A surface processing method and power transmission component includes transforming by high current density ion implantation (high intensity plasma ion processing) a surface region of a metal alloy into a hardened surface region at a temperature that is less than a heat treating temperature of the metal alloy. The metal alloy includes between 1.5 wt % and 15 wt % Ni, between 5 wt % and 30 wt % Co, up to 1.0 wt % carbon, and up to 15 wt % of a carbide-forming element, such as molybdenum, chromium, tungsten, vanadium or combinations thereof, that can react with carbon to form metal carbide precipitates of the form M₂C. The surface processing temperature, vacuum pressure, precursor gas flow and ratio, and time of processing are controlled to provide a desirable hardened surface region having a gradual transition in nitrogen concentration. A vapor deposition process deposits an amorphous hydrogenated carbon coating on the hardened surface region of the metal alloy. An intermediate coating between the coating and the hardened surface region promotes adhesion between the coating and hardened surface region.
METHOD FOR PROCESSING ALLOYS VIA HIGH-CURRENT DENSITY ION IMPLANTATION

BACKGROUND OF THE INVENTION

[0001] This invention relates to surface processing of a power transmission component and, more particularly, to methods of surface processing that minimize dimensional alteration and the identification of alloys that possess properties and microstructures conducive to surface processing in such a way that the processed alloy possesses desirable surface and core properties that render it particularly effective in applications that demand superior properties such as power transmission components. Absent the combination of alloy selection and processing that are taught herein, such superior properties would be unavailable.

[0002] 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 surface case provides wear and corrosion resistance while the core provides toughness and impact resistance.

[0003] There are various conventional methods for forming a hardened surface case on a power transmission component fabricated from a steel alloy. One conventional method, nitriding, utilizes gas, salt bath or plasma processing. The nitriding process introduces nitrogen to the surface of the component at an elevated temperature. The nitrogen reacts with the steel alloy to form the hardened surface case while the core of the component might retain the original hardness, strength, and toughness characteristics of the steel alloy. This conventional process provides a hardened surface case, however, the elevated temperatures of the nitriding process may over-temper the core and diminish its properties and/or induce dimensional distortion of the component such that additional grinding or dimensionalizing steps are required to bring the component into dimensional tolerance.

[0004] Accordingly, it is desirable to identify a class of alloys for a surface processing method that minimizes dimensional alteration of a power transmission component and essentially eliminates dimensionalizing processes subsequent to the case hardening process.

SUMMARY OF THE INVENTION

[0005] The surface processing method and power transmission component according to the present invention includes transforming a surface region into a hardened surface region at a temperature less than a tempering temperature of the metal alloy. The Fe-based metal alloy includes between 15 wt % Ni, between 5 wt % and 30 wt % Co, up to 1.0 wt % C, and up to 15 wt % of a carbide-forming element, such as Mo, Cr, W, or V and combinations thereof, that can react with the C to form a metal carbide precipitate of the form M₂C. A high current density ion implantation, also known as high intensity plasma ion processing, process is one technique that may be used to transform the surface region into a hardened surface region. The temperature, vacuum pressure, precursor gas flow and ratio, time of processing, and bias voltages are controlled during the high current density ion implantation nitriding process to provide a hardened surface having a gradual transition in nitrogen concentration. A temperature below the heat treating temperature of the metal alloy is utilized during the high current density ion implantation nitriding to maintain the crystal structure and metal alloy dimensions through the process.

[0006] A coating deposited on the hardened surface region of the metal alloy provides lubricity and wear resistance. The deposited coating is an amorphous hydrogenated carbon or other coating including a metal or transition metal. Alternatively, the deposited coating may be a hard or ultra-hard transition-metal compound, such as a carbide, boride, nitride, or oxide or mixture thereof, deposited by a vapor-deposition method such as physical vapor deposition (PVD), chemical vapor deposition (CVD), or plasma-assisted chemical vapor deposition (PACVD). An intermediate coating may be deposited between the coating and the hardened surface region to promote adhesion between the coating and hardened surface region. The intermediate coating is the transition metal as is included in the amorphous hydrogenated carbon coating.

[0007] The metal alloy and high current density ion implantation surface processing method according to the present invention minimize dimensional alteration of a power transmission component and essentially eliminate subsequent dimensionalizing processes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiment. The drawings that accompany the detailed description can be briefly described as follows.

[0009] FIG. 1 shows a schematic view of a metal alloy;

[0010] FIG. 2 shows a schematic view of a crystal structure;

[0011] FIG. 3 shows a schematic view of a metal alloy during surface processing;

[0012] FIG. 4 shows a schematic view of a metal alloy and hardened surface region;

[0013] FIG. 5 shows a schematic view of a plasma (ion) nitriding chamber;

[0014] FIG. 6 shows a nitrogen concentration profile over a depth of a hardened surface region;

[0015] FIG. 7 shows a schematic view of a nitride compound on a surface region of a metal alloy;

[0016] FIG. 8 shows a schematic view of a coating on a hardened surface region of a metal alloy; and

[0017] FIG. 9 shows a schematic view of a coating on an intermediate coating on a surface region of a metal alloy.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0018] FIG. 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 temperature. The tempering 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.

[0019] 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 strength is greater than about 140 ksi and in some examples the ultimate tensile strength is approximately 285 ksi and the yield strength 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.

[0020] Preferably, the alloy content of the metal alloy 10 and the tempering temperature satisfy the thermodynamic condition that the alloy carbide, M₂C, where M is a metallic carbide-forming element, is more stable than Fe₃C (a relatively coarse precipitate carbide), such that Fe₃C will dissolve and M₂C alloy carbides precipitate. The M₂C alloy carbide-forming elements contribute to the high strength and high toughness of the metal alloy 10 by forming a fine dispersion of M₂C 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 M₂C. Preferably, the metal alloy 10 includes between 1.5 wt % and 15 wt % Ni, between 5 wt % and 30 wt % Co, up to 1.0 wt % C, and up to 15 wt % of a carbide-forming element, such as Mo, Cr, W, or V and combinations thereof, which can react with the C to form metal carbide precipitates of the form M₂C. It is to be understood that the metal alloy 10 may include any one or more of the preferred alloy carbide-forming elements.

[0021] The carbide-forming elements provide strength and toughness advantages because they form a fine dispersion of M₂C. 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.

[0022] 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 ~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 (FIG. 2).

[0023] As illustrated in FIG. 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 martensitic structure and also transform the Fe₃C phase to M₂C 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 also lead to dimensional changes.

[0024] FIG. 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 FIG. 4. A high current density ion implantation, also known as high intensity plasma ion processing, 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.

[0025] The high current density ion implantation nitriding process is conducted in an appropriate reactor, an example of which is illustrated schematically in FIG. 5. The metal alloy 10 is placed in the reactor 34. The metal alloy 10 is placed in the high current density ion implantation 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.

[0026] 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 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 and 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.

[0027] 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 200V and 1500V to the cathode 38. Preferably, the bias voltage is between 700V and 1000V. 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 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.
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 reactors as well as reactors utilizing alternative surface processing processes may be used.

Under the preferred conditions, nitrogen from the nitrogen atmosphere 26 (FIG. 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 FIG. 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.

FIG. 7 shows a schematic view of a metal alloy 10 after another high current density ion implantation 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 alloy 10. Nitride compounds containing the alloying elements may form during the high current density ion implantation 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 high current density ion implantation nitriding processing conditions, however, the presence of these alloying elements may be required to acquire other characteristics in the metal alloy 10.

FIG. 8 shows a schematic view of a metal alloy 10 after a high current density ion implantation 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 $3 \times 10^{-15}$ m²m⁻²N⁻¹ in a slurry of Al₂O₃. 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.

Referring to FIG. 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.

Although a preferred embodiment of this invention has been disclosed, a worker of ordinary skill in this art

US 2006/0048857 A1
Mar. 9, 2006
would recognize that certain modifications would come within the scope of this invention. For that reason, the following claims should be studied to determine the true scope and content of this invention.

1. A surface processing method comprising the steps of:
transforming a surface region of a metal alloy into a hardened surface region at a temperature that is less than a heat treating temperature of the metal alloy.
2-26. (canceled)
27. The method as recited in claim 1, further comprising the steps of:
applying a heat treatment to said metal alloy; and
combining said step of applying a heat treatment with said step of transforming said surface region when at least one condition of said heat treatment corresponds to at least one condition of said hardened surface.
28. The method as recited in claim 27, wherein said at least one condition of said heat treatment is a temperature condition.
29. The method as recited in claim 1, further comprising the step of forming a coating on said hardened surface region.
30. The method as recited in claim 29, further comprising the step of forming an intermediate coating between said coating and said hardened surface region.
31. The method as recited in claim 1, wherein said transforming step includes processes selected from the group consisting of carburizing, nitriding, carbo-nitriding, nitro-carburizing, boronizing, and boriding.
32. The method as recited in claim 1, further comprising the step of transforming the surface region by high current density ion implantation.
33. The method as recited in claim 1, further comprising the step of nitriding said metal alloy, said nitriding step including transforming the surface region into a nitrogen-containing solid solution surface region.
34. The method as recited in claim 1, further comprising the step of using a gas atmosphere comprising between about 10% and 100% nitrogen to transform the surface region.
35. The method as recited in claim 1, further comprising the step of using a gas atmosphere pressure between 0.5 mtorr and 5.0 mtorr to transform the surface region.
36. The method as recited in claim 1, further comprising the step of inducing a bias voltage on the metal alloy between 200V and 1500V to transform the surface region.
37. The method as recited in claim 1, further comprising the step of using a plasma discharge voltage between 30V and 150V to transform the surface region by ionizing precursor processing gases.
38. The method as recited in claim 1, wherein said nitriding step further comprises the step of removing oxides on the surface region during the transforming of said surface region into said hardened surface region.
39. The method as recited in claim 1, wherein said nitriding step further comprises transforming the surface region of a metal alloy into the hardened surface region at a temperature between about 700° F. and 1000° F.
40. The method as recited in claim 1, wherein said nitriding step further comprises the step of forming a coating on the hardened surface region.
41. A surface processing method comprising the steps of:
solutionizing a metal alloy;
quenching said metal alloy;
reheating said quenched metal alloy to age said quenched metal alloy;
transforming a surface region of said metal alloy into a hardened region; and
combining said step of reheating with said step of transforming said surface region when at least one condition of said reheating step corresponds to at least one condition of said hardened surface.
42. The method as recited in claim 41, wherein said transforming step is performed at a temperature that is less than a temperature of said reheating step.
43. The method as recited in claim 41, further comprising the step of forming a coating on said hardened surface.
44. The method as recited in claim 43, further comprising the step of forming an intermediate coating between said coating and said hardened surface.
45. The method as recited in claim 41, further comprising the step of nitriding said metal alloy.
46. The method as recited in claim 41, further comprising the steps of:
refrigerating said quenched metal alloy; and
reheating said quenched metal alloy to temper said quenched metal alloy.
47. The method as recited in claim 41, wherein said solutionizing step includes the step of austenitizing said metal alloy.
48. A surface processing method comprising the steps of:
providing a metal alloy with an associated composition and associated heat treating conditions; and
transforming a surface region of said metal alloy to a hardened surface region at a temperature that is less than said heat treating conditions of said metal alloy.
49. The method as recited in claim 48, further comprising the step of forming a coating on said hardened surface.
50. The method as recited in claim 48, wherein said metal alloy comprises at least 5 wt % cobalt.
51. The method as recited in claim 48, wherein said metal alloy comprises at least 1.5 wt % nickel.
52. The method as recited in claim 48, wherein said metal alloy comprises up to 1.0 wt % carbon.
53. The method as recited in claim 48, wherein said metal alloy comprises less than 20 wt % of molybdenum, chromium, tungsten, or vanadium and combinations thereof.
54. The method as recited in claim 48, wherein said forming said coating step further comprises forming an amorphous hydrogenated carbon coating on said hardened surface region.
55. The method as recited in claim 49, wherein said forming said coating step further comprises forming an intermediate coating between said coating and said hardened surface.
56. The method as recited in claim 49, wherein said forming said coating step further comprises forming a metallic intermediate coating between said coating and said hardened surface.
57. The method as recited in claim 48, wherein said metal alloy is used in a power transmission system, a gear, a shaft, a spring, a bearing, or as armor plating.

* * * * *