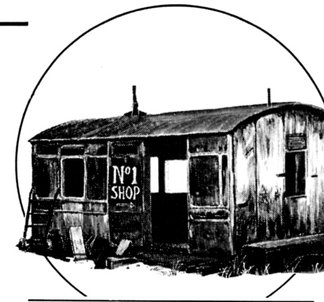
High Efficiency Worm Drives

Now in his 70th year, SID STUBBS is — as indicated by the letters M.I.Mech.E after his name — a highly-qualified engineer as well as being a well-known and long-standing modeller of great repute, particularly in the Manchester area where he lives. Over an extraordinarily long modelling career, he has helped a large number of less-skilled modellers achieve good results, and here, using school-level maths and plain language, he explains the secrets of his own make of high-efficiency worm-driven gearboxes:



Nº1 SHOP

TECHNICAL FORUM

The worm drive is almost certainly used on more model locomotives from 2mm to 10mm scale than any other type of drive. It has the merit of turning the transmission through 90° and, at the same time, providing the required reduction ratio, all in a single stage. It is quiet and needs no special shafts or bearings, the worm going on the motor shaft, the wheel on the driving axle.

Nevertheless, the worm drive has its enemies. Remarks such as '. . . the dreaded worm gear set' and '. . . the miserably inefficient worm and wheel which will not drive backwards' are examples that have appeared in the model press from time to time and, undoubtedly, the latter statement is believed implicitly by the majority of modellers.

It need not be true, as this article will attempt to prove. Since a worm and a screw are virtually one and the same — namely a helical thread wrapped around a cylinder — let us consider the 6mm metric screw shown in *Fig. 1a*. The pitch 'P' is the distance from one thread to the next, 'D' is the top diameter, 'd' the bottom diameter of thread and 'd_e' is the effective or pitch diameter of the thread where the actual load is deemed to act, halfway down the thread flank. The helix angle 'α' of the thread can now be calculated from the right-angled triangle (*Fig. 1b*) which shows one turn of the thread 'unravelled', one side being the 1mm pitch and one side being the circumference of the pitch diameter or $d_e \times \pi$ = 5.35 mm × 3.142 = 16.81 mm. By trigonometry (this is back to the old schooldays, so don't be put off!) formula 1:

$$\text{Tangent } \alpha = \frac{p}{16.81} = \frac{1}{16.81} = .0595 \qquad 1$$

$$\text{Helix angle } \alpha = 3°\,24' \qquad 2$$

This angle is so small that the worm wheel cannot 'slide' the worm screw round and thus cannot drive back. Indeed, if it were not so, the screw itself would not bind in a nut which is what it is supposed to do.

However, if we can increase this angle substantially, we can arrive at a value sufficiently large to permit driving back. *Fig. 2a* shows how the angle may be increased by doubling the pitch of the thread, leaving all the other dimensions alone.

Substituting in formula 1:

$$\text{Tangent } \alpha = \frac{2P}{16.81} = \frac{2}{16.81} = .1190$$

and angle $\alpha = 6°\,47'$ (virtually double).

Of course, this produces an odd-looking thread needing an odd-looking worm wheel but *Fig. 2b* shows how we can run a second thread halfway between the first. The end view shows how this second thread starts at 180° to the first and this is called a two-start worm as opposed to the first one, which is single-start. Equally, we can have three-start, four-start and so on. The optimum is reached when angle 'α' becomes 45°, as is the case with the skew gear which generally has about ten teeth and is really a short slice cut out of a multi-start worm. However, there is a penalty to pay. One turn of a single-start worm will advance the worm wheel one tooth, giving a 60:1 ratio if the worm wheel has 60 teeth, but one turn of a two-start worm advances two teeth, giving 30:1 ratio; 3-start gives 20:1, 4-start 15:1 and so on. If, therefore, you want 60:1 with a 4-start, the worm wheel will have 240 teeth and will probably be much larger than the loco driving wheel!

There is another way of increasing the helix angle 'α' by reducing the diameter of the worm screw. Let us suppose that we halve the screw in *Fig. 1a* to 3mm, keeping the pitch at 1mm. The effective diameter, 'd_e' will now be 2.35mm and substituting in formula 1:

$$\text{Tangent } \alpha = \frac{1}{2.35 \times 3.142} = \frac{1}{7.3837} = .1354$$

$$\text{Helix angle } \alpha = 7°\,43'$$

The bottom diameter, 'd' will now be only 1.7 mm and there will not be sufficient metal to allow a bore in the worm, but it is quite usual to cut such worms direct into the shaft. Unfortunately, we cannot do this when we are faced with using a plain shafted, standard motor. The point to note, however, is that, by a combination of multi-start worm and the smallest possible diameter, we can achieve a worm gear of such helix angle as to permit drive-back. Another valuable feature of a minimum diameter worm is that the inevitable friction between worm and worm-wheel occurs at minimum diameter and, since frictional torque (which represents wasted power) is dependent on the radius at which the friction occurs, the smaller the radius, the less the power waste.

Obviously, the higher the finish of worm and wheel tooth surface, the lower the friction; similarly, the lower the coefficient of friction of the metals employed, the better. In this connection, case-hardened steel for the worm and phosphor bronze for the worm wheel represent the ideal combination.

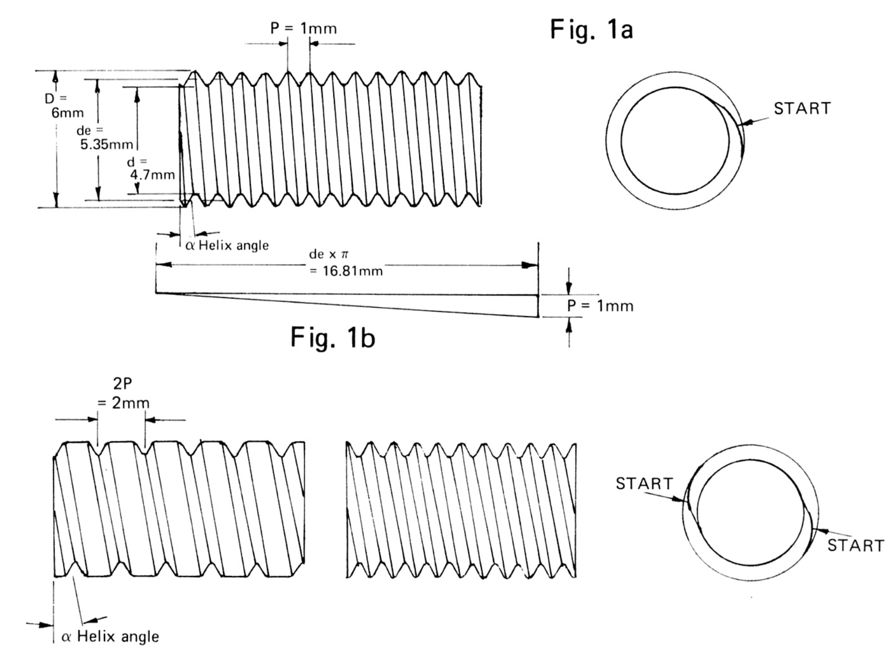


Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b

Finally, there will be a load reaction along the worm shaft caused by the worm driving the wheel round, and vice versa. This can set up considerable friction and consequent power loss in the bearings unless proper thrust bearings are employed and the usual model railway motors just don't have these, although some may be fitted with ball bearings which are not too bad. The best answer is to mount the worm separately with a flexible coupling to the motor. *Fig. 3* then shows how the 'blind' bush end of the shaft can accommodate a steel ball with the end of the worm shaft machined spherical, hardened and highly polished so that, in effect, one ball runs against another. Where the shaft must go through the bearing at the other end, two hardened and highly polished steel washers are fitted with three steel balls between, equally spaced at 120° by means of a brass washer 'cage' with three holes. Given a worm gear embodying all the foregoing, it will not only drive back but will have an efficiency over 70% which compares very favourably with that of the multiple-stage spur gearing which would be needed to achieve the same reduction.

So much for the theory — now the practical part. Some 35 years ago, I designed and made eight worm gear boxes to cover my projected requirements of eight 4mm/EM Midland locos. The input shaft is only 1mm diameter, the worm itself is $\frac{1}{8}$in diameter, 28 threads per inch and two-start while the worm wheel has 45 teeth giving a ratio of $22\frac{1}{2}$:1 which is about as large as can be accommodated in the space but which is quite suitable for use with the large, slow-running, heavy flywheel motors I also made (there being no decent motors on the market in those days). The helix angle is 12°34′, the worm is made from free-cutting mild steel which, having a high lead content, takes a very high finish and has a fairly low coefficient of friction. Attempts at cutting from silver steel or of casehardening proved counter-productive in this instance. The worm wheels were cut in manganese bronze as was the gear case, since this metal machines easily, has the strength of mild steel, has a reasonably low coefficient of friction and wears well. As I use a 'split' insulated axle with a $\frac{7}{32}$in diameter centre, the worm wheel was just bored to force on to this — no setscrew. I have since produced modified designs having steel bushes in the worm wheel to take $\frac{1}{8}$in or $\frac{3}{16}$in axles and setscrewed. All these gearboxes are reversible and the first one to be fitted in my Kirtley 0-6-0 has now done 35 years, running many miles, and is as good as the day it was fitted.

Some four years ago, I was visited by two leading members of the Gauge O Guild who were so impressed that they asked if I could make an O gauge version. One was duly designed $\frac{7}{4}$ths the size of the 4mm job and marketed through Barlow Models. I have now taken over the marketing and, having found the original O gauge box rather large (it has been used in Gauge 1), I brought out in 1988 a version only $\frac{8}{10}$ths the size. The worm shaft of this is $\frac{1}{16}$in diameter and the worm 0.175in diameter — 20 threads per inch, two-start. The 4mm version has been employed with success in Gauge O models, but only in light shunters and rail motors. After all, the input shaft *is* only 1mm diameter.

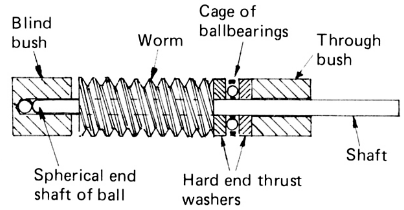
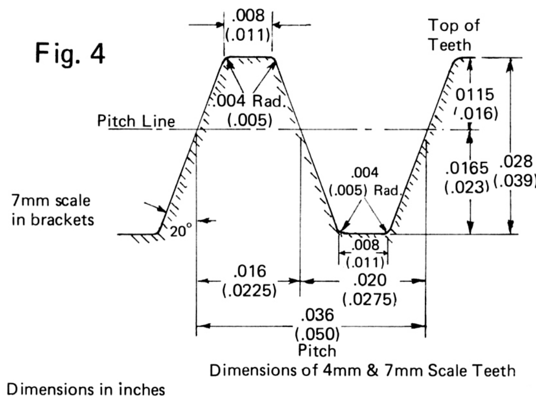
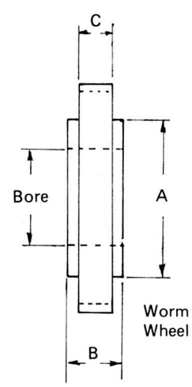


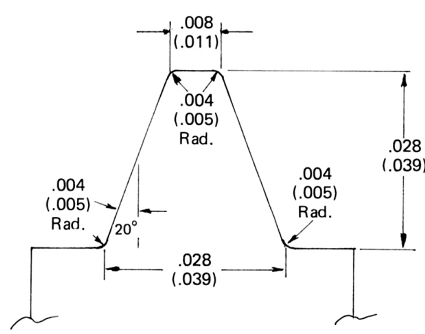
Fig. 3



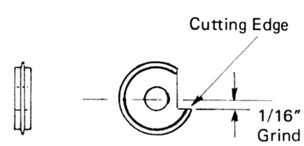
2 START WORM	4mm	7mm	WORM WHEEL	4mm	7mm
Length	.270	.385	Top Diam.	.535	.748
Top Diam.	.125	.175	Pitch Diam.	.512	.716
Pitch Diam.	.102	.143	Boss A	.312	.525
Threads per in.	28	20	Overall width B	.150	.190
Bore	.040 (1mm)	.0625 (1/16)	Tooth width C	.100	.150
			Bore	9/32	7/16

Worm and Wheel Dimensions





Dimensions of form tool periphery in inches
7mm sizes in brackets



Form Tool 5/8" Dia. x 1/8" thick
3/16" bore for 2BA bolt

Fig. 5

Since production of these gearboxes entails the use of a screwcutting lathe and a dividing head for cutting and hobbing the worm wheel, there would seem little value to most readers in going into a minutely-detailed account of what is entailed. However some readers will have such equipment plus a model engineering bent and, for their information, I propose to give a few details and dimensions from which they may well be able to do the necessary.

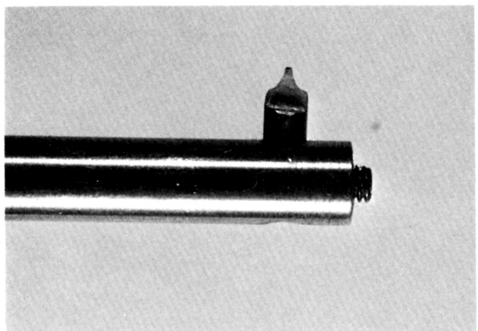
Originally, I employed worms cut to the 'minimum backlash' form of thread as laid down in British Standard 978:1941. I now use the 'backlash' form as shown in *Fig. 4* since, apart from making meshing a little less difficult, it also permits one form tool only for cutting the worm and the hob thread whereas the earlier form entailed different width tools. *Fig. 4* gives details of the 4mm and 7mm worms and wheels in tabular form and *Fig. 5* gives details of the circular form tool for screwcutting the threads. This tool is just a disc of silver steel with the form machined on the periphery. It is then heated cherry red and quenched in cold water. You can, with advantage, then temper it pale straw. After polishing to remove scale, grind a gash in the edge to leave the form as a cutting edge, bolt it to a piece of $\frac{3}{8}$in or $\frac{1}{2}$in steel bar and there is your form tool. This is an excellent idea for producing all manner of forms since it is so much easier to turn these shapes accurately on the lathe, rather than attempt to hand file or grind them. Lasts a lifetime, too!

Fig. 6 gives details of the gearbox bodies and covers. They are made from blanks parted-off $\frac{7}{8}$in or $1\frac{1}{4}$in diameter manganese bronze, bored and recessed off-centre using a 4-jaw independent chuck and the flats also faced off in the same chuck. The worm tunnel is bored at the correct centre distance by setting a worm wheel to run free on a peg in a piece of steel bar held in the vertical slide, and putting a worm on its shaft in a collet in the lathe mandrel. These gears are then carefully meshed together and adjusted by the cross-slide to their correct running distance, the cross-slide is locked, the gears removed and a blank box clamped on the peg whilst a drill in the collet is used to drill the tunnel. Start the hole with a 'Slocomb' bit to prevent wander. The recess must be machined central with the worm wheel bore *after* drilling the tunnel as to break into this recess with the drill could be disastrous. The box and cover having been drilled and tapped are bolted together and the flat on the cover sawn and filed to match the body. Finally a 12 BA (8BA) hole is tapped in from the far side to provide a setscrew to hold the loose, through-bearing bush. This screw also acts as an anchor for a torque arm to prevent the box turning round the axle in service. The blind bush is forced in at the other end of the tunnel.

The bushes are of phosphor bronze machined .150in long x $\frac{5}{32}$in diameter for the 4mm box and .225in long x 5mm for the 7mm, the diameter being 'force' or 'loose' fit as required. Bores are 1mm and $\frac{1}{16}$in respectively.

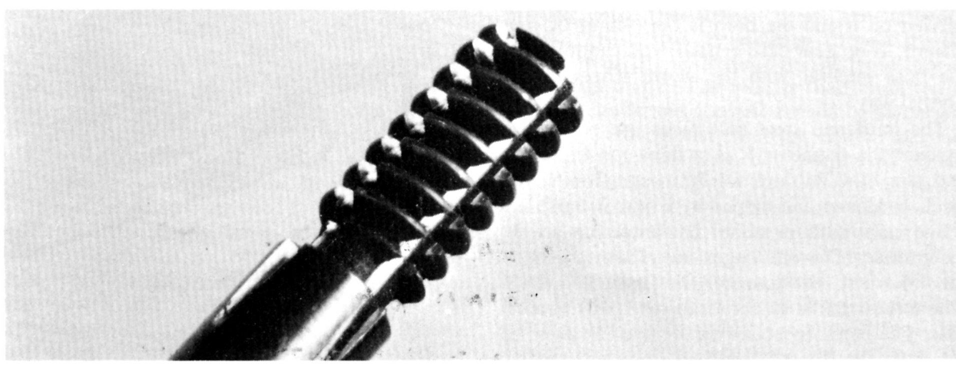
Of course, there is no compulsion to encase the gears in a gearbox. The bearings and worm can be secured direct to the chassis and the worm wheel meshed accurately, perhaps by inserting suitable packings under the bearing supports. However, this precludes the advantage of springing the driving wheels and it does give rise to the meshing problems which seem to beset some modellers. Also, the gears are no longer dust-proof, a useful feature in outdoor lines in particular.

In any case, it is necessary to cut the worm wheel teeth. The method of doing this is known as 'hobbing'. Essentially, if you were to take a plasticine blank wheel, capable of rotating freely on a stud and were to press a rotating worm into it, the worm would drive the blank round and, at the same time, generate a set of teeth in the periphery. Unfortunately, there is no guarantee that it would generate a precise whole number of teeth. If, instead of plasticine, you used the proper metal blank and employed a hardened steel worm with flutes cut in like a tap, known as a 'hob', you would also generate teeth, but it is necessary, first, to 'gash' the blank with the correct number of teeth, using a 'fly cutter' or similar, just a whisker smaller than the finished



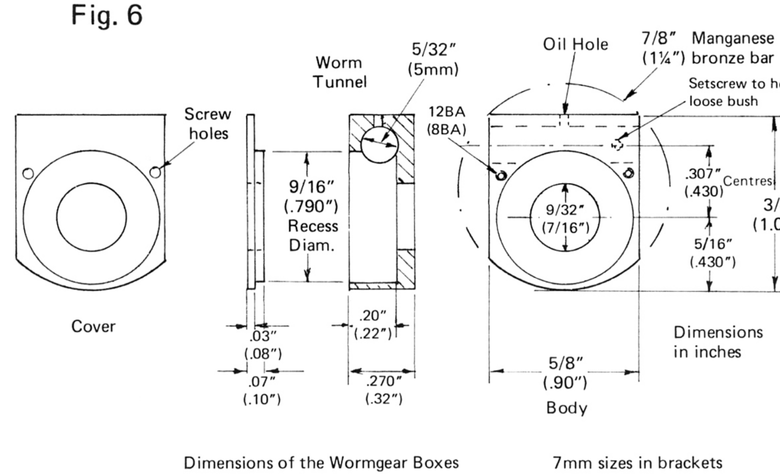
The fly cutter for gashing the worm teeth.

The circular form tool for machining the worm and the hob.



The hob. It can be sharpened with one of those thin slitting/grinding wheels used in small power hand-drills.

Fig. 6



Dimensions of the Wormgear Boxes 7mm sizes in brackets

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hob thread. The hob then drives the gashed blank round accurately and just skims the teeth to correct form and dimension. The initial 'gashing' is done on a dividing head with the blank set over at the thread helix angle; hobbing is performed with the hob in the lathe spindle and the blank set at the normal right-angles to the hob, assuming the hob is the same diameter as the worm. If larger, set the blank to the difference between the worm helix and hob helix. The hob is cut in silver steel with flutes milled or filed in and it is then hardened just as the threading tool.

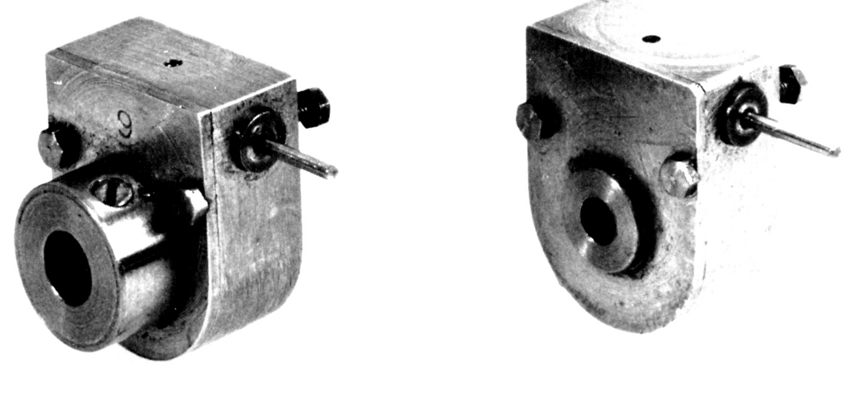
The hob will cut a 'throated' tooth form in the wheel if just sunk in, and this means careful setting sideways when meshing the worm and wheel. It also tends to increase friction. I traverse the worm wheel across, beneath the hob, whilst it is cutting by an amount equal to the wheel tooth face width — dimension 'C'. This gives a straight across tooth as drawn and has proved quite sufficient. I also use this method to cut ordinary gear wheels by turning the wheel blank through an angle equal to the hob helix when hobbing.

It remains only to press in a steel centre bush in the worm wheel, $\frac{9}{32}$in for 4mm, $\frac{7}{16}$in for 7mm, into which is fitted a grubscrew (10BA, 6BA). The bush is the width of the gearbox which is carried on it and the bore is $\frac{1}{8}$in (4mm) or $\frac{3}{16}$in (7mm). If no gear case is used, you can just turn the boss integral with the worm wheel in the normal way.

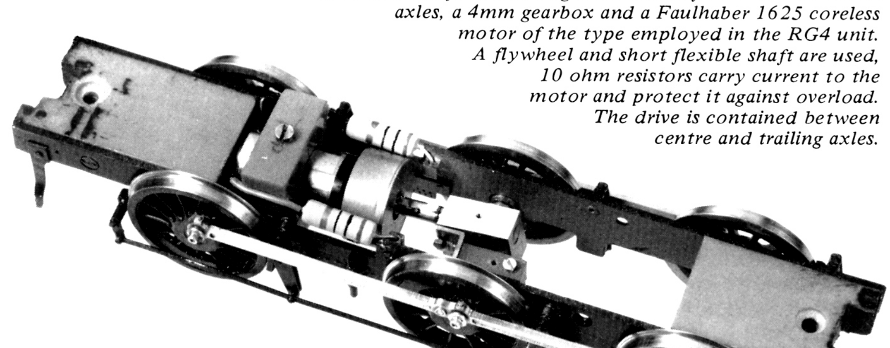
The hardened steel ball races are parted off washers $\frac{1}{8}$in diameter × $\frac{1}{64}$in thick for 4mm and and $\frac{11}{64}$in × .02in thick for 7mm, cut from silver steel, hardened and lapped to a mirror finish on a fine carborundum stone, finishing with jeweller's rouge. The ball cages are .150in diameter for 4mm and $\frac{3}{16}$in diameter for 7mm, $\frac{1}{32}$in thick with three 1mm holes for 1mm steel balls in each case. The 1mm steel balls are obtained by pushing out from the tips of used ball point pens using a .016 in diameter steel wire in a pin chuck. They are used for both sizes of wormgear except that the single ball in the blind bush of the 7mm box is $\frac{1}{16}$in diameter. These latter can be had from K. R. Whiston Ltd, New Mills, Stockport SK12 4PT who also sells the manganese bronze bar (B.S. CZ114). The worm shafts are 1mm and $\frac{1}{16}$in diameter respectively, silver steel being used, hardened and highly polished at the round thrust end. The worm must be a hard force fit on the shaft. If you can find 1mm or $\frac{1}{16}$in sewing needles, these will make excellent shafts.

Finally, run the gearbox in with the worm shaft gripped in a power drill, having lubricated the bearings, worm and wheel with a light oil. You can then pass a bolt through the axle bore, secure it with a nut, and with a screwdriver 'drive the gears back', thus completing the initial running in.

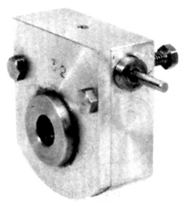
That, very briefly, is the story of high-efficiency worm drives. With the editor's permission, I propose to follow up with the application of these worm gears, connection to the motor, flywheels and current collection by insulated frames, obviating the need for rubbing collectors on the wheels which can be a source of undesirable friction besides raising other problems.



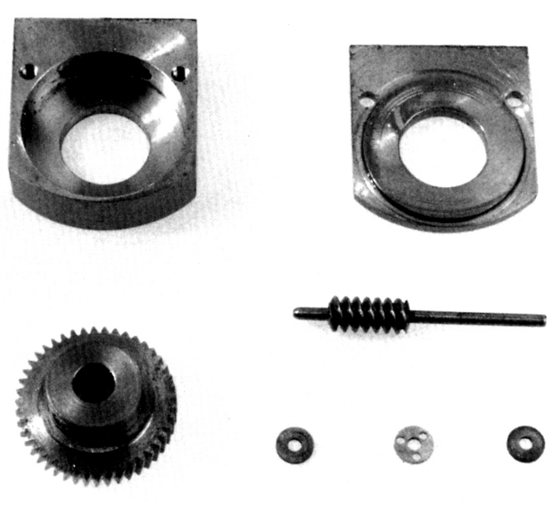
4mm scale gearboxes. That on the left has a flanged worm wheel boss extending outside to accommodate the 6 BA setscrew used with the 3/16in bore.



A 7mm 6-coupled shunting tank chassis fitted with insulated axles, a 4mm gearbox and a Faulhaber 1625 coreless motor of the type employed in the RG4 unit. A flywheel and short flexible shaft are used, 10 ohm resistors carry current to the motor and protect it against overload. The drive is contained between centre and trailing axles.



The 7mm scale gearbox.



The main parts of a 7mm gearbox.