Maraging steel in the British aerospace industry

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A detailed examination of a forging produced from single vacuum-melted material has shown the transverse ductility and toughness of maraging steel to be somewhat inferior to those of conventional steels at equivalent strength levels. Examination of other casts has confirmed this inferiority. Double vacuum melting is shown to be satisfactory in every respect. Results of alternating and fluctuating fatigues tests are given and it is concluded that shot peening raises the resistance of the material above that of low alloy steels. A technique to overcome plating difficulties is described. A number of aerospace components, including nitrided parts, are illustrated and described

concluded from the January issue

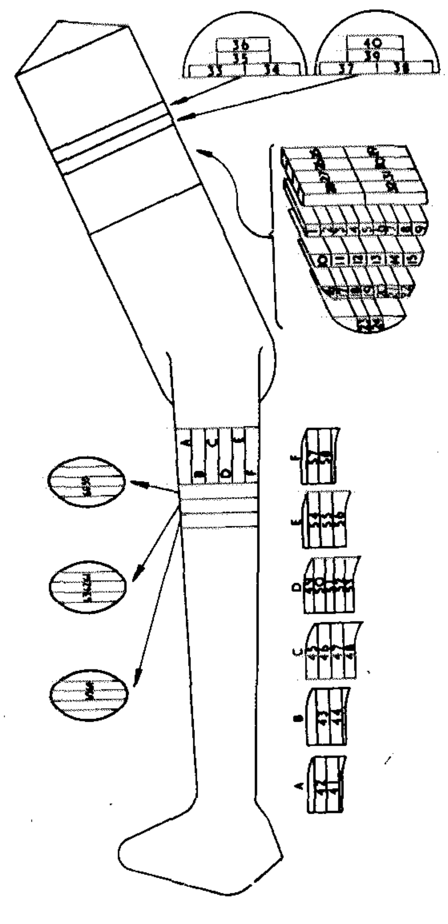
Fatigue properties

Several references have been made in recent years to the poor fatigue properties of maraging steel. A close study of the relevant reports has almost invariably indicated that comparisons were being drawn without adequate evidence. For example, rotating-bend tests were being compared with direct stress: specimens in one type of alloy extracted from a forging were being compared with specimens in maraging steel extracted from different positions in a forging of another size and shape, etc.: sometimes only a brief reference appears in the literature without any reference to the supporting evidence: for example, in the January 1968 issue of the journal *Materials Engineering*, the following statement is attributed to a materials specialist:

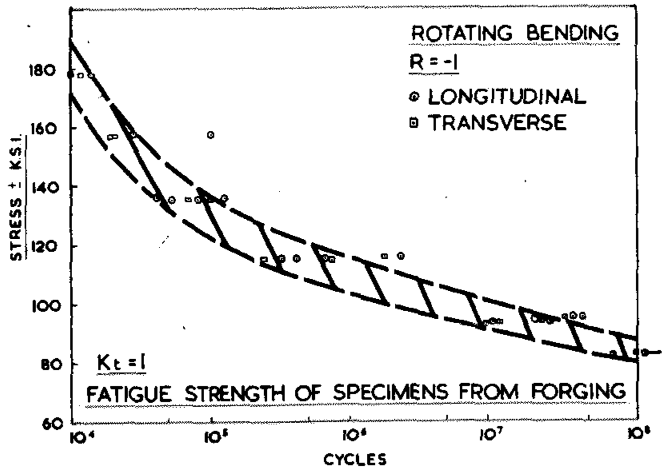
> 'The maraging steels have relatively low fatigue strength for steels of this strength level. Furthermore, their fatigue strength is too erratic and unpredictable for critical high strength aircraft parts'.

We have been unable to trace anywhere in the technical press comparative fatigue data between maraging steel and the conventional low-alloy steels where testing has been carried out on the same machines by the same research organization and using the same size and shape of specimen: this we set out to do.

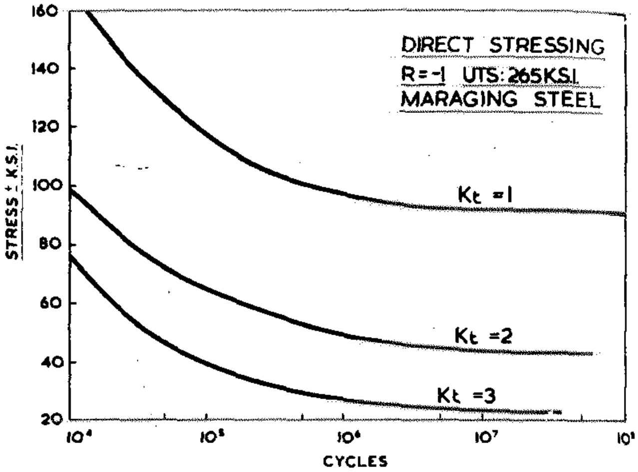
Our earliest investigation consisted of testing in rotating cantilever machines a large number of small specimens extracted from the remaining half of the tail-wheel forging. The location from which the specimens were extracted is shown in fig. 18. The size of the specimens was 2 × ¼ in. diam. Some specimens were polished before ageing and some after: some were tested in the vapour blasted condition and also, of course, a proportion of the specimens possessed longitudinal grain and some transverse grain. Contrary to results obtained by a number of investigators, no parti-



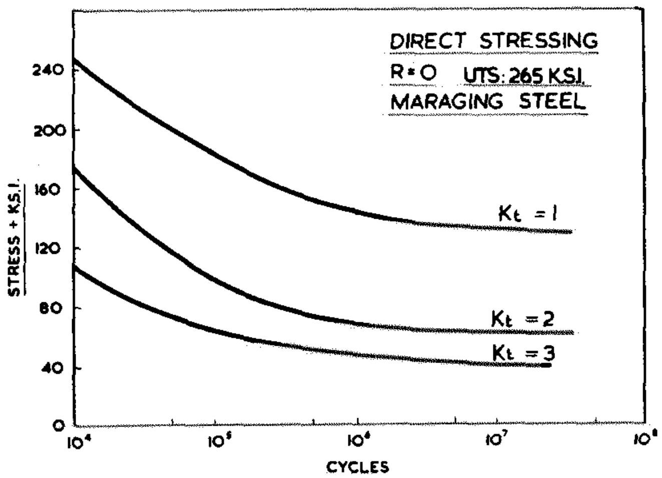
18 *Location of fatigue test specimens extracted from forging*



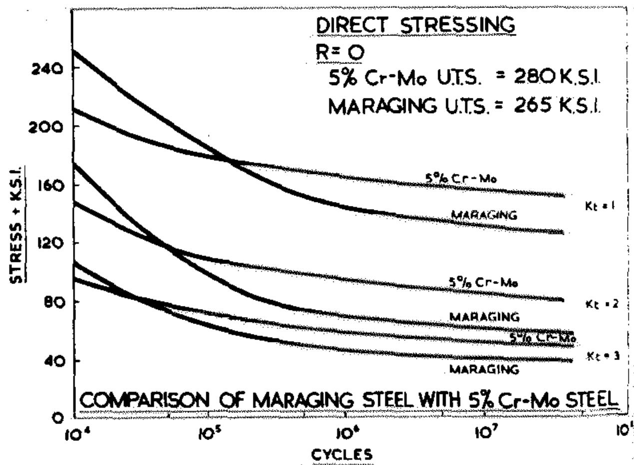
19 *Scatter band of rotating bending test results*



20 *Alternating stress results*



21 *Fluctuating stress results*



22a *Fluctuating-tension tests on two steels*

cularly significant difference was found between the specimens, irrespective of the surface conditions or grain direction. The scatter band of all the results is shown in fig. 19.

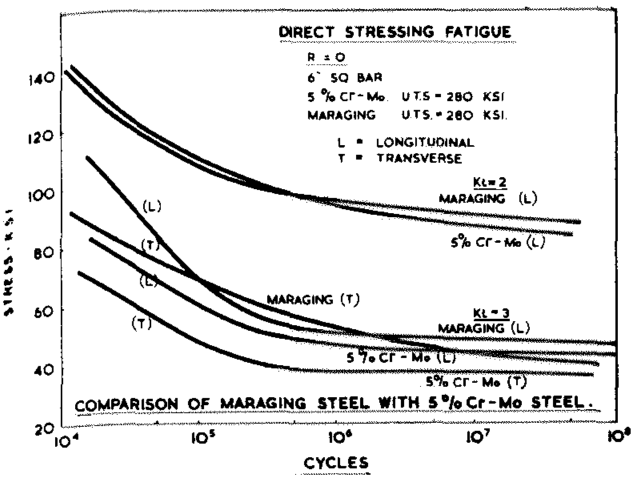
Our more recent tests have been carried out on specimens extracted from 6 in. square bar.

The results of alternating stress (R = –1) tests at three different levels of stress concentration are shown in fig. 20. The curve for smooth specimens compares reasonably well with the results obtained from the tail-wheel fork forging (fig. 19): the stress at 10^7 cycles of ± 92 ksi is equivalent to a fatigue/ultimate ratio of 0·35, which is lower than that normally obtained from low-alloy steels of comparable ultimate strength. The results of fluctuating stress (R = O) tests are shown in fig. 21. This form of fluctuating-tension stressing is more applicable to landing-gear design than tension-compression testing and these results have been used in conjunction with the (R = –1) results for constructing Gerber diagrams.

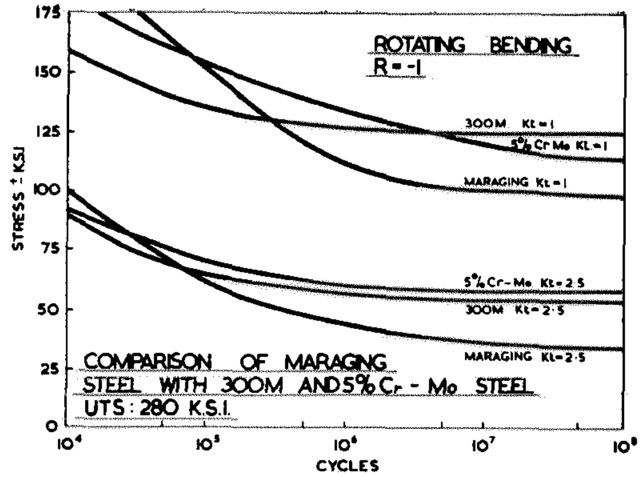
A comparison between the fluctuating-tension results for 265 ksi maraging steel and 5% Cr–Mo (H.11) material heat treated to 280 ksi is illustrated in fig. *22a*. Although the difference in ultimate tensile strengths has to be borne in mind, it will be noted that the maraging steel is, in general, inferior at cycles exceeding about 5×10^4 but it is superior at lower cycles. However, it will also be seen that at Kt = 3, a stress-concentration at which our landing-gear designers are particularly interested, this superiority of the 5% Cr–Mo material, at 10^7 cycles is reduced to approximately 16 ksi when compared with approxmiately 25 ksi for the tests carried out at Kt = 1 and Kt = 2.

Further comparative notched-fatigue fluctuating-tension tests have been carried out on another cast of maraging steel, and 5% Cr-Mo, heat treated to the same U.T.S. level of 280 ksi, in both the longitudinal and transverse grain direction. The results are illustrated in fig. *22b*, and it will be noted that in this instance the curves for the two steels at Kt = 2 are substantially the same, and at Kt = 3, the maraging steel is actually superior.

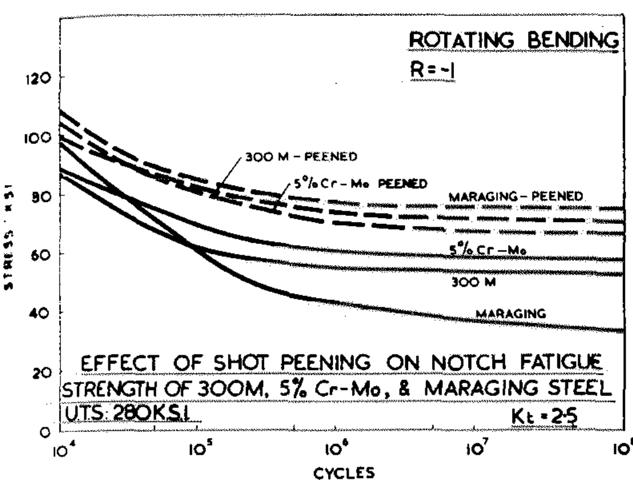
A comparison between maraging steel, 300M and 5% Cr–Mo alloys, all heat treated to the 280 ksi U.T.S. level and tested in alternating-stress (rotating-bending), both plain and notched, is shown in fig. 23. These results confirm the inferior high-life alternating-stress fatigue resistance indicated in the tests carried out on the 265 ksi maraging steel (fig. 20). The fatigue/ultimate ratio of the unnotched maraging steel at 10^7 cycles is 0·36, compared with that of 0·43 for the 5% Cr–Mo, and 0·44 for the 300M. However, the influence of shot peening (0·011 in. shot, arc height 0·0145A2), which we would normally consider necessary, especially in areas of stress concentration, is to



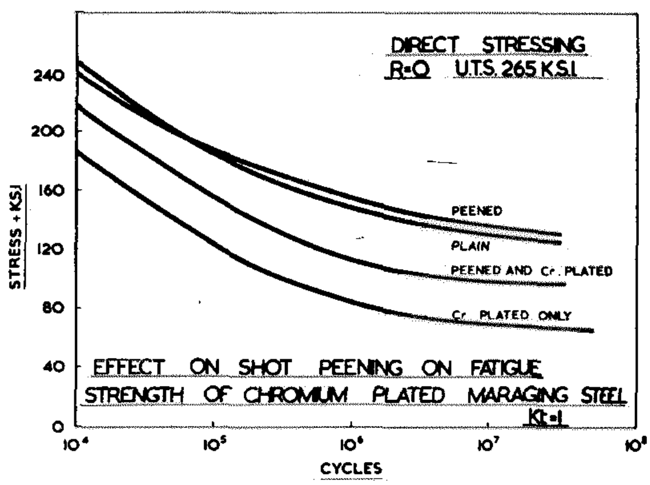
22b *Fluctuating-tension tests on two steels*



23 *Alternating-stress tests on two steels*



24 *Alternating stress comparison of two steels under the influence of shot peening*



25 *Fluctuating-tension tests on hard chromium plated maraging steel*

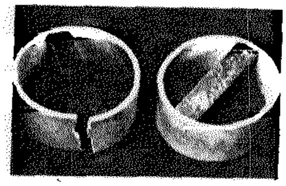
reverse the order of merit of the notched-fatigue strength of these three steels, so that maraging steel is superior to all lives between 10^4 and 10^8, fig. 24. It is probable that this proportionally greater improvement in the case of maraging steel is due to the higher yield/ultimate ratio of the alloy when compared with the more conventional materials.

Finally, we have investigated the effect of hard-chromium plating on the fatigue life of smooth specimens (we would never consider the application of chromium at areas of stress concentration), fig. 25. It will be noted that although the fatigue limit is significantly reduced when the chromium is applied to a plain (unpeened) surface, in the manner typical of a conventional high-tensile steel, a substantial improvement, although not a complete recovery, occurs with prior peening. It will also be seen from the graph that, as is to be expected, shot peening of an unnotched unplated surface results in very little gain in fatigue resistance.

Summing up, the results of the above tests have indicated that maraging steel appears to possess inferior alternating-stress fatigue properties at cycles-to-failure exceeding approximately 5×10^4, but it is superior at lower cycles. One series of tests in fluctuating-stress has confirmed this high-cycle inferiority, whilst a later series, using a higher strength material, has not. However, any comparative disadvantage which the steel may, in fact, possess can be eliminated by the application of controlled shot-peening in regions of stress-concentration or where chromium plating is to be applied to plain surfaces.

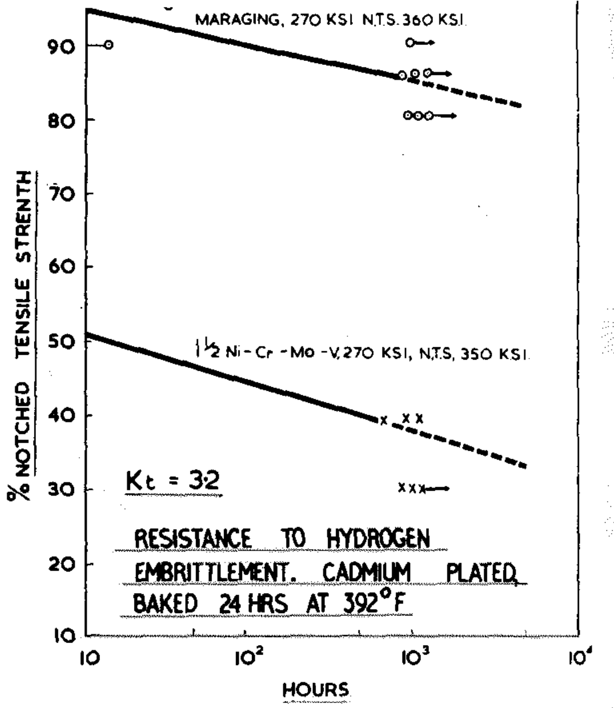
Our tests on all U.H.T.S., only some of which are described in this paper, have, like other investigations, shown more scatter than similar tests on lower tensile steels. There appears to be as much variation in fatigue properties between different casts of the same nominal composition as between steels of entirely different composition but with similar tensile strengths. It would appear that composition is not a very significant factor, and probably the nature and quantity of non-metallic inclusions are of greater importance. The results which we have obtained on maraging steel are certainly not such as to cause us any concern. Indeed, there is a strong case for believing that the behaviour of the alloy under service conditions, where the influence of high stress concentrations and of corrosion are so important, is superior to the conventional materials by virtue of its higher fracture-toughness and better corrosion resistance.

	3% Cr-Mo	MARAGING
BRIGHT CADMIUM (15 AMPS/SQ FT)		
AS PLATED	½, ¾	¼, ¾
DE-EMBRITTLED 24 HRS AT 400°F	¼, 2	32, 300
UNBRIGHTENED CADMIUM (10 AMPS/SQ FT)		
AS PLATED	¼, ¾	35, 80
DE-EMBRITTLED 24 HRS AT 400°F	6, 27	300, 750U

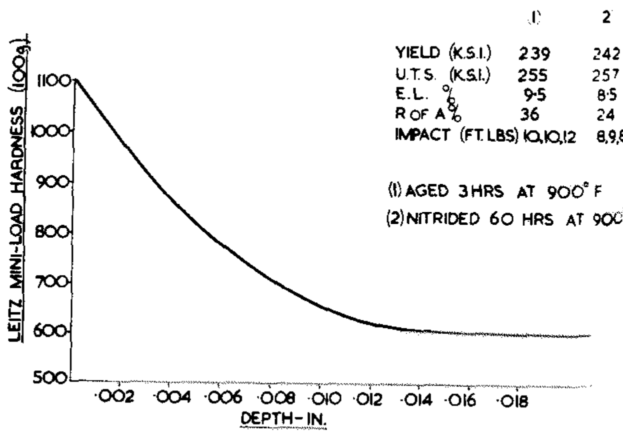


HYDROGEN EMBRITTLEMENT TEST RESULTS

26 *Tests carried out on uncracked and fractured ring specimens*



27 *Comparison of maraging steel with 1½ Ni-Cr-Mo-V*



28 *Effect of nitriding on core properties and surface hardness*

Plating

We have experienced some difficulty in obtaining a consistent level of satisfactory adhesion of chromium and cadmium plate: these difficulties were not revealed during the early tests on the simulated components shown in fig. 31; neither were they overcome by operating the pretreatment procedure recommended by INCO. This latter process consists of some 10 steps and includes two cathodic alkaline cleans, one anodic alkaline clean, an anodise in 25% sulphuric acid, a chromic/sulphuric dip and a nickel strike. It has been our experience that the chromic/sulphuric dip does not always remove the black smut (suggested to be a molybdenum compound) on the steel surface formed by the anodizing.

The process which we now use, and which we have found to be very satisfactory, is as follows:

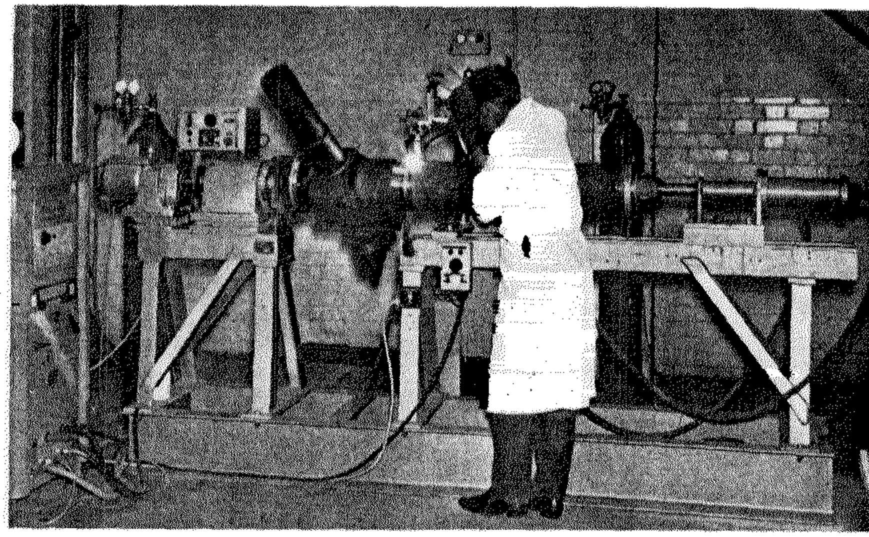
1. If maraging scale is present, remove by shot blasting. If this is not possible or permissible, treat as follows:
   - 1.1 Immerse in inhibited hydrochloric acid (*e.g.* Acitrol) for 20 min at 50°C (this softens the scale).
   - 1.2 Remove softened scale by either aqua blasting, wire brushing or bristle brushing with pumice powder.
   - 1.3 Wash in cold water then proceed as follows:
2. *Chromium plating*
   Immerse in plating solution with applied potential of 2 V and allow component to attain bath temperature, then raise current to plating current, in the order of 200 A/ft^2, and plate for required time.
3. *Cadmium plating*
   Immerse in plating solution with component anodic and plating voltage applied for about 30 sec, then make cathodic and plate for required time.
4. For steel surfaces ground after maraging, either vapour or aqua blast or bristle brush with pumice powder. After swilling in cold water, proceed as 2 or 3 above.

Hydrogen embrittlement

Ring specimens were extracted from the tail-wheel fork forging, previously referred to, in order to test the susceptibility of steel to hydrogen embrittlement following cadmium plating. The constant strain test as applied by the Dougla[s] Aircraft Corp. was employed, wherein a plated ring [is] stressed by compressing across a diameter and inserting int[o] the resultant oval a steel bar with radiused ends and of [a] predetermined length. The criterion of acceptability [is] based on the life to fracture, a period exceeding seven da[ys] being considered satisfactory.

Fig. 26 shows one of these rings (uncracked) tested alon[g] with a ring (fractured) of 3% Cr–Mo steel heat treated to [a] similar tensile strength of 270 ksi. Several rings in the marag[ing] steel and 3% Cr–Mo steel were plated both with an[d] without brighteners and the results are also shown in fig. 26. It will be noted that although maraging steel can be made t[o] embrittle, it is far less so than 3% Cr–Mo material, and als[o] the standard post-plating heat treatment of 24 h at 400°F (205°C) results in material considered to be free fro[m] embrittlement.

In more recent months the resistance to embrittlem[ent]



29 *T.I.G. welding of sliding cylinder and axle of main landing gear*

of maraging steel has been compared with that of a 1½ Ni–Cr–Mo–V material by sustained load notched-tensile testing. The results obtained are shown in fig. 27. It will be noted that whereas the Ni–Cr–Mo–V material will sustain only 35% of the N.T.S. for 1000 h, the maraging steel will sustain 80–85% for the same length of time.

It is our opinion, based on the results of these two tests, and similar confirmatory work elsewhere, that it is perfectly safe to plate maraging steel from conventional unbrightened cyanide baths, followed by the standard de-embrittling heat treatments, thus avoiding the necessity for applying either high-current density porous cadmium with its relatively expensive jigging requirements and poor throwing power, or the more expensive titanium-cadmium solution now considered desirable by many material engineers for the plating of conventional ultra-high tensile steels.

Nitriding

We have investigated the advantages, both from the technical and the production point of view, of applying nitriding to maraging steel. The effect on the core and case properties of nitriding for 60 h at 900°F (480°C), when compared with the normal ageing of 3 h at the same temperature, is shown in fig. 28. It will be noted that there is a small, but quite definite, reduction in ductility and toughness, but this is not considered to be detrimental in so far as our applications are concerned. With regard to the nitrided layer, it will be seen that the degree of surface hardness obtained (equivalent to approximately 1000 V.P.N.) together with the back-up of a 260 ksi core appears to offer a considerable advantage over the case-hardened alloys for such applications as gears, etc.

We originally set out to combine the ageing and nitriding cycles but this is not always suitable for components with very close dimensional tolerances. With this combined procedure, diametral shrinkage varies slightly from cast to cast although keeping more or less in the order of 0·001 in. Some 90% of the shrinkage takes place during the ageing treatment; and therefore our process for conforming to the very close tolerances almost invariably required is as follows:

(a) Machine component in solution annealed condition, leaving grinding allowance on close limits.
(b) Marage.
(c) Grind.
(d) Nitride (shrinkage now being in the order of only 0·00005–0·0001/in.).
(e) Finish hone or lap, or vapour blast, if required.

Incidentally, it is important to ensure that the recommended ageing temperature of the casts of steel to be used for nitriding is not lower than the nitriding temperature.

Welding

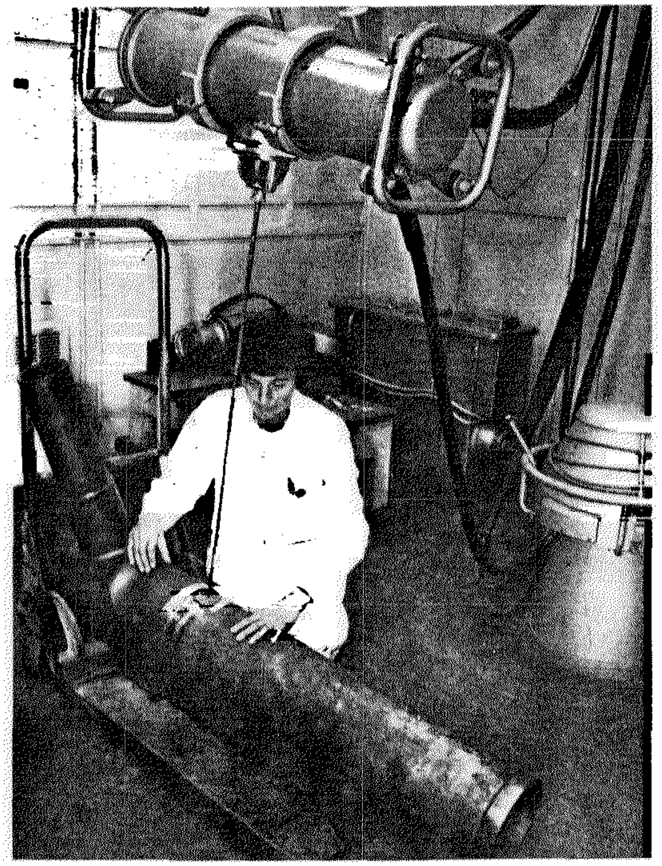
We have carried out a limited amount of work on the T.I.G. welding of large forgings, fig. 29. The finished weld comprised 34 passes of 0·048 in. diam. wire. The parts were solution-annealed prior to welding and subsequently aged as a final operation.

Fig. 30 shows a fabricated component being X-rayed. Results have been excellent and no difficulties have been encountered in these experiments. This component is at the present time being subjected to full-scale fatigue testing.

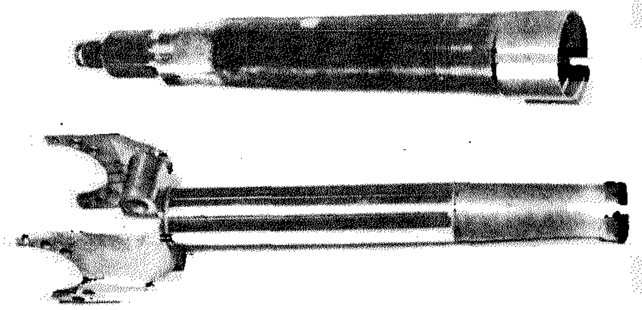
Production applications

Following on from our earlier detailed examination of the tail-wheel fork, we next produced several machined dummy parts to simulate the shapes of typical nose and main landing gear components. Fig. 31 (top) illustrates one such part of comparatively uniform section which was finish-machined in the soft condition, making allowances for a contraction of 0·0005 in./in. to take place during ageing. The part remained well within drawing limits after ageing. Fig. 31 also illustrates a somewhat more complex component on which experience of drilling and tapping was obtained: movement in this case was held to 0·001 in. In addition to machining tests, these parts were used for chromium and cadmium plating experiments and no trouble with either process was experienced (although on future production, certain troubles were encountered, see reference to 'plating').

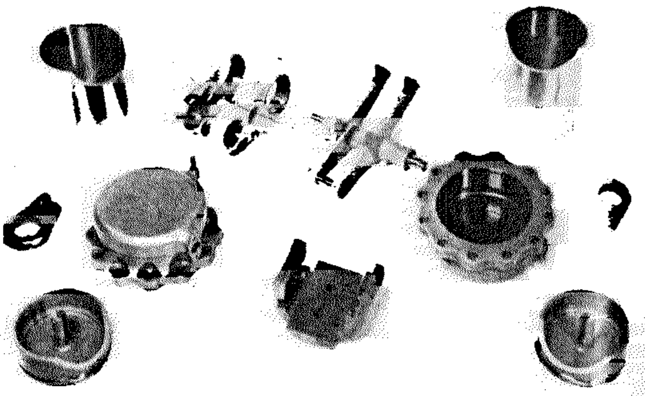
Since the time of the above tests, we have manufactured a large number and variety of landing gear and hydraulic components. A typical selection is illustrated in figs. 32, 33 and 34. It will be noted that several of the components are chromium and/or cadmium plated.



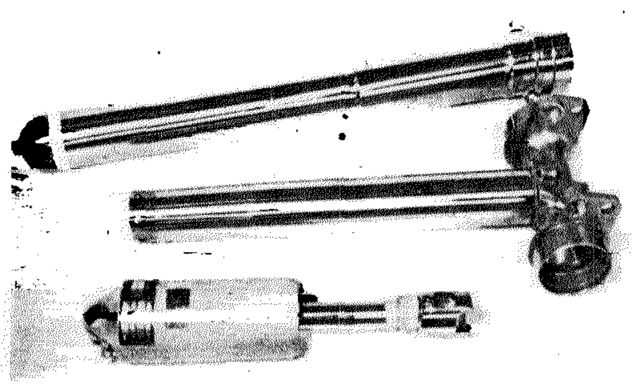
30 *X-ray examination of welded component*



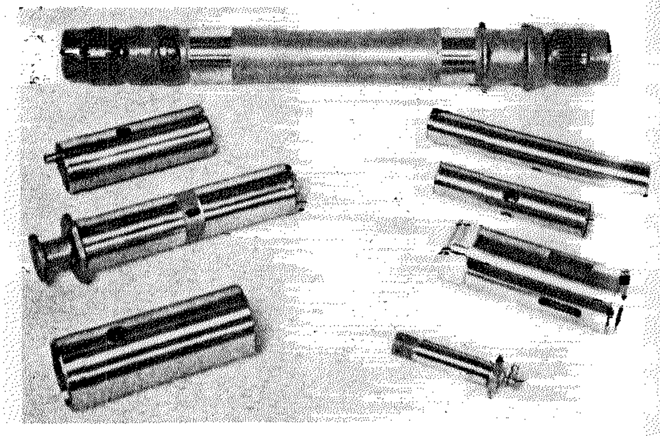
31 *Forgings simulating the shapes of typical nose and main landing gear components*



32 *Typical landing gear components, retraction lever, steering motor end caps and link, thrust block, pistons and sleeves, etc.*



33 *Hydraulic accumulator, main landing gear sliding member, and liquid spring*



34 *Typical landing gear axle, wheel lever pivot pins, etc.*

With regard to nitrided components, one of the most successful applications has been that of the rack-and-pinion steering mechanism of nose landing gears, fig. 35. When made in 200 ksi, 4¼ Ni-Cr-Mo case-hardened steel, considerable manufacturing difficulty was experienced due to distortion of the rack, quite apart from the fact that they were stressed to the limit in service. The changeover to nitrided maraging steel has resulted in an appreciable saving in weight: the components are designed to run at a maximum fatigue bending stress in the order of ± 55 ksi compared with a figure of 35 ksi for the case-hardened material.

Nitrided maraging fuel pump gears, fig. 35, are also proving more durable than their nitrided low-alloy counterparts. These gears have previously been manufactured from 3% Cr–Mo–V material (S.134), which possesses a cor strength of 220 ksi and all evidence at the present tim indicates that the harder back-up of the case, at least 55 RC results in an appreciable improvement in tooth life.

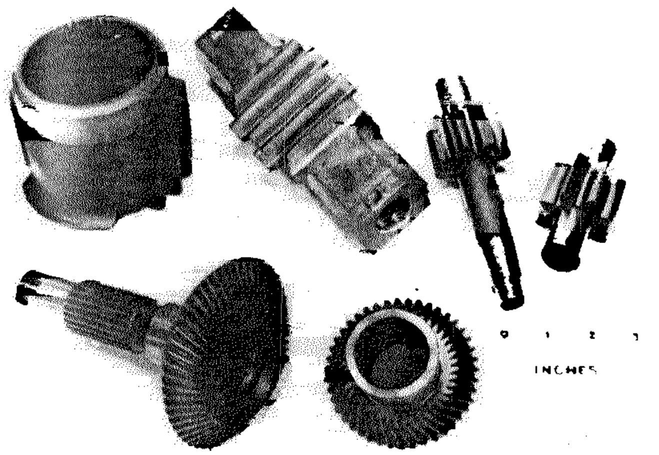
We have also investigated the design and productio advantages of using nitrided maraging steel helical sp and spiral bevel gears in our 'accessory-drive gearboxe fig. 35: the gears are manufactured without the necessity fo grinding after ageing. We have satisfactorily run the gears at a Hertz stress exceeding 200 ksi, whereas we kno that failure occurs with our existing case-hardened gears stresses in the order of 175 ksi (we actually design to a maxi mum Hertz stress of 150 ksi). From the point of view o fatigue, our case-hardened gears are designed to a maximum fatigue bending stress of 22 ksi, but we have every confidence of almost doubling this figure with nitrided maraging steel. Gears are currently being manufactured which are little more than half the face width of the case-hardened gears which they are to replace, and by this change-over we are significantly reducing the weight (and volume) of our gearboxes. Fig. 36 shows a set of spiral gears installed and ready for test.

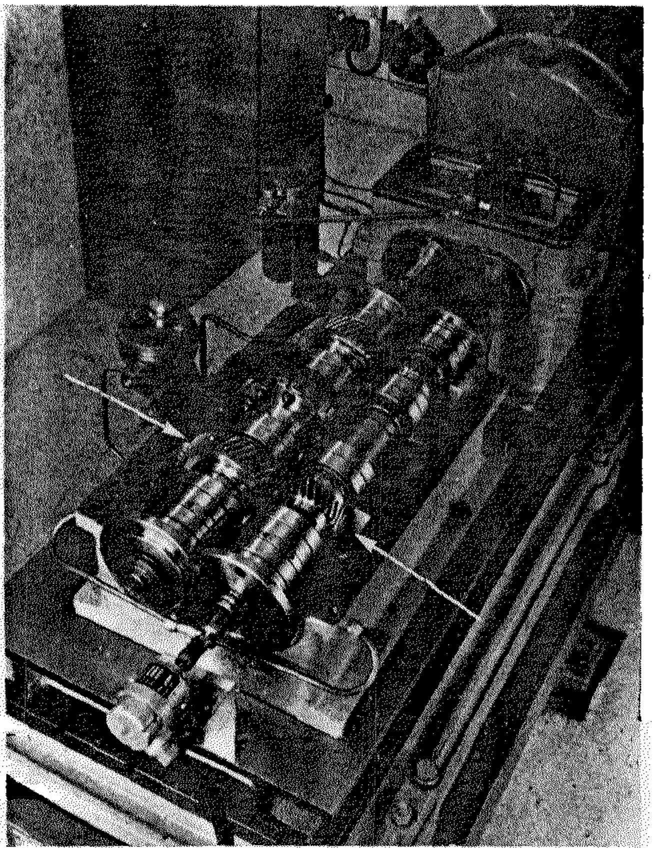
One aircraft, the landing gears of which contain a considerable quantity of maraging steel, is the VTOL Hawker Siddeley P.1127 Harrier, fig. 37. The use of this steel results not only in a minimum weight but in minimum volume, the latter being of particular importance in view of the small space available in the fuselage for the gear in the up-lock position.

Two other applications of maraging steel, not connected with the Dowty group of companies, may be of some interest:

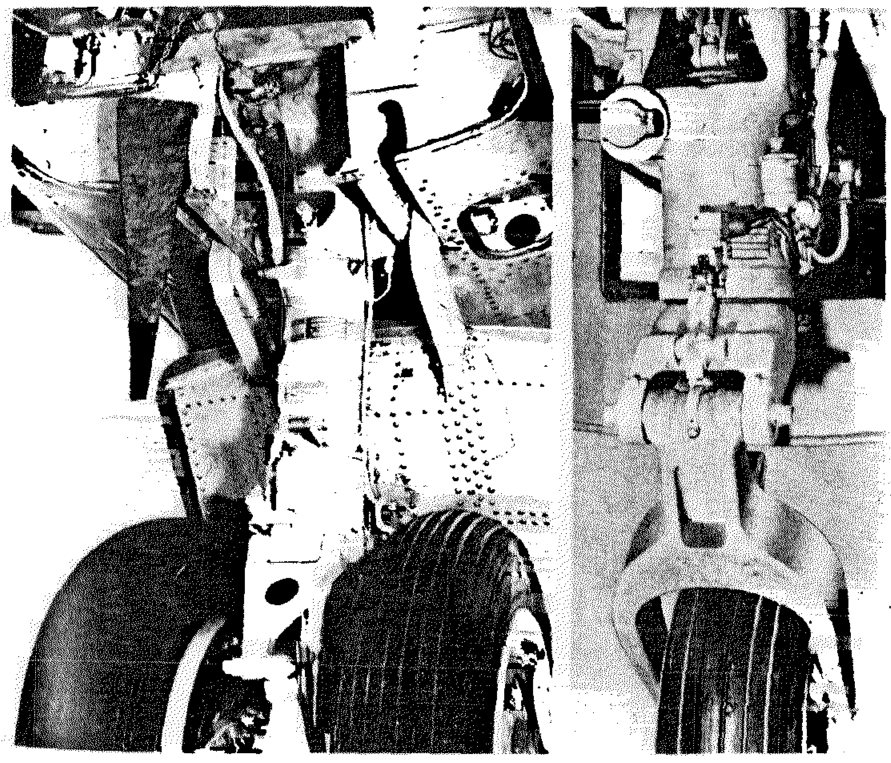
The M.L. Aviation Co. Ltd., White Waltham, have achieved important weight savings and improved performance in a range of 'ejector release units', fig. 38, by the use of double vacuum-melted material for all the highly stressed components.

35 *Nitrided rack and pinion, fuel pump and accessory gearbox gears*

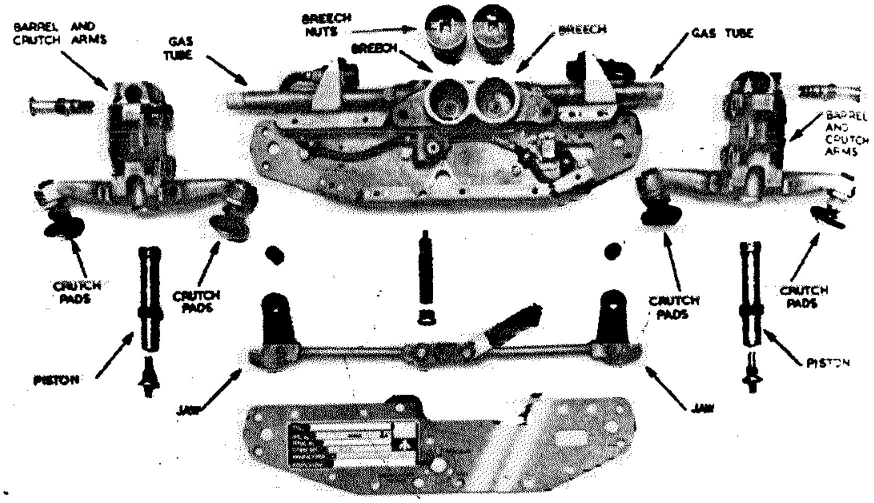




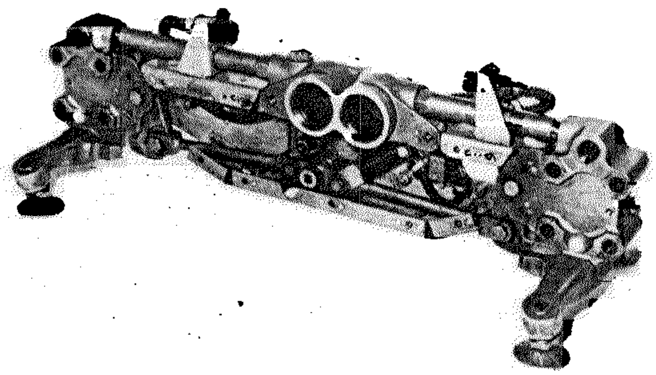
36 *Testing with cover removed showing maraging steel helical spur gears and slave gears*

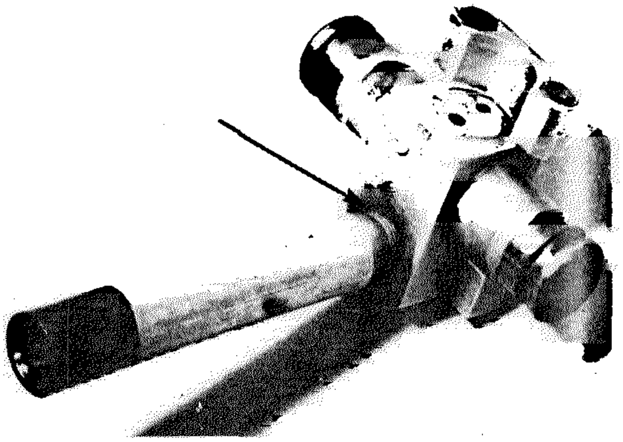


37 *Hawker Siddeley P.1127 Harrier main and nose landing gears. Shock absorber cylinders, axles, sliding tubes, wheel and retraction levers, steering rack, pinions and links, end caps, etc. in maraging steel*

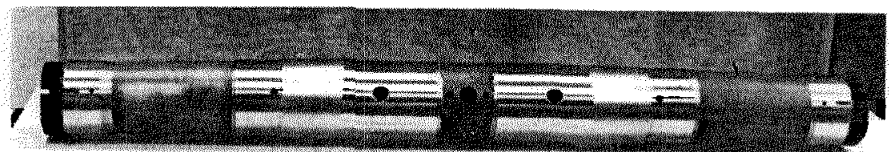


38 *Ejector release unit. All stressed components in maraging steel (arrowed)* ▶ ▼





39 *Brazed junction assembly*



40 *Main landing gear axle—super VC 10*

Safe ejection of the many varieties of store catered for by these units requires powerful variable-thrust rams to provide the energy necessary for forcing the store (*e.g.* a fuel tank or rocket carrier) clear of the airframe and for controlling the subsequent flight attitude of the plane. By the use of maraging steel it has been possible to design a unit down to a weight of only 16 lb, and yet which is capable of securing weights of up to 2100 lb during all flight conditions and which will eject the store with a velocity of up to 36 ft/sec, dependent upon the store weight.

Fig. 38 also shows an 'exploded' view of the unit, together with those components made of maraging steel. All these parts are machined to final dimensions prior to ageing.

One component in the unit, a junction assembly, is fabricated by brazing, fig. 39. Some initial difficulty was encountered when attempting to furnace-braze (hydrogen atmosphere) which entailed the heating of the box and components to 2110°F (1155°C). The parts were held during the brazing cycle in the temperature range of 1920–2110–1650°F (1050–1155–900°C) for a total time in the order of two hours, which resulted in grain-growth and embrittlement. However, a change-over to induction heating in a vacuum furnace, in which the work is maintained at the brazing temperature for a much shorter time, followed by cooling in an argon blast, has proved to be very satisfactory. A brazing alloy consisting of 82% copper:18% palladium is used in conjunction with a minimum amount of flux.

The British Aircraft Corporation, Weybridge, are successfully using maraging steel for the axles of the main landing gear of the Super VC10, fig. 40. The axle of the Standard VC10 is manufactured in 220 ksi material and the change-over to maraging steel on the larger aircraft has enabled the extra all-up-weight to be supported without increasing the dimensions of the axle. The components are machined from 6½ in. diam. bar of single vacuum-melted material, the latter being produced from high-quality raw materials as indicated in fig. 12.

Cost aspect

A cost assessment has been made for the production of several of our components when produced either in maraging steel or in a low-alloy steel of equivalent strength. In practically all cases the higher initial cost of the steel (about five times) has been more than offset by the appreciably lower processing costs. The percentage reduction varies from something in the order of 5% for a large steel forging requiring comparatively little machining, to 15% for a small component of intricate shape and design. This is quite apart from the many technical advantages of the material, and does not take into account any cost of special capital equipment, such as atmosphere-controlled furnaces, rigid cutting machinery, etc. often necessary for the production of components in low-alloy ultra-high tensile steels.

Conclusion

As a result of our experience with maraging steel, some of which has been described in this paper, we are of the opinion that this alloy has a definite part to play in the manufacture of highly-stressed aerospace components. Provided that the necessary care is taken at all stages of manufacture, the material offers many technical, production, and economic advantages over the conventional low-allow high-strength steels.

Clyde holds key to future of Scotland's iron and steel industry

'An entirely modern industry, specializing to meet local and export needs'—this is how two economists describe Scotland's iron and steel industry in a lively new study, 'Scotland—A New Look', published this week by Scottish Television Ltd. (50*s*.).*

The future of the iron and steel industry in Scotland lies in the decision to open up the Clyde as a major ore port, according to authors Geoffrey Credland and George Murray.

One of the most active industries in Scotland is construction and much of the steel requirements are being met by native production.

The newly established motor industry in Scotland has undoubtedly been instrumental in increasing production of sheet from a mere 1% of total production in 1962 to 26% in 1969, as stated by the Scottish Statistical Office.

An additional £5 million expenditure has been announced to provide extra ancillary plant at Ravenscraig and Garteosh to increase output of sheet and coil.

Iron-making has been concentrated in a few large works, with Colvilles, the largest producers, importing ore for their plants at Ravenscraig and Clyde Iron Works through the highly efficient ore terminal at Glasgow. Bairds, at Gartsherrie, and Carron Company, near Falkirk, are also large suppliers to the foundry industry.

A major new development, to pave the way for a break with the traditional centres of Glasgow and Motherwell, is the construction of a specialized iron foundry at Livingston by American Cameron Iron Works.

The iron industry produced a total of 1 251 000 tons in 1967 as opposed to 1 895 000 in 1962, according to the Scottish Statistical Office, while the steel industry turned out 2 600 000 tons of finished products in 1967 against the 1962 figure of 1 895 000 tons. The iron and steel industry currently has a work force of some 24 000.

The industry also contributes handsomely to Scotland's exports which now amount to 18·5% of her manufactures, compared with the U.K.'s average of 15·5%. These amount to a total of over £500 million a year, a jump of 50% since 1961.

'Scotland—A New Look' is a comprehensive survey of the Scottish economy. It takes a searching look at the new as well as traditional industries, development policy, finance and commerce and agriculture; Scotland's consumer markets and retail distribution patterns, the new towns, communications, Scotland's physical attributes and population distribution patterns. The new book represents a major revision, updating and widening of 'Scotland—The Vital Market' sponsored by STV three years ago. This quickly became recognized as a standard work on modern Scotland by libraries, universities and schools in many parts of the world.

*'Scotland—A New Look' (259 pp., 50*s*.), obtainable from STV Ltd., 70 Grosvenor Street, London, W.1.

Hardfaced rolling mill guides cut maintenance costs 97%

A steel rolling mill cut maintenance costs for roll stand floating guides by 97% through hardfacing instead of reforging and replacement, according to the Eutectic Institute for the Advancement of Maintenance and Repair Welding Techniques.

Floating guides are mounted in grooves of rollers that shape steel billets at 1000°C to square- and U-sections. Prior to hard-facing, guides wore up to 1 in. after a single eight-hour shift. They were then dismantled, reforged and reassembled. This operation took one hour. After eight shifts guides had to be scrapped. Fabrication of new parts took eight man-hours per guide.

Hard-faced guides wear less than 0·04 in. after eight hours. They are overlayed in position in just 10 minutes by the Microflo powder alloy process. The powder alloy, BoroTec 10009, has excellent abrasion and corrosion resistance and good hardness at high temperatures (RC 55–62). It also has a low coefficient of friction.

Hard-facing costs for eight, eight-hour shifts producing 1250 tons of U-section steel are £21. The comparative figure under the old system was £241. Estimated downtime savings are £458. Total savings for eight, eight-hour shifts are therefore £678.

The Microflo process is a fast, accurate technique for depositing hard-facing alloys in powder form. Deposit thickness is controlled down to 0·002 in. by a lever fitted to the welding torch. Overlays on guides are so smooth and accurate that finishing is unnecessary.

Cylinders in action. All wear-susceptible sufaces on the guide are overlayed with BoroTec 10009.