigation establishes the true cause of trouble. This state of affairs has applied particularly to failures of a number of ·22 calibre rifles investigated in recent years—none of these has been attributable to the design, material or workmanship in the rifle, faulty ammunition being the cause of trouble in all cases.

In one instance the rifle was blamed for faulty performance when firing ammunition made by a reputable U.S. manufacturer. It was reported that the muzzle velocity of the bullet was abnormally low, while the ammunition showed a high proportion of split cartridge cases and "blow-back" of propellant gases at the case mouth. Investigation of the rifle showed no feature of design, workmanship, functioning or dimensions which could have affected the performance of the ammunition. The latter, however, left much to be desired, the metallurgical condition of the brass cartridge case being the sole cause of the reported trouble. Firstly, hardness in the case wall was abnormally high, this feature preventing adequate expansion at the mouth on firing and effective gas sealing; high hardness was thus the cause of case-mouth blow-back. In addition, a considerable proportion of cases (5 to 10 per cent) contained laminations in the case wall while others showed incipient stress-corrosion cracks. These two features accounted for the high proportion of cases which split on firing. Regarding the latter feature, it was found that the cases gave 100 per cent failure in a accelerated test for susceptibility to stress-corrosion cracking. It was therefore fortunate that only a small percentage of cases had developed this type of crack prior to use; the use of a thin nickel plate on the outside of the case had undoubtedly prevented higher incidence of stress-corrosion cracking.

Another investigation into reported faulty rifle performance again cleared the name of the rifle and showed the ammunition to be defective. This was .22 calibre long rifle ammunition of European manufacture which used a gilding metal cartridge case in lieu of the more usual 70/30 brass case. In this instance the case had been manufactured to standard external dimensions and rim thickness, but had been made with an abnormally thin section of metal across the head—thickness across the head was 0.012 inch as compared with approximately 0.020 inch of metal in other ammunition. This feature resulted in the head being deeply indented by the firing pin of the rifle, some cases being so deeply marked as to give an incipient shear failure at the edge of the indentation. This effect, coupled with uneven density of propellant loading throughout the batch of ammunition, led to the propellant gases blowing through the indented area in a high proportion of cases, while in some a small disc (the area struck by the firing pin) was blown out of the case head and jammed into the firing pin hole of the rifle bolt. The incidence of this firing defect was of the order of 6 per cent in a new rifle with low head space, while it rose to nearly 50 per cent, with some complete case head separations, in a rifle with high head space.

Another complaint of faulty rifle performance followed a series of rifle failures which occurred when firing sporting ammunition of another European manufacture; fortunately the incidence of failure was of a small order, probably less than half of 0.1 per cent, as each failure was accompanied by extensive damage to the rifle breech, the bolt and furniture, and in some cases serious injury to the shooter. As usual, the rifle was at first held responsible until investigation showed clearly that the ammunition was at fault. Each failure was accompanied by complete separation of the cartridge case head, the full impact of firing being taken on the front face of the bolt with consequent damage to the rifle. Unlike previous investigations, no fault could be found in the cartridge case material (70/30 brass), dimensions or metallurgical condition. As a consequence every factor which might have influenced the failure was examined in turn and finally, after extensive firing trials, it was found that failures similar to those which started the investigation could be reproduced only by loading the ammunition with a double charge of propellant. Subsequent to this finding a large quantity of the ammunition was examined for evidence of double loading. This was done by both radiographic means and by breaking down individual rounds; in a total of 2500 rounds examined, one double-loaded cartridge was found, thus proving that this source of serious trouble was, in fact, occurring at the maker's works.

A recent investigation was made into the cause of very extensive damage to a .22 calibre rifle in which the breech casing was badly distorted, the bolt and rifle furniture shattered and the barrel split along the underside over a length of 4 inches at the breech end. In a report covering the circumstances of the mishap, the shooter stated that a standard round of a well known (and very reliable) brand of ammunition was used; further probing, however, revealed that the shooter himself had escaped injury and clearly indicated that the rifle had been fired by remote control in some kind of experiment. The rifle barrel was found to be sound and to be free from any metallurgical or other defect which could have contributed to such a failure. In addition, it was known from the previous investigation that a double-loaded cartridge could cause extensive damage to the bolt, breech casing and furniture. It was also known that this damage was never accompanied by damage to the actual barrel, not even slight permanent expansion of the chamber. In the rifle under investigation, it was found that the chamber had been grossly expanded before the barrel split, the rear end of the chamber, originally 0.230 inch diameter, having expanded to 0.274 inch before splitting commenced. This showed that the transverse ductility of the barrel steel was adequate, and proved beyond doubt that the rifle had been fired with a propellant charge well in excess of twice normal.

A failure due to the firearm itself, and not the ammunition, was one involving bursting of the lower barrel of a 12—gauge "under-and over" shot gun. The accident occurred when firing a high powered cartridge, which had been stored at an ambient temperature exceeding 110°F for a sufficient time to allow the propellant powder to become largely dehydrated. These circumstances tend to increase chamber pressure, in this case the increase being estimated as roughly twofold, viz. from a normal 3 to $3\frac{1}{2}$ tons/sq. inch to about 7 to 8 tons/sq. inch. In this particular shotgun, the burst lower barrel had been made from a plain medim carbon steel of very low quality with a high content of large silicate and sulphide non-metallic inclusions. In addition, one of the two deep-drilled extractor holes at the breech had been drilled off-line leaving a wall section of only 0.030 inch at the bottom end of the hole at a position about half way along the barrel chamber. Splitting during high pressure firing start at this position and continued over a length of $1\frac{1}{2}$ inches, the burst resulting in shattering of the breech casing and very serious injury to the shooter.