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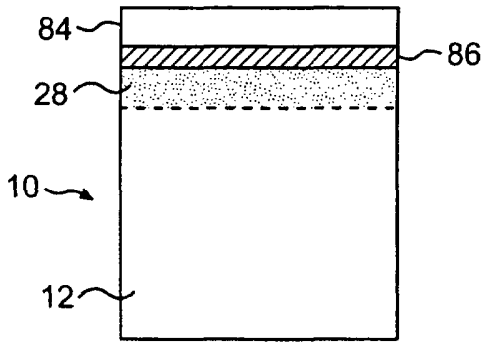
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(54) **Title:** COMPOSITION AND PROCESS FOR ENHANCED PROPERTIES OF FERROUS COMPONENTS



(57) **Abstract:** Components, such as gears and other transmission components, are formed by near-net-forging a high strength, high toughness ferrous metal alloy, surface processing metal alloy to form a hardened surface region, and coating the surface region with a lubricious coating.

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COMPOSITION AND PROCESS FOR ENHANCED PROPERTIES OF FERROUS COMPONENTS

BACKGROUND OF THE INVENTION

The present invention relates generally to the combination of near-net-shape (NNS) forging, a class of high-strength, high-toughness (HSHT) ferrous alloys, and the application of thermo-chemical processing to enhance the surface properties of the alloy class forgings. More particularly, the invention relates to applying the NNS forging, alloy selection, and thermo-chemical processing to gears and other components within power transmission systems.

Conventional methods for producing, for example, gears involve many sequential processing steps. Typically, a forged billet stock is hobbed to a rough, oversized finish shape and thermo-chemically processed by, for example, carburization, then slow cooled. This is followed by steps of re-austenitization, quenching, refrigerating by cryogenic treatment, tempering (aging), finish grinding, etch inspection, shot-peening, honing, and final inspection. These methods lead to extended manufacturing process time and increased costs.

Conventional hobbing of ferrous alloy blanks produces gear teeth shapes by cutting through any peripheral structural texture, or preferred grain orientation, that may be present in the blank from any prior forming operations, thereby reducing performance benefits that can accrue from the forming operations.

Alloys used for gear applications need, for example, the ability to withstand shear strain, bending fatigue loads, and surface degradation via pitting and contact wear. Conventional gear alloys are still limited in the strength and toughness required for very high performance applications.

Surface engineering processes, including thermo-chemical treatments, are typically required to improve the performance of conventional alloys. For iron-based metal alloy components, such as power-transmission components, it is often desirable to form a hardened

surface case around the core of the component to enhance component performance. The hardened or chemically altered surface case provides wear and corrosion resistance, while the core provides toughness, impact resistance, and bending-fatigue strength.

There are various conventional methods for forming a hardened surface case on a power-transmission component fabricated from a steel alloy, while retaining the original hardness, strength, and toughness characteristics of the alloy. Conventional methods used to achieve the properties include carburizing and nitriding; alternatively, novel, unconventional thermo-chemical processes, such as high current density ion implantation, may be applied to achieve or retain desired case and core properties.

The methods for forming a hardened surface case on gears, for example, also involve many sequential processing steps that increase manufacturing time and cost.

Thus, there remains a need for reducing the time and costs for manufacturing gears, improving the properties and performance attributes compared to cut gears, and identifying a class of alloys having improved strength and toughness that are suitable for the application of the thermo-chemical treatments.

SUMMARY OF THE INVENTION

The disadvantages and limitations of the background art discussed above are overcome by the present invention. With this invention, the near-net-shape forging process, producing a gear, for example, eliminates the need for hobbing the gear and augments the mechanical properties, which are further improved by the use of a class of HSHT ferrous alloys possessing improved high-strength and high-toughness. The alloy class has surface properties that may be enhanced through thermo-chemical surface processing via methods that also reduce manufacturing time and costs, and the surface roughness of as-processed articles may be isotropically superfinished via chemo-mechanical means to further enhance the surface properties, including pitting fatigue and wear resistance.

An embodiment of the invention is a method whereby a billet of alloy is near-net-shaped forged to the finished gear shape, but with a small stock allowance for any subsequent heat treatment and thermo-chemical surface processing prior to finish machining and superfinishing.

Another embodiment of the invention is a method wherein the gear alloy is a selected from a class of high-strength, high-toughness alloys.

Another embodiment of the invention is a method wherein the near-net-shape forged high-strength, high-toughness alloys are heat treated and thermo-chemically processed, such as to synergistically combine selected surface engineering and bulk alloy heat treatment steps, thereby effecting significant savings in processing times, cost, and delivery, while retaining the desired increase in performance capability.

Another embodiment of the invention is a method wherein the near-net-shape forging comprising the high-strength, high-toughness alloys that are heat treated and thermo-chemically processed to synergistically combine selected surface engineering and bulk alloy heat treatment steps, are further afforded a subsequent chemo-mechanical processing step to reduce the surface roughness and further enhance the resulting surface properties, while retaining the desired increase in bulk and surface performance capabilities.

It may therefore be seen that the present invention teaches the combination of near-net-shape (NNS) forging, a class of high-strength, high-toughness (HSHT) ferrous alloys and the application of thermo-chemical processing to enhance the surface properties of the alloy class forgings.

The combination comprises a novel approach to the improvement of component or system properties, for example, to enhance the bending- and surface-fatigue design allowables for gears and other components within power-transmission systems.

DESCRIPTION OF THE DRAWINGS

Figure 1 shows a schematic view of a metal alloy.

Figure 2 shows a schematic view of a crystal structure.

Figure 3 shows a schematic view of a metal alloy during surface processing.

Figure 4 shows a schematic view of a metal alloy and hardened surface region.

Figure 5 shows a schematic view of a plasma (ion) nitriding chamber.

Figure 6 shows a nitrogen concentration profile over a depth of a hardened surface region.

Figure 7 shows a schematic view of a nitride compound on a surface region of a metal alloy.

Figure 8 shows a schematic view of a coating on a hardened surface region of a metal alloy.

Figure 9 shows a schematic view of a coating on an intermediate coating on a surface region of a metal alloy.

DETAILED DESCRIPTION

Figure 1 shows a schematic view of a metal alloy 10, including a core 12 and a surface region 14 on the core 12. The metal alloy 10 is an iron-based alloy that is generally nitrogen-free and has an associated composition and hardening heat treatment, including a tempering or aging temperature. The tempering or aging temperature is dependent on the metal alloy 10 composition and is the temperature at which the metal alloy is heat processed to alter characteristics of the metal alloy 10, such as hardness, strength, and toughness.

The composition of the metal alloy 10 is essentially a Ni-Co secondary hardening martensitic steel, which provides high strength and high toughness. That is, the ultimate tensile strength of the metal alloy 10 is greater than about 170 ksi and the yield stress is greater than about 140 ksi and in some examples the ultimate tensile strength is approximately 285 ksi and the yield stress is about 250 ksi. High strength and high toughness provide desirable performance in such applications as power transmission components. Conventional vacuum melting and remelting practices are used and may include the use of gettering elements including, for example, rare earth metals, Mg, Ca, Si, Mn and combinations thereof, to remove impurity elements from the metal alloy 10 and achieve high strength and high toughness. Impurity elements such as S, P, O, and N present in trace amounts may detract from the strength and toughness.

Preferably, the alloy content of the metal alloy 10 and the tempering (aging) temperature satisfy the thermodynamic condition that the alloy carbide, M_2C where M is a metallic carbide-forming element, is more stable than Fe_3C (a relatively coarse precursor carbide), such that Fe_3C will dissolve and M_2C alloy carbides precipitate. The M_2C alloy carbide-forming elements contribute to the high strength and high toughness of the metal alloy 10 by forming a fine dispersion of M_2C precipitates that produce secondary hardening during a conventional precipitation-heat process prior to any surface processing. The preferred alloy carbide-forming elements include Mo and Cr, which combine with

carbon in the metal alloy 10 to form M_2C. Preferably, the metal alloy 10 includes between 1.5wt% and 15wt% Ni, between 5wt% and 30wt% Co, and up to 5wt% of a carbide-forming element, such as Mo, Cr, W, V or combinations thereof, which can react with up to approximately 0.5wt% C to form metal carbide precipitates of the form M_2C. It is to be understood that the metal alloy 10 may include any one or more of the preferred alloy carbide-forming elements.

The carbide-forming elements provide strength and toughness advantages because they form a fine dispersion of M_2C. Certain other possible alloying elements such as Al, V, W, Si, Cr, may also form other compounds such as nitride compounds. These alloying elements and the carbide-forming elements influence the strength, toughness, and surface hardenability of the metal alloy 10.

Typically, metal alloy 10 is hardened by heat treating above ~1500°F in the austenite phase region (austenitizing) to re-solution carbides, etc. It is then quenched and refrigerated at approximately – (minus) 100°F to transform the austenite structure to martensite. The latter is a very hard, brittle, metastable phase having a body-centered tetragonal (BCT) crystal structure because of the entrapped carbon atoms. Hence, at this stage, the core 12 and surface region 14 of the metal alloy 10 have a generally equivalent tetragonal crystal structure 16 (Figure 2).

As illustrated in Figure 2, the tetragonal crystal structure 16 includes atomic lattice sites 17 forming sides having length 18 which are essentially perpendicular to sides having length 20. In the tetragonal crystal structure 16, the length 18 does not equal the length 20. Subsequent aging heat treatments are used to both soften the martensite structure and also transform the Fe_3C phase to M_2C which strengthens the structure. The latter reaction tends to dominate, leading to secondary hardening. These reactions can lead to concomitant changes in crystal structure as the metastable martensitic BCT structure transitions to other phases, such as austenite and/or ferrite depending on the exposure temperature and time. It is to be understood that the iron-based alloy

may be formed instead with other crystal structures such as, but not limited to, face-centered cubic (e.g. austenite) and body-centered cubic (e.g. ferrite). These phase transitions may lead to dimensional changes.

Figure 3 shows a schematic cross-sectional view of the metal alloy 10 during transformation of the surface region 14 into a hardened surface region 28 as illustrated in Figure 4. A high current density ion implantation (high intensity plasma ion processing) nitriding process is used to form the hardened surface region, although other surface hardening processes may be utilized such as, but not limited to, nitrocarburizing, carburizing, boronizing, and chromizing.

The high current density ion implantation (high intensity plasma ion processing) nitriding process is conducted in an appropriate reactor, an example of which is illustrated schematically in Figure 5. The metal alloy 10 is placed in the reactor 34. The metal alloy 10 is placed in the high current density ion implantation (high intensity plasma ion processing) chamber 36 on a cathode 38. The cathode 38 provides a voltage bias to the metal alloy 10, thereby heating the metal alloy 10 to a desired temperature that is below the heat treating temperature, such as an aging or tempering temperature, of the metal alloy 10.

Heating the metal alloy 10 to a temperature above the heat treating temperature may alter the incumbent crystal structure 16, relieve residual stresses in the metal alloy 10, otherwise undesirably alter the microstructure and properties of the core, and undesirably alter the dimensions of the metal alloy 10. By utilizing a temperature that is typically below the heat treating temperature of the metal alloy 10, the strength, toughness, incumbent crystal structure 16, and dimensions of the metal alloy 10 are maintained through the high current density ion implantation (high intensity plasma ion processing) nitriding process. Subsequent processes to dimensionalize the metal alloy 10 or a power transmission component formed from the metal alloy 10 are eliminated. For the preferred metal alloy 10 composition the heat treating temperature is between 700°F and about 1000°F. For other compositions, the heat treating temperature may be different.

The chamber 36 includes a vacuum pump 40 which maintains a vacuum in the chamber 36 of the reactor 34. A sample bias device 42 provides a bias voltage of between 100V and 1500V to the cathode 38. Preferably, the bias voltage is between 150V and 700V. A thermocouple 44 attached to the cathode 38 detects the cathode 38 temperature and a cooling system 46 provides cooling capability to control the chamber 36 temperature. The chamber 36 is in fluid communication with precursor gases in storage tanks 48. The precursor gas storage tanks 48 may include gases such as nitrogen, hydrogen, and methane, although it should be noted that these gases are not all necessarily utilized during the high current density ion implantation (high intensity plasma ion processing) nitriding process. The conduit 50 connects the precursor gas storage tanks 48 to the inner chamber 40 and includes a gas metering device 52 to control the gas flow from the gas storage tanks 48. A plasma discharge voltage device at the filament 54 provides an ionizing voltage to a filament 56, which ionizes incoming gas from the conduit 50. The plasma discharge voltage at the filament is preferably between 30V and 150V and even more preferably is about 100V. It is to be understood that the configuration of the reactor 34 is not meant to be limiting and that alternative configurations of high current density ion implantation (high intensity plasma ion processing) reactors as well as reactors utilizing alternative surface processing processes may be used.

The temperature, vacuum pressure in the chamber 36, precursor gas flow and ratio, time of processing, filament bias voltage, and sample bias voltage are controlled during the high current density ion implantation (high intensity plasma ion processing) nitriding process to provide a hardened surface region 28 (Figure 4) on the metal alloy 10. The preferred conditions include a temperature between 700°F and about 1000°F, a pressure between about 0.5 mtorr and 5.0 mtorr in the chamber 36, a precursor gases mixture of nitrogen and hydrogen in the range 10 to 100% nitrogen and a preferred range of 80 to 100% nitrogen, and a time in the range of about 5 to 200 hours and a preferred range of 10 to 100 hours. Even more preferably, the conditions are controlled to a

temperature of about 800°F to about 875 °F, a pressure of 0.75 mtorr in the chamber 36 (Figure 5) and for a time of about twelve hours depending on the case depth required.

Under the preferred conditions, nitrogen from the nitrogen atmosphere 26 (Figure 3) in the chamber 36 diffuses into the surface region 14 of the metal alloy 10. The nitrogen interstitially diffuses into the surface region 14, thereby hardening the surface region 14 and transforming the surface region 14 into the hardened surface region 28. During this process, ions from the chamber 36 also bombard the surface region 14 without diffusing into the surface region 14. That is, the ions sputter the surface region 14 and thereby remove oxides and other impurities that may be present on the surface region 14. Additionally, the bias voltages utilized for the sample bias and filament voltage may provide the benefit of more favorable processing kinetics compared to other nitriding processes that utilize lower operating voltages, such as plasma (ion) nitriding.

Preferably, the hardened surface region 28 has a gradual transition in nitrogen concentration over a depth D between an outer surface 30 of the hardened surface region 28 and an inner portion 32 of the hardened surface region 28.

The line 62 in Figure 6 illustrates a gradual nitrogen concentration profile over the depth D. By comparison, the line 64 represents the nitrogen concentration profile of a generally abrupt nitrogen concentration. For the line 62, at a shallow depth into the hardened surface region 28 such as near the outer surface 30, the nitrogen concentration is relatively high compared to the nitrogen concentration in the core 12. At a deeper depth, such as near the inner portion 32, the nitrogen concentration is relatively low and approaches the nitrogen concentration of the core 12. It is to be understood that a variety of nitrogen concentration profiles may result from varying the preferred conditions.

Figure 7 shows a schematic view of a metal alloy 10 after another high current density ion implantation (high intensity plasma ion

processing) nitriding process. Utilizing a temperature towards the ends of the preferred range of 700°F and about 1000°F or utilizing an additional gas such as methane may result in the formation of a compound 68 of iron and nitrogen, such as the γ' or ε compounds, on the surface region 14. Formation of the compound 68 is generally not preferred if a coating will be subsequently deposited over the compound 68, however, the compound 68 may provide corrosion resistance for the metal alloy 10.

Additionally, alloying elements such as Al, V, W, Si, and Cr may be present in the metal alloy 10. Nitride compounds containing the alloying elements may form during the high current density ion implantation (high intensity plasma ion processing) nitriding process. The presence of the nitride compounds is generally detrimental to the mechanical properties of the metal alloy 10 and are particularly detrimental in a complex with iron nitride compounds that may be formed under certain nitriding processing conditions; however, the presence of these alloying elements may be required to acquire other characteristics in the metal alloy 10.

Figure 9 shows a schematic view of a metal alloy 10 after a high current density ion implantation (high intensity plasma ion processing) nitriding process. The metal alloy 10 includes a coating 84 on the hardened surface region 28, which preferably has a gradual nitrogen concentration profile and essentially does not include an iron and nitrogen compound, such as the γ' or ε compounds. The coating 84 is deposited on the hardened surface region 28 in a thickness between 0.5 micrometers and 10 micrometers by a vapor deposition or magnetron sputtering process, although other thicknesses may be desirable. Known chemical vapor deposition, physical vapor deposition, and plasma-assisted chemical vapor deposition are preferred vapor deposition processes; however, it is to be understood that other or hybrid deposition processes may be utilized.

The deposited coating 84 is a solid lubricious coating such as an amorphous hydrogenated carbon, although other coatings may be used. The amorphous hydrogenated carbon coating has a biaxial residual stress less than 800 MPa in compression at room temperature, is

thermally stable at temperatures over 400°F, and has an abrasive wear rate less than $3x10^{-15}$ $m^3m^{-1}N^{-1}$ in a slurry of Al_2O_3. The amorphous hydrogenated carbon coating may include a metal or transition metal such as titanium, chromium, tungsten or other transition metal to alter the lubricious characteristics of the coating 84. It should be noted that the above description represents a non-limiting example of the many types of a solid lubricious coating that may be applied to the surface of an alloy or component to improve certain performance characteristics.

Referring to Figure 9, an intermediate coating 86 may be deposited between the coating 84 and the hardened surface region 28 to strongly bond the coating 84 to the hardened surface region 28. The intermediate coating 86 bonds strongly to both the hardened surface region 28 and the coating 84. Preferably, the intermediate coating 86 is a metal and even more preferably it is the same transition metal as is included in the amorphous hydrogenated carbon coating. Generally, like materials, such as two metals, form stronger bonds than unlike materials, such as a metal and a non-metal. Therefore, the metal of the intermediate coating 86 strongly bonds to the metal hardened surface region 28 and to the transition metal in the amorphous hydrogenated carbon coating.

Methods for producing gears, for example, involve many sequential processing steps. Typically, a forged billet stock is hobbed to a rough, oversized finish shape and thermo-chemically processed by carburization, for example, then slow cooled. This is followed by the mandatory or optional steps of re-austenitization, quenching, refrigerating by cryogenic treatment, tempering (aging), finish grinding, etch inspection, shot-peening, honing and final inspection. The methods lead to extended manufacturing process time and increased costs.

The near-net-shape forging process, producing a gear, for example, eliminates the need for hobbing the gear. The near-net-forging process benefits mechanical properties by promoting the material flow to follow the contours of the gears. This texturing also leads to

microstructural alignment that promotes improvements in mechanical properties, including tooth bending fatigue.

When the gear material is selected from the the class of high-strength, high toughness ferrous alloys, the performance of the gear is further improved.

The alloy class has surface properties that may be enhanced through thermo-chemical surface processing via methods that also reduce manufacturing time and costs.

In addition, the performance characteristics of gears, bearings, and other components within a power-transmission system may be improved by the refinement in the roughness of the surfaces of such components through a process of superfinishing. One suitable superfinishing technique is described in U.S. Pat. No. 4,491,500, which discloses a process for refining metal surfaces in which a two-step process employing a liquid chemical is followed by a burnishing liquid. A relatively soft coating is formed, which is subsequently treated and physically removed. In the technique, a mass of elements, comprised of a quantity of objects with hard metal surfaces of arithmetic average roughness value in excess of about 15 microinches, is introduced into the container of mass finishing equipment. The mass of elements is wetted with a liquid substance capable of rapid reaction, under oxidizing conditions, to chemically convert the metal of the object surfaces to a stable film of substantially reduced hardness, and the mass is rapidly agitated, while maintaining the metal surfaces in a wetted condition with the liquid substance, to produce relative movement and abrasive contact among the elements thereof and to produce continuous oxygenation of the liquid substance. The reactivity of the liquid substance and the intensity of agitation of the mass are controlled to maintain the stable film on the metal surfaces at least at the level of visual perceptibility. Agitation is continued for a period sufficient to produce a finish of arthimetic average roughness less than about 14 microinches, and preferably less than about 10 microinches; thereafter, the objects will generally be treated to dissolve the stable film from the metal surfaces.

In the preferred embodiments of the technique, the mass of elements introduced into the mass finishing equipment will include a quantity of abrasive finishing media, and the agitation step will be carried out for a period of less than six hours. Generally, the surfaces will be of a metal selected from the group consisting of iron, copper, zinc, aluminum, titanium, and the alloys thereof, and the stable film will comprise an oxide, phosphate, oxalate, sulfate, and/or chromate of the substrate metal. Thus, the liquid substance utilized to chemically convert the metal of the object surfaces will usually be a solution containing one or more of the radicals: phosphate, oxalate, sulfate, chromate, and mixtures thereof, and in certain instances it will be preferred for the substance to additionally include an oxidizing agent; generally, the liquid substance will have an acidic pH value. Solutions containing phosphate and oxalate radicals in combination with a peroxide compound are often found to be particularly effective for refining ferrous metal surfaces, and may be produced from a tripolyphosphate salt, oxalic acid, and hydrogen peroxide.

It may therefore be appreciated from the above detailed description of the preferred embodiment of the present invention that the combination of selection of a member of the class of high-strength, high-toughness (HSHT) ferrous alloys and its processing to include near-net-shape (NNS) forging, thermo-chemical processing, a vibratory, chemo-mechanical process (chemically accelerated vibratory polishing), such as superfinishing, to enhance the surface properties of the alloy class forgings, and coating the surface;

comprises a novel approach to the improvement of component or system properties. For example, the combination enhances the bending- and surface-fatigue design allowables for gears and other components within power-transmission systems.

Accordingly, the primary advantages of the present invention include: the identification of near-net-shape forging processes that eliminate hobbing while imparting enhanced strength, including axial- and bending-fatigue strength, the use of a new class of ferrous alloys

possessing improved high-strength and high-toughness compared to conventional gear alloys, thermo-chemically processing them via conventional and/or novel means to enhance surface properties, reduction of the surface roughness of the as-thermo-chemically processed article, also to enhance surface properties and performance, and combining these elements in such a manner that the surface and bulk properties and performance are enhanced and manufacturing time and casts are reduced.

Although an exemplary embodiment of the present invention has been shown and described with reference to particular embodiments and applications thereof, it will be apparent to those having ordinary skill in the art that a number of changes, modifications, or alterations to the invention as described herein may be made, none of which depart from the spirit or scope of the present invention. All such changes, modifications, and alterations should therefore be seen as being within the scope of the present invention.

Although the foregoing description of the present invention has been shown and described with reference to particular embodiments and applications thereof, it has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the particular embodiments and applications disclosed. It will be apparent to those having ordinary skill in the art that a number of changes, modifications, variations, or alterations to the invention as described herein may be made, none of which depart from the spirit or scope of the present invention. The particular embodiments and applications were chosen and described to provide the best illustration of the principles of the invention and its practical application to thereby enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such changes, modifications, variations, and alterations should therefore be seen as being within the scope of the present invention as determined by the appended claims when

interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled.

CLAIMS

1. A method of producing a component, the method comprising:

near-net-shape forging a high strength, high toughness ferrous metal alloy to an essentially finished shape component; and

surface processing the component to form a hardened surface region.

2. The method of claim 1, wherein the componetnt is a power transmission component.

3. The method of claim 2, wherein the power transmission component is a gear.

4. The method of claim 1, wherein the surface processing comprises at least one of nitriding, nitrocarburizing, carburizing, boronizing, and chromizing.

5. The method of claim 4, wherein nitriding comprises high current density ion implantation.

6. The method of claim 1, and further comprising:

heat treating the component;

quenching the component;

refrigerating the component; and

termpering the component.

7. The method of claim 1, and further comprising:

forming a solid lubricious coating over the surface region.

8. The method of claim 7, wherein the solid lubricious coating comprises amorphous hydrogenated carbon.

9. The method of claim 8, wherein the solid lubricious coating includes a transition metal.

10. The method of claim 7, and further comprising:

forming an intermediate coating over the surface region prior to forming the solid lubricious coating.

11. The method of claim 10, wherein the intermediate coating comprises a metal.

12. The method of claim 11 wherein the solid lubricious coating comprises amorphous hydrogenated carbon the metal contained in the intermediate coating.

13. The method of claim 1, wherein the ferrous metal alloy comprises at least 5wt% cobalt, at least 1.5wt%nickel, up to 1.0wt% carbon, and up to 15wt% of molybdenum, chromium, tungsten, or vanadium and combinations thereof.

14. The method of claim 1 and further comprising:

reducing surface roughness of the component with a vibratory, chemo-mechanical process.

15. The method of claim 14, wherein the vibratory, chemo-mechanical process comprises superfinishing.

16. A method of producing a component, the method comprising:

near-net-forging a ferrous metal alloy to an essentially finished component shape;

transforming a surface region of the metal alloy to a hardened surface region; and

forming a coating over the hardened surface region.

17. The method of claim 16, wherein the metal alloy has a composition comprising at least 5wt% cobalt and at least 1.5% nickel.

18. The method of claim 16, wherein the metal alloy has a composition comprising up to 1.0wt% carbon, and up to 15wt% of molybdenum, chromium, tungsten, or vanadium and combinations thereof.

19. The method of claim 16, wherein the coating comprises an amorphous hydrogenated carbon coating.

20. The method of claim 16, and further comprising

forming an intermediate coating between the coating and the hardened surface region.

21. The method of claim 20, wherein the intermediate coating comprises a transition metal.

22. The method of claim 16 and further comprising:

reducing surface roughness with a vibratory, chemo-mechanical process, in which said vibratory, chemo-mechanical process is provided before and/or after said coating.

23. The method of claim 22, wherein the vibratory, chemo-mechanical process comprises superfinishing.

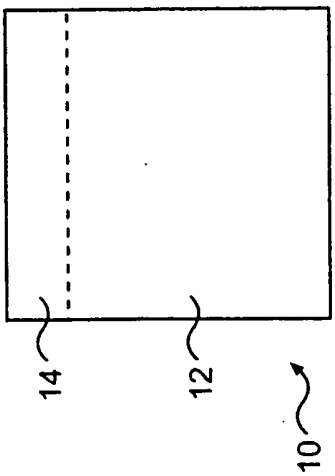


FIG. 1

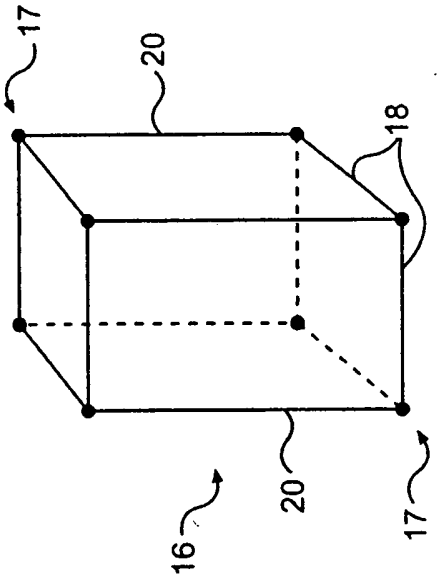


FIG. 2

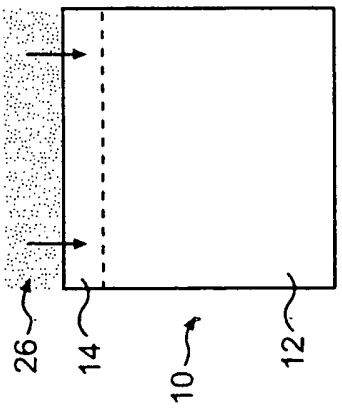


FIG. 3

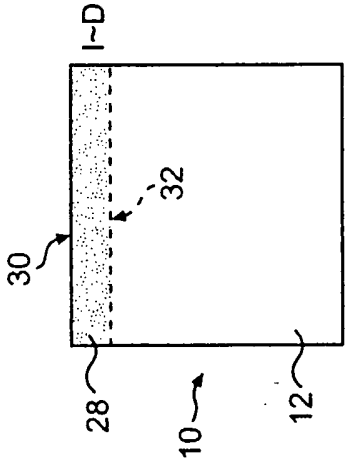


FIG. 4

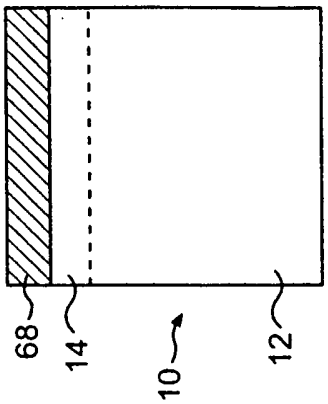


FIG. 7

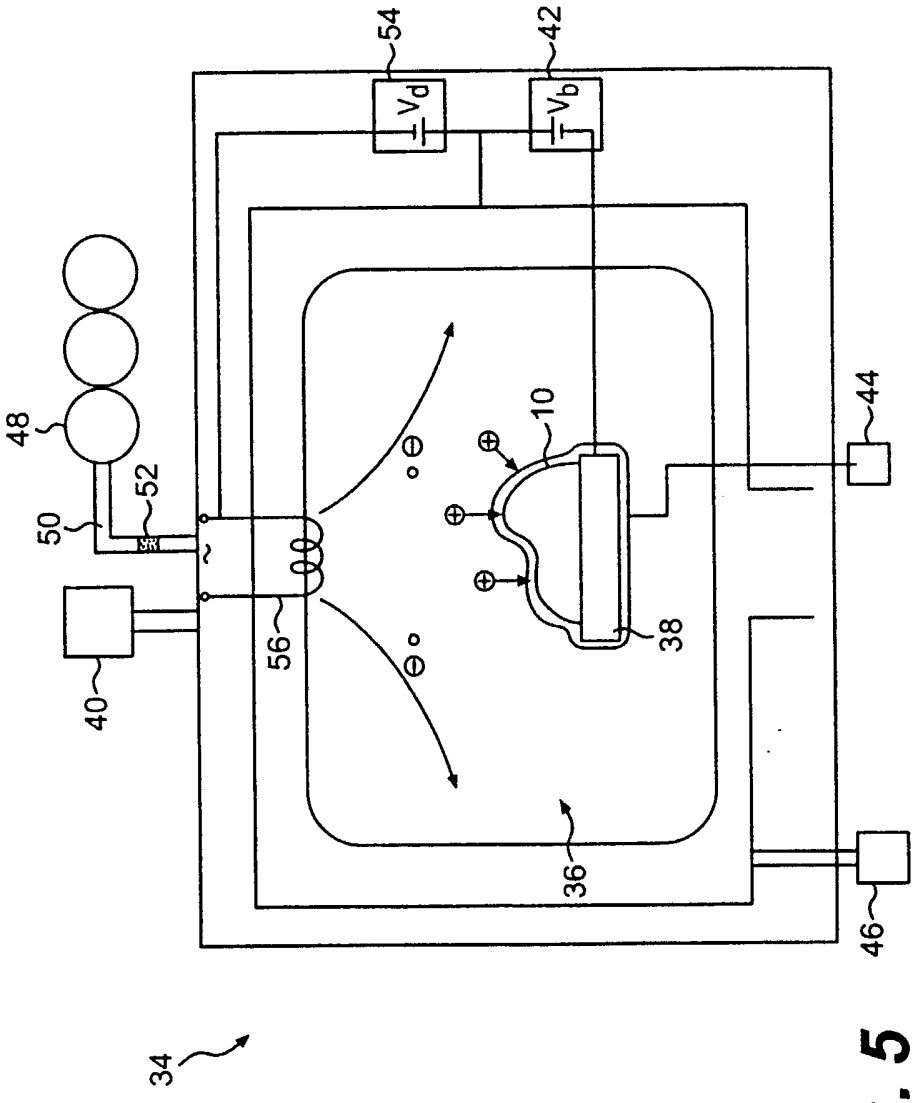


FIG. 5

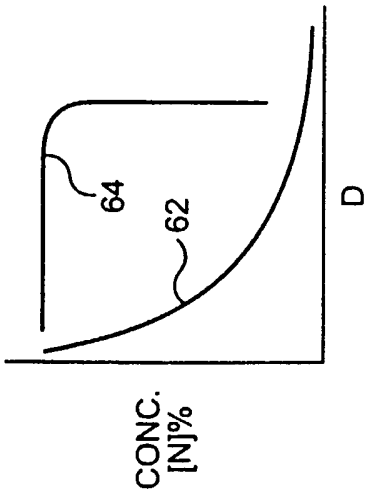


FIG. 6

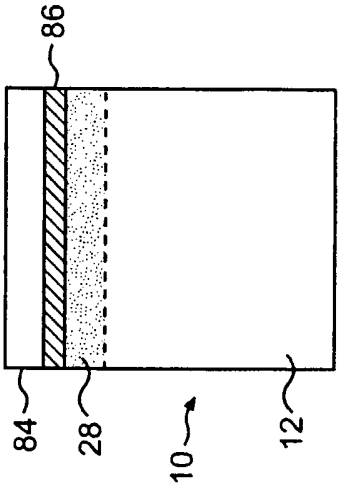


FIG. 9

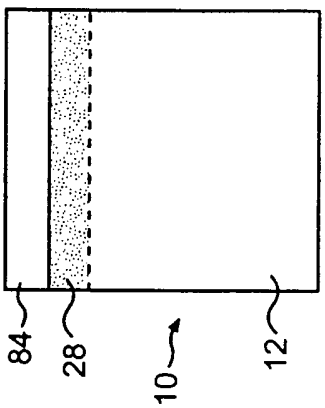


FIG. 8