METHOD AND SYSTEM FOR STRAIGHTENING LARGE DIAMETER SHAFTS BY SELECTIVE COLD ROLLING


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ABSTRACT
A method and system for straightening large diameter shafts by selective cold rolling by pressing a smaller roller against the shaft with alternating loads as the shaft is slowly rotated.

9 Claims, 2 Drawing Figures
METHOD AND SYSTEM FOR STRAIGHTENING LARGE DIAMETER SHAFTS BY SELECTIVE COLD ROLLING

BACKGROUND OF THE INVENTION

Large diameter shafts, such as, for example, propeller shafts, are subject to bending which can occur during manufacturing, processing or in subsequent use. Such bending can occur in the rough forging of the shaft and when machining to final dimensions. In lively forgings the final cut for a keyway or the like can create bends. Under some circumstances, such shafts will become bent after period of use or if a propeller, for example, strikes an obstruction. Acceptable limits of bend or eccentricity have been established and as a norm, a permissible eccentricity has been established at 7.4 thousandths of an inch for some operational uses. Above such a figure, mechanical and technical difficulties arise.

Heretofore, methods for the straightening of shafts have been devised including a “hot spot” method and a “peening” method. The hot-spot method involves quickly heating a local spot (on the outside of a bend) to an elevated temperature. As a result of the local heat, the heated region tends to expand, but also due to the elevated heat, the yield strength of the material is reduced. Due to these combined effects, the metal yields such that the shaft bulges slightly in the heated region. When the heat is removed, the metal then hardens and remains in the bulged position and the residual tensile stresses introduced into the outside of the bend of a shaft tend to straighten the shaft. The hot-spot method is characterized by the following intrinsic disadvantages:

1. The heating process is not accurately controllable.
2. The metallurgy of the shaft can be adversely affected.
3. The process is extremely slow; after each heating the entire shaft must be allowed to cool to a uniform temperature before the results can be assessed.

With the peening method, a hammer or equivalent technique is used to hammer or peen the shafting surface on the inside of a shaft bend. The residual compressive stresses thereby introduced into the shaft tend to straighten the shaft. The peening method entails the following intrinsic disadvantages:

1. The magnitude of the peening effort required to straighten shafts of large diameter, especially those of high tensile strength, exceeds that which can be accomplished with the usual peening techniques.
2. The residual stresses introduced into the shaft are distributed non-uniformly.
3. Peening subjects the shafting surface to possible damage.
4. Due to the superficial nature of the compressive residual stresses introduced, efforts to improve the surface finish of the shafting after peening by cutting a small amount of metal from the shaft will tend to destroy the effect achieved because the residual stresses in the metal removed from the shaft will not be uniform around the circumference of the shaft.

SUMMARY OF THE INVENTION

The selective cold rolling method of the invention involves the use of cold rolling equipment such as is commonly used in connection with propeller shafts on ships, however, instead of using a constant roller load and introducing residual compressive stresses uniformly around the circumference of a shaft, the roller load is varied selectively so as to use a higher roller load, with consequent higher residual compressive stresses, on the inside of a bend thereby tending to straighten the shaft. The selective cold rolling of a shaft is accomplished by pressing a small roller against the shaft with alternating loads as the shaft is slowly rotated. A specified length of the shaft is rolled by slowly advancing the roller along the shaft as it rotates.

The roller has a crowned face and is sized with radii of curvature which are much smaller than those of the shaft such that a very small elliptical contact area exists between the roller and the shaft. The combination of a heavy roller load on the shaft and the small contact area results in very large contact stresses between the shaft and roller. These stresses cause a yielding of the shaft material near the surface which then leaves a residual compressive stress in the material adjacent to the surface. By controlling the roller load, the magnitude and depth of the residual stress can also be controlled.

The residual stress over the yielded depth actually produces a residual force in the area adjacent to the shaft surface and it is this residual force which is utilized to straighten a shaft.

Advantages associated with the selective cold rolling method include the following:

1. The variables required to straighten a shaft can actually be calculated.
2. The method is easily controlled such that predictable results can be achieved.
3. The residual stresses introduced in the shaft are not distributed erratically.
4. The results achieved can be assessed immediately after a rolling operation.
5. The straightening can be accomplished by introducing residual compressive stresses completely around the shaft circumference but more deeply on one side of the shaft than the other; this permits a small amount of metal to be removed from the shaft without affecting the straightening results achieved.
6. The metallurgy of the shaft material is not adversely affected.

Other objects and advantages of the invention will be more readily apparent from the following detailed description of an embodiment thereof when taken together with the accompanying drawings in which:

FIG. 1 is a schematic plan view of a shaft straightening machine in accordance with the invention; and
FIG. 2 is a graph showing results obtained in practice of the present invention.

Referring now in detail to the drawings, there is shown in FIG. 2 the eccentricity in a shaft before and after straightening in accordance with the invention. The figures are for a 16 inch diameter shaft 470 inches long. It is to be noted that the maximum eccentricity
3 was found at approximately position H and indicated in inches from the shaft end. The eccentricity is indicated in thousandths of an inch. The shaft what was straightened had an initial eccentricity of approximately 17.5 thousandths of an inch and after straightening, the maximum eccentricity was approximately 3 thousandths of an inch. This eccentricity is well within the allowable limit as indicated above of 7.5 thousandths of an inch.

Apparatus usable in practicing the invention is shown schematically in FIG. 1 and basically is designed to accomplish a plurality of functions. The shaft to be straightened must be freely supported at two points with provisions to rotate it. The alternating roller loads have to be applied to the shaft as it turns without deflecting the shaft excessively, the roller loads must be adjustable, and the advance of the roller along the shaft has to be adjustable. A more detailed discussion of the apparatus will follow hereinafter but prior to this a discussion of the principles is deemed appropriate.

The use of a constant roller load around the shaft circumference would, of course, have no effect on the shaft since the forces on opposite sides oppose one another. However, the actual straightening process involves the application of a heavy roller load over a portion of the shaft circumference with a lesser load over the remainder of the shaft circumference. The residual force in the shaft produced by the heavy roller load is opposed by a smaller force on the opposite side, thus a couple is produced in the shaft due to the two different residual forces.

Since the residual forces produced in the shaft are due to compressive stresses, they tend to push or stretch the shaft in the longitudinal direction. With the heavier force pushing on one side, the couple produced in the rolled area causes the shaft to bow away from the heavy load, that is, a bend is produced with the convex side centered on the arc of the heavy roller load. Therefore, to straighten an existing bend in a shaft, the heavy roller load is located on the concave side of the bend in order to bend the shaft in the opposite direction until it is straight.

A single roller load over an arc would produce a straightening couple; however, the use of a reduced load over the remaining shaft circumference is necessary to facilitate machining the shaft after straightening. The reduced load over the entire circumference creates a uniform force around the shaft down to a depth corresponding to the reduced load with the effective straightening couple being produced over the increased depth of yielding in way of the heavy load. Therefore, after straightening the shaft, the surface of the shaft in way of the rolled area can be machined down to a depth corresponding to the reduced load without upsetting the non-uniform force and straightening couple. This allows final machining of a shaft after straightening without affecting its straightness.

In order to assure that an area is fully cold rolled, the advance of the roller along the shaft during one shaft revolution cannot exceed the minor semi-axis of the elliptical contact area between the shaft and roller. Since the contact area and its axes vary with the roller load, the advance has to be adjusted for different load. As the load increases the advance can also be increased somewhat. The advance is determined by the reduced roller load since it has the smaller area.

An analytical procedure is used to determine the rolling variables based on the dimensions of a shaft, the location of the bend in a shaft, and the eccentricity of the shaft. With this information, the location and length to be rolled, the two roller loads, the rolling arcs for the two loads, and the speed of advance can all be calculated.

The shape and eccentricity of a shaft is determined by supporting the shaft at two points and rotating it. Dial indicators are placed at regular intervals along its length, and the indicator readings or shaft runouts are recorded for every 90° of rotation. The eccentricity values (runout divided by two) are then plotted on a polar plot (looking axially along the shaft) to determine the angle at which the maximum eccentricities occur. Having determined this angle the shaft eccentricities are then plotted and the longitudinal location of the bend and the shaft eccentricity can then be determined. In some cases the plots may show several bends in one or more planes which indicates the need to roll the shaft in several different locations with the proper rolling variables determined for each location.

As pointed out above, several functions are required as regards the apparatus. The shaft has to be freely supported at two points with provisions to rotate it. The alternating roller loads have to be applied to the shaft as it turns without deflecting the shaft excessively, the roller loads must be adjustable, and the advance of the roller along the shaft has to be adjustable. FIG. 1 schematically shows such apparatus used to straighten a shaft by selective cold rolling.

The shaft 10 is supported by lathe centers 12 at each end as shown although the shaft could be supported by steady rests on its span, rather than with lathe centers, or by any other method which would allow the shaft to turn. The shaft is driven by a variable speed drive motor 14 in a usual manner. A carriage assembly 16 is operatively mounted on the machine and driven in a known manner through a carriage drive screw 18.

The actual cold rolling assembly consists of two diametrically opposed hydraulic cylinders, including backup cylinder 20 and roller cylinder 22. Cold rolling roller 24 is actuated by roller cylinder 22 and a babbitted backup pad 26 is actuated by backup cylinder 20. The cylinders 20 and 22 are of the same size and supported on a common carriage and are cross-connected so that the roller load on the shaft is opposed by the load on the babbit pad, thus the babbit pad simply acts as a backup support for the heavy roller load and prevents the roller forces from deflecting the shaft and transmitting any loads to the shaft supports. Additionally, the use of the two cross-connected cylinders with the balanced loads allows the roller and pad to freely follow the movement of a bent shaft as it rotates. Since two different roller (and "backup" pad) loads are required as the shaft rotates, a hydraulic oil supply capable of supplying the different pressures is required. To this end a high pressure oil supply source 28 is provided and a low pressure source 30 is also provided. The high and low pressures are alternately applied to the cylinders 20 and 22 by means of an electrically or pneumatically operated two position valve 32. The two hydraulic pressures can be supplied by two adjustable pumps, a single pump feeding two adjustable regulators or relief valves, or by gas-oil accumulators with adjustable pressures.
The two position valve 32 is controlled by a switch, such as a cam switch 34 which is located adjacent to shaft 10 and is actuated by a cam 36 attached to the shaft. The cam 36 is simply, in the shown embodiment, a flexible strip which is taped to the shaft over the arc of either the heavy load or light load, depending on how the valve is piped to the oil supplies. In either case, the cam is located to actuate the switch and the valve such that the valve routes the high pressure oil to the roller over the desired arc and the low pressure oil over the remaining circumference of the shaft.

In operation, the carriage assembly which supports the two cylinders is slowly advanced down the shaft as the shaft is rotated. The advance or feed on the carri-

age is fully adjustable to allow for different roller loads. The apparatus as shown utilizes a lathe normally used to machine shafting. The shaft is rotated by the headstock. The carriage assembly for the cylinders is designed to rest on a carriage for a tool post. Since the tool post is moved along the lathe by the lead screw and has a fully adjustable speed, this also provides an adjustable advance speed for the roller. To simplify piping, the accumulators and associated piping are located on the carriage assembly. Flexible hoses are used to connect the accumulators to the supply source. The roller as used has a crowned face and is sized with radii of curvature which are much smaller than those of the shaft, such that a very small elliptical contact area exists between the roller and the shaft. The combination of a heavy roller load on the shaft and the small contact area results in very large contact stresses between the shaft and roller. These stresses cause a yielding of the shaft material near the surface which then leaves a residual compressive stress in the material adjacent to the surface. By controlling the roller load, the magnitude and depth of the residual stress can also be controlled. The residual stress over the yielded depth actually produces a residual force in the area adjacent to the shaft surface and it is this residual force which is utilized to straighten the shaft.

Following is an operative set of instructions for straightening, by cold rolling, of a propeller shaft, such as indicated at 10 in FIG. 2.

1. Determine Location & Magnitude of Bend - Prior to straightening, determine the location and magnitude of the bend by supporting the shaft section between lathe centers with no steady rests and take dial indicator readings at least every four feet along the shaft length. Tabulate the runout at each station by clock positions. Additional readings may be required to determine the exact location of maximum runout. Based on the measured eccentricity (one half of runout) and the location of the bend, calculate the two roller loads and arcs and the rolling length required to straighten the shaft. Mark the arc for the heavy load on the side opposite the maximum runout. Also mark the rolling length on the shaft with its location centered about the point of maximum runout. This is the potential area to be cold rolled.

2. Method of Cold Straightening
   a. Set up cold rolling machine as shown in FIG. 1.
   b. Charge the H.P. accumulator to a pressure corresponding to the heavy load.
   c. Charge the L.P. accumulator to a pressure corresponding to the light load.
   d. Support the shaft in lathe centers with one steady rest located forward of the area to be cold rolled.
   e. Cold rolling is to be initially accomplished for a distance of approximately one half of the calculated length.
   f. Rotate the shaft to obtain a shaft surface speed of about 15 feet per minute (approx. 2 RPM) and set the cold rolling machine at the rate of feed corresponding to the light roller load.
   g. As the shaft rotates and the beginning of the heavy load arc approaches the hardening roller open valve 32 to high pressure. As the end of the heavy arc approaches the hardening roller, close valve to high pressure and open valve to low pressure. As the beginning of the heavy arc approaches the hardening roller again close valve to low pressure and open valve to high pressure. Repeat this cycle every revolution, transferring fluid as necessary from the L.P. to the H.P. accumulator until the cold rolling operation has continued approximately one half of the calculated length.
   h. Isolate the H.P. and L.P. accumulators and back the roller and steady rest away from the shaft. Take dial indicator readings to determine the amount of runout with the shaft supported by lathe centers only.
   i. The next step will depend upon the determined amount of movement of the shaft due to the initial cold rolling. If the shaft has straightened considerably more or less than expected for rolling over half of the calculated length, some adjustment to the roller loads or lengths may be necessary. If the shaft is straightening as expected then rolling over the remaining length can be completed.
   j. After the shaft has been straightened within the desired tolerances or to the maximum extent feasible, dial indicator readings are taken at the locations used in Step 1 and recorded.

We claim:
1. A method of straightening a bent shaft comprising:
   A. supporting and rotating the shaft;
   B. applying alternately a heavy roller load and a lesser roller load to the surface of the shaft while rotating, and wherein:
   i. the roller load is applied by a roller having a crowned face with a radius of curvature considerably smaller than that of the shaft such that a very small elliptical contact area exits between the roller and the shaft; the roller load being such that residual compressive stresses are induced in the material of the shaft adjacent to the surface;
   ii. during a revolution the heavy roller load is applied to the concave side of the bend, with the lesser load being applied over the remaining shaft circumference, the resulting compressive stresses thereby producing a residual force which straightens the shaft;
   iii. that side of the shaft opposite to the roller loads is supported with a back-up pad to prevent roller forces from deflecting the shaft; and
   C. advancing the position of application of the roller loads along the shaft as it rotates.
2. A method as claimed in claim 1, wherein an assembly for the method consists of two diametrically opposed hydraulic cylinders with the roller actuated by one cylinder and a back-up pad supported by the other cylinder, said cylinders being cross-connected to a fluid pressure source so that the roller load on the shaft is opposed by the back-up pad.

3. A method as claimed in claim 1, wherein the advance of the roller along the shaft during one shaft revolution does not exceed the minor semi-axis of the elliptical contact area between the shaft and roller.

4. A method as claimed in claim 3, including determining the location and length to be rolled, the two roller loads, the size and shape of the roller, the rolling arcs for the two loads, and the speed of advance based on measurements of the eccentricity of the shaft.

5. A method as claimed in claim 4, including marking an arc on the side opposite the maximum runout for a substantial distance axially on either side of the point of maximum runout and indicating the potential area to be cold rolled, high roller pressure being initiated as the beginning of the marked arc approaches the hardening roller and, as the end of the arc approaches the hardening roller, high pressure being terminated and low pressure being applied, with the cycle being repeated for each shaft revolution.

6. A method as claimed in claim 2, including high and low pressure sources for said cylinders, and a two-position valve operable for selectively applying high or low pressures to said cylinders.

7. A method as claimed in claim 6, including sensor means adjusted to actuate the valve such that the valve routes the high pressure oil to the roller over the desired arc of the shaft and the low pressure oil over the remaining circumference of the shaft.

8. A method of straightening a bent shaft comprising:

A. supporting and rotating the shaft;
B. cold rolling the shaft by applying alternately a heavy roller load and a lesser roller load to the surface of the shaft while rotating to produce internal stress in the shaft, and wherein:
   i. the roller load is applied by a roller having a crowned face with a radius of curvature considerably smaller than that of the shaft such that a very small elliptical contact area exists between the roller and the shaft, the roller load being such that residual compressive stresses are induced in the material of the shaft adjacent to the surface;
   ii. during a revolution the heavy roller load is applied to the concave side of the bend, with the lesser load being applied over the remaining shaft circumference, the resulting compressive stresses thereby producing a residual force which straightens the shaft;
   iii. that side of the shaft opposite to the roller loads is supported with a back-up pad to prevent roller forces from deflecting the shaft; and
C. advancing the position of application of the roller loads along the shaft as it rotates, whereby the internal stress results in straightening of the shaft. * * * * *