Nov. 3, 1959 E. WILDHABER 2,910,808

METHOD AND APPARATUS FOR GRINDING GEARS

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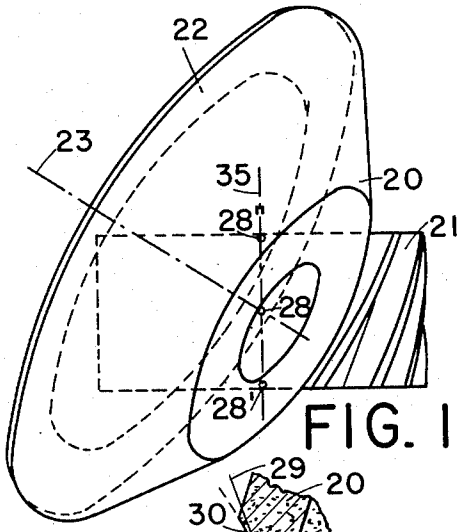


FIG. 1

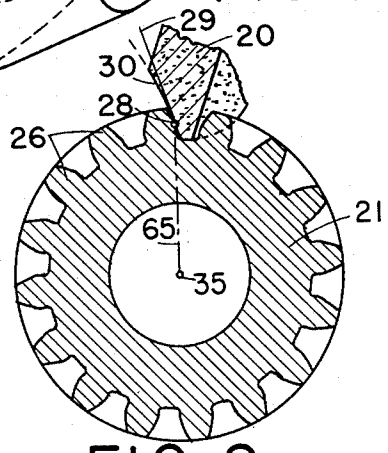


FIG. 2

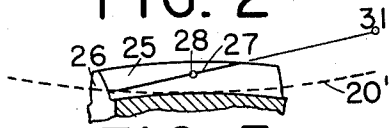


FIG. 3

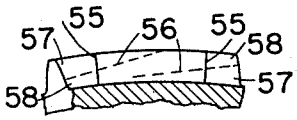


FIG. 7

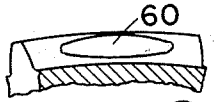
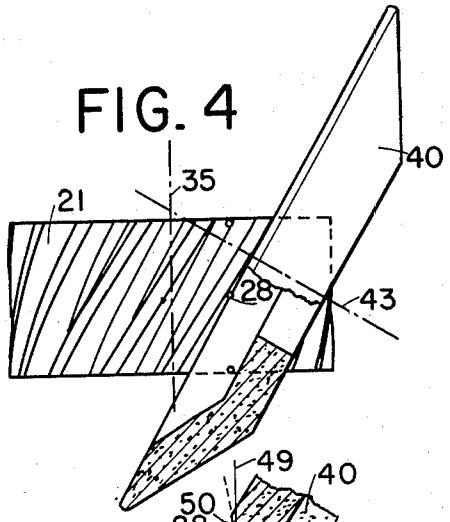


FIG. 8

FIG. 4



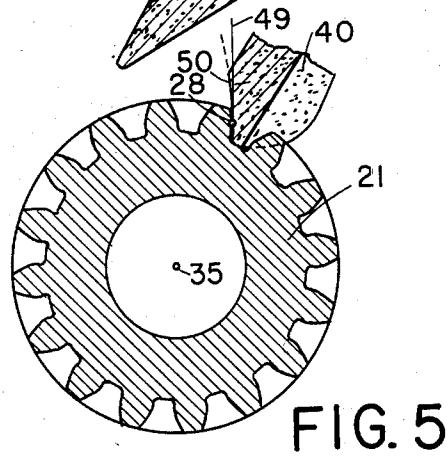


FIG. 5

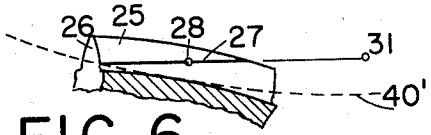


FIG. 6

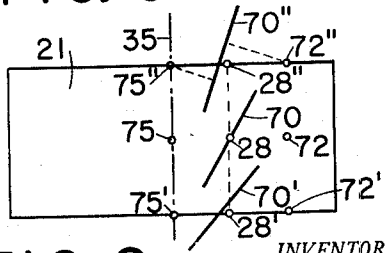


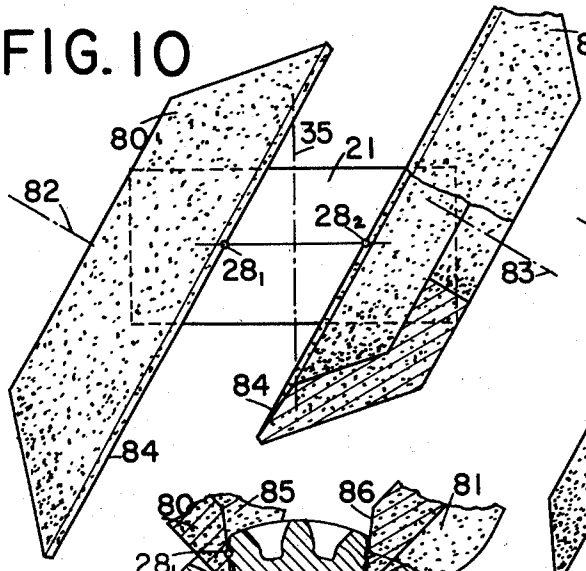
FIG. 9

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FIG. 10



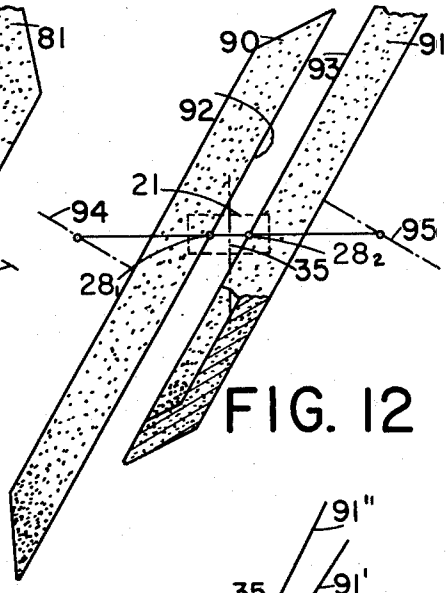


FIG. 12

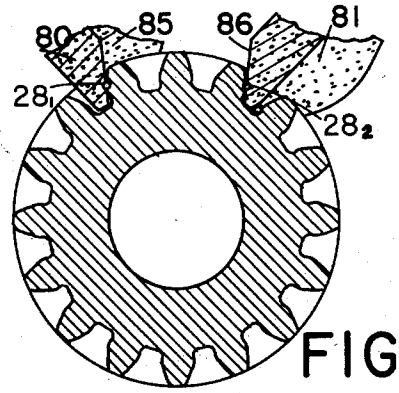


FIG. 11

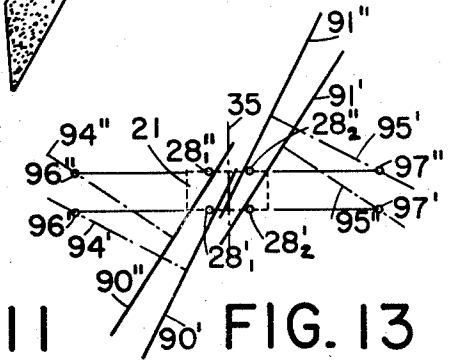


FIG. 13

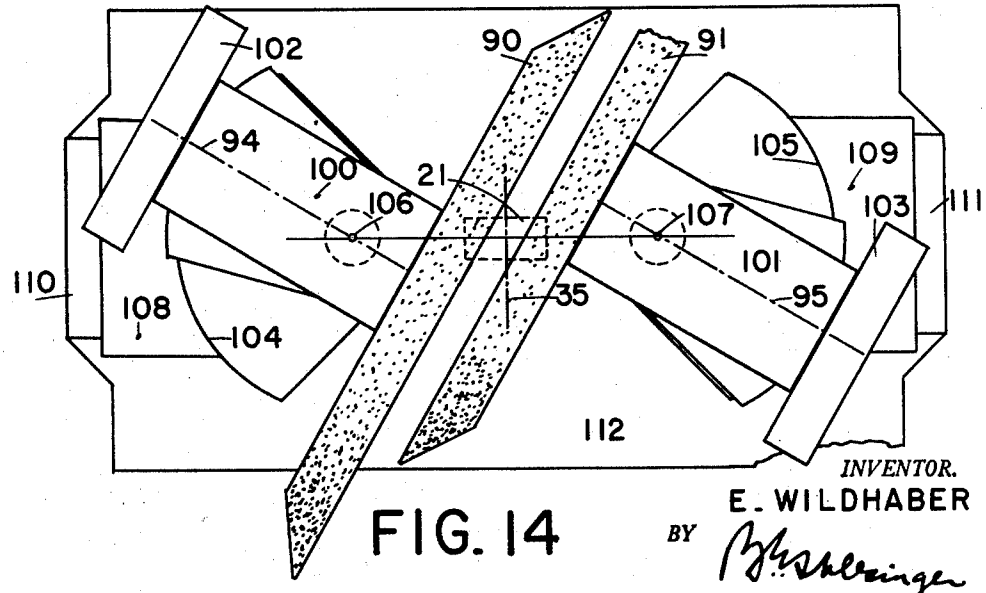


FIG. 14

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METHOD AND APPARATUS FOR GRINDING GEARS

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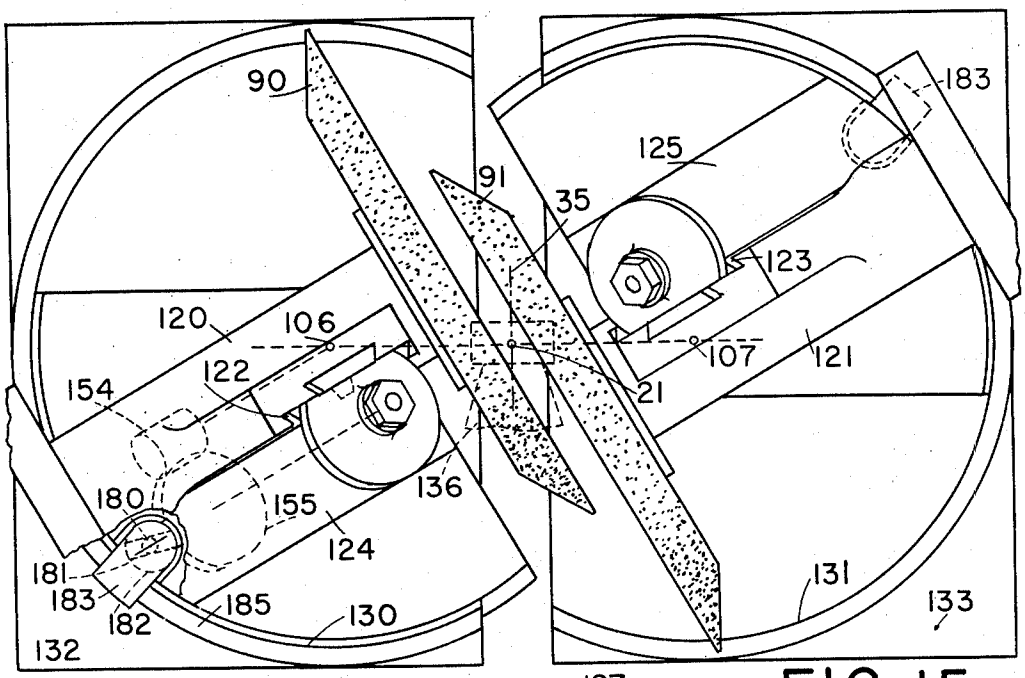


FIG. 15

FIG. 17

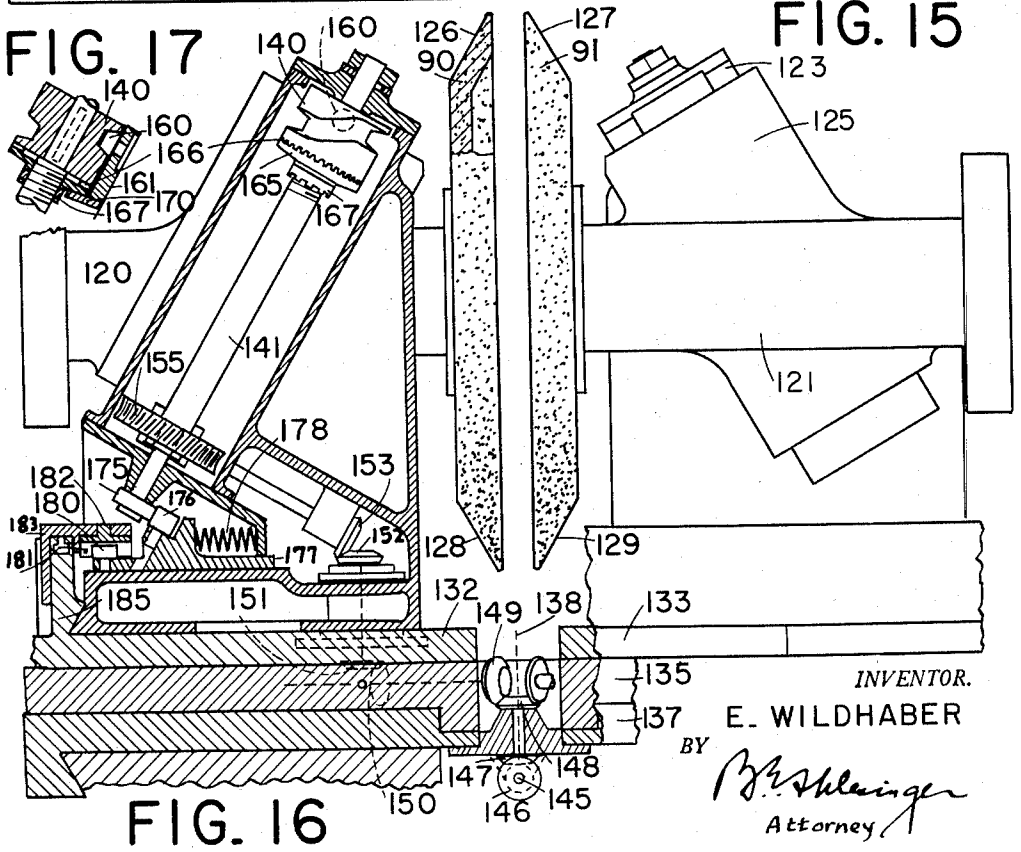


FIG. 16

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2,910,808

METHOD AND APPARATUS FOR GRINDING GEARS

Ernest Wildhaber, Brighton, N.Y.

Application January 15, 1954, Serial No. 404,224

28 Claims. (Cl. 51—55)

The present invention relates to the production of gears, and more particularly to the grinding of the tooth sides of cylindrical gears, such as spur, helical and herringbone gears, worms, etc. In a more specific aspect, the invention is especially useful in the grinding of the tooth sides of helical gears and worms.

A primary object of the present invention is to provide a method and apparatus for grinding the tooth sides of cylindrical gears with substantially flat or plane-faced grinding wheels so that the same wheel or wheels can be used in grinding gears of a given normal pitch regardless of their tooth numbers.

Another object of the invention is to grind the tooth sides of cylindrical gears with flat or plane-faced grinding wheels in such a way as to produce localization of bearing or ease-off at the tooth ends.

Another object of the invention is to grind the tooth sides of cyindrical gears with localization of bearing or ease-off at the tooth ends, where the ease-off is under full control as to where it is applied.

Another object of the invention is to grind the sides of helical teeth with flat-faced grinding wheels in such a way that the teeth of mating gears bear in a localized area when run in their exact meshing position under light load, and that the shape of this tooth bearing area can be controlled and altered at will.

Another object of the invention is to provide a method of and means for grinding involute helical gear teeth with a pair of flat-faced grinding wheels in a helical grinding motion, but without the use of generating roll and in such way that the grinding contact on opposite sides of the teeth ceases nearly simultaneously at the tooth ends.

Still another object of the invention is to provide a method and apparatus for grinding helical teeth with eased-off tooth ends with a pair of flat-faced grinding wheels in unidirectional grinding passes, where the wheels are moved depthwise into and out of engagement with the workpiece at the two ends, respectively, of the grinding strokes, so that the wheels will be clear of the workpiece during each return stroke and so that the work may be rotated during each return stroke to permit the grinding wheels to enter different tooth spaces on successive grinding strokes.

A further object of the invention is to effect ease-off or localization of tooth bearing in helical gears by advancing the grinding wheels toward the surfaces engaged thereby adjacent both ends of the grinding strokes, and by turning the wheels very slightly about parallel pivots in time with the grinding strokes, and about the same pivots about which the wheels are adjusted to conform with the helix angle of the teeth.

A still further object of the invention is to provide a method and apparatus for grinding helical gears with two wheels, in which the grinding wheels are advanced individually for ease-off in the same direction, in which they are moved depthwise into engagement with the work, and along a line inclined at an acute angle to the axis of each wheel.

Still another object of the invention is to provide a method for grinding gears of the character described which can be performed on a relatively simple machine.

Other objects of the invention will be apparent hereinafter from the specification and from the recital of the appended claims.

In the drawings:

Fig. 1 is a view illustrating one embodiment of the present invention and showing a flat faced grinding wheel in grinding engagement with a helical gear;

Fig. 2 is a fragmentary section taken at right angles to the axis of the gear of Fig. 1, and showing the gear in full but showing the grinding wheel only fragmentarily;

Fig. 3 is a view of a tooth of the gear showing the line of contact between the tooth surface and the substantially flat grinding surface of the wheel;

Fig. 4 is a view illustrating another embodiment of the invention, showing a grinding wheel in grinding engagement with a helical gear but showing the grinding wheel partly in section;

Fig. 5 is a section similar to Fig. 2 taken at right angles to the gear of Fig. 4 and showing the grinding wheel only fragmentarily;

Fig. 6 is a view, similar to Fig. 3, of a gear tooth, taken along the axis of the grinding wheel of Figs. 4 and 5 and showing the line of grinding contact between the wheel and tooth;

Fig. 7 is a view, similar to Fig. 3, of a gear tooth, showing the effect of lengthwise ease-off or localization of the tooth bearing;

Fig. 8 is a view, similar to Fig. 7, of a gear tooth showing the desired form of complete ease-off, consisting of lengthwise and profilewise ease-off or localization of the tooth bearing;

Fig. 9 is a diagrammatic view, corresponding specifically to Figs. 4 to 6, and showing how lengthwise ease-off at the tooth ends is attained by the present invention;

Fig. 10 is a somewhat diagrammatic view, similar to Fig. 4, but showing the use of a pair of grinding wheels for simultaneously grinding opposite sides of the teeth of a helical gear, and showing also wheels with slightly internal grinding surfaces;

Fig. 11 is a section through the gear of Fig. 10 taken at right angles to the gear axis and showing fragmentarily only the grinding wheels which are in engagement therewith;

Fig. 12 is a diagrammatic view, similar to Fig. 4, showing a pair of grinding wheels having substantially plane grinding surfaces in engagement with a gear blank, the contour of the gear blank being indicated in dotted lines;

Fig. 13 is a diagram corresponding to Fig. 12 and illustrating the way of obtaining controlled ease-off or localization of tooth bearing;

Fig. 14 is a more or less diagrammatic view illustrating the construction of a grinding machine for practicing the present invention and showing particularly the adjustments and motions required;

Fig. 15 is a diagrammatic view, similar to Fig. 14, and showing a machine constructed according to another embodiment of the invention;

Fig. 16 is a view, partly broken away, taken at right angles to the view of Fig. 15 and in a direction perpendicular to the axes of the grinding wheels; and

Fig. 17 is a fragmentary axial section of the control cam and cooperating parts of the machine of Figs. 15 and 16, the section being taken in a plane perpendicular to the drawing plane of Fig. 16.

In the method of the present invention flat or plane surfaced grinding wheels are employed; and the tooth pro-

files produced are preferably of involute form. The profile of the grinding surface in an axial section is substantially straight and does not change with change in wheel diameter. The same wheel profile is used during the whole life of the wheel. Preferably two wheels are used, for grinding, respectively, opposite sides of the teeth. The two wheels are set so that their grinding surfaces face each other. Ease-off is attained by advancing the wheels toward the tooth surfaces engaged thereby at the ends of the grinding strokes. The wheels are turned very slightly about parallel pivots in time with the grinding strokes, and about the same pivot about which the wheels are adjusted to conform to and produce the helix angle of the teeth. The grinding wheels are advanced individually for ease-off in the same direction in which they are moved depthwise into engagement with the work piece, that is, each is advanced along a line inclined at an acute angle to the axis of the grinding wheel.

Referring now to the drawings by numerals of reference and first to the embodiment of the invention shown in Figs. 1 to 3 inclusive, **20** denotes the grinding wheel, and **21** the gear which is to be ground, here a helical gear. The grinding wheel may have a plane or flat grinding surface **22** which is perpendicular to the axis **23** of the wheel. The flat surface **22** of the wheel will then contact a side **25** (Fig. 3) of a tooth **26** of the work along a line **27** which passes through a mean point **28** of the tooth profile.

One aim of the present invention, however, is to achieve localization of tooth bearing, or ease-off of the mating tooth surfaces at the tooth ends.

Profile ease-off is attained according to one embodiment of the invention by slightly curving the profile of the grinding surface. This is indicated with much exaggeration in Fig. 2 at **30**. The tangent **29** at mean point **28** to the grinding profile **30** of the wheel lies in a plane perpendicular to the wheel axis. If the profile were exactly straight and coinciding with the tangent **29** then the grinding surface would be exactly a plane. The grinding profile **30** used is very slightly concave and contacts the tangent **29** at mean point **28**. It departs from the tangent **29** at the ends of the active grinding surface in accordance with the small amount of profile ease-off desired on the gear teeth. It would not be visible in the drawing unless exaggerated. It does not show up visibly in the shape of the line of contact **27** (Fig. 3). Without ease-off the grinding line **27** is exactly a straight line, which can be considered the projection of a line parallel to the axis of the workpiece. This line may pass through any point of contact, as point **28**.

Fig. 3 shows that the whole working depth of the tooth surface **25** may be covered by grinding lines **27**, provided that the grinding wheel is sufficiently large. The outline of the grinding wheel is shown in dotted lines at **20'**. Point **31** is the point at which the line **27** comes closest to the axis of the grinding wheel. It is the projection of this axis to the grinding line **27**. This point should be well outside of the tooth side **25** to avoid or reduce uneven wheel wear. Each element of the line **27** has a counterpart on the axial profile of the grinding surface, a corresponding element of the axial profile. The latter element is smaller than the element of line **27**, and has a varying proportion thereto. At point **31** this proportion is zero. This means that the wheel profile tends to wear off rapidly at this point.

With a large enough wheel the point **31** can be kept well outside of the active portion of the grinding line **27**. The wheel should also be large enough and be so positioned that the grinding line **27** reaches far enough down on the tooth profile so that the entire working surface of the teeth is swept thereby.

The grinding wheel is set to the helix angle of the teeth **26**, at the mean point **28**, by adjusting it about a radial pivot **65** passing through point **28**; and it is inclined at the pressure angle of the tooth at that point. The grinding plane, or its tangent plane at **28**, is then inclined to said pivot at the normal pressure angle at **28**.

If truly helical teeth are desired, without ease-off at the tooth ends, then the grinding process would consist solely in providing a feeding motion between the rotating wheel and the workpiece **21** along and about the axis **35** of the workpiece, whereby the motions along and about the axis **35** are in constant proportion. No additional generating roll is required where large wheels are employed.

Ease off at the tooth ends

It has been tried to apply ease-off at the ends of helical gear teeth by advancing the grinding wheel more toward the tooth surface at both ends of the teeth. This advance depends on the feed position, that is, on the distance of a considered position from the middle position, and is approximately proportionate to the square of this distance. It may be applied either depthwise or normal to the tooth surface, for instance, along the wheel axis. But regardless of the direction in which it is applied, it produces about the same result if used alone. It can be demonstrated mathematically that the localized bearing area thus obtained is bounded by inclined lines **56**, which coincide with different positions of the lines of contact between the tooth surface and the grinding wheel. It is the area between the dotted lines **56** in Fig. 7. This area extends across the tooth surface at a bias. Here too much stock has been removed from the diagonal corners **57**, and too little, if any, from the diagonal corners **58**.

One object of the invention is to apply ease-off exactly where it is desired. Distinction should be made between lengthwise ease-off and profilewise ease-off.

The lengthwise ease-off desired consists in easing off the tooth ends straight, without bias bearing. If we disregard profile ease-off for the moment this means that when the mating gears are run on their exact centers with a light load, they should bear in a localized area bounded at its ends by lines extending straight up and down the tooth profiles like the area between the straight lines **55** in Fig. 7.

The present invention permits attaining a substantially square or rectangular bearing area bounded by lines **55**, if profile ease-off is disregarded. It permits attaining an oval bearing area **60** (Fig. 8) when profile ease-off is added to the lengthwise ease-off. This oval area produced by combined lengthwise and profilewise ease-off is the bearing shape generally desired. However, any other shape is also attainable in accordance with the present invention. Full control of the localization and ease-off of the tooth bearing is attained.

To secure truly helical teeth without lengthwise ease-off in the embodiment of Figs. 1 to 3 inclusive a rotating grinding wheel is fed along the axis **35** of the workpiece and the workpiece is turned on its axis in time with said axial feed motion. The mean point **28** of grinding contact thereby moves for instance from a position **28'** (Fig. 1) at the lower gear end to a position **28''** at the upper gear end. The total grinding stroke is somewhat longer.

When ease-off is applied at the tooth ends, the mean points of the eased-off end profiles should be ground in the immediate proximity of the points **28'**, **28''** to avoid changes of pressure angle at those points. In other words, the flat faced grinding wheel **20** should not only be advanced toward the surface being ground, adjacent both ends of the grinding passes, but it should also be tilted so that grinding contact will remain in the immediate proximity of the original contact position at which ease-off is zero.

In accordance with the present invention the grinding wheel is tilted as it goes through the grinding path about the same axis about which it is set for the helix angle of the teeth or about an axis parallel thereto. Thus, it may be tilted about a radial axis **65** (Fig. 2) which lies in the drawing plane of Fig. 2 and which projects as the point **28** in Fig. 1.

This changing tilt corresponds to the changing helix angle of the eased-off tooth curve which passes through mean point **28** and is tangent to the helix at that point. The length of this curve increases with the face width F of the gear, and also depends on the helix ψ.

It amounts to: $\frac{E}{\cos \psi}$

In a development to a plane, the considered mean helix is a straight line; and the line which we want to substitute therefore through ease-off is a convex curve tangent to the straight line at its mid point **28**. The curve recedes from its mean tangent toward both ends to a given separation z at both ends. It increases essentially like the square of the distance from the mean point. Thus, at a distance halfway from the middle to an end of a tooth it is one-fourth of the separation at the end, that is, ¼ z.

The inclination of the curve, or its helix angle, changes in direct proportion to its length. On the side engaged by the grinding wheel in Fig. 1, the helix angle changes from a larger value at or immediately adjacent point **28'** to its mean value at point **28**, and to a smaller value at point **28''**. The helix angle change is like the helix angle change of a large circular arc which has a given separation z at its ends from its mean tangent.

The large radius R_m of this circle is tied up with the separation z at distance

$$\frac{F}{2 \cos \psi}$$

from its point of tangency **28** as follows:

$$z=\left(\frac{F}{2 \cos \psi}\right)^2\left(\frac{1}{2R_m}\right)$$

The inclination i of the ends of the curve relative to the middle is the proportion of the distance

$$\frac{F}{2 \cos \psi}$$

to the radius R_m.

$$i=\left(\frac{F}{2 \cos \psi}\right)\frac{1}{R_m}$$

in radian measure.

Through transformation

$$i=\frac{4z \cos \psi}{F}$$

This is the change in the helix angle from the middle to one end point. The total change in helix angle from point **28'** to point **28''** amounts to $(2i)$.

Accordingly the grinding wheel should be tilted or swung on pivot axis **65** in direct proportion to the feed along the gear axis **35** at a rate of $(2i)$ between grinding positions **28'** and **28''**. Simultaneously the grinding wheel should be advanced from the position at zero ease-off toward the surface engaged thereby adjacent both ends of the grinding strokes, to produce the required separations of the eased-off curve from the true helix.

This advance may be made in any desired direction. Of these directions two are especially attractive. One is along the axis of the grinding wheel, and the other along a straight line inclined to the wheel axis at an acute angle as will further be described.

This advance can be expressed mathematically in terms of the distance y of the grinding wheel position axially of the workpiece from its mean position shown in Fig. 1. When the mean grinding point is in position **28''**, then the corresponding distance y_0 is equal to distance **28–28''** and equal to ½ F. The advance z' is measured in terms of the separation it produces. The actual movement of the grinding wheel is proportional to z' but may be different depending on the direction of advance.

$$z'=z\left(\frac{y}{y_0}\right)^2; \text{ and } y_0=\tfrac{1}{2}F \qquad (1)$$

Likewise the tilt i' of the grinding wheel at positions y can be expressed as:

$$i'=i\left(\frac{y}{y_0}\right); \text{ and } i=\frac{4z \cos \psi}{F} \qquad (2)$$

Similar conditions exist in the embodiment of Figs. 4 to 6. Here too the advance should be proportional to z' and the tilt i' should vary along the grinding pass as expressed in Equation 2. In this case there is only one angular setting between the grinding wheel and the workpiece. It is the setting for helix angle. The grinding plane, that is, the tangent plane to the grinding surface at mean point **28**, is inclined to the gear axis **35** at an angle known as the base helix angle in the case of involute teeth. It can be considered as obtained from the helix angle and pressure angle inclination of the axis **23** of the grinding wheel **20** (Fig. 1) by turning this axis about the gear axis **35** until it is parallel to the drawing plane. Its angular position then coincides with the angular setting of the axis **43** of the grinding wheel **40** shown in Fig. 4.

As shown in Fig. 4, the grinding wheel **40** is bodily displaced as compared with mean point **28**. Its axis and body has a different position lengthwise of the gear axis **35** than the mean point **28** around which grinding contact centers. It is displaced toward the upper end of the gear **21**, that is, it is displaced from the point **28** toward the side of increasing distance of the grinding surface from the axis **35** of the gear. The reason for this is readily seen in Fig. 6. It is bodily displaced so that its outline **40'** more closely follows the tooth bottom and embraces the grinding line **27** to a sufficient depth. In this way the grinding line within the wheel outline covers all of the working depth of the tooth. Profile ease-off may be attained, as in the embodiment of Figs. 1 to 3, by using a wheel profile **50** which is very slightly concave and which contacts the tangent **49** at mean point **28** of the working profile. As before, this tangent lies in a plane perpendicular to the wheel axis. As before, the wheel profile would not show up different from its tangent if its curvature were not greatly exaggerated in Fig. 5.

The relationship between z and i expressed in Equation 2 produces a square bearing essentially as indicated in Fig. 7 by the full lines **55**, or it can produce a bearing such as indicated at **60** in Fig. 8 when profile ease-off is added.

Any changes can be made in the shape of the tooth bearing area if desired. To slant the bearing toward the direction of the dotted lines **56**, an angle i is used which is smaller than given by Equation 2. To slant the tooth bearing in the opposite direction an angle i is used which is larger than given by Equation 2. The amount of ease-off can be changed by assuming a different separation z.

Fig. 9 illustrates the ease-off procedure diagrammatically as applied to the embodiment of Figs. 4 to 6. The heavy lines **70** indicate the grinding plane. The middle position corresponds to Fig. 4 with grinding contact at mean point **28**. In the initial position **70'**, where grinding contact is made immediately adjacent position **28'** of the mean point of the unrelieved profile, the grinding plane is tilted at the aforesaid angle i to its mean position **70**. At the end position the grinding plane **70''** is tilted at the same angle i to its mean position, but it is tilted in the opposite direction. During the grinding pass from **28'** to **28''** the grinding plane is swung continuously in one direction in proportion to the feed lengthwise of the gear axis **35**. It is swung about a pivot axis perpendicular to the drawing plane of Fig. 9 and coinciding with the various positions of the mean point of grinding contact. During the grinding pass this axis passes through positions **28'**, **28**, **28''**.

Adjacent both ends of the grinding pass the wheel is advanced toward the tooth surface engaged thereby from its position at zero ease-off. Its advance corresponds to

z' as given in Equation 1, and to z in the positions **28'**, **28''**. The grinding planes **70'** and **70''** are seen to be advanced over the positions **28'**, **28''** which correspond to zero ease-off. The advance, as well as the angle i, are very much exaggerated in Fig. 9.

In practice it is desirable to swing the grinding plane about an axis offset from the mean grinding point, as, for instance, about an axis which is at **72** in the mean grinding position and at **72'**, and **72''** at the positions corresponding to position **28'**, **28''**, respectively. The advance of the grinding wheel with respect to its new pivot then has to be altered accordingly. In view of the very small motions involved the mathematical procedures applying to infinitesimal displacements can be used with high accuracy.

The distance of the grinding plane **70''** from new pivot **72''** is made up of the distance of the grinding plane from pivot **28''** and of the distance of pivot **72''** from the grinding plane if this plane were to pass through point **28''**.

If the inclination of the grinding plane **70** to the direction of the gear axis **35** is denoted by ψ_b, and x_0 denotes the distance **28–72**, which is equal to **28'–72'** and to **28''–72''**, then the advance z'' of the grinding wheel along its axis, as compared with its middle position is found to amount to:

$$z''=z'+i' x_0 \sin \psi_b - \tfrac{1}{2} i'^2 x_0 \cos \psi_b \qquad (3)$$

at any position y. The rate of advance is no longer zero at the middle position. But it still is an advance at a varying rate at least on one side. It may be a negative advance or withdrawal on the opposite side.

When the new pivot is displaced in the opposite direction as, for instance, to 75 in the middle position, and to **75'**, **75''** in the end positions, then the distance x_0=28–75 should be introduced as a negative quantity in the above equation for z''.

The above equation applies for lateral displacements of the pivot in a plane perpendicular to the gear axis. If the pivot is displaced a distance x_n in normal direction, that is, perpendicular to the grinding plane **70**, then the advance of the grinding wheel from the new pivot amounts to:

$$z''=z'-\tfrac{1}{2} i'^2 x_n$$

The second term is negligible. In this case then the advance z'' is practically unchanged by the normal pivot shift. Any general pivot shift can be made up of a lateral shift x_0 and a normal x_n.

Two grinding wheels

When two wheels are used, both wheels are preferably mounted on axes which are parallel in the middle position of the grinding stroke, with their substantially flat grinding surfaces facing each other.

Figs. 10 and 11 illustrate one such case. In Fig. 10 the gear **21** is indicated by its contour and by its axis **35** only. The axes **82** and **83** of the two grinding wheels **80** and **81** are here parallel; and the two grinding wheels are seen to be bodily displaced relative to each other lengthwise of the gear axis **35**. In other words, they have different axial positions. These are provided for the same reasons as described for a single wheel with reference to Figs. 4 to 6. They enable the wheels to let the grinding line go down far enough toward the tooth bottom.

Figs. 10 and 11 also illustrate a feature of a modification of my invention. Here the profile ease-off is not attained by using a slightly concave grinding profile on an otherwise plane wheel surface. It is attained with a straight grinding profile **84** on a grinding surface **85** or **86** which is slightly internal.

The grinding surface is here an internal conical surface which contacts the tooth surface in a very slightly concave curve. In the mid position shown in Figs. 10 and 11 this line of contact passes through the mean point of contact 28_1, for one wheel, and 28_2 for the other wheel. The tangent to said curve at each of the points 23_1, 28_2 lies in the theoretical, unrelieved tooth surface. At both sides of this point the curve reaches somewhat to the inside of the unrelieved surface, increasingly so with increasing distance from said point. It thereby produces ease-off at the profile ends.

Either way of producing profile ease-off on helical teeth may be used with a substantially flat grinding surface, or even a combination of both methods. The use of slightly internal grinding surfaces increases the distance between the two grinding wheels **80** and **81**. When a combination of both described methods of achieving profile ease-off is used, it is done with the purpose of keeping the points of contact **28** at the section perpendicular to the gear axis exactly mean points of the tooth profiles so that the two grinding lines have the same position lengthwise of the gear axis.

When two wheels are used, the two engaged tooth profiles are symmetrically positioned with respect to the center line of either a tooth or a tooth space. With this restriction the two described methods of applying profile ease-off may give the desired position of the points **28** only approximately if used one or the other. The combination of the two methods however permits overcoming this restriction and placing the point **28** at the exact height on the profile where it is desired. It should be understood, however, that satisfactory gears can be produced also without placing point **28** at the exact middle of the height of the tooth profile.

Fig. 12 shows the use of a pair of wheels **90** and **91** with essentially plane grinding surfaces **92** and **93**. The wheel profiles of axial sections are concaved so slightly that the curvatures does not show up in the drawing. The wheel shape is like that described in connection with Figs. 4 and 5. The tangent at the mean point of the active wheel profile lies in a plane perpendicular to the wheel axis. As in Fig. 10 the flat grinding surfaces **92**, **93** face each other and the axes **94**, **95** of the grinding wheels are parallel in the mid position. The two wheels are bodily displaced with respect to each other along the axis **35** of the work piece **21**. Each wheel is advanced along the gear axis from the grinding region toward the side of increasing distance from the axis **35** of the workpiece.

Fig. 12 shows the grinding wheels more nearly in the right proportions. The grinding wheels employed in the present invention are preferably comparatively large.

While Fig. 12 illustrates the mean position of the grinding pass or grinding stroke, which is the same as for a helical gear without ease-off, Fig. 13 diagrammatically illustrates with exaggeration the grinding wheel positions when the mean points adjacent points **28'**, **28''** of the end profiles are being ground. Both wheels are diagrammatically indicated by their essentially plane grinding surfaces. These have positions **90'**, **90''** and **91'**, **91''** when the grinding region is at opposite ends of the gear teeth. In the positions **90'**, **91'** as well as in the positions **90''**, **91''** the two wheels are tilted in opposite directions from their mean positions; and their grinding planes are advanced beyond the mean points $28_1'$, $28_1''$, $28_2'$, $28_2''$ of the teeth without ease-off.

The positions of the wheel **91** have already been described fully with reference to Fig. 9. Diagonally opposite positions of the two wheels correspond to each other. Thus the wheel **90''** at the left is inclined to the axis **35** of workpiece **21** at the same angle as the wheel **91'** at the right. It is advanced beyond the point $28_1''$ by the same amount as the wheel **91'** is advanced beyond the point $28_2'$.

The two wheels move together. Feeding motion between the pair of wheels and the workpiece is effected along the axis **35** of the work piece and about said axis in known manner. The motions along the axis **35** and

about this axis are timed with each other to produce the helical teeth. Ease-off at the tooth ends is obtained by advancing the wheels toward the tooth sides engaged thereby adjacent both ends of the grinding passes, and by swinging the wheels slightly in opposite directions about axes passing through the mean points 28_1, 28_2 of grinding contact.

The wheels may also be swung instead about other suitable axes perpendicular to the direction of the gear axis **35**, for instance, about axes **96'**, **97'** at one end of the grinding pass, and about axes **96''**, **97''** near the other end of the grinding stroke. When the grinding wheels are swung about displaced pivot axes, the advance of the wheels from these pivot axes should be modified in the manner described with reference to Fig. 9.

Grinding apparatus

Fig. 14 is a diagrammatic view of one form of wheel head constructed according to the present invention. In this view many known features have been omitted which do not pertain to the invention. What is shown is the novel arrangement of parts, and their displacements or motion.

The grinding wheels **90** and **91** are rotatably mounted in holders **100**, **101**, respectively, and are driven by pulleys **102**, **103** from a suitable power source. The holders **100**, **101** are swingable along ways **104**, **105**, respectively, about pivot axes **106**, **107**, respectively. The ways **104**, **105** form parts of slides **108**, **109**, respectively, which are adjustable along ways **110**, **111**, respectively, radially toward and away from the workpiece **21**. The ways **110**, **111** are parts of a common slide **112**, which is adjustable or movable along the axis **35** of the workpiece **21**.

It should be noted that the pivot axes **106**, **107** are offset from the axis **35** of the workpiece. They are parallel; and they are perpendicular to the direction of the work axis **35**. They are positioned on one side of the respective grinding wheels **90**, **91**, each on the side opposite to the grinding side of the wheel. They intersect the axes **94**, **95** of the wheels.

With the pivot axis offset in the manner shown the angular setting for the helix angle displaces the grinding wheels bodily in the direction desired so that the two wheels have different positions along the gear axis **35**. The radial adjustments of the slides **108** and **109** produce different spreads of the grinding faces as required on gears of different tooth numbers. At a given pitch and helix angle the spread or separation of the grinding faces increases with increasing tooth number of the workpiece.

Means for advancing the grinding wheels toward the surfaces engaged thereby at both ends of the grinding passes, as well as means for swinging the wheels very slightly on their pivot axes **106**, **107** are not shown in this diagram. The diagram shown in Figs. 15 and 16 may be used for this purpose; or each grinding wheel may be advanced along its axis in place of the depthwise advance shown in the last-named embodiment.

In the embodiment of Figs. 15 and 16, the grinding wheels **90** and **91** are rotatably mounted in holders **120**, **121**, respectively, which are movable along inclined ways **122**, **123**, respectively, of pivot members **124**, **125**. On each pivot member the ways extend in the direction of an element **127**, **127**, respectively (Fig. 16), of the back cone **128**, **129**, respectively, of the grinding wheel. More broadly they extend along lines **126**, **127** intersecting the respective wheel axes at acute angles.

For dressing, a grinding wheel is advanced slightly along the ways **122**, **123** to advance the old grinding surface beyond its true position, and the wheel is then dressed off. By using ways of the shown inclination, the advance of the wheel toward the dressing diamond does not have to be split up into two motions, but is a single motion.

In accordance with this embodiment of my invention feed in the same direction as for dressing is used for advancing a wheel toward the surface engaged thereby adjacent both ends of each grinding path to ease off the tooth ends.

Preferably the teeth are ground in unidirectional grinding passes or grinding strokes, and the workpiece is rotated between successive grinding strokes so that each wheel enters a different tooth space in each successive stroke. This process requires disengaging the wheel completely from the workpiece at the end of each grinding stroke, and reengaging it before the start of the next grinding stroke. This depthwise displacement of the grinding wheel, the clapping, is in a direction inclined at an acute angle to the axis of the grinding wheel, and in accordance with the invention it may be made in the same direction in which the wheel is advanced for dressing. Also the advance of the wheel for ease-off is made in the same direction as for clapping.

Each pivot member **124**, **125** is adjustable about a pivot axis **106**, **107** and may be oscillated thereon. In addition to the pivot itself, circular guide ways **130**, **131** are provided on a pair of slides **132**, **133** to control the displacement of the pivot members **124**, **125** thereon about the pivot axes **106**, **107**, respectively.

The slides **132**, **133** are adjustable on a common swivel plate **135** (Fig. 16) toward and away from the work axis **35**. The work may be mounted in a chuck **136** (Fig. 15).

The swivel plate **135** rests on a slide **137** which is movable in the direction of the axis **35** of the work piece and is adjustable thereon about a central axis **138**. The latter is parallel to the pivot axes **106**, **107** and intersects the axis **35** of the workpiece at right angles. Slide **137** may be used for adjustment or for feed along the work axis **35**. Slide **137** and swivel plate **135** are not shown in Fig. 15.

The swivel plate **135** permits of displacing the two pivots **106**, **107** so that they have different positions lengthwise of the work axis **35**, and thus provides a more universal machine than that illustrated in Fig. 14.

The clapping motion of each grinding wheel is effective by a barrel-type cam **140** (Figs. 16 and 17) which is rigidly secured to a shaft **141** that is rotatably mounted in each pivot member **120**, **121**. Shaft **41** extends parallel to the inclined ways **122** or **123**, and is geared to turn around once per grinding cycle. Only one shaft **141** is shown in the drawings. The shaft **141** for pivot member **121** is identical with that shown, and is driven in identical manner. Each shaft **141** performs as many complete turns as there are grinding strokes. It is driven from a fast-running shaft **145** (Fig. 16), that extends parallel to the adjustment of the base slide **137**, through bevel gears **146**, **147**, **148**, **149**, **150**, **151**, **152**, **153**, a worm (not shown) worm wheel **155**, and connecting shafts. Bevel gears **152**, **153**, the worm, and the worm wheel **155** are mounted in the corresponding pivot member **120** or **121**.

Each barrel cam **140** acts on a conical roller **160** that is mounted on a small slide **161** (Fig. 17). This slide is adjustable in the holder **120** (or **121**) lengthwise of the wheel element **126** or **127**.

If desired the cam **140** may be shaped to do not merely the wheel clapping, but also to give the advance of the wheel adjacent both ends of the grinding passes for ease-off.

A more universal design is obtained by providing a specific ease-off cam. This cam **165** is secured to the barrel cam **140**, and is adjustable thereon about its axis of rotation. It contains coupling teeth **166** engaging counterpart teeth provided on the cam **140**. A nut **167** serves to hold the coupling teeth in engagement. The turning position of the cam **165**, that is, its timing, is changed by shifting the two sets of mating coupling teeth after disengagement.

The cam **165** contains a slightly tapered working sur-

face which engages the flat abutment 170 (Fig. 17) secured to slide 161. During the grinding pass itself, the axial position of the slide 161 and of the grinding wheel is controlled by cam 165, while the barrel cam 140 controls the axial position during the remainder of the cycle. The track on the barrel cam has to be kept wide enough in the portion corresponding to grinding so that the cam 140 does not interfere with the small motion constrained by the cam 165.

The working surface of the cam 165 is nearly flat on account of its small taper, a taper possible because of the very small motion to be produced by the cam. Contact between the cam and the plane abutment 170 is intimate, and resembles contact in a bearing. High stresses are thereby avoided.

As the wheel moves toward the tooth surface engaged thereby during each grinding pass it should also be swung on its pivot 106 or 107 in time with the grinding pass and in direct proportion with it. This is done by a disc cam 175 (Fig. 16) which is secured to the shaft 141 at one end thereof and which engages the roller 176. This roller is mounted on a slide 177 pressed toward the cam 175 by a spring 178. Slide 177 carries another roller 180 which engages the straight slot 181 of a disc 182 (Fig. 15). The angularity of said slot can be adjusted by adjusting the disc 182 angularly in an L-shaped part 183. The latter is adjustable about the pivot axis 106 or 107 on a circular flange 185 provided on the slide 132, and can be clamped thereon.

When the disc 182 is adjusted so that its slot 181 is inclined to the direction of travel of the roller 180 and the slide 177, the pivot member carrying the slide 177 and the grinding wheel is rocked on its pivot axis during motion of the slide 177. It is rocked because slot 181 and disc 182 are rigidly connected with the part 183 which is clamped to the slide 132.

The amount of the minute swinging or rocking motion of each wheel is controlled with the adjustable inclination of the slot 181 of the associated disc 182. The more the slot is inclined from the direction of travel of the roller 180 the larger will be the rocking motion.

While the swing of the pivot members is adjustable for amount, the other part of the ease-off motion, namely, the part supplied by the cam 165 is adjustable only for timing. To enlarge or reduce its motion another cam is substituted. A given cam produces essentially a given ease-off at the tooth ends.

To facilitate cam changes, cam 165 is preferably open at one side like a horseshoe, and an opening may be provided in the pivot member 120.

While I have shown plain bearings in the diagrammatic views, anti-friction means may be used to ease the minute swinging motion on the pivots 106, 107. Also springs may be used to keep out backlash.

In operation the feeding motion between the pair of rotating grinding wheels 90, 91 and the workpiece 21 is provided along and about the axis 35 of the workpiece. At the end of each grinding stroke the wheels are withdrawn in the direction of the elements 126, 127 of their respective back cones; and they are advanced again into working position in that direction just prior to the start of grinding contact. This clapping motion is effected by the barrel cams 140 which engage the conical rollers 160. The rollers 160 are adjustably but rigidly mounted on holders 124, 125, as the case may be.

Prior to dressing, the small slide 161 is adjusted downwardly in Figs. 16 and 17 a small amount with respect to its holder, either by hand or automatically. This adjustment lifts the holder upwardly so that its wheel is advanced along the cone element 126 or 127. It is then dressed off and trued.

Ease-off at the tooth ends is attained by moving the wheel very slightly along element 126 or 127 at a varying rate at each grinding pass by cam 165 to effect an advance over its position at zero ease-off adjacent both ends of the grinding pass. Simultaneously each grinding wheel is swung on its pivot axis 106, 107 in time with the grinding stroke and in proportion to it. This is done by disc cam 175 acting through roller 176 and slide 177.

The axis of the workpiece may be arranged either vertically or horizontally; and the feed motion along the axis of the workpiece, the grinding stroke or pass, may be performed by either the workpiece or the pair of grinding wheels. The turning motion about the axis of the work is preferably performed by the work.

Helical teeth can be ground by a process of continuous uniform rotation of the workpiece, or by any other known process and adding to it the steps disclosed here.

While the invention has been described in connection with the grinding of gears which have parallel axes, and particularly helical gears with parallel axes, it applies to the grinding of side tooth surfaces of other helical gears also, such as worms and other heelically-toothed members which mesh with their axes angularly disposed to the axes of their mating gears.

While the invention has been described, therefore, in connection with several different embodiments thereof, it will be understood that it is capable of further modification, and this application is intended to cover any variations, uses, or adaptations of the invention following, in general, the principles of the invention and including such departures from the present disclosure as come within known or customary practice in the art to which the invention pertains and as may be applied to the essential features hereinbefore set forth and as fall within the scope of the invention or the limits of the appended claims.

Having thus described my invention what I claim is:

1. In a machine for grinding the tooth surfaces of cylindrical gears, a rotary work support, a base, a tool support adjustably pivoted on said base, a grinding wheel journaled on said tool support for rotation about an axis angularly disposed to the pivotal axis of said tool support, means for effecting relative movement between the tool and work supports in the direction of the axis of rotation of the work support to effect alternate grinding and return strokes of the wheel, means for moving said wheel at a varying rate toward the tooth surface engaged thereby during portions of each grinding stroke, and means for swinging the tool support about its pivot on each grinding stroke.

2. In a machine for grinding the tooth surfaces of cylindrical gears, a rotary work support, a base, a tool support adjustably pivoted on said base, a grinding wheel journaled on said tool support for rotation about an axis angularly disposed to the pivotal axis of said tool support, said grinding wheel having an approximately plane grinding surface and a conical rear surface, means for adjusting said grinding wheel on said tool support along an element of said rear surface, means for effecting relative movement between the tool and work supports to effect alternate grinding and return strokes of the wheel, means for moving said wheel at a varying rate toward the tooth surface engaged thereby along said element during portions of each grinding stroke, and means for swinging said tool support on its pivot in time with each grinding stroke.

3. In a machine for grinding the tooth surfaces of cylindrical gears, a rotary work support, an adjustably pivoted tool support, a grinding wheel rotatably mounted on said tool support for rotation about an axis angularly disposed to the pivotal axis of said tool support, means for displacing said grinding wheel on said tool support along a straight line intersecting said axis of the grinding wheel at an acute angle, means for effecting reciprocating movements between the tool and work supports in the direction of the axis of rotation of the work support to effect alternate grinding and return strokes of the wheel, means for moving said wheel at a varying rate toward the tooth surface engaged thereby along said straight line

during portions of each grinding stroke, and means for swinging said tool support on its pivot in time with each grinding stroke.

4. In a machine for grinding the tooth sides of cylindrical gears, a rotary work support, a pair of pivoted tool supports, a holder mounted on each tool support, a pair of grinding wheels, that have approximately plane grinding surfaces, rotatably mounted on said holders with their grinding surfaces facing each other, said wheels being adapted to engage simultaneously opposite tooth sides of the workpiece, means for effecting a relative feed motion between said work support and said grinding wheels lengthwise of the tooth sides being ground, means for displacing each of said holders on its tool support in a direction toward and away from the tooth side engaged by the grinding wheel that is mounted on said holder during each grinding cycle, a pair of slides on which said tool holders are pivoted, each of said slides being adjustable toward and from the axis of rotation of the work support, and the pivot axes of said tool holders being parallel and each being disposed on the side of its wheel opposite to the grinding surface of the wheel.

5. In a machine for grinding the tooth sides of cylindrical gears, a rotary work support, a pair of pivoted tool supports, a holder mounted on each tool support, a pair of grinding wheels, that have approximately plane grinding surfaces, rotatably mounted on said holders with their grinding surfaces facing each other, said wheels being adapted to engage simultaneously opposite tooth sides of the workpiece, means for effecting a relative feed motion between said work support and said grinding wheels lengthwise of the tooth sides being ground, means for displacing each of said holders on its tool support in a direction toward and away from the tooth side engaged by the grinding wheel that is mounted on said holder during each grinding cycle, a pair of slides on which said tool holders are pivoted, each of said slides being adjustable toward and from the axis of rotation of the work support, and the pivot axes of said tool holders being parallel and having the grinding wheels disposed between them, and the pivotal axis of each tool support being disposed at right angles to the axis of rotation of its grinding wheel.

6. In a machine for grinding the tooth sides of cylindrical gears, a rotary work support, a pair of pivoted tool supports, a holder mounted on each tool support, a pair of grinding wheels, that have approximately plane grinding surfaces, rotatably mounted on said holders with their grinding surfaces facing each other, said grinding wheels being adapted to engage simultaneously opposite tooth sides of the workpiece means for displacing each of said holders on its tool support in a direction toward and away from the tooth side engaged by the respective grinding wheel, a pair of slides on which said tool holders are pivoted, each of said slides being adjustable toward and from the axis of said work support, the pivotal axes of the two tool supports being parallel and having the grinding wheels disposed between them, and the pivotal axis of each tool support being disposed at an angle to the axis of rotation of its grinding wheel and being positioned on the side of its grinding wheel opposite to the grinding side of the wheel, means for effecting relative reciprocatory movements between the tool and work supports in the direction of the axis of the work support to effect alternate grinding and return strokes of the wheels, means for displacing said holders at a varying rate during each grinding stroke, and means for swinging said tool supports simultaneously in opposite directions on their respective pivots during each grinding stroke and in time therewith.

7. In a machine for grinding the tooth sides of cylindrical gears, a rotary work spindle, a pair of pivoted tool supports, a holder mounted on each tool support, a pair of rotary grinding wheels, that have approximately plane working surfaces, mounted on the two holders with their axes of rotation approximately parallel and with their approximately flat working surfaces facing each other, said grinding wheels being adapted to engage simultaneously opposite tooth sides of the workpiece, guide means for displacing each of said holders on its tool support in a direction toward and away from the tooth side engaged by its grinding wheel, a pair of slides laterally adjustable with respect to the axis of rotation of the work spindle and on which said tool supports are pivoted, the pivotal axes of the two tool supports being parallel and having the grinding wheels disposed between them, the pivotal axis of each tool support intersecting the axis of rotation of its grinding wheel at right angles and being disposed on the side of its grinding wheel opposite to the grinding surface of the wheel, means for effecting relative reciprocatory movements between the work spindle and the tool supports to effect alternate grinding and return strokes of the wheels, means for displacing each of said holders along said guide means at a varying rate during each grinding stroke, and means for swinging said tool supports simultaneously in opposite directions on their respective pivot axes during each grinding stroke and in time therewith.

8. In a machine for grinding the tooth sides of cylindrical gears, a rotary work spindle, a pair of pivoted tool supports, a holder mounted on each tool support, a pair of rotary grinding wheels, that have approximately plane grinding surfaces, rotatably mounted on said holders with their grinding surfaces facing each other, said grinding wheels being adapted to engage simultaneously opposite tooth sides of the workpiece, guide means for displacing said holders on their respective tool supports, each in a direction toward the tooth side engaged by the wheel supported on the holder, a pair of slides adjustable toward or from the axis of rotation of the work spindle and on which said tool supports are pivoted on parallel axes, a common swivel plate supporting said slides, and a common slide on which said swivel plate rests and on which said swivel plate is angularly adjustable about an axis parallel to the pivotal axes of said tool supports.

9. In a machine for grinding the tooth sides of cylindrical gears, a rotary work spindle, a tool support for rotatably mounting a grinding wheel, means for rotating said grinding wheel, means for effecting rectilinear feeding motion between said work spindle and tool support, means for turning said work spindle on its axis of rotation, and means for swinging said tool support about a pivotal axis angularly disposed to the axes of rotation of the grinding wheel and work spindle in time with and approximately in proportion to said feeding motion, said pivotal axis having a position varying relatively to the bodily position of the work spindle during said feeding motion.

10. The method of grinding a side tooth surface of a rotary cylindrical gear, which comprises providing a grinding wheel that has an approximately plane working surface free of convex curvature, engaging said working surface with said tooth surface of the gear, rotating said grinding wheel on its axis, and effecting feeding motion between said grinding wheel and gear in the direction of the axis of rotation of the gear while simultaneously swinging the grinding wheel about a pivotal axis angularly disposed to its axis of rotation in time with said feeding motion, to change the inclination of said plane working surface to said gear axis from one end of said tooth surface to the other end, said pivotal axis having a position varying relatively to the bodily position of the work during said feeding motion.

11. The method of grinding a side tooth surface of a rotary cylindrical gear which comprises engaging a grinding wheel, that has a grinding surface of other than convex profile shape, with a side surface of the gear, rotating the wheel on its axis with said grinding surface in engagement with said side surface, and effecting rectilinear feeding motion between the wheel and the gear, while rela-

tively advancing the grinding wheel toward said side surface adjacent both ends of said feeding motion, and while relatively swinging the wheel on an axis angularly disposed to the axes of the grinding wheel and of the gear, to change the inclination of said grinding surface to the axis of said gear.

12. The method of grinding a side tooth surface of a rotary helically toothed gear which comprises engaging a grinding wheel with said side surface, rotating the wheel on its axis with its working surface in engagement with said side surface, simultaneously rotating said gear on its axis of rotation, and simultaneously effecting feeding motion between the wheel and said gear in the direction of the axis of rotation of said gear in time with the rotation of said gear thereby to effect a relative helical motion about and in the direction of the axis of said gear while relatively advancing the wheel toward said side surface adjacent both ends of said feeding motion, and while relatively swinging the wheel on an axis disposed at right angles to the axis of the wheel and fixed with respect to the wheel axis, said swinging motion being continuous in one direction during said feeding motion.

13. The method of grinding a side tooth surface of a rotary helically toothed gear which comprises engaging a grinding wheel with said side surface, rotating the wheel on its axis with its working surface in engagement with said side surface, smultaneously rotating said gear on its axis of rotation, simultaneously effecting feeding motion between the wheel and said gear in the direction of the axis of rotation of said gear in time with the rotation of said gear, while relatively advancing the wheel toward said side surface adjacent both ends of said feeding motion, and while relatively swinging the wheel on an axis disposed at right angles to the axis of the wheel, the axis of swing of the wheel being disposed on the side of the wheel opposite to that which engages said side tooth surface, and said swinging motion being proportional to the axial distance travelled during said feed motion.

14. The method of grinding the side tooth surfaces of a rotary gear, which comprises engaging a grinding wheel, that has a grinding surface of other than convex profile shape, with said side tooth surface, and rotating the wheel on its axis with said grinding surface in engagement with side side tooth surface, while effecting a reciprocatory motion between the wheel and gear in the direction of the axis of rotation of said gear to grind a side tooth surface of said gear on the relative stroke of the wheel in one direction axially of said gear and to return the wheel relatively to initial position on the return stroke, disengaging and reengaging the wheel and gear in a depthwise direction at the end and at the start, respectively, of each grinding stroke, rotating the gear on its axis between successive grinding strokes so that the wheel enters a different tooth space of the gear on each successive grinding stroke, advancing the wheel toward the side tooth surface engaged thereby in said depthwise direction at a varying rate during each grinding stroke, and swinging the wheel on an axis angularly disposed to the axes of the wheel and of the gear in time with the grinding strokes to produce crowned teeth.

15. The method of grinding a rotary helically toothed gear; which comprises engaging a grinding wheel that has a grinding surface that has a slightly concave axial profile, with a side tooth surface of said gear, and rotating the wheel on its axis with said grinding surface in engagement with said side tooth surface, while effecting a feeding motion between the wheel and said gear in the direction of and about the axis of rotation of said gear in a relative helical path, relatively advancing the wheel toward the side tooth surface engaged thereby at a varying rate during said feeding motion, and swinging the wheel on an axis angularly disposed to the axes of the wheel and of said gear, said swinging motion being continuous in one direction during said feeding motion.

16. The method of grinding a rotary helically toothed gear, which comprises engaging the working surface of a grinding wheel with a side tooth surface of said gear, and rotating the wheel on its axis, while effecting a feeding motion between the wheel and said gear about and in the direction of the axis of rotation of said gear in a relative helical path, relatively advancing the wheel toward said side tooth surface at a varying rate during said feeding motion, and simultaneously swinging the wheel about an axis angularly disposed to the axis of the wheel in time with said feeding motion and continuously in one direction during said feeding motion.

17. The method of grinding a rotary helically toothed gear, which comprises engaging a grinding wheel, which has a slightly internal grinding surface, with a side tooth surface of the gear, with said grinding surface in engagement with said side tooth surface, and rotating the wheel on its axis, while effecting a feeding motion between the wheel and the gear about and in the direction of the axis of rotation of said gear in a relative helical path, relatively advancing the wheel toward said side tooth surface at a varying rate during said feeding motion, and simultaneously swinging the wheel on an axis angularly disposed to the axes of the wheel and gear, said swinging motion being continuous in one direction during said feeding motion.

18. The method of grinding a rotary gear, which comprises engaging a grinding wheel that has a working surface of other than convex profile shape, with a side tooth surface of said gear with said working surface in engagement with said side tooth surface, and rotating the wheel on its axis, while effecting a feeding motion between the wheel and gear in the direction of the axis of rotation of said gear, relatively advancing the wheel toward said side tooth surface at a varying rate during said feeding motion, and simultaneously effecting a separate relative swinging movement of the wheel relative to the gear on an axis angularly disposed to the axes of the grinding wheel and of said gear, said swinging motion being continuously in one direction during said feeding motion.

19. The method of grinding a rotary gear, which comprises engaging a grinding wheel, that has a working surface of other than convex profile shape, with a side tooth surface of the gear with said working surface in engagement with said side tooth surface, and rotating the wheel on its axis, while effecting a feeding motion between the wheel and gear in the direction of the axis of rotation of said gear, relatively advancing the wheel toward said side tooth surface adjacent both ends of the feeding motion, said advance being along a straight line inclined at an acute angle to the grinding surface, and simultaneously effecting a separate swinging movement of the wheel relative to the gear in time with said feeding motion on an axis angularly disposed to the axes of the grinding wheel and of the gear.

20. The method of grinding a rotary gear which comprises engaging a grinding wheel, that has a working surface of other than convex profile shape, with a side tooth surface of the gear with said working surface in engagement with said side tooth surface and rotating the wheel on its axis, while effecting a relative reciprocatory motion between the wheel and said gear in the direction of the axis of rotation of said gear to produce alternate grinding and return strokes, moving the wheel relative to the gear depthwise in opposite directions at opposite ends of each grinding stroke along a straight line which intersects the axis of the wheel and which is inclined at an acute angle to its active grinding surface, to disengage and engage, respectively, the wheel and gear at opposite ends of each grinding stroke, advancing the grinding wheel along said straight line at a varying rate during each grinding stroke, and simultaneously relatively swinging the wheel on an axis angularly disposed to the axes of the wheel and gear in time with each grinding stroke.

21. The method of grinding a rotary helically toothed gear which comprises engaging the grinding surfaces of

a pair of grinding wheels, each of which has a grinding surface of other than convex profile shape, with different tooth surfaces of the gear with their grinding surfaces facing each other and with their axes of rotation paralleled and offset and with the wheels displaced bodily relative to each other along the axis of rotation of said gear, and effecting feeding motion between the wheels and said gear in a relative helical path about and in the direction of the gear axis.

22. The method of grinding a rotary helically toothed gear which comprises engaging the grinding surfaces of a pair of grinding wheels, each of which has a grinding surface of other than convex profile shape, with different tooth surfaces of said gear with their grinding surfaces facing each other and with their axes paralleled and inclined to the axis of rotation of said gear and with the wheels displaced bodily relative to each other along the gear axis, each wheel being displaced from the average position of the two wheels in a direction toward the side of increased separation of the extended grinding surface from the axis of said gear, and rotating the wheels on their respective axes while effecting feeding motion between said wheels and said gear in a relative helical path about and in the direction of the axis of said gear.

23. The method of grinding a rotary helically toothed gear, which comprises engaging the grinding surfaces of a pair of grinding wheels, that have grinding surfaces of other than convex profile shape, with different tooth surfaces of said gear with the axis of rotation of said gear inclined to the axes of the wheels, rotating the wheels on their axes, and effecting feeding motion between the wheels and said gear in a relative helical path in the direction of and about the axis of rotation of said gear, advancing the wheels toward the surfaces engaged thereby at a varying rate during said feeding motion and simultaneously swinging the wheels in opposite directions about axes angularly disposed to the respective wheel axes and to the axis of rotation of said gear in time with said feeding motion.

24. The method of grinding a rotary helically toothed gear, which comprises engaging the grinding surfaces of a pair of grinding wheels, that have grinding surfaces of other than convex profile shape, with different tooth surfaces of said gear, rotating the wheels on their respective axes, and effecting feeding motion in a relative helical path between the wheels and gear in the direction of and angularly about the axis of rotation, advancing the wheels respectively toward the surfaces engaged thereby at a varying rate during said feeding motion and simultaneously swinging the wheels in opposite directions about parallel axes angularly disposed to the axes of the wheels in time with said feeding motion.

25. The method of grinding a rotary cylindrical gear which comprises engaging the grinding surfaces of a pair of grinding wheels, that have grinding surfaces of other than convex profile shape, with different tooth surfaces of said gear, rotating the wheels on their respective axes, and effecting feeding motion between the wheels and gear in the direction of the axis of rotation of said gear, advancing the wheels individually toward the respective tooth surfaces engaged thereby at a varying rate during said feeding motion, and simultaneously swinging the wheels in opposite directions about axes angularly disposed to their respective axes in time with said feeding motion to produce crowned teeth.

26. The method of grinding a rotary helically toothed gear which comprises engaging the grinding surfaces of a pair of grinding wheels, that have grinding surfaces of other than convex profile shape, with different tooth surfaces of said gear with the axes of the wheels approximately parallel and with the grinding surfaces of the wheels facing each other and with the wheels displaced bodily relative to each other along the axis of rotation of said gear, rotating the wheels on their respective axes, and effecting feeding motion in a relative helical path between the wheels and said gear about and in the direction of the axis of rotation of said gear, advancing the wheels toward the respective tooth surfaces engaged thereby at a varying rate during said feeding motion, and simultaneously swinging the wheels in opposite directions on separate axes in time with said feeding motion, the two last-named motions of each grinding wheel being separate and individually controllable.

27. In a machine for grinding the tooth surfaces of cylindrical gears, a rotary work support, a pivoted tool support, a rotary grinding wheel journaled on said tool support, said tool support having its pivotal axis angularly disposed to the axis of rotation of the wheel, a slide on which said tool support is adjustably pivoted, said slide being adjustable toward and from said work support, means for adjusting said tool support and said slide in a plane perpendicular to the axis of rotation of said work support, means for effecting a relative reciprocatory movement between the tool and work supports in the direction of said axis of the work support to effect alternate grinding and return strokes of the wheel, means for approaching the grinding wheel to the tooth surface engaged thereby at a varying rate during each grinding stroke, and means for swinging said tool support about its pivot in time with each grinding stroke.

28. In a machine for grinding the tooth surfaces of cylindrical gears, a rotary work support, a pivoted tool support, a rotary grinding wheel journaled on said tool support, said tool support having its pivotal axis angularly disposed to the axis of rotation of the wheel, a slide on which said tool support is adjustably pivoted, said slide being adjustable toward and from said work support, means for adjusting said tool support and said slide laterally toward and away from the axis of rotation of said work support, means for effecting a relative reciprocatory movement between the tool and work supports in the direction of the axis of rotation of said work support to effect alternate grinding and return strokes of the wheel, a rotary shaft, means for rotating said shaft at a rate of one full turn for each grinding and return stroke of the wheel, a cam secured to said shaft for moving the tool support at a varying rate toward the gear tooth surface engaged thereby during portions of each grinding stroke, and other means operatively connected with said shaft for swinging said tool support on its pivot in time with each grinding stroke.

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