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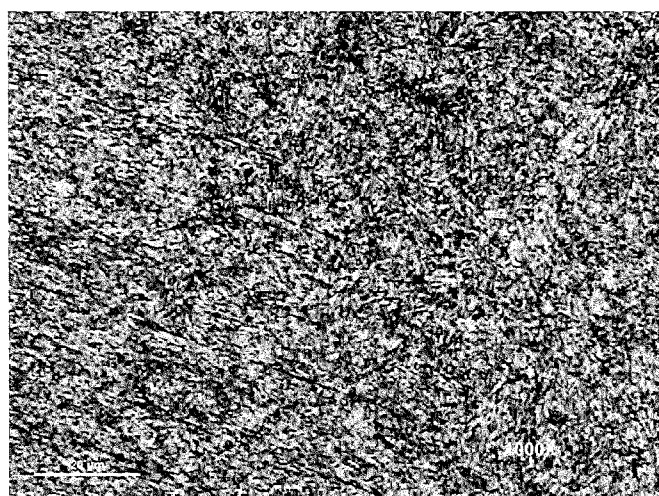


FIG. 3

(57) Abstract: In one aspect, methods of forming tooling articles from tool steel powder compositions via additive manufacturing techniques are described herein. A method of forming a tooling article comprises consolidating powder alloy into the tooling article via an additive manufacturing technique and heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC. The tooling article can be formed of an alloy composition comprising 0.2-2 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron. As described herein, the method can further comprise hot isostatic pressing the tooling article prior to the heating treatment.





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TOOL STEEL ARTICLES FROM ADDITIVE MANUFACTURING

RELATED APPLICATION DATA

The present application claims priority pursuant to Article 8 of the Patent Cooperation Treaty to United States Patent Application Serial Number 15/667,390 filed August 2, 2017 which is incorporated herein by reference in its entirety.

FIELD

The present invention relates articles produced by additive manufacturing techniques and, in particular, to methods of producing tool steel articles via additive manufacturing techniques.

BACKGROUND

Additive manufacturing (AM) generally encompasses processes in which digital 3-dimensional (3D) design data is employed to fabricate an article or component in layers by material deposition and processing. Various techniques have been developed falling under the umbrella of additive manufacturing. Additive manufacturing offers an efficient and cost-effective alternative to traditional article fabrication techniques based on molding processes. With additive manufacturing, the significant time and expense of mold and/or die construction and other tooling can be obviated. Further, additive manufacturing techniques make an efficient use of materials by permitting recycling in the process and precluding the requirement of mold lubricants and coolant. Most importantly, additive manufacturing enables significant freedom in article design. Articles having highly complex shapes can be produced without significant expense allowing the development and evaluation of a series of article designs prior to final design selection.

A wide variety of steels are employed in tooling applications. For example, wrought tool steels hardened and/or tempered to 50-70 HRC are common in tooling applications. However, the beneficial mechanical properties of wrought tool steels can be lost by other tooling fabrication techniques. Articles produced with tool steel powders by powder metallurgical techniques, for example, can exhibit dramatic reductions in hardness, tensile strength, toughness and elongation.

SUMMARY

In one aspect, methods of forming tooling articles from tool steel powder compositions via additive manufacturing techniques are described herein. In some embodiments, the tooling articles exhibit properties comparable to wrought tool steels, thereby overcoming disadvantages encountered with prior techniques employing powder alloy compositions. Briefly, a method of forming a tooling article comprises consolidating powder alloy into the tooling article via an additive manufacturing technique and heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC. The tooling article can be formed of an alloy composition comprising 0.2-2 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron. As described herein, the method can further comprise hot isostatic pressing the tooling article prior to the heating treatment.

In another aspect, tooling articles formed according to methods described herein are provided. In some embodiments, a tooling article is produced according to the process comprising consolidating powder alloy into the tooling article via an additive manufacturing technique and heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC.

These and other embodiments are described in greater detail in the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an optical micrograph illustrating microstructure of wrought H13 tool steel that has been heat treated according to industrial techniques.

FIG. 2 is an optical micrograph illustrating the microstructure of an H13 tool steel article formed by SLM followed by hot isostatic pressing and heat treatment according to parameters set forth herein.

FIG. 3 is an optical micrograph illustrating the microstructure of an H13 tool steel article formed by binder jetting followed by hot isostatic pressing and heat treatment according to parameters set forth herein.

DETAILED DESCRIPTION

Embodiments described herein can be understood more readily by reference to the following detailed description and examples and their previous and following descriptions. Elements, apparatus and methods described herein, however, are not limited to the specific embodiments presented in the detailed description and examples. It should be recognized that these embodiments are merely illustrative of the principles of the present invention. Numerous modifications and adaptations will be readily apparent to those of skill in the art without departing from the spirit and scope of the invention.

Methods of forming tooling articles from tool steel powder compositions via additive manufacturing techniques are described herein. A method, in some embodiments, comprises consolidating powder alloy into the tooling article via an additive manufacturing technique and heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC. The tooling article is formed of an alloy composition comprising 0.2-2 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron.

Turning now to specific steps, the powder alloy can be consolidated into the tooling article by several processes depending on the additive manufacturing technique employed. In some embodiments, for example, the powder alloy is consolidated into the tooling article via laser melting according to selective laser melting (SLM). In selective laser melting, an electronic file detailing the design parameters of the tooling article is provided. The laser melting apparatus spreads a layer of powder alloy in a build box. The build box can be under vacuum or inert atmosphere to avoid oxidation and/or other changes to the powder alloy. A laser beam melts and fuses selected regions of the powder alloy layer according to the design parameters of that layer. The build box is subsequently lowered, and a new layer of powder alloy is spread. The layer-by-layer melting and fusion process is repeated according to the electronic file until the tooling article is completed. In other embodiments, the powder alloy is consolidated into the tooling article via laser sintering according to a similar process. The tooling article consolidated via laser melting or laser sintering can be at least 95 percent theoretic density. In other embodiments, the tooling article can be at least 98 percent or at least 99 percent theoretical density.

Alternatively, the powder alloy can be consolidated by an organic binder and sintered to provide the tooling article. For example, binder jetting can provide a green tooling article formed of the powder alloy. In the binder jetting process, an electronic file detailing the design parameters of the green part is provided. The binder jetting apparatus spreads a layer of the powder alloy in a build box. A printhead moves over the powder layer depositing liquid binder according to design parameters for that layer. The layer is dried, and the build box is lowered. A new layer of powder alloy is spread, and the process is repeated until the green article is completed. Liquid binder can comprise any species not inconsistent with the objectives of the present invention. In some embodiment, liquid binder is organic binder and comprises one or more polymeric species. For example, liquid binder can comprise a polyvinylpyrrolidone (PVP)-polyethylene glycol (PEG) composition in polyglycol ether solvent. Other organic binders are also possible including polyethylene glycol monomethyl ether, polyvinyl alcohol, polyvinyl butyral and waxes.

The green article is subsequently sintered to provide the tooling article. Green tooling articles described herein can be sintered under conditions and for time periods to provide sintered articles having the desired density. In some embodiments, for example, green tooling articles are sintered to a density of at least 95 percent theoretical density. The green part can be vacuum sintered or sintered under a hydrogen or argon atmosphere at temperatures of 500°C to 2000°C. In some embodiments, the sintering temperature is 1300°C to 1560°C. Moreover, sintering times can range from 10 minutes to 20 hours. Temperatures can be ramped or stepped and held for various time periods prior to reaching peak sintering temperature. For example, in some embodiments, sintering temperature is stepped to 600-800°C and then to 900-1100°C prior to reaching peak sintering temperature of 1350-1450°C, the peak sintering temperature being below the melting point of the powder alloy composition. Hold times at each of the temperature steps can range from 1-5 hours, in some embodiments. The sintered tooling article, in some embodiments, can be at least 95 percent theoretic density. In other embodiments, the sintered tooling article can be at least 98 percent or at least 99 percent theoretical density. In further embodiments, the sintered tooling article can be fully dense.

Individual layers formed by the additive manufacturing technique during construction of the tooling article can generally range from 5 μm to 500 μm . In some embodiments, individual layers have thickness selected from Table I.

Table I – AM Individual Layer Thickness (μm)

1-500
5-200
5-100
10-80
20-70
5-50

As described herein, the tooling article is formed of an alloy composition comprising 0.2-0.7 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron. Powder alloys enabling these compositional parameters in the tooling article can be employed in the additive manufacturing technique. In some embodiments, powder alloy consolidated into the tooling article by the additive manufacturing process has compositional parameters selected from Table II.

Table II – Powder Alloy Compositions

Powder Alloy	Fe bal.	C wt. %	Mn wt. %	Si wt. %	Cr wt. %	Ni wt. %	Mo wt. %	W wt. %	V wt. %	Co wt. %
1	Fe bal.	0.35-0.45	0.25-0.7	0.8-1.2	3.0-3.75	0-0.3	2-3	0	0.25-0.75	0
2	Fe bal.	0.33-0.43	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.1-1.6	0	0.3-0.6	0
3	Fe bal.	0.3-0.4	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.25-1.75	1-1.7	0-0.5	0
4	Fe bal.	0.32-0.45	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.1-1.75	0	0.8-1.2	0
5	Fe bal.	0.35-0.45	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	0	4-5.25	0	0
6	Fe bal.	0.32-0.45	0.2-0.5	0.2-0.5	4-4.75	0-0.3	0.3-0.55	3.75-4.5	1.75-2.2	4-4.5
7	Fe bal.	0.23-0.36	0.15-0.4	0.15-0.5	3-3.75	0-0.3	0	8.5-10	0.3-0.6	0
8	Fe bal.	0.3-0.4	0.15-0.4	0.15-0.4	1.75-3.75	0.3	0	10-11.75	0.25-0.5	0
9	Fe bal.	0.25-0.35	0.15-0.4	0.15-0.6	11-12.75	0.3	0	11-12.75	0.75-1.25	0
10	Fe bal.	0.42-0.53	0.15-0.4	0.15-0.4	2.5-3.5	0-0.3	0	14-16	0.4-0.6	0
11	Fe bal.	0.22-0.32	0.15-0.4	0.15-0.4	3.75-4.5	0-0.3	0	14-16	0.4-0.6	0
12	Fe bal.	0.45-0.55	0.15-0.4	0.15-0.4	3.75-4.5	0-0.3	0	17.25-19	0.75-1.25	0
13	Fe	0.5-0.6	0-0.5	0.75-1.10	4.75-5.5	0-0.3	1.15-1.65	1-1.5	0	0

	bal.									
14	Fe bal.	0.45-0.55	0-0.5	0.95-1.15	4.75-5.5	1.25-1.75	1.3-1.8	0	0.8-1.4	0
15	Fe bal.	0.3-0.5	0.1-1	0.5-1.5	2.5-6	0-0.3	0.2-3.5	0.5-5.5	0.2-2.5	0-5
16	Fe bal.	0.2-0.6	0.1-0.5	0.1-0.6	1.5-13	0-0.3	0	8-20	0.2-1.5	0
17	Fe bal.	0.7-1.5	0.1-1	0.1-1	3-5	0-0.3	3-12	1-11	0.8-3.5	0-13
18	Fe bal.	0.7-1.5	0.1-1	0.1-1	3-5	0-0.3	3-12	1-11	0.8-3.5	4.5-13
19	Fe bal.	0.75-0.9	0.1-0.5	0.2-0.5	3.25-4.25	0-0.3	8-9.5	1.2-2.2	0.9-1.4	0
20	Fe bal.	0.75-1.1	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.25-5.75	5.25-7	1.5-2.5	0
21	Fe bal.	0.9-1.2	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.5-7	5-7	2-3	0
22	Fe bal.	1-1.3	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.5-6.75	5-7	2.5-4	0
23	Fe bal.	1.2-1.45	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4-5.75	5-6.75	3.5-5	0
24	Fe bal.	0.95-1.1	0.1-0.5	0.2-0.6	3.25-4.25	0-0.3	8-9.3	1.4-2.2	1.5-2.5	0
25	Fe bal.	0.8-1.1	0.1-0.5	0.2-0.5	3.5-5	0-0.3	7.5-9	0	1.6-2.4	0
26	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.25-4.5	0-0.3	7.5-9.25	1.2-2.4	1-1.4	4.3-5.6
27	Fe bal.	0.8-0.95	0.1-0.5	0.1-0.5	3.25-4.25	0-0.3	8.75-10.25	1.1-2.2	1-1.4	7.5-9
28	Fe bal.	0.8-0.95	0.1-0.5	0.2-0.5	3.25-4.25	0-0.3	7.5-9.5	1.3-2.2	1.7-2.5	7.5-9
30	Fe bal.	0.8-0.9	0.1-0.5	0.2-0.5	3.5-4.75	0-0.3	4.3-5.7	5.3-6.9	1.6-2.3	4.3-5.6
31	Fe bal.	0.8-0.9	0.1-0.5	0.2-0.5	3.5-4.75	0-0.3	4.3-5.7	5.4-6.6	1.6-2.3	7.5-9
32	Fe bal.	1-1.2	0.2-0.6	0.1-0.5	3.5-4.75	0-0.3	3-4.5	6-7.2	1.7-2.3	4.5-6
33	Fe bal.	1-1.2	0.1-0.5	0.1-0.7	3.3-4.3	0-0.3	8.8-10.1	1.1-1.9	0.9-1.4	7.6-8.8
34	Fe bal.	1.1-1.3	0.2-0.5	0.1-0.7	3.3-4.3	0-0.3	7.3-8.6	2.2-3.1	1.4-1.8	7.6-8.8
35	Fe bal.	1-1.3	0.2-0.5	0.2-0.6	3.8-4.9	0-0.3	5.8-7.2	4.8-6	1.7-2.3	11-12.3
36	Fe bal.	1.2-1.35	0.2-0.5	0.3-0.7	3.5-4.5	0-0.3	7.8-8.8	1.8-2.3	2.8-3.5	7.5-9
37	Fe bal.	1-1.2	0.1-0.5	0.2-0.5	3.3-4.2	0-0.3	9-10.2	1.25-1.9	1.1-1.4	4.5-5.5
38	Fe bal.	1.4-1.55	0.1-0.5	0.1-0.5	3.3-4.2	0-0.3	4.7-5.6	9.3-10.7	2.6-3.3	7.8-10.2
39	Fe bal.	1.2-1.4	0.1-0.5	0.1-0.5	3.3-4.2	0-0.3	9.8-11.2	5.6-6.7	1.7-2.2	0
40	Fe bal.	0.6-1.7	0.1-1	0.1-1	3-5.5	0-0.3	0-1	10-20	0.5-6	0-15
41	Fe bal.	0.6-0.9	0.1-0.5	0.2-0.5	3.6-4.6	0-0.3	0	17-19	0.8-1.4	0

42	Fe bal.	0.7-1	0.2-0.5	0.2-0.5	3.6-4.6	0-0.3	0-1	17.3-19.2	1.7-2.5	0
43	Fe bal.	0.6-0.9	0.1-0.5	0.2-0.5	3.6-4.6	0-0.3	0.3-1	17.3-19.2	0.7-1.3	4.2-6
44	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.6-5.1	0-0.3	0.4-1.3	17.3-19.2	1.7-2.5	6.8- 9.7
45	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.8-5	0-0.3	0.3-1.1	18.3-21.5	1.3-2.2	10.8- 13.2
46	Fe bal.	0.7-0.9	0.2-0.5	0.2-0.5	3.6-4.6	0-0.3	0.3-1.1	13-15	1.7-2.3	4-6
47	Fe bal.	1.4-1.7	0.1-0.5	0.1-0.5	3.6-5.2	0-0.3	0-1	11.5-13.2	4.3-5.3	4.5- 5.5
48	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.7	3.6-4.6	0-0.3	3.8-4.8	0	0.7-1.3	0
49	Fe bal.	0.8-1	0.1-0.5	0.2-0.7	3.3-4.5	0-3	3.8-5	0.7-1.7	1.6-2.3	0

Powder alloy used in the additive manufacturing technique can have any particle size not inconsistent with the objectives of the present invention. In some embodiments, powder alloy has an average particle size of 10-200 μm . In other embodiments, the powder alloy can have average particles size of 15-150 μm . The powder alloy can also have average particle size less than 10 μm or less than 1 μm , in further embodiments. For certain AM techniques, including binder jetting, the powder alloy may have average particle size of 50 nm to less than 1 μm .

Subsequent to formation by the additive manufacturing technique or process, the tooling article is heat treated to provide the tooling article hardness of at least 35 HRC. Hardness values recited herein are determined according to ASTM E-18-02 Standard Test Method for Rockwell Hardness of Metallic Materials. In some embodiments, hardness of the tooling article after heat treatment has a value selected from Table III.

Table III – Hardness of Heat Treated Tooling Article (HRC)

40-50
40-60
45-55
50-60
50-57

Heat treating the tooling article, in some embodiments, comprises the steps of annealing, hardening and at least one tempering cycle. In some embodiments, two or three tempering cycles can be part of heat treating the tooling article. Temperatures and times of various steps of the heat treatment can be selected according to several considerations including but not limited to

the tool steel alloy composition, the intended use and operating environment of the tooling article as well as size and/or dimensions of the tooling article. In some embodiments, peak annealing temperature is in the range of 540°C to 900°C. For example, peak annealing temperature can range from 815°C to 900°C, in some embodiments. Annealing times can generally range from 1 to 15 hours, wherein the tooling article experiences peak annealing temperatures for a time period of 0.5-3 hours. After holding at peak temperature, the tooling article can be cooled at any desired rate. In some embodiments, the tooling article is cooled to 600-700°C for 1-2 hours and slow cooled to 500°C for stress relieving prior to the hardening step of the heat treatment. Annealing temperatures, times and cooling rates can be dependent on several considerations including, but not limited to, alloy composition of the tooling article and dimensions of the tooling article.

Subsequent to annealing, the tooling article can be hardened. Hardening can generally include one or more preheating steps. In some embodiments, the tooling article is heated to 450-570°C and then to 800-900°C. After the preheating steps, the tooling article experiences peak hardening temperature of 1000-1300°C followed by quenching. In some embodiments, peak hardening temperature occurs in a range selected from Table IV.

Table IV – Peak Hardening Temperature (°C)

980-1210
1090-1300
1175-1300
1000-1050
1000-1020

Quenching can occur in neutral salt baths, in some embodiments. Total time for hardening can be 1-4 hours with exposure to peak temperature for a time period of 0.5-2 hours. Following hardening, the tooling article can undergo at least one tempering cycle. Tempering cycles are conducted at 400-820°C for individual time periods of 1-3 hours. In some embodiments, one or more tempering cycles are conducted at temperatures selected from Table V.

Table V – Tempering Temperatures (°C)

500-820
500-715
400-650

520-620

In some embodiments, the annealing step is skipped and the heat treatment comprises hardening and at least one annealing cycle.

As described herein, the tooling article can be subjected to hot isostatic pressing (HIP) prior to heat treating. Hot isostatic pressing can be administered under inert atmosphere for up to 4 hours at pressures of 3 MPa to 250 MPa and temperatures of 1150°C to 1400°C. In some embodiments, for example, pressures of 50 to 150 MPa and temperatures of 1150°C to 1220°C are employed in hot isostatic pressing of the tooling article. Peak hot isostatic pressing temperatures are generally less than the melting point of the alloy composition. Temperature, time and pressure of hot isostatic pressing can be selected according to several considerations including, but not limited to, tool steel alloy composition, porosity of the tooling article prior to pressing and desired porosity of the tool article post hot isostatic pressing. In some embodiments, hot isostatic pressing conditions are administered to render the tooling article at least 98 percent theoretical density prior to heat treating. Hot isostatic pressing conditions can be set to ensure the tooling article is at least 99 percent theoretical density prior to heat treating. In some embodiments, the tooling article is fully dense subsequent to hot isostatic pressing. Tooling articles formed by selective laser melting, selective laser sintering and/or binder jetting and sintering can be subjected to hot isostatic pressing prior to heat treating.

In some embodiments, hot isostatic pressing can be combined with hardening in a single step. The tooling article, for example, can be hot isostatically pressed under conditions described herein. Subsequent to completion of hot isostatic pressing, the hardening cycle begins without cooling the tooling article to room temperature or slightly above room temperature. In some embodiments, for example, temperatures are cooled 850-900°C subsequent to hot isostatic pressing to begin hardening. After cooling to 850-900°C, the tooling article experiences peak hardening temperature of 1000-1020°C followed by quenching. Alternatively, hot isostatic pressing temperature can be extended into the hardening cycle followed by a brief hold at 1000-1020°C and then quenching. One or more tempering cycles can follow the combined hot isostatic pressing and hardening.

In addition to high hardness, heat treating can enhance tensile strength and fracture toughness of the tooling article. The heat treated tooling article can have tensile strength of at

least 1200 MPa. Tensile strength values recited herein are determined according to ASTM E8-15a – Standard Test Methods for Tension Testing of Metallic Materials. In some embodiments, the heat treated tooling article has tensile strength selected from Table VI.

Table VI – Tensile Strength of Heat Treated Tooling Article (MPa)

1200-2200
1500-2200
1700-2100
1800-2000
1850-2200
1900-2200
2000-2200

A heat treated tooling article can also exhibit fracture toughness of at least 2 J. Fracture toughness values recited herein are determined according ASTM E23-16b Standard Test Method for Notched Bar Impact testing of Metallic Materials. In some embodiments, the heat treated tooling article has tensile strength selected from Table VII.

Table VII – Fracture Toughness of Heat Treated Tooling Article (J)

2-25
2-15
2-10
3-8
4-10
7-12
8-15
10-25

As described herein, the heat treated tooling article is formed of an alloy composition comprising 0.2-0.7 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-5 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron. In some embodiments, the heat treated tooling article is formed of an alloy composition comprising 0.3-0.5 weight percent carbon, 0.1-1 weight percent manganese, 0.5-1.5 weight percent silicon, 2.5-6 weight percent chromium, 0-0.3 weight percent nickel, 0.2-3.5 weight percent molybdenum, 0.5-5.5 weight percent tungsten and 0.2-2.5 weight percent vanadium and the balance iron. In other embodiments, a heat treated tooling article is formed of an alloy

composition comprising 0.2-0.6 weight percent carbon, 0.1-0.5 weight percent manganese, 0.1-0.6 weight percent silicon, 1.5-13 weight percent chromium, 0-0.3 weight percent nickel, 8-20 weight percent tungsten, 0.2-1.5 weight percent vanadium and the balance iron. In some embodiments, a heat treated tooling article is formed of an alloy composition comprising 0.7-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5 weight percent chromium, 0-0.3 weight percent nickel, 3-12 weight percent molybdenum, 1-11 weight percent tungsten, 0.8-3.5 weight percent vanadium, 0-13 weight percent cobalt and the balance iron. Moreover, a heated treated tooling article can be formed of an alloy composition comprising 0.6-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5.5 weight percent chromium, 0-0.3 weight percent nickel, 0-1.5 weight percent molybdenum, 10-20 weight percent tungsten, 0.5-6 weight percent vanadium, 0-15 weight percent cobalt and the balance iron. In additional embodiments, heat treated tooling articles may be formed of an alloy composition selected from Table VIII.

Table VIII – Alloy Compositions of Heat Treated Tooling Article

Alloy Comp	Fe bal.	C wt. %	Mn wt%	Si wt%	Cr wt. %	Ni wt. %	Mo wt. %	W wt. %	V wt. %	Co wt. %
1	Fe bal.	0.35-0.45	0.25-0.7	0.8-1.2	3.0-3.75	0-0.3	2-3	0	0.25-0.75	0
2	Fe bal.	0.33-0.43	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.1-1.6	0	0.3-0.6	0
3	Fe bal.	0.3-0.4	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.25-1.75	1-1.7	0-0.5	0
4	Fe bal.	0.32-0.45	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	1.1-1.75	0	0.8-1.2	0
5	Fe bal.	0.35-0.45	0.2-0.5	0.8-1.2	4.75-5.5	0-0.3	0	4-5.25	0	0
6	Fe bal.	0.32-0.45	0.2-0.5	0.2-0.5	4-4.75	0-0.3	0.3-0.55	3.75-4.5	1.75-2.2	4-4.5
7	Fe bal.	0.23-0.36	0.15-0.4	0.15-0.5	3-3.75	0-0.3	0	8.5-10	0.3-0.6	0
8	Fe bal.	0.3-0.4	0.15-0.4	0.15-0.4	1.75-3.75	0.3	0	10-11.75	0.25-0.5	0
9	Fe bal.	0.25-0.35	0.15-0.4	0.15-0.6	11-12.75	0.3	0	11-12.75	0.75-1.25	0
10	Fe bal.	0.42-0.53	0.15-0.4	0.15-0.4	2.5-3.5	0-0.3	0	14-16	0.4-0.6	0
11	Fe bal.	0.22-0.32	0.15-0.4	0.15-0.4	3.75-4.5	0-0.3	0	14-16	0.4-0.6	0
12	Fe bal.	0.45-0.55	0.15-0.4	0.15-0.4	3.75-4.5	0-0.3	0	17.25-19	0.75-1.25	0
13	Fe bal.	0.5-0.6	0-0.5	0.75-1.10	4.75-5.5	0-0.3	1.15-1.65	1-1.5	0	0

14	Fe bal.	0.45-0.55	0-0.5	0.95-1.15	4.75-5.5	1.25-1.75	1.3-1.8	0	0.8-1.4	0
15	Fe bal.	0.3-0.5	0.1-1	0.5-1.5	2.5-6	0-0.3	0.2-3.5	0.5-5.5	0.2-2.5	0-5
16	Fe bal.	0.2-0.6	0.1-0.5	0.1-0.6	1.5-13	0-0.3	0	8-20	0.2-1.5	0
17	Fe bal.	0.7-1.5	0.1-1	0.1-1	3-5	0-0.3	3-12	1-11	0.8-3.5	0-13
18	Fe bal.	0.7-1.5	0.1-1	0.1-1	3-5	0-0.3	3-12	1-11	0.8-3.5	4.5- 13
19	Fe bal.	0.75-0.9	0.1-0.5	0.2-0.5	3.25-4.25	0-0.3	8-9.5	1.2-2.2	0.9-1.4	0
20	Fe bal.	0.75-1.1	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.25-5.75	5.25-7	1.5-2.5	0
21	Fe bal.	0.9-1.2	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.5-7	5-7	2-3	0
22	Fe bal.	1-1.3	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4.5-6.75	5-7	2.5-4	0
23	Fe bal.	1.2-1.45	0.1-0.5	0.2-0.5	3.5-5	0-0.3	4-5.75	5-6.75	3.5-5	0
24	Fe bal.	0.95-1.1	0.1-0.5	0.2-0.6	3.25-4.25	0-0.3	8-9.3	1.4-2.2	1.5-2.5	0
25	Fe bal.	0.8-1.1	0.1-0.5	0.2-0.5	3.5-5	0-0.3	7.5-9	0	1.6-2.4	0
26	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.25-4.5	0-0.3	7.5-9.25	1.2-2.4	1-1.4	4.3- 5.6
27	Fe bal.	0.8-0.95	0.1-0.5	0.1-0.5	3.25-4.25	0-0.3	8.75- 10.25	1.1-2.2	1-1.4	7.5-9
28	Fe bal.	0.8-0.95	0.1-0.5	0.2-0.5	3.25-4.25	0-0.3	7.5-9.5	1.3-2.2	1.7-2.5	7.5-9
30	Fe bal.	0.8-0.9	0.1-0.5	0.2-0.5	3.5-4.75	0-0.3	4.3-5.7	5.3-6.9	1.6-2.3	4.3- 5.6
31	Fe bal.	0.8-0.9	0.1-0.5	0.2-0.5	3.5-4.75	0-0.3	4.3-5.7	5.4-6.6	1.6-2.3	7.5-9
32	Fe bal.	1-1.2	0.2-0.6	0.1-0.5	3.5-4.75	0-0.3	3-4.5	6-7.2	1.7-2.3	4.5-6
33	Fe bal.	1-1.2	0.1-0.5	0.1-0.7	3.3-4.3	0-0.3	8.8-10.1	1.1-1.9	0.9-1.4	7.6- 8.8
34	Fe bal.	1.1-1.3	0.2-0.5	0.1-0.7	3.3-4.3	0-0.3	7.3-8.6	2.2-3.1	1.4-1.8	7.6- 8.8
35	Fe bal.	1-1.3	0.2-0.5	0.2-0.6	3.8-4.9	0-0.3	5.8-7.2	4.8-6	1.7-2.3	11- 12.3
36	Fe bal.	1.2-1.35	0.2-0.5	0.3-0.7	3.5-4.5	0-0.3	7.8-8.8	1.8-2.3	2.8-3.5	7.5-9
37	Fe bal.	1-1.2	0.1-0.5	0.2-0.5	3.3-4.2	0-0.3	9-10.2	1.25-1.9	1.1-1.4	4.5- 5.5
38	Fe bal.	1.4-1.55	0.1-0.5	0.1-0.5	3.3-4.2	0-0.3	4.7-5.6	9.3-10.7	2.6-3.3	7.8- 10.2
39	Fe bal.	1.2-1.4	0.1-0.5	0.1-0.5	3.3-4.2	0-0.3	9.8-11.2	5.6-6.7	1.7-2.2	0
40	Fe bal.	0.6-1.7	0.1-1	0.1-1	3-5.5	0-0.3	0-1.5	10-20	0.5-6	0-15
41	Fe bal.	0.6-0.9	0.1-0.5	0.2-0.5	3.6-4.6	0-0.3	0	17-19	0.8-1.4	0
42	Fe	0.7-1	0.2-0.5	0.2-0.5	3.6-4.6	0-0.3	0-1	17.3-19.2	1.7-2.5	0

	bal.									
43	Fe bal.	0.6-0.9	0.1-0.5	0.2-0.5	3.6-4.6	0-0.3	0.3-1	17.3-19.2	0.7-1.3	4.2-6
44	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.6-5.1	0-0.3	0.4-1.3	17.3-19.2	1.7-2.5	6.8- 9.7
45	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.5	3.8-5	0-0.3	0.3-1.1	18.3-21.5	1.3-2.2	10.8- 13.2
46	Fe bal.	0.7-0.9	0.2-0.5	0.2-0.5	3.6-4.6	0-0.3	0.3-1.1	13-15	1.7-2.3	4-6
47	Fe bal.	1.4-1.7	0.1-0.5	0.1-0.5	3.6-5.2	0-0.3	0-1	11.5-13.2	4.3-5.3	4.5- 5.5
48	Fe bal.	0.7-0.9	0.1-0.5	0.2-0.7	3.6-4.6	0-0.3	3.8-4.8	0	0.7-1.3	0
49	Fe bal.	0.8-1	0.1-0.5	0.2-0.7	3.3-4.5	0-3	3.8-5	0.7-1.7	1.6-2.3	0

FIG. 1 is an optical micrograph illustrating microstructure of wrought H13 tool steel that has been heat treated according to industrial techniques. The wrought H13 tool steel of FIG. 1 exhibited the properties listed in Table IX.

Table IX – H13 Tool Steel Properties

Forming Direction	Forming Operation	Hardness (HRC)	Strength (MPa)	Elongation (%)	Toughness (J)
Parallel	Wrought	52	1882	10	7
Perpendicular	SLM	52	1956	6	3
Parallel	Binder Jetting	54	1968	4	9

Articles were also formed of the same H13 tool steel composition using the AM techniques of SLM and binder jetting according to the methods described herein. FIG. 2 is an optical micrograph illustrating the microstructure of an H13 tool steel article formed by SLM followed by hot isostatic pressing and heat treatment according to parameters set forth herein. The SLM-HIP-heat treated H13 tool steel exhibited the properties listed in Table IX. Moreover, FIG. 3 is an optical micrograph illustrating the microstructure of an H13 tool steel article formed by binder jetting followed by hot isostatic pressing and heat treatment according to parameters set forth herein. The binder jet-HIP-heat treated H13 tool steel exhibited the properties listed in Table IX. As provided in Table IX, the H13 tool steel articles formed by SLM and binder jetting followed by HIP and heat treatment have properties comparable to or exceeding wrought H13 tool steel.

Accordingly, various tooling articles of complex shape and/or structure can be formed from tool steel compositions disclosed herein without significant losses in mechanical properties. Tooling articles made according to methods described herein can find application in any desired

field. Moreover, the additive manufacturing processes employed in the present methods can enable tooling structures and architectures not possible with current tooling fabrication techniques. Tooling articles described herein, for example, can be rotary tooling apparatus including drills, drill bodies, hydraulic chucks, reducer sleeves for hydraulic chucks, reamer heads, reamer shanks, milling cutters, collets, expansion sleeves, adapters and shrink fit extensions, cutting tools, clamps, boring bars and tool holders.

In another aspect, tooling articles formed according to methods described herein are provided. In some embodiments, a tooling article is produced according to the process comprising consolidating powder alloy into the tooling article via an additive manufacturing technique and heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC. Heat treating the tooling article, in some embodiments, comprises the steps of annealing, hardening and at least one tempering cycle, as described above. In some embodiments, two or three tempering cycles can be part of heat treating the tooling article. Temperatures and times of various steps of the heat treatment can be selected according to several considerations including but not limited to the tool steel alloy composition, the intended use and operating environment of the tooling article as well as size and/or dimensions of the tooling article. A tooling article produced according to methods described herein can have any compositional, microstructural and/or mechanical properties described above. Moreover, processes employed to form the tooling articles can include any combination of process steps described herein.

CLAIMS

1. A method of forming a tooling article comprising:
consolidating powder alloy into the tooling article via an additive manufacturing technique; and
heat treating the tooling article to provide the tooling article hardness of 35 to 65 HRC, wherein the tooling article is formed of an alloy composition comprising 0.2-2 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron.
2. The method of claim 1, wherein the alloy composition comprises 0.3-0.5 weight percent carbon, 0.1-1 weight percent manganese, 0.5-1.5 weight percent silicon, 2.5-6 weight percent chromium, 0-0.3 weight percent nickel, 0.2-3.5 weight percent molybdenum, 0.5-5.5 weight percent tungsten and 0.2-2.5 weight percent vanadium and the balance iron.
3. The method of claim 1, wherein the alloy composition comprises 0.2-0.6 weight percent carbon, 0.1-0.5 weight percent manganese, 0.1-0.6 weight percent silicon, 1.5-13 weight percent chromium, 0-0.3 weight percent nickel, 8-20 weight percent tungsten, 0.2-1.5 weight percent vanadium and the balance iron.
4. The method of claim 1, wherein the alloy composition comprises 0.7-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5 weight percent chromium, 0-0.3 weight percent nickel, 3-12 weight percent molybdenum, 1-11 weight percent tungsten, 0.8-3.5 weight percent vanadium, 0-13 weight percent cobalt and the balance iron.
5. The method of claim 1, wherein the alloy composition comprises 0.6-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5.5 weight percent chromium, 0-0.3 weight percent nickel, 0-1.5 weight percent molybdenum, 10-20 weight percent tungsten, 0.5-6 weight percent vanadium, 0-15 weight percent cobalt and the balance iron.

6. The method of claim 1, wherein the tooling article exhibits elongation of at least 2% subsequent to the heat treating.
7. The method of claim 1, wherein the tooling article exhibits elongation of 3-20% subsequent to the heat treating.
8. The method of claim 1, wherein the tooling article exhibits fracture toughness of at least 2 J subsequent to heat treating.
9. The method of claim 1, wherein the tooling article exhibits fracture toughness of 5-25 J subsequent to heat treating.
10. The method of claim 1, wherein the tooling article exhibits tensile strength of 1200-2200 MPa subsequent to heat treating.
11. The method of claim 1, wherein the tooling article exhibits tensile strength of 1900-2000 MPa.
12. The method of claim 11, wherein the tooling article has hardness of 50-60 HRC.
13. The method of claim 1 further comprising hot isostatic pressing the tooling article prior to heating treating.
14. The method of claim 13, wherein the tooling article is at least 95 percent theoretical density prior to hot isostatic pressing.
15. The method of claim 13, wherein the tooling article has hardness of 50-65 HRC.
16. The method of claim 1, wherein the tooling article is at least 98 percent theoretical density prior to the heat treating

17. The method of claim 1, wherein layers provided by the additive manufacturing technique during formation of the tooling article have individual thickness of 5 μm to 500 μm .
18. The method of claim 1, wherein the powder alloy is consolidated into the tooling article via laser sintering of the powder alloy.
19. The method of claim 1, wherein the powder alloy is consolidated into the tooling article via laser melting of the powder alloy.
20. The method of claim 1, wherein powder alloy is consolidated via an organic binder and sintered to provide the tooling article.
21. The method of claim 20, wherein the tooling article has hardness of 50-60 HRC and tensile strength of 1800-2200 MPa.
22. The method of claim 1, wherein heat treating comprises annealing, hardening and at least one tempering cycle.
23. The method of claim 22, wherein peak temperature of the annealing is 850°C to 900°C.
24. The method of claim 22, wherein hardening occurs at a peak temperature of 1000°C to 1020°C followed by quenching.
25. The method of claim 24, wherein the at least one tempering cycle occurs at a temperature of 530°C to 570°C.
26. The method of claim 1, wherein the heat treating consists essentially of hardening and at least one tempering cycle.
27. The method of claim 13, the heat treating consists essentially of hardening and at least one tempering cycle.

28. The method of claim 27, wherein the hot isostatic pressing and hardening are combined into a single step.

29. A tooling article produced according to the process comprising:
consolidating powder alloy into the tooling article via an additive manufacturing technique; and
heat treating the tooling article to provide the tooling article hardness of 50 to 60 HRC and elongation of 3-15 percent, wherein the tooling article is formed of an alloy composition comprising 0.2-2 weight percent carbon, 0-1 weight percent manganese, 0-1.5 weight percent silicon, 0-0.3 weight percent nickel, 0-15 weight percent cobalt, at least two of chromium, molybdenum, tungsten and vanadium in a combined amount of 5-25 weight percent and the balance iron.

30. The tooling article of claim 29, wherein the alloy composition comprises 0.3-0.5 weight percent carbon, 0.1-1 weight percent manganese, 0.5-1.5 weight percent silicon, 2.5-6 weight percent chromium, 0-0.3 weight percent nickel, 0.2-3.5 weight percent molybdenum, 0.5-5.5 weight percent tungsten and 0.2-2.5 weight percent vanadium and the balance iron.

31. The tooling article of claim 29, wherein the alloy composition comprises 0.2-0.6 weight percent carbon, 0.1-0.5 weight percent manganese, 0.1-0.6 weight percent silicon, 1.5-13 weight percent chromium, 0-0.3 weight percent nickel, 8-20 weight percent tungsten, 0.2-1.5 weight percent vanadium and the balance iron.

32. The tooling article of claim 29, wherein the alloy composition comprises 0.7-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5 weight percent chromium, 0-0.3 weight percent nickel, 3-12 weight percent molybdenum, 1-11 weight percent tungsten, 0.8-3.5 weight percent vanadium, 0-13 weight percent cobalt and the balance iron.

33. The tooling article of claim 29, wherein the alloy composition comprises 0.6-1.5 weight percent carbon, 0.1-1 weight percent manganese, 0.1-1 weight percent silicon, 3-5.5 weight

percent chromium, 0-0.3 weight percent nickel, 0-1.5 weight percent molybdenum, 10-20 weight percent tungsten, 0.5-6 weight percent vanadium, 0-15 weight percent cobalt and the balance iron.

34. The tooling article of claim 29 having fracture toughness of 5-25 J subsequent to the heat treating.

35. The tooling article of claim 29 having tensile strength of 1900-2200 MPa.

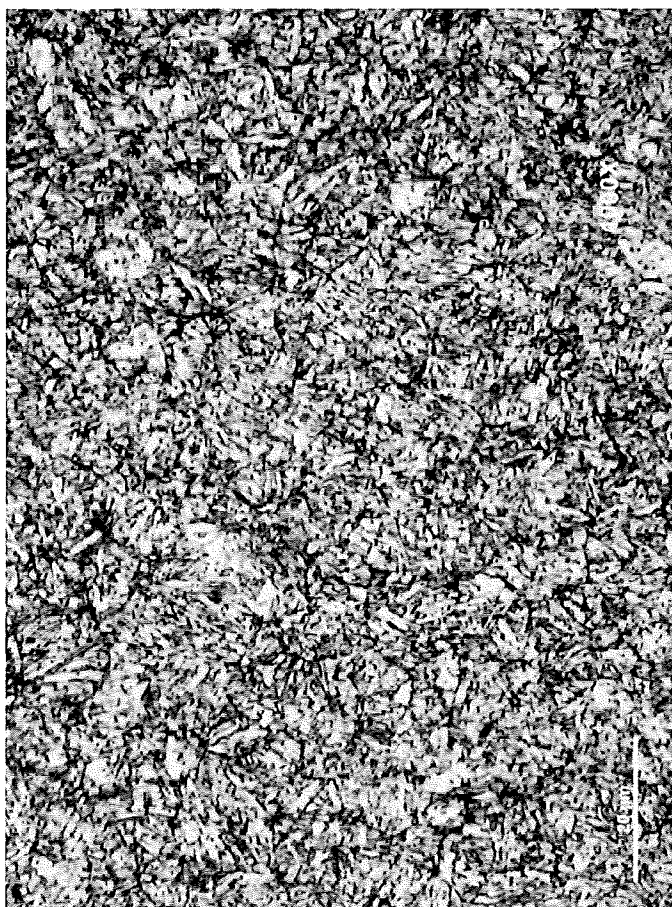


FIG. 1

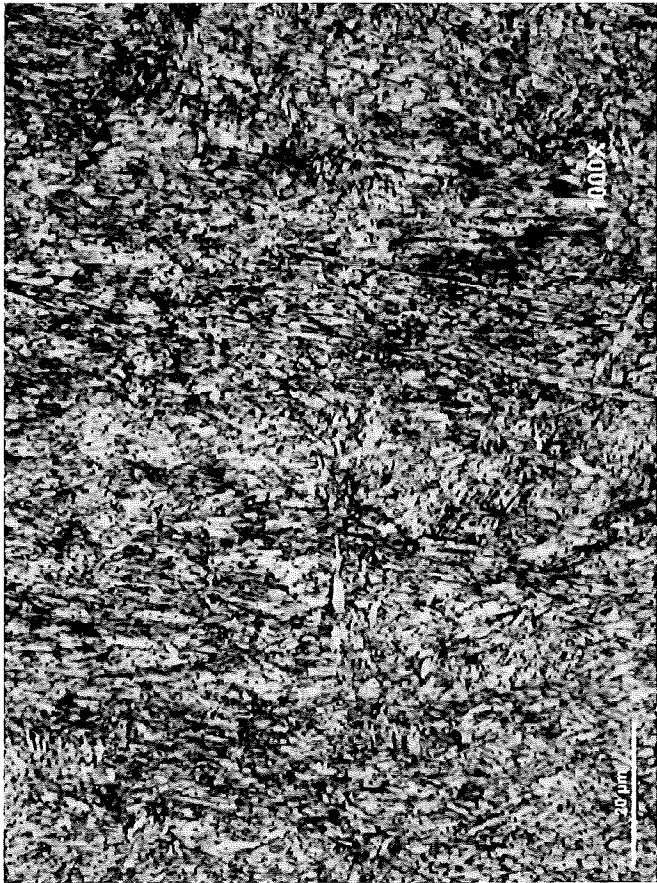


FIG. 2

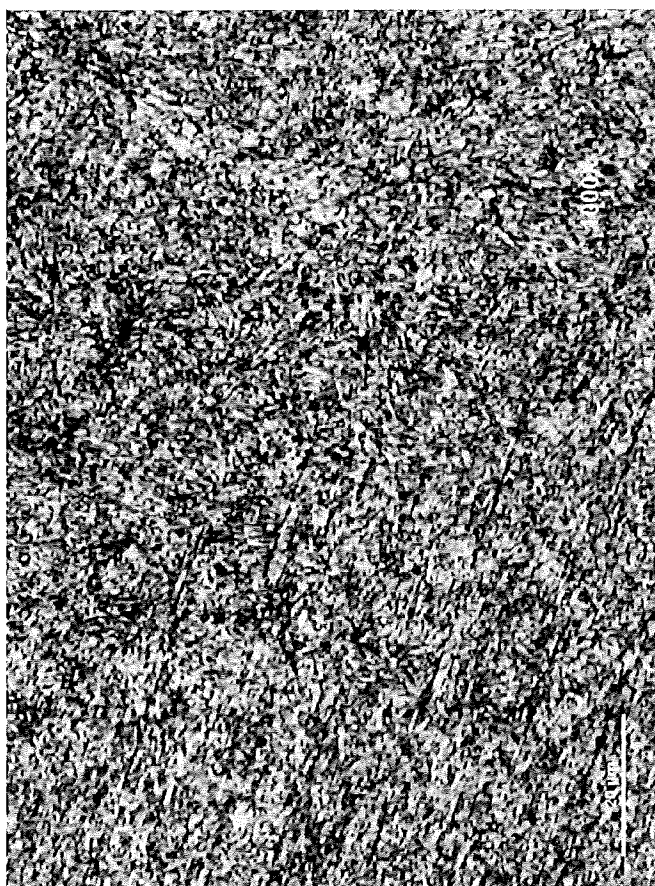


FIG. 3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/044962**A. CLASSIFICATION OF SUBJECT MATTER****B22F 3/24(2006.01)i, B22F 3/105(2006.01)i, B22F 5/00(2006.01)i, C22C 38/08(2006.01)i, C22C 38/12(2006.01)i, C22C 38/44(2006.01)i, C22C 38/46(2006.01)i, B33Y 10/00(2015.01)i, B33Y 70/00(2015.01)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)

B22F 3/24; B22F 1/00; B22F 3/105; B22F 3/15; B23B 27/14; C22C 19/03; C22C 38/00; C22C 38/12; C22C 38/46; C22C 38/60; B22F 5/00; C22C 38/08; C22C 38/44; B33Y 10/00; B33Y 70/00

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: additive manufacturing, tensile strength, hardness, elongation, fracture toughness, heat treatment, annealing, quenching, tempering, hardening

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016-0215375 A1 (DAIDO STEEL CO., LTD.) 28 July 2016 See paragraphs [0008]-[0009], [0050]-[0070] and claim 1.	1-12, 17-21, 29-35
Y		13-16, 22-28
Y	US 2016-0332236 A1 (STOYANOV, PANTCHO) 17 November 2016 See paragraph [0019] and claim 10.	13-16, 27-28
Y	WO 2016-099390 A1 (UDDEHOLMS A.B.) 23 June 2016 See page 10, lines 5-12.	22-28
A	JP 2014-105373 A (CANON INC.) 09 June 2014 See paragraphs [0020], [0035]-[0046] and claims 1-5.	1-35
A	JP 06-256897 A (SUMITOMO METAL IND., LTD.) 13 September 1994 See paragraph [0023] and claim 1.	1-35



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

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"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

22 November 2018 (22.11.2018)

Date of mailing of the international search report

22 November 2018 (22.11.2018)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/044962

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