The method of attaching and adjusting first and second members includes providing a first member having an outer surface and a second member. The second member is affixed to the outer surface of the first member at a desired axial position along the length of the first member and in a desired angular orientation. Subsequent to affixing the second member to the first member, the shape and/or dimensions of the second member is adjusted by increasing the density of at least a region of the second member. The densification may be accomplished by, for example, a mechanical working technique such as roller burnishing, coining, sizing, shot peening, or laser impacting. In one embodiment of the invention, the method may be adapted to the production of combustion engine camshafts from separately provided camshaft tubes and cam lobes.
FIGURE 1
(Prior Art)
Provide Tube.

If desired, centerless grind tube.

Provide metallurgical powder blend.

Place metallurgical powder in cam lobe mold.

Compact, sinter and size the metallurgical powder to form a cam lobe.

Heat cam lobe above predetermined temperature.

Precisely position the cam lobe on the tube.

Repeat positioning and heating steps with additional cam lobes or other components to be attached to the tube.

Roller burnish the cam shaft lobe surfaces.

If desired, heat treat the camshaft surfaces.

Cam shaft assembly complete.

FIGURE 3
FIGURE 4
METHOD OF FABRICATING CAMSHAFTS

CROSS-REFERENCE TO RELATED APPLICATIONS
Not Applicable.

FEDERALLY SPONSORED RESEARCH
Not Applicable.

TECHNICAL FIELD AND INDUSTRIAL APPLICABILITY OF THE INVENTION

The present invention is generally directed to a method for attaching first and second members, and subsequently adjusting the shape and/or dimensions of at least one of the members. More particularly, the present invention is directed to a method of attaching one or more cam lobes and other individual camshaft components, such as, for example, sprockets, bearings races and gears, to a camshaft tube at desired angular and axial orientations about the tube, and subsequently adjusting the shape and/or dimensions of at least one of the attached elements. In this way, the cam lobes and components may be adjusted to meet dimensional tolerances necessary for proper assembly of the camshaft into a combustion engine or other apparatus.

The method of the present invention may be utilized in applications wherein it is desirable to attach first and second members and subsequently adjust the shape and/or dimensions of at least one of the members. Examples of such applications include the fabrication of camshafts for internal combustion engines and other applications and the assembly of complex gear forms on rotatable shafts. The present method is particularly useful when applied in the fabrication of camshafts wherein cam lobes and, possibly, other camshaft elements such as sprockets, bearings races, and gears, are installed in precise locations on the outer surface of a camshaft tube. Camshafts fabricated according to the method of the invention may be used to engage push rods, lifters, impellers, rotors, gears, or other movable members.

DESCRIPTION OF THE INVENTION

BACKGROUND

Camshafts for piston-driven internal combustion engines typically include several cam lobes with lobe-shaped outer surfaces that operate to move push rods, lifters, or other movable members in a precise pattern. As the camshaft rotates, the cam lobes must engage the movable members at proper positions and with proper timing. Therefore, the cam lobes must be positioned on the camshaft at precise relative axial positions and angular orientations.

A camshaft 10 of a typical construction adapted for use in an internal combustion engine is depicted in FIG. 1. The camshaft 10 generally includes a camshaft tube 11. Several cam lobes 12 are affixed to the outer surface of the camshaft tube 11. Other camshaft components such as, for example, gear 16, may be affixed to the outer surface of the camshaft tube 11. Although generally referred to herein as a "camshaft tube", that element, although typically hollow, need not be cylindrical and may have any overall shape and uniform or non-uniform cross-section suitable for receiving and rotating the several cam lobes and other camshaft components. Accordingly, "camshaft tube" is used herein to refer generally to the central rotating component of a camshaft to which the cam lobes are affixed and is not limited to any particular cylindrical or non-cylindrical configuration.

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The lobe-shaped region of each cam lobe has a predetermined shape and is dimensioned to accurately control movement of the movable member it engages. More specifically, the profile of the cam lobe 12, and particularly the shape and dimensions of the lobe-shaped region 13, are such that as the camshaft tube 11 rotates, the motion of the cam lobe 12 imparts a precise rocking or reciprocating motion to the movable member it engages. In FIG. 1, for example, the movable members illustrated adjacent a cam lobe 12 are a lifter 14 and a push rod 15. As the camshaft 10 rotates, the surfaces of the cam lobes 12, along with their various angular and axial positions along the length of the camshaft tube 11, work in conjunction to properly move the push rods 15 of the engine in a desired pattern and timing. This synchronized motion ensures that the intake and exhaust valves of all engine cylinders operate correctly.

Camshafts combining a camshaft tube and several cam lobes traditionally were manufactured as a single component by casting or forging. This method of fabrication is time-consuming and expensive, and produces camshafts with limited dimensional accuracy. Therefore, extensive grinding and/or polishing is required to shape the individual cam lobes and other camshaft components and appropriately adjust the shape and dimensions of the surfaces of each of the components. Absent such extensive finishing work, the cam lobes would not properly engage their associated movable members. Forged or cast camshafts are necessarily composed of material of a substantially homogenous chemical composition. This is a disadvantage inasmuch as it may be undesirable for the camshaft tube and the cam lobes to have substantially different physical properties so as to optimally withstand the significantly different mechanical forces experienced by the several components.

To address the deficiencies inherent in the casting and forging methods of camshaft fabrication, more recently camshafts have been fabricated by separately producing the camshaft tube and the cam lobes and then installing the cam lobes onto the outer surface of the camshaft tube at desired locations. In the case of the camshaft 10 of FIG. 1, for example, individual cam lobes 12 having a configuration as generally shown in FIG. 2 may be separately fabricated and then positioned about the camshaft tube 11. The components are assembled by disposing the camshaft tube 11 through the bore 17 in each cam lobe, and then affixing the cam lobes 12 to the outer surface of the camshaft tube 11 in desired axial positions and angular orientations. This fabrication method provides greater flexibility relative to the casting and forging methods, and the materials from which the camshaft tube, the cam lobes, and the other components installed on the camshaft are constructed may differ. For example, the cam lobes may be produced from a material particularly resistant to thermal stress and repetitive contact fatigue, while the camshaft tube may be produced from less expensive material such as a machined mild steel.

Fabricating camshafts by installing separately produced cam lobes onto a camshaft tube has the inherent disadvantage that the cam lobes and other camshaft elements must be precisely positioned when affixed. Also, the surfaces of each cam lobe must have the required shape and dimensions so that it is precisely oriented relative to each other cam lobe surface and relative to the camshaft tube. Accordingly, when fabricating camshafts in this manner, after the cam lobes are installed on the camshaft tube it is common to grind the surfaces of the cam lobes using one or more grinding steps so as to adjust each cam lobe profile and, possibly, adjust the relative angular orientations of the several cam lobes.
alternate process, the internal diameter of each cam lobe is ground to adjust the tolerances that will be achieved once the cam lobes have been installed on the camshaft tube. Grinding the internal diameters or exterior surfaces of the cam lobes in a precise manner is problematic and, for example, accurately grinding cam lobes produced from powder metal material can be complex and expensive. More generally, grinding of cam lobes requires the use of expensive grinding machines, is a relatively slow process, and requires expensive grinding wheels that must be replaced often.

Accordingly, a need exists for a method of fabricating camshafts wherein cam lobes produced separately from the camshaft tube may be affixed to the exterior surface of the camshaft tube at precise axial positions and angular orientations, and then the cam lobes may be adjusted to proper shape and/or dimensions without employing a grinding operation. More generally, the inventor perceives that a need exists for a method of attaching first and second members wherein, subsequently, the shape and/or dimensions of at least one of the members may be adjusted by a technique other than grinding.

**SUMMARY OF THE INVENTION**

The present invention addresses the above-described needs by providing a method of conveniently attaching and adjusting first and second members. The method includes providing a first member having an outer surface and a second member. The second member is affixed to the outer surface of the first member at a desired axial position along the length of the first member and in a desired angular orientation. The second member may be affixed to the first member using any suitable known technique. Such affixation techniques include, for example, shrink fitting, interference fitting, welding, mechanical or chemical fusing, or any other technique for permanently affixing one member onto a surface of another member at a predetermined position and orientation. Subsequent to affixing the second member to the first member, the shape and/or dimensions of the second member is adjusted by increasing the density of at least a region of the second member. The densification may be accomplished by, for example, a mechanical working technique such as roller burnishing, coining, sizing, shot peening, or laser impacting.

According to one embodiment of the present invention, the second member includes an aperture that is sized so that the first member may be disposed within the aperture when the second member is at a temperature greater than a predetermined temperature. The second member is heated to a temperature above the predetermined temperature, and the first and second members are then positioned so that the first member is disposed within the aperture of the second member at a desired axial position and angular orientation relative to the first member. The second member is then cooled to a temperature below the predetermined temperature to securely affix the second member to the first member in the desired axial position and angular orientation. The shape and/or dimensions of at least a region of the second member is then appropriately adjusted by increasing the density of at least a region of the second member. As just noted, the densification may be provided by mechanically working a surface of the second member.

The method of the present invention is particularly suited to the fabrication of camshafts and may be applied to attach cam lobes, sprockets, bearing races, gears and other camshaft elements to a camshaft tube. The camshaft tube includes an outer surface that may be, for example, cylindrical or of any alternate, non-cylindrical configuration adapted to the intended use of the camshaft. When the present invention is adapted as a method of fabricating camshafts, at least one cam lobe is provided. The cam lobe is affixed to the outer surface of the camshaft tube at a predetermined axial position and angular orientation. The cam lobe may be affixed to the camshaft tube using any known technique suitable for permanently affixing one metallic member onto a surface of another metallic member at a predetermined position and orientation. Such techniques include, for example, interference fitting and shrink fitting. Other affixation techniques include known techniques of fusing metallic members together by a welding or sintering operation. Once the cam lobe is appropriately affixed to the outer surface of the camshaft tube, the shape and/or dimensions of at least a surface region of the cam lobe is adjusted by densifying at least a region of the cam lobe. The densifying operation may be accomplished by a mechanical working technique such as roller burnishing, sizing, coining, shot peening, and laser impacting, or by any other densification method suitable for adjusting the tolerance of the cam lobe once assembled onto the camshaft tube.

In embodiments of the camshaft fabrication method wherein the cam lobe is affixed to the camshaft tube using a shrink fitting technique, the cam lobe is provided with an aperture therethrough sized so that when the cam lobe is heated above a predetermined temperature the aperture expands and the camshaft tube may be disposed therethrough. The cam lobe is heated to a temperature above the predetermined temperature, and the cam lobe and camshaft tube are then positioned so that the camshaft tube is disposed through the aperture and is at a desired axial position and angular orientation relative to the camshaft tube. The cam lobe is then cooled to reduce the size of the aperture and to securely engage the external surface of the camshaft tube and fix the position of the cam lobe relative to the tube. Once the cam lobe has been affixed to the camshaft tube in this way, at least a region of the cam lobe is densified by, for example, a roller burnishing, sizing, coining, shot peening, or laser impacting technique, or another suitable mechanical working technique. The densification step is carried out so as to appropriately adjust the shape and/or dimensions of at least a region of the outer surface of the cam lobe to meet required tolerances.

Roller burnishing is a cold mechanical working technique known to those of ordinary skill in the art and consists generally of applying pressure to the part surface by rolling. More particularly, roller burnishing has been applied in other applications to adjust the dimensions of components formed of powder metal and other metallic materials. To the knowledge of the present inventor, however, roller burnishing has not been applied as a means to adjust the tolerances of cam lobes or other components installed on the camshaft tube of an assembled camshaft. When applied to powder metal parts, roller burnishing also may work to harden the surface of the part. Roller burnishing and other mechanical working techniques are not a metal removal technique. Thus, they differ fundamentally from grinding techniques, wherein the shape and/or dimensions of a part are adjusted by removing material from a surface of the part.

In the method of the present invention, any region of the outer surface of the one or more cam lobes of the assembled camshaft may be roller burnished or otherwise mechanically worked or densified to adjust part shape and/or dimensions. In this way, the outer surface of the one or more cam lobes of the camshaft will properly engage the associated moveable member when the camshaft is assembled into a comb-
bustion engine or other device. Moreover, roller burnishing or other densification techniques may be employed to adjust the shape and/or dimensions of other components once affixed in proper positions about the camshaft tube using the method of the present invention. Such other components may include, for example, gears, bearing races, and sprockets.

Cam lobes employed in the method of the present invention may be composed of any material having properties suitable for that application. The method of the present invention for fabricating camshafts is, however, particularly suited to the assembly of camshafts from cam lobes formed from metallurgical powders by press-and-sinter techniques. Such cam lobes preferably are produced from a powder metal material that is resistant to wear and rolling contact fatigue, and that may be roller burnished or otherwise densified or mechanically worked to appropriately adjust the shape and/or dimensions of the surface of the cam lobes. The present invention has found that cam lobes having the following preferred composition, on a weight percentage basis, provide excellent rolling contact fatigue and wear resistance properties: about 90% to about 99.7% iron, 0 to about 2.0% nickel, 0 to about 1.0% molybdenum, about 0.3% to about 2.0% carbon, 0 to about 3.0% copper, and 0 to about 3.0% chromium. It is noted that compositions that are not strictly within the foregoing compositional ranges also may be used to prepare cam lobes according to the present invention. Additional materials that may be used in the production of cam lobes according to the method of the present invention will be apparent to those of ordinary skill in the art on consideration of the present description of the invention. Thus, the foregoing preferred powder metal composition should not be considered to limit the scope of the present invention.

The reader will appreciate the foregoing details of the present invention, as well as others, upon consideration of the following detailed description of embodiments of the invention. The reader also may comprehend such additional details upon using the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is broadly directed to a method of attaching a first member and a second member and subseq-
sliding contact under heavy loads. The foregoing properties are particularly important to the proper functioning of cam lobes, which are subjected to high cyclic stresses and heavy loads for prolonged periods.

The preferred powder compositional ranges set forth above should not be considered to limit the scope of the method of the present invention. It is believed that powder compositions outside the above compositional ranges also may be used in the method of the present invention to form cam lobes having acceptable rolling contact fatigue and wear resistance properties. For example, it is believed that acceptable properties may be achieved if the powders include nickel and/or molybdenum in excess of 2.0% and 1.0% upper limits, respectively, indicated above, but the cost of such powders would be increased without a significant increase in rolling contact endurance limit or hardness in the finished material. Nevertheless, powder mixes including copper, nickel, and/or molybdenum in amounts in excess of the above preferred ranges may be desirable to provide an improvement in properties other than rolling contact endurance or wear resistance. Such other properties include, for example, tensile strength and dimensional control.

Sinterhard powders also may be used in the method of the present invention to fabricate cam lobes or other components that are to be installed on the camshaft tube. Sinterhard powders include a balance of carbon and alloying elements that will form parts having hardnesses greater than about RC 25 directly from the sintering furnace after cooling at cooling rates that may be achieved in the furnace. Parts having hardnesses in excess of RC 25 are typically produced from sinterhard powders using a sintering furnace that is specially designed to gas cool the sintered parts at an accelerated rate, in the 120–200°F/min. range. More recently, high-alloy content sinterhard powders have been developed that provide hardnesses greater than RC 25 on cooling at the much lower rate of about 40°F/min.

More generally, it is preferred that the powders used in the method of the present invention will develop a hardness less than RC 20, and more preferably less than RC 12, after an initial press and sinter. It also is preferred that such sintered parts are capable of developing hardnesses in the RC 30–60 range after a heat treatment subsequent to the press and sinter. The relatively low pre-heat treatment hardness (less than RC 20) allows the material to be easily deformed to adjust tolerances, while the much higher hardnesses achieved on heat treating the material provide the material with wear resistance adequate to withstand cyclic sliding under heavy loads. Preferred powders also are those that may be formed by the method of the present invention into materials that exhibit tensile strengths in excess of 80 ksi and rolling contact endurance limits greater than 225 ksi after heat treatment. As used herein, the rolling contact endurance limit is the greatest cyclic load able to be withstood by a part without failure for 20 million rolling contact cycles.

With regard to providing the several cam lobes, the method shown in FIG. 3 includes the steps of providing the desired metallurgical powder, providing a mold in the desired cam lobe profile, placing the metallurgical powder into the mold, and then compacting, sintering, and optionally, sizing or coining the metallurgical powder to provide a near-net shape cam lobe. Other camshaft components that are to be affixed on the outer surface of the camshaft tube may be fabricated by a similar powder metal technique to provide components with desired properties. Although it is preferred that the cam lobes and other components that are to be affixed to the camshaft tube are fabricated by powder metal techniques, it will be understood that any suitable alternate fabrication technique known in the art may be used. Such alternate techniques include, for example, casting, forging and machining.

A more specific example of a process for fabricating cam lobes that may be used in the method of the invention is as follows. A metallurgical powder having a composition within the preferred compositional range set out above is compacted in a cam lobe mold at a pressure greater than 25 tons per square inch (tsi). The green compact is then sintered at a temperature greater than 3000°F. A further dimensional accuracy or density is desired, the sintered compact may be repressed or sized at a pressure greater than 30 tsi. Experience has shown that applying such press, sinter, and repress conditions to powders within the above-described preferred compositional ranges yields a cam lobe having a density of between 6.8 to 7.4 grams/cc. A more specific example of a possible press, sinter, and repress technique that may be used to produce the cam lobes and other components is the method described in U.S. Pat. No. 5,613,180. Powder metal material produced to the method of the present invention shown in FIG. 7, which is a plot of rolling contact fatigue properties is illustrated in FIG. 7, which is a plot of rolling contact endurance limit versus density. The curve was generated using data from powder metal materials produced by several known powder metal fabrication techniques. HFA material, for example, is indicated on the graph to have relatively high density and, consequently, typically has a relatively high endurance limit, in excess of 225 ksi.

After the camshaft tube and the cam lobes and other components to be affixed to the camshaft tube have been provided, the camshaft is assembled. In the embodiment of the method of the present invention shown in FIG. 3, each cam lobe and other component to be mounted on the outer surface of the camshaft tube includes an aperture. The aperture of each cam lobe and other components is sized such that the camshaft tube may be disposed through the aperture and the component properly positioned thereon only if the component has first been heated to a temperature above a predetermined temperature. During the assembly process, the camshaft tube remains at or near ambient temperature. When heated above the predetermined temperature, the aperture through the particular component expands to a size that will allow the camshaft tube to be disposed therethrough. Once properly axially and angularly positioned, the heated component is then cooled, the com-
ponent's aperture shrinks and forcefully contacts the camshaft tube's outer surface, and the component is thereby secured in the selected position. In that way, one or more cam lobes and/or other component is affixed about the camshaft tube by a shrink fit.

As further indicated in FIG. 3, each cam lobe and other component is first heated to a temperature necessary to expand the apertures therethrough so that the camshaft tube may be disposed through the apertures and the components positioned at desired axial positions and angular orientations about the camshaft tube. Cam lobes fabricated from metalurgical powders by one of the techniques described immediately above typically must be heated to above 500° F. Of course, the temperature above which a particular component must be heated may be readily determined by actual testing in advance of assembling the camshaft. Above the predetermined temperature, the aperture of the cam lobe or other component may be positioned about the camshaft tube and precisely axially positioned and angularly oriented. The cam lobe is then cooled. The cooling step shrinks the aperture, providing a shrink fit with the external surface of the camshaft tube. The cooling may be accomplished by, for example, spraying liquid nitrogen or liquid carbon dioxide in the inner diameter of the camshaft tube, if hollow, to indirectly cool the components affixed thereto. Cooling also may be accomplished by directly spraying the above-mentioned liquids, or by directing a cooled gaseous stream or a cooled air and water spray, onto the surface of the heated cam lobe or other component. It will be understood that any other suitable method of cooling that will cause the components' apertures to shrink may be used.

The several cam lobes and other components may be individually affixed about the camshaft tube by the above shrink fit technique in precise axial positions and angular orientations. In an alternate technique for assembling the camshaft components, the cam lobes and other components may be secured in jigs located at precise relative positions and so that the apertures in the several components are coaxially aligned. The components are then heated by electrical induction or another technique to a temperature at which their apertures have suitably expanded to receive the camshaft tube. The camshaft tube is then disposed through the aligned apertures to a precise position relative to the several heated components, and the components are then cooled to shrink fit the components about the outer surface of the camshaft tube. Other shrink fit assembly sequences will be apparent to one of ordinary skill upon considering the present description of the invention, and all such sequences are intended to be encompassed by the appended claims.

Other techniques for affixing cam lobes and other camshaft components to the camshaft tube may be used in place of the above-described shrink fit technique. For example, the components may be welded or otherwise fused or bonded to the outer surface of the camshaft tube. In such cases, the cam lobes need not be formed with an aperture for the camshaft tube. The camshaft tube's outer surface, and the component is thereby affixed about the camshaft tube and precisely axially positioned and angularly oriented. The cam lobe is then cooled. The cooling step shrinks the aperture, providing a shrink fit with the external surface of the camshaft tube. The cooling may be accomplished by, for example, spraying liquid nitrogen or liquid carbon dioxide in the inner diameter of the camshaft tube, if hollow, to indirectly cool the components affixed thereto. Cooling also may be accomplished by directly spraying the above-mentioned liquids, or by directing a cooled gaseous stream or a cooled air and water spray, onto the surface of the heated cam lobe or other component. It will be understood that any other suitable method of cooling that will cause the components' apertures to shrink may be used.

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A second possible roller burnishing technique designed by the present inventor for use in the method of the present invention is shown in FIG. 5. The master roller 50 is in the form of a “pattern” and has the exact profile desired for the finished cam lobe. The master roller 50 rotates about a fixed axis 51 and directs a primary roller 52. Through a follower arrangement 53 mounted to a hydraulic cylinder 54, the movement of the primary roller 52 caused by rotation of the master roller 50 directs the path of the secondary roller 55, which contacts the cam lobe 56 to be roller burnished. The hydraulic cylinder 54 applies pressure to the surfaces of both the master roller 50 and the cam lobe 56. Because both the master roller 50 and the cam lobe 56 are rotatably mounted about fixed rotational axes 51 and 57, respectively, the follower arrangement acts to density the surface of the rotating cam lobe 56 to the profile of the master roller 50. As with the apparatus of FIG. 4, several master roller/primary roller/follower arrangements may be provided to match the arrangement of cam lobes along the assembled camshaft. In that way, only a single rolling operation need be carried out on each assembled camshaft to adjust the tolerances of the cam lobes. The apparatus also may be adapted to simultaneously adjust the tolerances of other components affixed to the outer surface of the camshaft tube. To the inventor’s knowledge, a roller burnishing machine adapted to receive an assembled camshaft and to roller burnish, either individually or simultaneously, the cam lobes and other components affixed to the camshaft tube is heretofore unknown.

FIG. 6 depicts a third possible adaptation of roller burnishing, conceived by the present inventor, and which does not incorporate a master roller. The movement of the roller 61 is directed by computer numerical control to move in a precise pattern in the directions indicated by the double-headed arrow to appropriately shape the surface of the cam lobe 62. A series of rollers 61 may be provided, programmed for movement as necessary, to allow roller burnishing of all of the cam lobes and other components of a fully assembled camshaft in one operation.

Again referring to FIG. 3, following the roller burnishing or other densification step, the cam lobes and other components may be surface heat treated to increase the fatigue strength and wear resistance of their outer surfaces. The heat treating procedure typically involves heating the surface of the components by electromagnetic induction or flame heating to a temperature of 1400–1800°F. The heated components are then quenched in, for example, an oil or polymer quenching medium. Oil quenching typically provides less distortion and a smaller tendency toward cracking after surface quenching than polymer quenching and is, therefore, preferred. If a sinterhard powder is used to form the cam lobes, the cooling rate necessary on quenching can be substantially reduced, from an oil quench cooling rate of about 1000°F/min. down to 200°F/min. or less. The lower cooling rate would result in far less distortion and tendency to crack. The quenched parts may then be tempered to relieve stresses within the material. Preferably, the heat treatment increases the hardness of the cam lobes and other heat treated components affixed to the camshaft tube to the RC 30–60 range to enhance the wear resistance of the components.

As evidence of the advantageous fatigue and wear resistance expected of camshafts produced according to the present method, powder metal materials were prepared and tested in the following examples.

**EXAMPLE 1**

Powder mixes 1–4 were prepared by blending metal powders, powdered graphite, and lubricant as follows:

<table>
<thead>
<tr>
<th>Powder Mix</th>
<th>Ni</th>
<th>Mo</th>
<th>Cr</th>
<th>Cu</th>
<th>C</th>
<th>Endurance Limit (ksi)</th>
<th>Hardness (RC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>1.0</td>
<td>0.03</td>
<td>3</td>
<td>0.5</td>
<td>264</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>0.07</td>
<td>0.9</td>
<td>0.3</td>
<td>3</td>
<td>0.5</td>
<td>256</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>0.55</td>
<td>347</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>1.8</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>288</td>
<td>33</td>
</tr>
</tbody>
</table>

Thus, the final parts exhibited hardnesses in the RC 30–RC 60 range and endurance limits well in excess of 225
ksi after the heat treatment. Such material would be particularly suited for use as cam lobes, which are subjected to large cyclic stresses and heavy loads over prolonged periods. When using the material to produce camshaft cam lobes, near net shape cam lobes would be separately produced but not subjected to the final heat treatment (quench and temper) steps until the cam lobes were affixed to the camshaft tube in proper axial positions and angular orientations using a shrink fitting technique or another suitable affixation technique.

**EXAMPLE 2**

A powder mix was prepared by blending 98.5 weight % Hoeganaes 4600V alloy powder (1.8% nickel-0.6% molybdenum-balance iron); 1.0 weight % Pyron 2600 copper powder; 0.5 weight % Southwest Graphite 1642 graphite powder; and 0.65 weight % Lanza Atomized Acrawax. Three samples of the powder mix were separately compacted at 50 tsi, then sintered at 2050°F in an N₂-3% H₂ atmosphere for about 30 minutes in a belt sintering furnace. The sintered specimens each included an aperture therethrough and were assembled about the outer surface of individual solid shafts of about 0.250 inch in diameter using a press fitting technique. The assembled specimens were mounted onto a lathe used for roller burnishing by retracting the expandable arbor of the lathe and then installing one of the 0.250 inch diameter shafts in its place. Thus, the shafts replaced the arbor during roller burnishing and simulated the installation of a cam lobe/cam shaft tube assembly on a roller burnishing machine which, as proposed herein, is specifically adapted to receive an assembled camshaft.

Once installed on the lathe, the surface of the power metal part affixed to the shaft was roller burnished to achieve desired tolerances. The parts were then induction hardened by re-heating to 1400–1600°F for 0.5–30 seconds and then quenching in oil, followed by a 300°F temper. The heat treated parts exhibited hardnesses of RC 33-36. During rolling contact fatigue testing, the shafts served to locate and adjust at least one of the shape and the dimensions of the cam lobe.

It is to be understood that the present description illustrates those aspects of the invention relevant to a clear understanding of the invention. Certain aspects of the invention that would be apparent to those of ordinary skill in the art and that, therefore, would not facilitate a better understanding of the invention have not been presented in order to simplify the present description. Although the present invention has been described in connection with certain embodiments, those of ordinary skill in the art will, upon considering the foregoing description, recognize that many modifications and variations of the invention may be employed. All such variations and modifications of the invention are intended to be covered by the foregoing description and the following claims.

<table>
<thead>
<tr>
<th>Part</th>
<th>Time to Failure</th>
<th>Endurance limit (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 hr. 22 min.</td>
<td>288</td>
</tr>
<tr>
<td>2</td>
<td>10 hr. 57 min.</td>
<td>364</td>
</tr>
<tr>
<td>3</td>
<td>11 hr. 57 min.</td>
<td>368</td>
</tr>
</tbody>
</table>

We claim:

1. A method of providing a camshaft, the method comprising:
   - providing a camshaft tube having an outer surface;
   - providing a cam lobe having an aperture therethrough sized to be received about the outer surface of the camshaft tube when said cam lobe is at a temperature greater than a predetermined temperature;
   - heating the cam lobe to a temperature greater than the predetermined temperature;
   - positioning the camshaft tube and the cam lobe so that the camshaft tube is disposed through the aperture of the cam lobe and the cam lobe is at a predetermined position and angular orientation relative to the camshaft tube;
   - cooling the cam lobe to a temperature below the predetermined temperature to affix the cam lobe to the outer surface of the camshaft tube at the predetermined position and angular orientation;
   - increasing the density of at least a region of the cam lobe to adjust at least one of the shape and the dimensions of the cam lobe.

2. The method of claim 1 wherein increasing the density of at least a region of the cam lobe comprises mechanically working at least a region of the surface of the cam lobe by at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting to adjust at least one of the shape and the dimensions of the cam lobe.

3. The method of claim 1 wherein providing the cam lobe comprises:
   - placing a metallurgical powder into a void of a mold;
   - consolidating the metallurgical powder within the mold to form a compact;
   - sintering the compact; and
   - compressing the sintered compact.

4. The method of claim 3 wherein compressing the sintered compact comprises coining the sintered compact.

5. The method of claim 4 wherein sintering the compact comprises heating the compact to a temperature of at least 2000°F.

6. The method of claim 1 wherein the predetermined temperature is greater than 500°F.

7. The method of claim 3 wherein consolidating the metallurgical powder comprises applying pressure greater than 25 ksi to the metallurgical powder.

8. The method of claim 3 wherein sintering the compact comprises heating the compact at 2000 to 2350°C.

9. The method of claim 3 wherein compressing the sintered compact comprises applying pressure greater than 30 tsi to the sintered compact.

10. The method of claim 3 wherein the metallurgical powder comprises, in weight percent based on the total weight of the powder, 90 to 99.7% iron, 0 to 2.0% nickel, 0 to 1.0% molybdenum, 0.3 to 2.0% carbon, 0 to 3.0% copper, and 0 to 3.0% chromium.

11. The method of claim 3 wherein the hardness of the compact after sintering the compact but before compressing the compact is less than RC 20.

12. The method of claim 1 wherein the cam lobe has a density of 6.8 to 7.6 g/cc.

13. The method of claim 1 wherein increasing the density of at least a region of the cam lobe comprises compressing at least a region of a surface of the cam lobe greater than 0.002 inch.

14. The method of claim 1 wherein increasing the density of at least a region of the cam lobe comprises compressing...
The method of claim 1 further comprising:

- At least a region of the surface of the cam lobe greater than 0.002 to less than 0.01 inch.
- Adjusting at least one of the shape and the dimensions of the camshaft tube by grinding at least a region of the outer surface of the camshaft tube.
- Wherein heating at least a region of the outer surface of the camshaft tube comprises centerless grinding at least a region of the outer surface of the camshaft tube.

The method of claim 15 wherein heating at least a region of the outer surface of the camshaft tube comprises centerless grinding at least a region of the outer surface of the camshaft tube.

The method of claim 17 wherein heating at least a region of the outer surface of the camshaft tube comprises centerless grinding at least a region of the outer surface of the camshaft tube.

The method of claim 1 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 21 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 25 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 29 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 33 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 37 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 39 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 41 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.

The method of claim 43 wherein heating at least a region of the outer surface of the camshaft tube comprises shrinking at least a region of the outer surface of the camshaft tube.
induction heating the camshaft tube and the cam lobe to 1400 to 1800° C.; and
quenching the camshaft tube and the cam lobe in at least one of an oil and a polymer.

42. A method of providing a camshaft, the method comprising:
providing a camshaft comprising a camshaft tube and a cam lobe securely affixed to the camshaft tube; and
subsequent to providing the camshaft, increasing the density of at least a region of the cam lobe to adjust at least one of the shape and the dimensions of the cam lobe.

43. The method of claim 42 wherein increasing the density of at least a region of the cam lobe comprises mechanically working the cam lobe.

44. The method of claim 43 wherein mechanically working the cam lobe comprises at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting.

45. The method of claim 42 wherein increasing the density of at least a region of the cam lobe comprises compressing at least a region of the surface of the cam lobe greater than 0.002 inch.

46. The method of claim 42 wherein increasing the density of at least a region of the cam lobe comprises compressing at least a region of the surface of the cam lobe greater than 0.002 to less than 0.01 inch.

47. The method of claim 42 further comprising:
heat treating the cam lobe to increase the hardness of at least a region of the surface of the cam lobe.

48. The method of claim 47 wherein the hardness of at least a region of the surface of the cam lobe is in the range of RC 50 to RC 60 after heat treating the cam lobe.

49. The method of claim 47 wherein heat treating the cam lobe comprises:
induction heating the cam lobe to 1400 to 1800° C.; and
quenching the cam lobe in at least one of an oil and a polymer.

50. A method of making a camshaft, the method comprising:
providing a camshaft tube having an outer surface;
providing a cam lobe having an aperture therethrough securely affixing the cam lobe to the camshaft by heating the cam lobe to a temperature at which the camshaft tube may be disposed through the aperture, positioning the camshaft tube through the aperture and positioning the cam lobe at a desired position and angular orientation on the camshaft tube, and cooling the cam lobe to shrink the aperture and securely affix the cam lobe to the outer surface of the camshaft tube at the predetermined position and angular orientation; and
subsequent to securely affixing the cam lobe to the camshaft, increasing the density of at least a region of the cam lobe to adjust at least one of the shape and the dimensions of the cam lobe.

51. The method of claim 50 wherein increasing the density of at least a region of the cam lobe comprises mechanically working at least a region of a surface of the cam lobe.

52. The method of claim 51 wherein mechanically working at least a region of a surface of the cam lobe comprises using at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting.

53. The method of claim 50 wherein the a temperature at which the camshaft tube may be disposed through the aperture is greater than 500° C.

54. A method of making a camshaft, the method comprising:
securely affixing a cam lobe to an outer surface of a shaft; and
subsequent to securely affixing the cam lobe to the shaft, altering at least one of the shape and the dimensions of the cam lobe by increasing the density of at least a portion of the cam lobe.

55. The method of claim 54 wherein increasing the density of at least a portion of the cam lobe comprises mechanically working the cam lobe.

56. The method of claim 55 wherein mechanically working at least a portion of the cam lobe comprises at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting.

57. The method of claim 54 wherein the shaft is hollow.

58. The method of claim 54 wherein affixing the cam lobe to the shaft comprises at least one technique selected from mechanically connecting the cam lobe to the shaft, fusing the cam lobe to the shaft, sintering the cam lobe to the shaft, and shrink fitting the cam lobe to the shaft.

59. A method of making a camshaft, the method comprising:
providing a camshaft including at least one cam lobe securely affixed to an outer surface of a shaft; and
subsequent to providing the camshaft, altering at least one of the shape and the dimensions of the cam lobe by increasing the density of at least a portion of the cam lobe.

60. The method of claim 59 wherein increasing the density of at least a portion of the cam lobe comprises mechanically working the cam lobe.

61. The method of claim 59 wherein mechanically working at least a portion of the cam lobe comprises at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting.

62. The method of claim 59 wherein the shaft is hollow.

63. The method of claim 59 wherein affixing the cam lobe to the shaft comprises at least one technique selected from mechanically connecting the cam lobe to the shaft, fusing the cam lobe to the shaft, sintering the cam lobe to the shaft, and shrink fitting the cam lobe to the shaft.

64. A method of adjusting at least one of the shape and the dimensions of a camshaft, wherein the camshaft includes at least one cam lobe securely affixed to an outer surface of a shaft, the method comprising:
altering at least one of the shape and the dimensions of the cam lobe by increasing the density of at least a portion of the cam lobe.

65. The method of claim 64 wherein increasing the density of at least a portion of the cam lobe comprises mechanically working the cam lobe.

66. The method of claim 64 wherein mechanically working at least a portion of the cam lobe comprises at least one technique selected from roller burnishing, sizing, coining, shot peening, and laser impacting.

67. The method of claim 64 wherein the shaft is hollow.

68. The method of claim 64 wherein affixing the cam lobe to the shaft comprises at least one technique selected from mechanically connecting the cam lobe to the shaft, fusing the cam lobe to the shaft, sintering the cam lobe to the shaft, and shrink fitting the cam lobe to the shaft.