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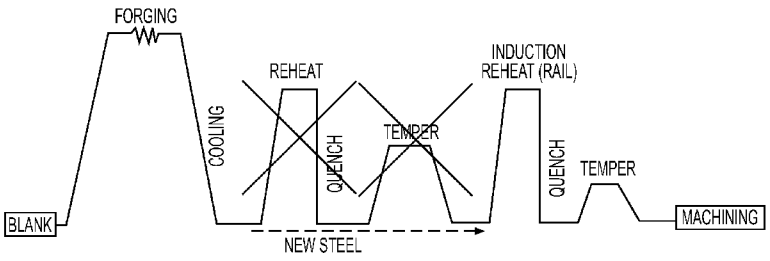


FIG. 1

(57) Abstract: A method of producing a forged steel part is disclosed to include providing a steel billet having a composition including 0.25 - 0.40 wt.% C, 1.50 - 3.00 wt.% Mn, 0.30 - 2.00 wt.% Si, 0.00 - 0.150 wt.% V, 0.02 - 0.06 wt.% Ti, 0.010 - 0.04 wt.% S, 0.0050 - 0.0150 wt.% N, 0.00 - 1.00 wt.% Cr, 0.00 - 0.30 wt.% Mo, 0.00 - 0.003 wt.% B, and a balance of Fe and incidental impurities. The method may further include heating the steel billet to an austenization temperature of approximately 1150 degrees C to 1350 degrees C, hot forging the steel billet to form the steel part, and controlled air cooling the forged steel part after the hot forging. The method may still further include induction heating select portions of the forged steel part after the controlled air cooling to increase the hardness of the select portions of the forged steel part, followed by quenching and tempering before the final machining.

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Description

AIR-HARDENABLE BAINITIC STEEL WITH ENHANCED MATERIAL CHARACTERISTICS

Technical Field

The present disclosure relates generally to an air-hardenable bainitic steel and, more particularly, to an air-hardenable bainitic steel with enhanced material characteristics.

Background

Structural components for machinery, such as track links used on the undercarriage of track-type earth moving machines, are required to have material characteristics that include good yield strength, good wear resistance, good toughness, and good rolling contact fatigue resistance. Track links used on the tracks of a track-type machine such as a bulldozer or other earth moving equipment are well known in the industry. A track link typically has a lower portion, or the body of the link, and an upper portion, or the rail portion of the link. It is important that the rail portion of the track link have high surface hardness, whereas the body portion of the track link can have lower surface hardness for increased machinability. A high surface hardness in the rail portion is necessary because the rail portion is subjected to severe wear and spallation from continuous contact with track rollers. A lower surface hardness in the body portion of the track link allows holes for bushings to be more easily machined into the body portion. The lower surface hardness of the body portion of the track link also allows for a press fit between a bushing and the hole in the track link body without creating excessive residual stresses.

The manufacturing processes for obtaining the desired material characteristics in a track link or other structural component have typically included hot forging the component from a steel billet, followed by cooling, reheating to austenization temperatures, quenching, and tempering. These heat treatment processes may then be followed by additional heating of at least select portions of the component, quenching again, and tempering again before the final machining. Processing of a track link includes first heating a steel part to approximately 1150 - 1350 degrees C to bring the material to an austenite phase field, and then hot forging the part. The part is then slowly cooled to room

temperature, followed by two heat treatment processes. In the first heat treatment process the track link is reheated to austenization temperature, quenched to room temperature, and then tempered to a hardness of approximately 30 - 39 Rockwell C hardness (HRC). In the second heat treatment process just the rail portion of the track link is locally reheated by induction, quenched to room temperature, and tempered to a hardness of 51 - 57 HRC. These heat treatment processes result in the track link having a hard rail and a softer body. The body of the link is then machined into final shape. The heat treatment processes add significantly to the expense of producing the components, and also require significant capital expenditures for furnaces, as well as ongoing maintenance expenses.

One attempt to produce alternative types of steel having good wear and rolling contact fatigue resistance coupled with improved levels of ductility toughness and weldability is described in U.S. Patent No. 5,879,474 to Bhadeshia ("the '474 patent") that issued on March 9, 1999. The '474 patent discloses a steel for use in making a steel rail, where the steel is purported to provide a high strength, wear and rolling contact fatigue resistant microstructure comprising carbide free "bainite" with some high carbon martensite and retained austenite in the head of the rail.

Although the alloy steel disclosed in the '474 patent may provide improved wear and rolling contact fatigue resistance, still further improvements in manufacturing costs and material characteristics may be possible. In particular, the '474 patent describes the use of significant quantities of expensive alloying elements such as Chromium (Cr) and Molybdenum (Mo) to achieve improved levels of rolling contact fatigue strength, ductility, bending fatigue life and fracture toughness, coupled with rolling contact wear resistance similar to or better than those of the current heat treated pearlitic rails.

The bainitic microalloyed steel produced in accordance with the chemistry and processes of the present disclosure solves one or more of the problems set forth above and/or other problems in the art.

Summary

In one aspect, the present disclosure is directed to a method of producing a forged steel part, including providing steel billet having a composition including, on a weight basis:

C: 0.25 - 0.40 wt.%,
Mn: 1.50 - 3.00 wt.%,
Si: 0.30 - 2.00 wt.%
V: 0.00 - 0.15 wt. %,
Ti: 0.02 - 0.06 wt.%,
S: 0.010 - 0.04 wt. %,
N: 0.0050 - 0.0150 wt.%,
Cr: 0.00 - 1.00 wt.%,
Mo: 0.00 - 0.30 wt.%,
B: 0.00 - 0.005 wt.%, and
a balance of Fe and incidental impurities, heating the steel billet to an austenization temperature of approximately 1150 degrees C to 1350 degrees C, hot forging the steel billet to form the steel part, and controlled air cooling the forged steel part after the hot forging.

In another aspect, the present disclosure is directed to an air-hardenable bainitic steel part having a composition including, on a weight basis:

C: 0.25 - 0.40 wt.%,
Mn: 1.50 - 3.00 wt.%,
Si: 0.30 - 2.00 wt.%
V: 0.00 - 0.15 wt. %,
Ti: 0.02 - 0.06 wt.%,
S: 0.010 - 0.04 wt. %,
N: 0.0050 - 0.0150 wt.%,
Cr: 0.00 - 1.00 wt.%,
Mo: 0.00 - 0.30 wt.%,
B: 0.00 - 0.003 wt.%,
a balance of Fe and incidental impurities, and a microstructure that is greater than 50% by volume bainitic microstructure throughout the entire steel part.

In yet another aspect, the present disclosure is directed to a forged steel part manufactured to have a chemical composition including, on a weight basis:

C: 0.25 - 0.40 wt.%,
Mn: 1.50 - 3.00 wt.%,
Si: 0.30 - 2.00 wt.%
V: 0.00 - 0.15 wt. %,
Ti: 0.02 - 0.06 wt.%,
S: 0.010 - 0.04 wt. %,
N: 0.0050 - 0.0150 wt.%,
Cr: 0.00 - 1.00 wt.%,
Mo: 0.00 - 0.30 wt.%,
B: 0.00 - 0.003 wt.%,

a balance of Fe and incidental impurities, a microstructure that is greater than 50% by volume bainitic microstructure throughout the entire steel part, and the forged steel part being manufactured by hot forging, controlled air cooling after the hot forging to produce a bainitic microstructure of greater than 50% bainite throughout the forged steel part, and final machining.

Brief Description of the Drawings

Fig. 1 is a schematic diagram of an exemplary disclosed process eliminating typical heat treating steps;

Fig. 2 is a continuous cooling transformation (CCT) diagram for producing the microstructure of an exemplary embodiment of the disclosure; and

Fig. 3 is a flowchart depicting an exemplary disclosed method that may be used to produce an exemplary microalloyed bainitic steel with enhanced characteristics.

Detailed Description

A microalloyed, air-hardenable, predominantly bainitic steel with enhanced strength, wear, and toughness characteristics is disclosed. The microalloyed, bainitic steel may be economically produced without requiring many of the heat treatment processes previously thought necessary to achieve desired strength, wear, and toughness characteristics. As shown in Fig. 1, the

typical heat treatment processes following hot forging of a steel part may include cooling, reheating to austenization temperature, quenching, and tempering. These heat treatment processes may then be followed by reheating select portions of the steel part a second time using induction, quenching a second time, and tempering a second time before the final machining. At least the first sequence of heat treatment steps involving reheating, quenching, and tempering may be required with conventional hot forging processes in order to obtain desired strength and toughness characteristics, while at the same time ending up with a part that is not too hard for machining. Significant cost savings may be achieved if at least some of these intermediate heat treatment processes can be eliminated. Capital investments for heat treatment capacity, and maintenance costs on the furnaces and other equipment may be reduced. In certain implementations of this disclosure the microalloyed, bainitic steel may be provided with the necessary composition and cooling after hot forging to arrive at a hardness of approximately 50 - 55 Rockwell C hardness (HRC) without even requiring the induction reheating, quenching, and tempering before final machining.

A predominantly bainitic microstructure according to various implementations of this disclosure is a microstructure that consists of at least 50% by volume of a bainitic microstructure. Certain embodiments may have at least 70% by volume of a bainitic microstructure. Other embodiments may have at least 85% by volume of a bainitic microstructure. Bainite is a microstructure that forms in steels at temperatures of approximately 250–550 °C (depending on alloy content). Bainite is one of the decomposition products that may form when austenite (the face centered cubic crystal structure of iron) is cooled past a critical temperature of 727 °C (1340 °F) depending on alloy content. A bainitic microstructure may be similar in appearance and hardness characteristics to tempered martensite.

A fine, non-lamellar structure, bainite commonly consists of cementite and dislocation-rich ferrite. The high concentration of dislocations in the ferrite present in bainite makes this ferrite harder than it normally would be. As shown in the continuous cooling transformation (CCT) diagram of Fig. 2, the temperature range for transformation to bainite (250–550 °C) is between those for pearlite and martensite. When formed during continuous cooling, the cooling

rate to form bainite is more rapid than that required to form pearlite, but less rapid than that required to form martensite (in steels of the same composition). In accordance with various implementations of this disclosure, a microalloyed steel having the chemistry discussed in more detail below may be initially heated to austenization temperatures of approximately 1150 - 1350 °C or greater. The steel may then be hot forged into the desired shape, and control cooled from the forging temperature to achieve a bainitic microstructure. For the cooling after hot forging, atmospheric cooling or forced air cooling using a blower may be conducted. In various alternative implementations, the steel may be cooled rapidly down to about the eutectoid transformation temperature, and then cooled slowly over a range from about 900 to 500 °C. In still further alternative implementations, the steel may be cooled quickly to about 500 to 300 °C after hot forging, and may be kept at an equilibrium temperature somewhere in the range from about 500 to 300 °C to promote bainite transformation.

The cooling rate may be determined by reference to a CCT diagram, to know the range for cooling rates passing through the bainite transformation region and, thereby, controlling to the determined cooling rate range. The CCT diagram may have been previously prepared, stored in a database, or otherwise made available for control of the cooling process. The forged product may be air cooled using fans or other means of circulating the cooling air to achieve a cooling rate that falls approximately within the range from 0.5 to 5 °C per second, or 30 to 300 °C per minute, when cooling between approximately 900 °C and 500 °C. Most alloying elements will lower the temperature required for the maximum rate of formation of bainite, though carbon is the most effective in doing so. Bainite generally has a hardness that is greater than the typical hardness of pearlite and less than the hardness of martensite. Pearlite in the microstructure may contribute to reduced toughness. The composition and processing of the microalloyed steel according to various embodiments of this disclosure are selected to avoid or at least minimize the amount of pearlite present. In commercial practice a small amount of pearlite, such as less than 2 percent by volume, may unavoidably be present, particularly in the center of large sections, but care is taken to minimize its presence and effects.

The bainite microstructure essentially has a two-phase microstructure composed of ferrite and iron carbide or cementite. Depending on the composition of the austenite during the hot forging process, and the cooling rate after hot forging, there is a variation in the morphology of the resulting bainite. The resulting microstructures are referred to as upper bainite or lower bainite. Upper bainite can be described as aggregates of ferrite laths that usually are found in parallel groups to form plate-shaped regions. The carbide phase associated with upper bainite is precipitated at the interlath regions, and depending on the carbon content, these carbides can form nearly complete carbide films between the lath boundaries. Lower bainite also consists of an aggregate of ferrite and carbides. The carbides precipitate inside of the ferrite plates. The carbide precipitates are on a very fine scale and in general have the shape of rods or blades. For this reason, the bainitic microstructure becomes useful in that no additional heat treatments are required after initial cooling to achieve a hardness value between that of pearlitic and martensitic steels. The material characteristics of the microalloyed and forged steel can vary over a large range depending on the particular types and quantities of alloying elements included in the composition. When steel contains sufficient amounts of Si and/or Al, the carbide formation can be significantly retarded such that carbide does not have enough time to form during the continuous cooling process, resulting in a mixed microstructure of bainitic ferrite and retained austenite. This type of bainitic microstructure may be referred to as “carbide free” bainite. It has been found that such bainite may provide superior toughness to conventional types of bainite. The composition of alloying elements included in accordance with various embodiments of this disclosure results in a steel part having the strength, hardness, and toughness characteristics previously only achieved by including the intermediate heat treatment steps following hot forging of reheating to austenization temperature, quenching, and tempering.

The advantageous material characteristics discussed above are found to be achieved to a greater extent as the percentage by volume of bainitic microstructure is increased. Accordingly, a part that is 70% by volume bainitic microstructure may exhibit greater strength, hardness, and toughness characteristics than a part that is 50% by volume bainitic microstructure balanced with ferrite and/or pearlite type of microstructure. Additionally, a part

that is 85% or greater by volume bainitic microstructure may exhibit even further enhanced characteristics of strength, hardness, and toughness than the part that is 70% by volume bainitic microstructure balanced with ferrite and/or pearlite type of microstructure. As shown in Fig. 1, intermediate heat treatment steps of reheating to austenization temperature, quenching, and tempering may be eliminated before the final machining of a forged product in accordance with various implementations of this disclosure. Induction reheating of select portions of the steel part, such as the rail portion of a track link used in contact with the tracks on earth moving machinery, may be included to achieve enhanced hardness and strength characteristics for certain parts or portions of parts. The increased hardness can also improve the wear resistance of the selected portions of the steel part. The alloying elements that are added to the composition in accordance with various embodiments of this disclosure may also be selected to obtain the desired volume percentages of bainitic microstructure throughout the part, regardless of the different cooling rates that may be experienced in different sections or portions of the part having different thicknesses.

It has been discovered in various implementations of this disclosure that the bainitic microstructure obtained after controlled air-cooling may also exhibit the same or similar hardness and strength characteristics as were previously achieved by following hot forging with quenching, reheating, quenching again, and tempering. A microalloyed steel may exhibit a martensitic microstructure after rapid cooling from hot forging temperatures through quenching in oil or water. The martensitic microstructure may have a Rockwell C hardness (HRC) of 50 after quenching depending on the carbon content of the steel. Typical methods of processing this martensitic microstructure steel may then include reheating back up to austenitic temperatures of approximately 800 °C - 950 °C, quenching again, and then tempering by reheating again to approximately 500 °C - 590 °C in order to soften the steel to approximately HRC 30. The controlled air cooling process for producing a predominantly bainitic microstructure according to various implementations of this disclosure may result in the same hardness of HRC 30 without all of the quenching, reheating, quenching and tempering steps previously required. As mentioned above, the predominantly bainitic microstructure may contain greater than 50% by volume

of bainitic microstructure. The hardness after air cooling in accordance with this disclosure may fall within the range from approximately 35 - 45 HRC. The types and quantities of microalloying elements included in the composition of the air-hardenable, bainitic steel in accordance with various embodiments may also enable achievement of hardness levels after air cooling that fall approximately in the range from 40 - 55 HRC.

The microalloyed steel according to various implementations of this disclosure may have a chemical composition, by weight, as listed in Table 1:

Constituents	Concentration by weight (%)
Carbon	0.25 - 0.40
Manganese	1.50 - 3.00
Titanium	0.02 - 0.06
Vanadium	0.00 - 0.15
Silicon	0.30 - 2.00
Nitrogen	0.0050 - 0.0150
Optional Sulfur	0.010 - 0.040
Optional Chromium	0.00 - 1.00
Optional Molybdenum	0.00 - 0.30
Optional Boron	0.00 - 0.005
Iron and other residual elements	Balance

Table 1: Composition of microalloyed steel in weight percent.

Carbon (C) contributes to the attainable hardness level as well as the depth of hardening. In accordance with various implementations of this disclosure, the carbon content is at least 0.25% by weight to maintain adequate core hardness after tempering and is no more than about 0.40% by weight to assure resistance to quench cracking and steel toughness. It has been found that if the carbon content is more than about 0.40% by weight, water quenching may cause cracking or distortion in complex-shaped articles and, in such cases, a less drastic quench medium such as oil may be required. Therefore an advantageous range of C is from approximately 0.25 - 0.40 wt.%. The microalloyed, bainitic steel according to various implementations of this disclosure may be air cooled in accordance with select cooling curves on the CCT diagram of Fig. 2.

Manganese (Mn) is a low cost allow and contributes to the deep hardenability and is therefore present in most hardenable alloy steel grades. The disclosed alloy steel contains manganese in an amount of at least 1.50% by weight to assure adequate core hardness and contains no more than about 3.00% to prevent manganese segregation and the formation of blocky retained austenite.

Silicon (Si) in amounts between approximately 0.30 - 2.00 wt.%, along with the Mn, allows the steel according to this disclosure to form a predominantly bainitic microstructure following air cooling from hot forging temperatures. The Si may also help deoxidation of the molten steel, as well as contributing to the formation of a carbide-free bainite with improved toughness when sufficient Si is added into the steel.

Chromium contributes to the hardenability of the present steel alloy and may be added in small amounts not exceeding 1.00% by weight in order to allow for adjustment of the CCT curve to form a predominantly bainitic microstructure after air cooling. More Chromium increases steel cost.

Small amounts of other elements including Molybdenum (Mo) and Boron (B) may also be added to allow for further adjustment of the CCT curve to form a predominantly bainitic microstructure after air cooling.

Vanadium (V) and Nitrogen (N), despite their small quantities, may also be important ingredients in the present alloy steel composition, and may be added to provide precipitation hardening and to realize a consistently measurable enhancement of case and core hardness. Nitrogen combines with the titanium in the steel to form titanium carbonitrides to prevent grain coarsening during the reheat prior to forging and during the cooling after hot forging. Without Ti and N, the forged steel may have large prior austenite grain sizes, resulting in poor toughness.

The remainder of the alloy steel composition is essentially iron, except for nonessential or residual amounts of elements which may be present in small amounts. Titanium (Ti) may also be provided in amounts approximately between 0.02 - 0.06% to form titanium carbonitrides to prevent grain coarsening before and after forging. Sulphur (S), which in small amounts may be beneficial in that it promotes machining, may also be provided in small enough amounts so as to not contribute to any loss of ductility and toughness. Phosphorus (P) in an amount over 0.05% may cause embrittlement, and preferably the upper limit

should not exceed 0.035%. Other elements generally regarded as incidental impurities may be present within commercially recognized allowable amounts.

Manufactured articles, such as track links, having the above stated composition, may be advantageously initially formed to a desired shape by hot forging after heating up the microalloyed steel to austenization temperatures of approximately 1150 - 1350 °C. The formed articles are then controlled cooled as described above to produce a predominantly bainitic microstructure. Select portions of the hot forged articles, such as the rail portions of a track link, may then receive additional heat treatment by induction heating the select portions, quenching, and tempering before final machining to a desired final dimension.

Fig. 3 illustrates an exemplary method that may be used to produce a predominantly bainitic microalloyed steel part in accordance with various implementations of this disclosure. Fig. 3 will be discussed in more detail in the following section to further illustrate the disclosed concepts.

Industrial Applicability

The steel and method of making the steel in accordance with various implementations of the present disclosure may reduce costs by eliminating heat treatment steps typically performed after hot forging. The disclosed microalloyed, forged, air-hardenable bainitic steel may provide similar hardness, strength, and toughness characteristics to previously hot forged and heat treated steel parts, but without requiring all of the heat treatment processes. The microalloying elements in combination with the controlled air cooling may produce a predominantly bainitic microstructure after air cooling from hot forging temperatures. Select portions of the steel parts produced in accordance with the composition and processes of this disclosure may be further hardened if desired using localized induction heating followed by quenching and tempering. Alternatively, the composition of the bainitic steel in accordance with this disclosure may be adjusted within the disclosed ranges, and air cooled in order to achieve a hardness after air cooling falling in the range from approximately 50 - 55 HRC with no further heat treatment.

The steel part produced in accordance with various advantageous implementations of this disclosure exhibits material characteristics that may include a body hardness of 35 - 45 HRC after air cooling for good machinability

with no heat treatment, a body yield strength that is greater than 1000 mega-pascals (MPa) after the air cooling, a hardness at the portions that have been additionally hardened through selective induction heating of greater than approximately 50 HRC, and a body toughness of approximately 20 Joules or greater in the Charpy impact test at room temperature.

As shown in Fig. 3, at step 320 a microalloyed steel having the composition shown above in Table 1 may be heated to austenization temperatures of approximately 1150 degrees C to 1350 degrees C. The types of parts being manufactured in accordance with various implementations of this disclosure may include parts that require good machinability in at least one portion, high yield strength, good wear characteristics, and good toughness. One exemplary application of the disclosed compositions and processes is for track links used in the tracks of a track-type machine such as a bulldozer or other earth moving equipment. The size of the parts determines the size of a steel billet that is initially heated to austenization temperatures in accordance with step 320.

At step 322, the heated billet may be hot forged to a desired configuration. After the hot forging, step 324 may include air cooling the hot forged product at a cooling rate that results in the formation of a predominantly bainitic microstructure throughout the hot forged part. As shown by the CCT diagram of Fig. 2, the cooling rate may be chosen to avoid the formation of a large amount of martensitic microstructure or a predominantly ferrite and pearlite microstructure. In various implementations of this disclosure, the hot forged steel may be cooled at a rate that falls approximately in the range from 0.5 to 5 degrees C per second as the steel cools from approximately 900 degrees C to approximately 500 degrees C. In various alternative implementations, the weight percentages of the alloying elements in the composition of the steel may be varied in order to change the phase transformation curves on the CCT diagram, and achieve the desired predominantly bainitic microstructure at cooling rates achieved by transporting the hot forged steel parts along a conveyor at ambient temperatures. The microalloyed steel may also be advantageously provided with a composition that achieves the desired bainitic microstructure and hardness levels throughout the part even at the different cooling rates that may be experienced by different sections of the part having different thicknesses. The predominantly bainitic microstructure may be a

microstructure with greater than 50% bainite, or more advantageously greater than 70% bainite, or still more advantageously greater than 85% bainite throughout the hot forged steel part. The hardness levels throughout the entire forged steel part after air cooling may fall within the range from approximately 35 - 45 HRC. In other advantageous embodiments, the hardness levels throughout the forged steel part may fall within the range from approximately 40 - 55 HRC after air cooling with no further heat treatment.

At step 326, select portions of the steel part may be induction heated in order to achieve higher hardness levels. In the exemplary implementation of a track link, a high surface hardness may be desired for the rail portion because the rail portion may be subjected to severe wear from continuous contact with track rollers. A lower surface hardness in the body portion of the track link allows holes for bushings, pins, and bolts to be more easily machined into the body portion. The lower surface hardness of the body portion of the track link also allows for a press fit between a bushing and the hole in the track link body without creating excessive residual stresses. In various exemplary embodiments, the hardness of the induction heated portions of the steel part may fall within the range from approximately 50 - 57 HRC.

At step 328, after select portions of the steel part have been induction heated, at least these heated portions of the steel part may be quenched, using techniques such as directed sprays of quenching fluids onto the induction heated areas of the part. Following quenching, at step 330, the steel part may be reheated to tempering temperatures in order to improve its toughness. Final machining may then occur at step 332.

It will be apparent to those skilled in the art that various modifications and variations can be made to the disclosed microalloyed steel and method of forming the steel into a finished part without departing from the scope of the disclosure. Alternative implementations will be apparent to those skilled in the art from consideration of the specification and practice disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope of the disclosure being indicated by the following claims and their equivalents.

Claims

1. A method of producing a forged steel part, comprising:

providing steel billet having a composition comprising, on a weight basis:

C: 0.25 - 0.35 wt.%,
Mn: 1.50 - 3.00 wt.%,
Si: 0.30 - 2.00 wt.%
V: 0.10 wt. %,
Ti: 0.02 - 0.06 wt.%,
S: 0.015 - 0.04 wt. %,
N: 0.01 wt.%,
Cr: 0.00 - 0.30 wt.%,
Mo: 0.00 - 0.03 wt.%,
B: 0.00 - 0.003 wt.%, and
a balance of Fe and incidental impurities;

heating the steel billet to an austenization temperature of approximately 1150 degrees C to 1350 degrees C;

hot forging the steel billet to form the steel part; and

controlled air cooling the forged steel part after the hot forging.

2. The method according to claim 1, wherein the controlled air cooling is performed at a rate to produce a body hardness for the steel part of approximately 35 - 45 Rockwell C hardness (HRC) after the controlled air cooling.

3. The method according to claim 1, wherein the controlled air cooling is performed at a rate to produce a yield strength for the steel part of approximately greater than 1000 mega-pascals (MPa) after the controlled air cooling.

4. The method according to claim 1, wherein the controlled air cooling is performed by moving the forged steel part along a conveyor at ambient temperatures.

5. The method according to claim 1, wherein the composition of the steel billet is selected such that the controlled air cooling of the forged steel part and resultant different rates of cooling of sections of the forged steel part having different thicknesses results in a microstructure throughout the entire forged steel part after the controlled air cooling of approximately greater than 50% by volume of bainitic microstructure.

6. The method according to claim 1, wherein the composition of the steel billet is selected such that the controlled air cooling of the forged steel part and resultant different rates of cooling of sections of the forged steel part having different thicknesses results in a hardness level throughout the entire forged steel part after the controlled air cooling of approximately greater than 35 - 45 HRC.

7. The method according to claim 1, wherein a toughness of at least an inner portion of a body of the steel part after the controlled air cooling is approximately greater than or equal to 20 Joules at room temperature in accordance with the Charpy impact test.

8. The method according to claim 1, further including induction heating select portions of the forged steel part after the controlled air cooling to increase hardness of the select portions of the forged steel part.

9. The method according to claim 8, wherein the hardness of the select portions of the forged steel part after induction heating is greater than approximately 50 HRC.

10. An air-hardenable bainitic steel part having a composition comprising:

C:	0.25 - 0.35 wt.%,
Mn:	1.50 - 3.00 wt.%,
Si:	0.30 - 2.00 wt.%
V:	0.00 - 0.10 wt. %,
Ti:	0.02 - 0.06 wt.%,
S:	0.015 - 0.04 wt. %,

N: 0.00 - 0.01 wt.%,

Cr: 0.00 - 0.40 wt.%,

Mo: 0.00 - 0.05 wt.%,

B: 0.00 - 0.003 wt.%,

a balance of Fe and incidental impurities; and

a microstructure that is greater than 50% by volume bainitic microstructure throughout the entire steel part.

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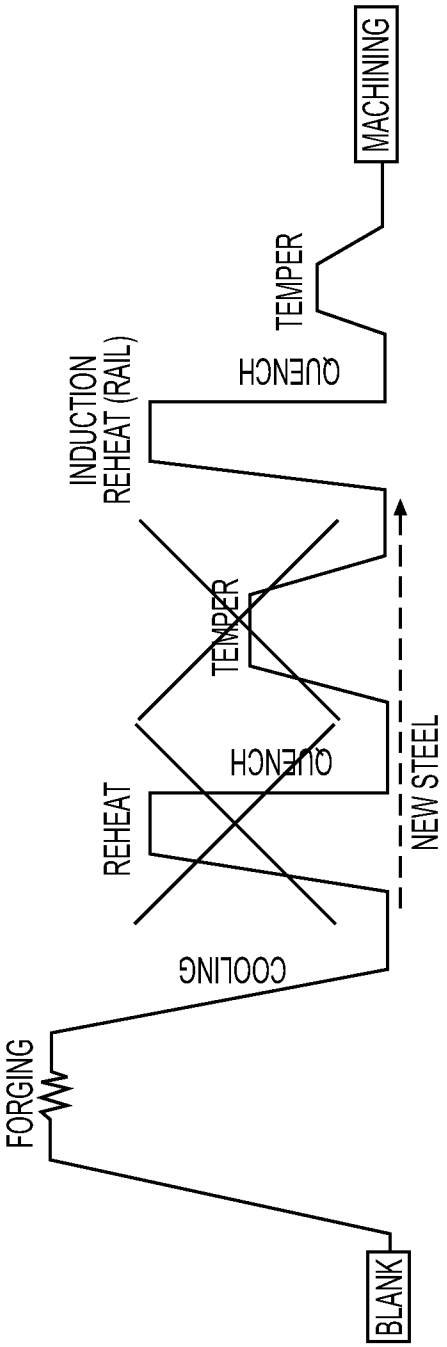


FIG. 1

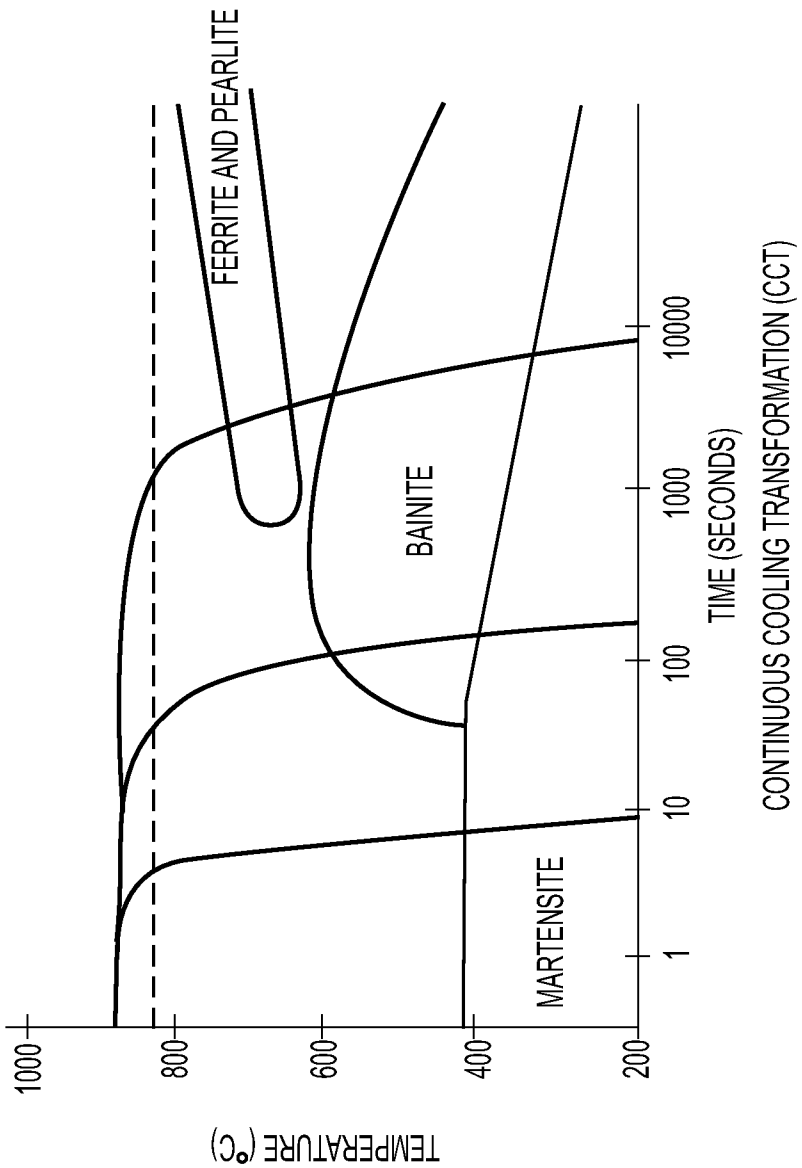

FERRITE AND PEARLITE
BAINITE
MARTENSITE
1000
800
600
400
200
1
10
100
1000
10000
TIME (SECONDS)
TEMPERATURE (°C)
CONTINUOUS COOLING TRANSFORMATION (CCT)

FIG. 2

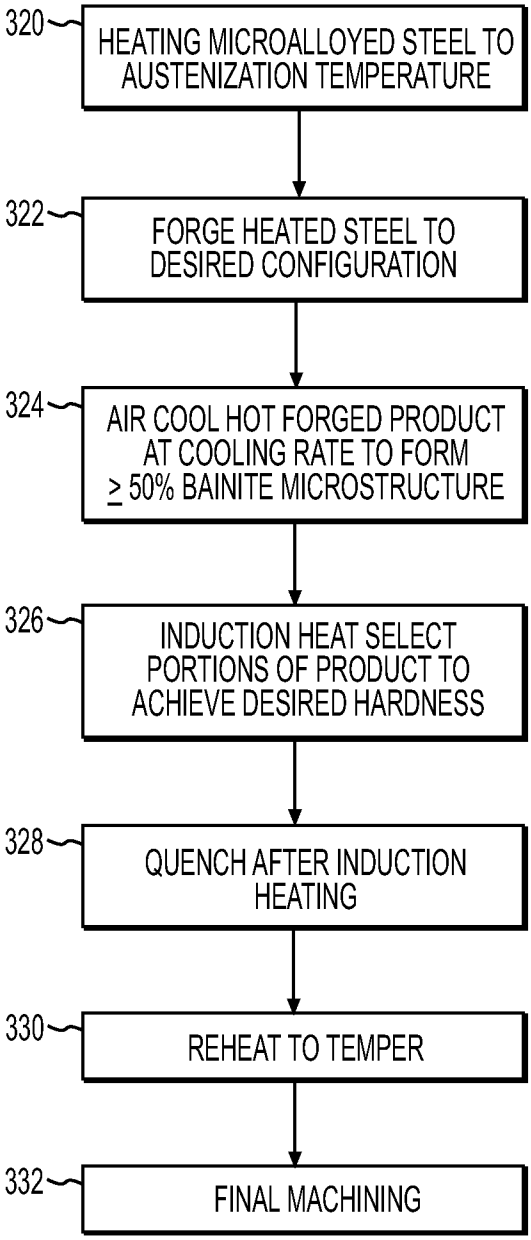

320
HEATING MICROALLOYED STEEL TO AUSTENIZATION TEMPERATURE
322
FORGE HEATED STEEL TO DESIRED CONFIGURATION
324
AIR COOL HOT FORGED PRODUCT AT COOLING RATE TO FORM ≥ 50% BAINITE MICROSTRUCTURE
326
INDUCTION HEAT SELECT PORTIONS OF PRODUCT TO ACHIEVE DESIRED HARDNESS
328
QUENCH AFTER INDUCTION HEATING
330
REHEAT TO TEMPER
332
FINAL MACHINING

FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/031201

A. CLASSIFICATION OF SUBJECT MATTER

C21D 8/00(2006.01)i, C21D 7/13(2006.01)i, C22C 38/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C21D 8/00; C22C 38/24; C22C 38/22; C22C 38/00; C23C 8/26; C21D 7/13

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: steel, forging, composition, alloy, carbon, manganese, silicon, hardness, and bainite

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5660648 A (TAKADA et al.) 26 August 1997 See abstract; column 6, lines 11-24; and claims 1,2,5,6,9.	10
Y		1-7
A		8,9
Y	US 2007-0119519 A1 (OKONOGI et al.) 31 May 2007 See abstract; paragraphs [0018],[0019]; and claim 1.	1-7
A	US 5601667 A (TAKAHASHI et al.) 11 February 1997 See abstract; and claims 1,2.	1-10
A	US 2012-0288397 A1 (BARBOSA et al.) 15 November 2012 See abstract; paragraphs [0079]-[0083]; and claim 1.	1-10
A	JP 08-176733 A (SUMITOMO METAL IND. LTD.) 09 July 1996 See abstract; and claims 1-3.	1-10

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 July 2014 (02.07.2014)	**04 July 2014 (04.07.2014)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/031201

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5660648 A	26/08/1997	EP 0648853 A1	19/04/1995
		EP 0648853 A4	26/07/1995
		EP 0648853 B1	19/05/1999
		JP 06-287679 A	11/10/1994
		JP 3139876 B2	05/03/2001
		WO 94-23085 A1	13/10/1994
US 2007-0119519 A1	31/05/2007	DE 102006055922 A1	05/07/2007
		DE 102006055922 B4	28/03/2013
		JP 2007-146232 A	14/06/2007
		JP 4385019 B2	16/12/2009
		US 7815750 B2	19/10/2010
US 5601667 A	11/02/1997	CN 1039033 C	08/07/1998
		CN 1115581 A	24/01/1996
		EP 0674012 A1	27/09/1995
		EP 0674012 A4	19/03/1997
		JP 07-109518 A	25/04/1995
		JP 3300500 B2	08/07/2002
		KR 10-0180939 B1	18/02/1999
		WO 95-10635 A1	20/04/1995
US 2012-0288397 A1	15/11/2012	BR PI0901378 A2	21/12/2010
		CA 2757754 A1	06/10/2011
		CN 102439190 A	02/05/2012
		EP 2557196 A1	13/02/2013
		JP 2013-523999 A	17/06/2013
		KR 10-2012-0125945 A	19/11/2012
		MX 2011010440 A	04/11/2011
		RU 2011140167 A	20/04/2013
		WO 2011-120108 A1	06/10/2011
		WO 2011-120108 A8	24/11/2011
JP 08-176733 A	09/07/1996	JP 2979987 B2	22/11/1999