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(54) **SINGLE-PIECE EXTENDED LAMINAR FLOW INLET LIPSKIN**

(57) Methods are disclosed for forming metal work-pieces made from a heat-treatable metal that has been shaped and tempered according to specified protocols that facilitate formation of large contoured unitary metal

structures having welds that are retained in the finished structure, and finished metal structures made according to such methods.

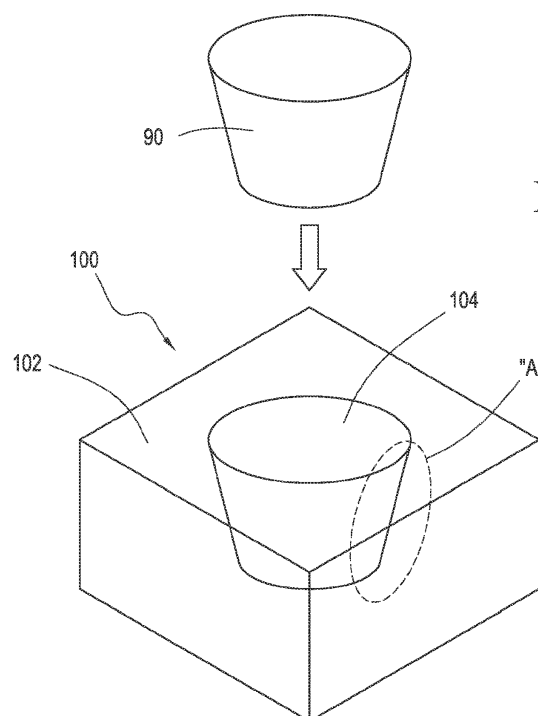


FIG. 10

EP 3 406 750 A1

Description

[0001] The present invention relates generally to the field of fabricating metal structures. More specifically, the present disclosure of the invention relates to manufacturing a metal structure or component comprising shaping the metal structure or component while in specified heat-treatment conditions, and introducing a friction stir weld into the metal structure or component with the friction stir weld being maintained in the finished component. Still more specifically, the present disclosure of the invention relates to the manufacture of components and assemblies used to make lipskins for aircraft engine nacelles.

[0002] Laminar flow is the smooth, uninterrupted flow of air over the contour of wings, fuselages, or other parts of an aircraft in flight. Laminar flow is most often found at the front of a streamlined body. If the smooth flow of air is interrupted, turbulence is created, which can result in drag acting on the body. Increases in deviation away from optimal laminar flow at aircraft surfaces can result in an increase in fuel consumption, and therefore a commensurate increase in cost of operation.

[0003] Many known aircraft engines, for example jet engines and turbofan jet engines are surrounded by an annular, barrel-shaped nacelle. At least some known nacelles include a lipskin at the leading edge, or inlet, of the nacelle. While some large structures have been formed in a unitary fashion to reduce transverse weld lines or other couplings that could impact laminar flow, such unitary forming processes (e.g. spin-forming, etc.) are time-consuming, expensive and difficult or impractical in terms of size limitations for producing spin-formed lipskins of a desired, large size. Further, spin-formed lipskins may exhibit undesirable waves or ripples that could adversely affect laminar flow, leading to undesirable turbulence, increased fuel consumption, and/or increased cost of operation.

[0004] In attempts to solve the potential restrictiveness of spin-forming or other processes, some known methods for lipskin construction for aircraft engine nacelles have included the introduction of friction stir welds during lipskin construction, followed by removal of the welds during shaping, finishing, and other manufacturing processes, and further followed by the introduction of additional coupling components and parts (e.g. doublers). However, additional processing steps are often time-consuming, and the addition of parts in an aircraft assembly is often undesirable due to the commensurate increase in weight, assembly complexity, manufacturing time, additional inspections, etc., all of which can increase the overall cost of operating and maintaining the aircraft.

[0005] Aspects of the present disclosure of the present invention are directed to methods for forming metal lipskins for engine nacelles and the lipskins and nacelles so formed, as well as structures comprising the nacelles that comprise the lipskins, where the introduction of at least one "fly-away" weld (including without limitation,

one friction stir weld), and forming processes of a metal lipskin occurs in specified conditions of the metal such that the "fly-away" weld is maintained in the finished lipskin.

[0006] An aspect of the present disclosure of the invention is directed to a method according to the invention for making a heat-treated structure formed of metal, the method preferably comprising performing a first heat-treating process on a roughly-shaped metal workpiece in an annealed condition, to transition the roughly-shaped metal workpiece from an annealed condition to a first hardened condition, with the roughly-shaped metal workpiece comprising at least one friction stir weld; forming the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the first hardened condition, with the shaped metal workpiece comprising one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece; and performing a second heat-treating process on the shaped workpiece to transition the shaped metal workpiece from the first hardened condition to a second hardened condition.

[0007] The step of forming the roughly-shaped metal workpiece into a shaped metal workpiece preferably comprises using at least one forming process to shape the roughly-shaped metal workpiece into the shaped metal workpiece.

[0008] The shaped metal workpiece can be a near-finally-shaped metal workpiece, with a method preferably further comprising forming the near-finally-shaped metal workpiece into the finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

[0009] The shaped metal workpiece can comprise a finally-shaped metal workpiece, with a method preferably further comprising using a plurality of forming processes to shape the roughly-shaped metal workpiece into the finally-shaped metal workpiece.

[0010] The forming process preferably includes a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process and combinations thereof.

[0011] The disclosure is also directed to a method according to the invention for making a heat-treated structure formed of metal, the method preferably comprising performing a first heat-treating process on a roughly-shaped metal workpiece to transition the roughly-shaped metal workpiece into a first hardened condition to produce a first-hardened metal workpiece, the roughly-shaped metal workpiece being in an annealed condition and comprising at least one friction stir weld; performing a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened metal workpiece to a second hardened condition to produce a second-hardened metal workpiece; forming the second-hardened metal workpiece into a shaped metal workpiece, said shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped

metal workpiece.

[0012] The steps of performing the first heat-treating process and second heat-treating process preferably further comprise performing at least one age-hardening process on the roughly-shaped metal workpiece in the first hardened condition; and performing at least one age-hardening process on the shaped metal workpiece in the second hardened condition, wherein the first hardened condition comprises a first age-hardened condition and the second hardened condition comprises a second age-hardened condition.

[0013] The shaped metal workpiece preferably comprises a friction stir weld.

[0014] The shaped metal workpiece can comprise a near-finally-shaped workpiece, the method preferably further comprising forming the near-finally-shaped metal workpiece into a finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

[0015] The shaped metal workpiece can comprise a near-finally-shaped metal workpiece the method preferably further comprising the step of using a plurality of forming processes to shape the near-finally-shaped metal workpiece into the finally-shaped workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

[0016] The shaped metal workpiece can comprise a near-finally-shaped metal workpiece and preferably further comprises the step of using at least one explosion forming process to shape the near-finally-shaped metal workpiece into the finally-shaped workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

[0017] Preferably before the step of performing a first heat-treating process on a roughly-shaped metal workpiece, a metal sheet is preferably formed into the roughly-shaped metal workpiece while the metal sheet is in the annealed condition.

[0018] The step of forming a metal sheet preferably further comprises rolling the metal sheet into the roughly-shaped metal workpiece.

[0019] The step of forming a metal sheet preferably further comprises forming the metal sheet, while the metal sheet is in the annealed condition; and using at least one forming process forming process to form the metal sheet, with the forming process including a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process or combinations thereof.

[0020] The step of forming a metal sheet into the roughly-shaped metal workpiece while the metal sheet is in the annealed condition preferably further comprises forming the sheet into a conical or frusto-conical metal workpiece.

[0021] The steps of performing the first heat-treating process and second heat-treating process preferably comprise performing at least one age-hardening process on the roughly-shaped metal workpiece in the first hardened condition; and/or preferably performing at least one

age-hardening process on the on the shaped metal workpiece in the second hardened condition; wherein the first hardened condition comprises a first age-hardened condition, and the second hardened condition comprises a second age-hardened condition.

[0022] The step of performing a first heat-treating process preferably comprises performing a natural aging process on the roughly-shaped metal workpiece.

[0023] The step of performing a first heat-treating process preferably comprises solution heat-treating the metal and natural aging the roughly-shaped metal workpiece.

[0024] The step of performing a first heat-treating process preferably further comprising performing a T-4 heat-treating process on the roughly-shaped metal workpiece.

[0025] Performing a second heat-treating process preferably comprises performing an artificial aging process on the shaped metal workpiece.

[0026] Performing the second heat-treating process preferably comprises performing a solution heat-treating process on the shaped metal workpiece; and performing an artificial aging process on the shaped metal workpiece.

[0027] Performing the second heat-treating process preferably comprises performing a T-6 heat-treating process.

[0028] Forming the roughly-shaped metal workpiece into the shaped workpiece preferably comprises using at least one forming process selected from the group consisting of a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; and an explosion forming process to shape the roughly-shaped metal workpiece into the shaped workpiece.

[0029] The shaped workpiece can be a near-finally-shaped metal workpiece, the method preferably further comprising forming the near-finally-shaped metal workpiece into a finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

[0030] The shaped metal workpiece can be a finally-shaped metal workpiece and further preferably comprises forming the roughly-shaped metal workpiece into a finally-shaped metal workpiece using at least one forming process including a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process and combinations thereof.

[0031] A further aspect of the present disclosure of the invention is directed to a metal structure according to the present invention that is formed according to any of the aforementioned methods.

[0032] The metal preferably comprises aluminum or an aluminum alloy.

[0033] The metal structure can be annularly-shaped.

[0034] The metal structure is preferably a lipskin for use in an engine nacelle assembly.

[0035] In another aspect of the invention, the metal structure is a heat-treated structure in the second hard-

ened condition.

[0036] According to another aspect of the invention, the present disclosure is further directed to a metal structure for use on an aircraft comprising a metal that has been heat-treated, with the metal structure comprising at least one friction stir weld.

[0037] A further aspect of the present disclosure of the invention is directed to a nacelle assembly according to the invention for use on an aircraft, the assembly comprising a lipskin made from a metal that has been heat-treated, with the lipskin comprising at least one friction stir weld.

[0038] A further aspect of the present application is directed to structures comprising the lipskin made from a metal that has been heat-treated, with the lipskin comprising at least one friction stir weld, the structures including, without limitation, manned and unmanned aircraft, manned and unmanned rotorcraft, manned and unmanned spacecraft, manned and unmanned terrestrial vehicles, manned and unmanned surface water borne vehicles, manned and unmanned sub-surface water-borne vehicles, rockets, missiles, etc.

[0039] The disclosure also includes the following examples:

1. A method for making a heat-treated structure formed of metal such as an engine nacelle for an aircraft, which structure retains a weld, preferably a friction stir weld, the method comprising:

performing a first heat-treating process on a roughly-shaped metal workpiece to transition the roughly-shaped metal workpiece into a first hardened condition, the roughly-shaped metal workpiece comprising the weld retained in the heat-treated structure formed of metal.

2. The method according to example 1, wherein the roughly-shaped metal workpiece is in an annealed condition.

3. The method according to examples 1 or 2, further comprising performing a second heat-treating process on the first hardened metal workpiece to transition the first hardened metal workpiece to a second hardened condition to produce a second hardened metal workpiece.

4. The method according to any of the preceding examples, further comprising forming the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the hardened condition, the shaped metal workpiece comprising one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece.

5. The method according to examples 3 or 4, comprising forming the second hardened metal workpiece into a shaped metal workpiece does need a

said shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece.

6. The method according to example 5, wherein the shaped metal workpiece is, or comprises, a near-finally-shaped metal workpiece, the method further comprising:

forming the near-finally-shaped metal workpiece into the finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.

7. The method according to examples 5 or 6, wherein the shaped metal workpiece comprises a finally-shaped metal workpiece, the method further comprising using one or more forming processes to shape the roughly-shaped metal workpiece into the finally-shaped metal workpiece.

8. The method according to example 7, wherein the forming process is selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

9. The method according to any of the preceding examples, wherein, before the step of performing the heat-treating process on the roughly-shaped metal workpiece, a metal sheet is formed into the roughly-shaped metal workpiece while the metal sheet is in the annealed condition.

10. The method according to example 9, wherein the step of forming a metal sheet comprises rolling the metal sheet into the roughly-shaped metal workpiece.

11. The method according to examples 9 or 10, wherein the metal sheet is in an annealed condition, and is formed into the roughly-shaped metal workpiece by a process selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

12. The method according to any of the preceding examples, wherein the roughly-shaped workpiece is a conical-shaped metal workpiece or a frusto-conical-shaped metal workpiece.

13. The method according to any of the preceding examples, wherein the steps of performing the heat-treating process further comprise: performing at least one age-hardening process on the roughly-shaped metal workpiece in the first

and/or second hardened condition, preferably wherein the age-hardening process is a natural aging process.

14. The method according to examples 13, wherein the step of performing the heat-treating process further comprises solution heat-treating the metal. 5

15. The method according any one of the preceding examples, wherein performing the heat-treating process comprises performing a T-4 heat-treating process on the roughly-shaped metal workpiece. 10

16. The method according to any of examples 3 to 15, wherein performing the second heat-treating process comprises performing an artificial aging process on the shaped metal workpiece and/or performing a solution heat-treating process on the shaped metal workpiece. 15

17. The method according to any one of examples 3 to 16, wherein performing the second heat-treating process comprises performing a T-6 heat-treating process. 20

18. A metal structure obtainable according to the method of any of the preceding examples. 25

19. The metal structure according to examples 18, wherein the metal comprises aluminum or an aluminum alloy. 30

20. The metal structure according to examples 18 or 19, wherein the structure is annularly-shaped. 35

21. The metal structure according examples 18, 19 or 20, wherein the metal structure is a lipskin for use in a nacelle for an aircraft. 40

22. A nacelle for use on an aircraft, the nacelle comprising a lipskin comprising at least one friction stir weld. 45

23. The nacelle according to examples 22, wherein the lipskin comprises a metal structure according to any of the examples 18-20. 50

24. An aircraft comprising a nacelle according to any of the examples 22 or 23. 55

25. A method of making a heat treated aircraft engine nacelle which comprises a friction stir weld, comprising the steps of performing a first heat-treating process on a roughly-shaped metal workpiece comprising the friction stir weld to transition the roughly-shaped metal workpiece into a hardened condition, which heat-treating process comprises solution-heat treating.

A. A method (10, 20) for making a heat-treated structure formed of metal, the method comprising:

i. performing (14, 22) a first heat-treating process on a roughly-shaped metal workpiece (90) in an annealed condition, to transition the roughly-shaped metal workpiece from an annealed condition to a first hardened condition, said roughly-shaped metal workpiece comprising at least one friction stir weld (92);

ii. forming (16, 24) the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the first hardened condition, the shaped metal workpiece comprising one of a near-finally-shaped metal workpiece (114b, 114c, 114d) or a finally-shaped metal workpiece (114e, 120); and

iii. performing (18, 26) a second heat-treating process on the shaped workpiece to transition the shaped metal workpiece from the first hardened condition to a second hardened condition.

B. The method (10, 20) according to Example A, wherein forming (16, 24) the roughly-shaped metal workpiece (90) into a shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises using at least one forming process to shape the roughly-shaped metal workpiece into the shaped metal workpiece.

C. The method (10, 20) according to Example A or B, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) is a near-finally-shaped metal workpiece (114b, 114c, 114d), the method further comprising:

i. forming the near-finally-shaped metal workpiece into the finally-shaped metal workpiece (114e, 120) while the near-finally-shaped metal workpiece is in the second hardened condition.

D. The method (10, 20) according to any one of Examples A to B, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises a finally-shaped metal workpiece (114e, 120), the method further comprising:

i. using (52) a plurality of forming processes to shape the roughly-shaped metal workpiece (90) into the finally-shaped metal workpiece.

E. The method (10, 20) according to any one of Examples A to D, wherein the forming process is selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

F. A method (30, 40, 50, 60) for making a heat-treated structure formed of metal, the method comprising:

- i. performing (32) a first heat-treating process on a roughly-shaped metal workpiece (90) to transition the roughly-shaped metal workpiece into a first hardened condition to produce a first-hardened metal workpiece, the roughly-shaped metal workpiece being in an annealed condition and comprising at least one friction stir weld (92);
- ii. performing (34) a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened metal workpiece to a second hardened condition to produce a second-hardened metal workpiece; and
- iii. forming (36, 37) the second-hardened metal workpiece into a shaped metal workpiece (114b, 114c, 114d, 114e, 120), said shaped metal workpiece being in one of a near-finally-shaped metal workpiece (114b, 114c, 114d) or a finally-shaped metal workpiece (114e, 120).

G. The method (30, 40, 50, 60) according to Example F, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises the at least one friction stir weld (92).

H. The method (30, 40, 50, 60) of Example F or G, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises a near-finally-shaped workpiece (114b, 114c, 114d), the method further comprising:

- i. forming (42) the near-finally-shaped metal workpiece into a finally-shaped metal workpiece (114e, 120) while the near-finally-shaped metal workpiece is in the second hardened condition.

I. The method (30, 40, 50, 60) according to any one of Examples F to H, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises a near-finally-shaped metal workpiece (114b, 114c, 114d) and further comprising the step of:

- i. using a plurality of forming processes (52) to shape the near-finally-shaped metal workpiece into the finally-shaped workpiece (114e, 120) while the near-finally-shaped metal workpiece is in the second hardened condition.

J. The method (30, 40, 50, 60) according to any one of Examples F to I, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) comprises a near-finally-shaped metal workpiece (114b, 114c, 114d) and further comprising the step of:

- i. using at least one explosion forming process to shape the near-finally-shaped metal workpiece into the finally-shaped workpiece (114e, 120) while the near-finally-shaped metal workpiece is in the second hardened condition.

K. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to J, wherein, before the step of performing (14, 22, 32) a first heat-treating process on a roughly-shaped metal workpiece (90), further comprising:

- i. forming (12) a metal sheet into the roughly-shaped metal workpiece while the metal sheet is in the annealed condition.

L. The method (10, 20, 30, 40, 50, 60) according to Example K, wherein the step of forming (12) a metal sheet further comprises:

- i. rolling the metal sheet into the roughly-shaped metal workpiece.

M. The method (10, 20, 30, 40, 50, 60) according to Example K or L, wherein the step of forming (12) a metal sheet further comprises:

- i. forming the metal sheet, while the metal sheet is in the annealed condition, said forming process selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

N. The method (10, 20, 30, 40, 50, 60) according to any one of Examples K to M, wherein the step of forming (12) a metal sheet into the roughly-shaped metal workpiece (90) while the metal sheet is in the annealed condition further comprises:

- i. forming the sheet into a roughly-shaped workpiece (114b, 114c, 114d), wherein said roughly-shaped workpiece is a conical-shaped metal workpiece or a frusto-conical-shaped metal workpiece.

O. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to N, wherein the steps of performing (14, 18, 22, 26, 32, 34) the first heat-treating process and second heat-treating process further comprise:

- i. performing at least one age-hardening process on the roughly-shaped metal workpiece (90) in the first hardened condition; and
- ii. performing at least one age-hardening proc-

ess on the on the shaped metal workpiece (114b, 114c, 114d, 114e, 120) in the second hardened condition;

iii. wherein the first hardened condition comprises a first age-hardened condition, and the second hardened condition comprises a second age-hardened condition. 5

P. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to O, wherein the step of performing (14, 22, 32) a first heat-treating process comprises: 10

i. performing a natural aging process on the roughly-shaped metal workpiece (90). 15

Q. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to P wherein the step of performing (14, 22, 32) a first heat-treating process comprises: 20

i. solution heat-treating the metal and natural aging the roughly-shaped metal workpiece (90). 25

R. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to Q, wherein performing (14, 22, 32) a first heat-treating process comprises:

i. performing a T-4 heat-treating process on the roughly-shaped metal workpiece. 30

S. The method (10, 20, 30, 40, 50, 60) of any one of Examples A to R, wherein performing (18, 26, 34) a second heat-treating process comprises: 35

i. performing an artificial aging process on the shaped metal workpiece (114b, 114c, 114d, 114e, 120). 40

T. The method (10, 20, 30, 40, 50, 60) of any one of Examples A to S, wherein performing (18, 26, 34) a second heat-treating process comprises:

i. performing a solution heat-treating process on the shaped metal workpiece (114b, 114c, 114d, 114e, 120); and 45

ii. performing an artificial aging process on the shaped metal workpiece. 50

U. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to T, wherein performing (18, 26, 34) a second heat-treating process comprises performing a T-6 heat-treating process. 55

V. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to U, wherein forming (16,

24) the roughly-shaped metal workpiece into a shaped workpiece comprises:

i. using at least one forming process selected from the group consisting of:

ii. a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

W. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to V, wherein the shaped workpiece (114b, 114c, 114d, 114e, 120) is a near-finally-shaped metal workpiece (114b, 114c, 114d), the method further comprising:

i. forming the near-finally-shaped metal workpiece into the finally-shaped metal workpiece (114e, 120) while the near-finally-shaped metal workpiece is in the second hardened condition.

X. The method (10, 20, 30, 40, 50, 60) according to any one of Examples A to W, wherein the shaped metal workpiece (114b, 114c, 114d, 114e, 120) is a finally-shaped metal workpiece (114e, 120) and further comprising:

i. forming the roughly-shaped metal workpiece (90) into the finally-shaped metal workpiece using at least one forming process selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

Y. A metal structure formed according to the method (10, 20, 30, 40, 50, 60) of any one of Examples 1 to X.

Z. The metal structure according to Example Y wherein the metal comprises aluminum or an aluminum alloy.

AA. The metal structure according to Example Y or Z, wherein the structure is annularly-shaped.

BB. The metal structure according to any one of Examples Y to AA, wherein the structure is a lipskin (120) for use in an engine nacelle (132).

CC. The metal structure according to any one of Examples Y to BB, wherein the metal structure is a heat-treated structure in the second hardened condition.

DD. A nacelle (132) for use on an aircraft (130), the nacelle comprising:

i. a lipskin (120) made from a metal that has been heat-treated, said lipskin comprising at least one friction stir weld (92).

EE. The nacelle (132) of Example DD, wherein the lipskin (120) is formed using the method (10, 20, 30, 40, 50, 60) of any one of Examples 1 to 24.

[0040] Having thus described variations of the disclosure of the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

- figure 1 is a flowchart illustrating an exemplary forming method of the present invention;
- figure 2 is a flowchart illustrating an exemplary method of the present invention;
- figure 3 is a flowchart illustrating an exemplary method of the present invention;
- figure 4 is a flowchart illustrating an exemplary method of the present invention;
- figure 5 is a flowchart illustrating an exemplary method of the present invention;
- figure 6 is a flowchart illustrating an exemplary method of the present invention;
- figure 7 is a flowchart illustrating an exemplary method of the present invention;
- figures 8A, 8B, and 8C are cross-sectional side-views of a workpiece progressing through stages of a forming process from a rough-shaped metal workpiece into a shaped, near-finally shaped and finally-shaped metal workpiece, according to aspects of the present invention;
- figure 9 is a perspective view of a roughly-shaped metal workpiece in a frusto-conical orientation;
- figure 10 is a perspective view of a roughly-shaped metal workpiece being oriented into a forming block of a forming process, according to aspects of the present invention;
- figures 11A, 11B, 11C, 11D, and 11E are cross sectional side views of forming blocks in a forming process used to transform a roughly-shaped metal workpiece into a near-finally-shaped and finally-shaped metal workpiece;
- figure 12 is a perspective view of a final-shaped metal workpiece as lipskin for an nacelle made according to aspects of the present invention; and
- figure 13 is a perspective view of an aircraft comprising an engine nacelle.

[0041] Methods for constructing unitary, or single-piece, aircraft engine lipskins that can provide improved laminar flow are disclosed herein. The methods and apparatuses disclosed herein provide a lightweight, efficient, reproducible and high-performance engine nacelle lipskin made from a heat-treatable metal that has been shaped and tempered according to specified protocols that facilitate unitary formation of a large contoured metal

structure without requiring introduction of additional components to structurally reinforce areas of the unitary structure where welds occur. That is, in the structures and methods according to aspects of the present application, the welds made in the structures are retained in the finished structure.

[0042] Retention of the welds in structures used in aircraft (e.g. lipskins on aircraft nacelle assemblies) allows such welds to be so-called "fly-away" welds that are retained in the finished structure. Without being bound to any particular theory, the shaping of the metals used to make the lipskins, according to aspects of the present disclosure of the invention, is predominantly conducted and accomplished while the metal is in the annealed condition. The order of shaping in the annealed condition can allow for weld retention in a finished product due to internal metal stresses being managed in a predetermined way that obviates the need to remove such welds and introduce additional reinforcing components that would complicate the manufacturing process and add weight to a structure comprising the lipskin.

[0043] For the purposes of the present disclosure of the invention, "heat-treatable metals" refer to heat-treatable metals that include aluminum and the 2000-, 4000-, 6000-, and 7000-series aluminum alloys.

[0044] According to aspects of the present disclosure of the invention, a metal workpiece in the annealed state can be formed into a roughly-shaped metal workpiece by being subjected to at least one forming process. For the purpose of the present disclosure, super-plastic processes, super-plastic/diffusion bond processes, form-die processes, and explosive-forming processes are examples of a forming process and may be equivalently and interchangeably referred to as "forming processes".

[0045] Explosive-forming processes may be equivalently and interchangeably referred to as "explosion-molding", "explosive molding", "explosion-forming" or "high-energy hydroforming" (HEHF) processes. An explosive-forming process is a metalworking process where an explosive charge is used to supply the compressive force (e.g. a shockwave) to a metal workpiece against a form (e.g. a mold) otherwise referred to as a "die". Explosive-forming is typically conducted on materials and structures of a size too large for forming such structures using a punch or press to accomplish the required compressive force. According to one explosive-forming approach, a metal workpiece, up to several inches thick, is placed over or proximate to a die, with the intervening space, or cavity, optionally evacuated by a vacuum pump. The entire apparatus is submerged into an underwater basin or tank, with a charge having a predetermined force potential detonated at a predetermined distance from the metal workpiece to generate a predetermined shockwave in the water. The water then exerts a predetermined dynamic pressure on the workpiece against the die at a rate on the order of milliseconds. The die can be made from any material of suitable strength to withstand the force of the detonated charge such as,

for example, concrete, ductile iron, etc. The tooling should have higher yield strength than the metal workpiece being formed.

[0046] Explosive forming processes are sometimes divided into two groups, depending upon the position of the explosive charge relative to the workpiece. According to the "stand off" method, a workpiece is placed over a die with the intervening space evacuated by a vacuum, with the entire assembly immersed under water, preferably in a basin or tank. The explosive material is then placed at a predetermined distance from the assembly and detonated. According to the "contact method", an explosive charge is placed in direct contact with the workpiece and the detonation produces interface pressures on the workpiece surface up to several million pounds per square inch (psi).

[0047] Superplastic forming is a forming process that typically uses high temperature and gas pressure to form particular materials onto a single step mold. Superplastic forming can create very detailed metal parts including aluminum and titanium. Superplasticity is the ability of a material to experience extremely high elongations on the order of 200% or more. For a material to elicit superplastic behavior, there are typical criteria including, for example, an extremely fine grain size (a few micrometers or less), with generally uniform and equiaxed grain structure; high temperatures (usually on the order of half the melting temperature); low strain rates (e.g. on order of 10^{-2} /seconds or lower).

[0048] Friction stir welding (FSW) refers to a process for the solid-state joining of two workpieces using a non-consumable tool without melting the material of the workpiece(s). Heat is generated by friction between a rotating tool and the workpiece, resulting in a softened region proximate to the FSW tool. As the FSW tool proceeds along a desired joining line, the tool mechanically intermixes the material of the workpieces to be joined. In this way, hot and softened metal of the workpieces is forged by the mechanical pressure that is applied by the FSW tool, resulting in a solid state deformation of dynamic recrystallization of the workpiece materials without melting the workpieces. While aspects of the present disclosure of the invention describe producing and retaining friction stir welds in the metals used, the present disclosure contemplates, without limitation, any type of welds can be "fly-away welds". As explained above, "fly-away welds" refer to welds in components and parts that remain in the part or component as used in flight. In other words, "fly-away welds" are retained in the finished structures as opposed to being removed from the structures before use.

[0049] According to the present disclosure of an embodiment of the invention, a heat-treated structure is a structure, preferably a metal structure, that is exposed to heat-treating. Heat-treating for metals (especially metal alloys) manipulates the properties of the metal by controlling rates of diffusion and the rate of cooling within a metal's microstructure. Heat-treating predictably alters

the mechanical properties of a metal, manipulating properties including hardness, strength, ductility, elasticity, etc. The present specification discloses first heat-treating processes and second heat-treating processes to achieve metal workpieces having a particular "state" or heat-treatment "condition". According to the present disclosure, for aluminum alloys, the heat-treatment conditions include an annealed condition, a first hardened condition, and a second hardened condition.

[0050] For aluminum alloys, the annealed condition is used to describe alloys used for sheet workpieces made by some shaping processes. The annealed condition is the lowest strength condition for a metal alloy workpiece. Annealing is a heat treatment that alters the physical properties of a material to increase ductility and reduce hardness, making the material more "workable". In annealing, atoms migrate in a material's crystalline lattice, with the number of dislocations decreasing, leading to a change in ductility and hardness. A dislocation refers to the primarily linear defects present throughout a material's crystalline structure and the internal stresses caused thereby. Annealing conditions for aluminum alloys vary according to individual aluminum alloys, but generally require exposing the aluminum alloy to a temperature of from about 650°F (343.3°C) to about 770°F (410°C) for 2 to 3 hours, followed by slow cooling to about 500°F (260°C) followed by uncontrolled cooling rates to room temperature. Specific temperatures, times, cooling rates, etc. can differ from the examples above, depending upon which metal (e.g. aluminum alloy) is being treated.

[0051] The "T" temper designation for heat-treated (e.g. heat-treatable) aluminum and aluminum alloys includes a number that indicates a basic type of treatment. Of particular interest for the present disclosure are the T4 and T6 conditions. As used herein, the T4 condition is an example of a "first hardened condition". A T4 condition indicates that the T4 treated alloy has incurred a solution heat treatment and, has naturally aged to a stable condition. As used herein, the T6 condition is an example of a "second hardened condition". A T6 condition indicates that the T6 treated alloy has been solution heat treated and, without any significant cold working, has been artificially aged to achieve additional precipitation hardening to become stable metalurgically.

[0052] According to an aspect of the present disclosure of the invention, an aluminum alloy may be provided in the annealed condition as a sheet of material (i.e., the "O" condition) with either partial or full anneal cycles intermittently conducted on the aluminum alloy. The annealed aluminum alloy is brought to the first hardened condition, such as the T4 condition, via a solution heat treatment, and bringing the aluminum alloy sheet to a temperature above 900°F (482.2°C) for a time that is dependent on the particular alloy and the thickness of the sheet followed by quenching in water or glycol. The aluminum alloys selected are precipitation age-hardenable, allowing the alloys to naturally age at room temperature. If desired, the aging in the T4 condition may be tailored

by placing the alloy in the T4 condition in dry ice or in a freezer. The alloy sheet in the first hardened condition (e.g., the T4 condition) may then be formed into a roughly-shaped metal workpiece that includes introducing at least one friction stir weld introduced in the annealed condition to shape the metal workpiece as desired. According to a contemplated aspect, in the case of forming lipskins for aircraft engine nacelles, the alloy in the annealed condition is shaped and friction stir welded to a roughly-shaped metal workpiece, and then the alloy in the first hardened condition is shaped or to a near-finally-shaped metal workpiece or finally-shaped workpiece.

[0053] According to aspects of the present disclosure of the invention, during the first-hardened process, the alloy is subjected to at least one forming process that includes, for example, an explosive forming process, to create the near-finally-shaped metal workpiece or the finally-shaped metal workpiece. According to contemplated aspects, most of the forming of the aluminum alloy into the near-finally-shaped metal workpiece is conducted with the alloy in the first hardened condition (e.g., the T4 condition). The near-finally-shaped metal workpiece is then brought to a second hardened condition (i.e. T6 condition) by artificially aging the metal workpiece. For example, for aluminum alloy Al-2219, the cycle time and temperature is 375°F (190.5°C) for 36 hours.

[0054] Figures 1-7 are flowcharts describing aspects of the present disclosure of the invention. Consistent with particular aspects of the present disclosure, figure 1 is directed to a method 10 for making a heat-treated structure formed of metal. The method 10 includes forming 12 a metal sheet into a roughly-shaped metal workpiece having a friction stir weld while the metal sheet is in an annealed condition. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below.

[0055] Method 10 includes step 12 performed in a manner consistent with aspects of the present disclosure of the invention using forming processes such as rolling or other physical shaping means suitable to physically transform and shape a metal from a first, or initial, orientation to a subsequent orientation. Further forming processes to transform metal to a roughly-shaped metal workpiece, as contemplated by aspects of the present disclosure, may take place in step 12 including subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. The roughly-shaped state of the metal workpiece, according to aspects of the present disclosure, therefore contemplates the state of the metal work-piece between the initial form of a metal (e.g., a metal sheet that may be substantially planar) and a shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece that has been subjected to subsequent forming processes after attaining the roughly-shaped metal workpiece.

[0056] The method 10 further includes performing 14

a first heating-treating process on the roughly-shaped metal workpiece to transition the roughly-shaped metal workpiece from an annealed condition to a first hardened condition. The roughly-shaped metal workpiece includes the at least one friction stir weld (e.g., friction stir weld 92 shown in figure 9). When the metal workpiece is aluminum or an aluminum alloy, the first hardened condition is the T4 condition. The method 10 includes forming 16 the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the first hardened condition. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120 as shown in figure 9 and figures 11B, 11C, 11D, 11E, and FIG 12, which is described in more detail below. According to aspects of the present disclosure of the invention, the shaped metal workpiece retain and includes the friction stir weld 92 introduced to the roughly-shaped metal workpiece as shown in figure 9. The shaped metal workpiece comprises one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece.

[0057] According to aspects of the present disclosure of the invention, method 10 includes forming 16 processes used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpieces include subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. When an explosive-forming process is used in step 16, the explosive-forming process also includes the quenching step of the first heat-treating process.

[0058] Aspects of the method 10 include performing 18 a second heat-treating process on the shaped workpiece to transition the shaped metal workpiece from the first hardened condition to produce a second hardened condition. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is a T6 condition. At least one forming process can be performed while the metal is in the second hardened condition. However, all of the forming processes on the roughly-shaped workpiece (e.g., forming the roughly-shaped metal workpiece into the shaped metal workpiece) may be completed while the metal is in the first hardened condition.

[0059] Consistent with particular aspects of the present disclosure of the invention, figure 2 is directed to a method 20 for making a heat-treated structure formed of metal. The method described in figure 2 is similar to the method outlined in figure 1, except the method 20 contemplates starting with a roughly-shaped metal workpiece rather than, for example, a flat sheet of metal. The method 20 includes performing 22 a first heat-treating process on a roughly-shaped metal workpiece in an annealed condition to transition the roughly-shaped metal workpiece from an annealed condition to a first hardened condition, with the roughly-shaped metal workpiece comprising at least one friction stir weld introduced to the metal workpiece in the annealed condition. One example

of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The first hardened condition of the metal is in the T4 condition when the metal workpiece is aluminum or an aluminum alloy.

[0060] The method 20 further includes forming 24 the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the first hardened condition, with the shaped metal workpiece being one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece. According to aspects of the present disclosure of the invention, the forming process(es) 24 used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece includes subjecting the roughly-shaped metal workpiece to at least one forming process that includes super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120, as shown in figures. 11B, 11C, 11D, 11E, and FIG 12, and which is described in more detail below. According to aspects of the present disclosure, the shaped metal workpiece retains and includes the friction stir weld 92 introduced to the roughly-shaped metal workpiece as shown in figure 9. When an explosive-forming process is used in step 24, the explosive-forming process also includes the quenching step of the first heat-treating process.

[0061] The method 20 further includes performing 26 a second heat-treating process on the shaped workpiece to transition the shaped metal workpiece from the first hardened condition to produce a second hardened condition. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition. At least one forming process can be performed while the metal is in the second hardened condition. However, as contemplated by method 20, all of the forming processes on the roughly shaped metal workpiece (e.g., forming the roughly-shaped metal workpiece into the shaped metal workpiece) may be completed while the metal is in the first hardened condition.

[0062] Consistent with particular aspects of the present disclosure of the invention, figure 3 is directed to a method 30 for making a heat-treated structure formed of metal. Whereas FIGs 1 and 2 outline methods, 10 and 20 respectively, where the roughly-shaped metal workpiece is formed into a shaped metal workpiece in the first hardened condition, as shown in figure 3, a method 30 is further defined such that at least some forming of the metal workpiece into the shaped metal workpiece occurs after the metal workpiece is in the second hardened condition. The method 30 includes performing 32 a first heat-treating process on a roughly-shaped metal workpiece in an annealed condition (with the workpiece in an annealed condition including at least one friction stir weld)

to transition the roughly-shaped metal workpiece into a first hardened condition to produce a first-hardened metal workpiece. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The first hardened condition of the metal is the T4 condition when the metal workpiece is aluminum or an aluminum alloy.

[0063] The method 30 further includes performing 34 a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened workpiece a second hardened condition to produce a second-hardened metal workpiece. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition.

[0064] The method 30 further includes forming 36 the second-hardened metal workpiece into a shaped metal workpiece, with the shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped workpiece. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120 as shown in figures. 11B, 11C, 11D, 11E, and FIG 12, which is described in more detail below. According to aspects of the present disclosure of the invention, the shaped metal workpiece retains and includes the friction stir weld 92 introduced to the roughly-shaped metal workpiece as shown in figure 9. According to aspects of the present disclosure of the invention, in method 30, forming processes 36 used to transform a roughly-shaped metal workpiece into the shaped (i.e. near-finally-shaped or finally-shaped) metal workpiece includes subjecting the metal workpiece to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. As contemplated by method 30, all of the forming processes on the roughly shaped metal workpiece (e.g. forming the roughly-shaped metal workpiece into the shaped metal workpiece) may be completed while the metal is in the second hardened condition.

[0065] Consistent with particular aspects of the present disclosure of the invention, figure 4 is directed to a method 40 for making a heat-treated structure formed of metal. Whereas figures 1 and 2 outline methods, 10 and 20 respectively, where the roughly-shaped metal workpiece is formed into a shaped metal workpiece in the first hardened condition, as shown in figure 4, a method 40 is further defined such that at least some forming of the metal workpiece into the shaped metal workpiece occurs after the metal workpiece is in the second hardened condition. Further, as compared with the method 30 outlined in figure 3, in figure 4 the metal workpiece is formed into a near-finally-shaped and finally-shaped metal workpiece while the metal workpiece is in the second hardened condition. The method 40 includes performing 32 a first heat-treating process on a roughly-shaped metal workpiece (with the workpiece in an annealed condition including at least one friction stir weld) to transition the roughly-shaped metal workpiece into a

first hardened condition to produce a first-hardened metal workpiece. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The first hardened condition of the metal is the T4 condition when the metal workpiece is aluminum or an aluminum alloy.

[0066] The method 40 further includes performing 34 a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened workpiece to a second hardened condition to produce a second-hardened metal workpiece. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition.

[0067] The method 40 further includes forming 37 the second-hardened metal workpiece into a near-finally-shaped metal workpiece. An example of a near-finally-shaped metal workpiece is the metal workpiece 114d as shown in figure 11D, which is described in more detail below. According to aspects of the present disclosure of the invention, the shaped metal workpiece retains and includes the friction stir weld 92 introduced to the roughly-shaped metal workpiece as shown in figure 9. According to aspects of the present disclosure of the invention, the method 40, in step 37 the forming processes used to transform a roughly-shaped metal workpiece into the near-finally-shaped metal workpiece includes subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof.

[0068] The method 40 further includes forming 42 the near-finally shaped metal workpiece into the finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition. According to aspects of the present disclosure of the invention, the method 40, forming processes 42 used to transform a roughly-shaped metal workpiece into the shaped (i.e. near-finally-shaped or finally-shaped) metal workpiece including subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. An example of the finally-shaped metal workpiece is the metal workpiece 114e and 120 as shown in figure 11E and figure 12, which is described in more detail below. As contemplated by method 40, all of the forming processes on the roughly shaped metal workpiece (e.g., forming the roughly-shaped metal workpiece into the near-finally-shaped metal workpiece and the finally-shaped metal workpiece) may be completed while the metal is in the second hardened condition

[0069] Consistent with particular aspects of the present disclosure of the invention, figure 5 is directed to a method 50 for making a heat-treated structure formed of metal. Figures 1 and 2 outline methods, 10 and 20 respectively, where the roughly-shaped metal workpiece is formed into a shaped metal workpiece in the first hardened condition. Further, as compared with the method 30 outlined in figure 3, in figure 4 (method 30) and figure

5 (method 50) the metal workpiece is formed into a shaped (figure 5) or near-finally-shaped (figure 4) metal workpiece while the metal workpiece is in the second hardened condition. Figure 5 further specifies, in step 52, using a plurality of forming processes to form the shaped metal workpiece into a finally-shaped metal workpiece while in the second hardened condition. The method 50 includes performing 32 a first heat-treating process on a roughly-shaped metal workpiece in an annealed condition (with the workpiece in an annealed condition including at least one friction stir weld) to transition the roughly-shaped metal workpiece into a first hardened condition to produce a first-hardened metal workpiece. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The first hardened condition of the metal is the T4 condition when the metal workpiece is aluminum or an aluminum alloy.

[0070] The method 50 further includes performing 34 a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened workpiece to a second hardened condition to produce a second-hardened metal workpiece. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition.

[0071] The method 50 further includes forming 36 the second-hardened metal workpiece into a shaped metal workpiece, with the shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped workpiece. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120 as shown in figures 11B, 11C, 11D, 11E, and figure 12, which is described in more detail below. According to aspects of the present disclosure of the invention, in method 50, forming processes 36 used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece includes subjecting the metal workpiece to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. As contemplated by method 50, all of the forming processes on the roughly shaped metal workpiece (e.g., forming the roughly-shaped metal workpiece into the shaped metal workpiece) may be completed while the metal is in the second hardened condition.

[0072] The method 50 further includes using 52 a plurality of forming processes to form the shaped metal workpiece into the finally-shaped metal workpiece while the shaped metal workpiece is in the second hardened condition, with the forming processes set forth above for use in step 36 also contemplated as available forming methods in step 52. An example of the finally-shaped metal workpiece is the metal workpiece 114e and 120 as shown in figure 11E and figure 12, which is described in more detail below.

[0073] Consistent with particular aspects of the

present disclosure of the invention, figure 6 is directed to a method 60 for making a heat-treated structure formed of metal. Method 60 is similar to method 50 outlined in figure 50, but includes forming 62 a metal sheet into a roughly-shaped metal workpiece including a friction stir weld, while the metal sheet is in the annealed condition. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The roughly-shaped state of the metal workpiece, according to aspects of the present disclosure of the invention, therefore contemplates the state of the metal work-piece between the initial form of a metal (e.g., a metal sheet that may be substantially planar) and a shaped (i.e., near-finally-shaped, or finally-shaped) metal workpiece that has been subjected to subsequent forming processes after attaining the roughly-shaped metal workpiece.

[0074] The method 60 further includes performing 32 a first heat-treating process on the roughly-shaped metal workpiece in an annealed condition (with the workpiece in an annealed condition comprising at least one friction stir weld) to transition the roughly-shaped metal workpiece into a first hardened condition to produce a first-hardened metal workpiece. The first hardened condition of the metal is the T4 condition when the metal workpiece is aluminum or an aluminum alloy.

[0075] The method 60 further includes performing 34 a second heat-treating process on the first-hardened metal workpiece to transition the first-hardened workpiece a second hardened condition to produce a second-hardened metal workpiece. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition.

[0076] The method 60 further includes forming 36 the second-hardened metal workpiece into a shaped metal workpiece, with the shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped workpiece. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120 as shown in figures 11B, 11C, 11D, 11E, and figure 12, which is described in more detail below. According to aspects of the present disclosure of the invention, the forming processes in the method 60 used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece includes subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof.

[0077] Method 60 further includes using 52 a plurality of forming processes to form the near-finally shaped metal workpiece into the finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition, with the forming processes set forth above for use in step 36 also contemplated as available forming methods in step 52. An example of the finally-shaped metal workpiece is the metal workpiece

114e and 120 as shown in figure 11E and figure 12, which is described in more detail below.

[0078] Consistent with particular aspects of the present disclosure of the invention, figure 7 is directed to a method 70 for making a heat-treated structure formed of metal. The method 70 described in figure 7 is similar to the method outlined in figure 1, except the method 70 contemplates 72 performing at least one age-hardening process on the roughly-shaped metal workpiece in the first hardened condition, and performing 74 at least one age-hardening process on the shaped metal workpiece in the second hardened condition. Method 70 therefore includes forming 12 a metal sheet into a roughly-shaped metal workpiece having a friction stir weld while the metal sheet is in an annealed condition. Step 12 is performed in a manner consistent with aspects of the present disclosure of the invention using forming processes including forming processes such as rolling or other physical shaping means suitable to physically transform and shape a metal from a first, or initial, orientation to a subsequent orientation. Further forming processes to transform metal to a roughly-shaped metal workpiece, as contemplated by aspects of the present disclosure of the invention, may take place in step 12 including subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof. One example of the roughly-shaped metal workpiece is the metal workpiece 90 having at least one friction stir weld 92 as shown in figure 9, which is described in more detail below. The roughly-shaped state of the metal workpiece, according to aspects of the present disclosure of the invention, therefore contemplates the state of the metal workpiece between the initial form of a metal (e.g., a metal sheet that may be substantially planar) and a shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece that has been subjected to subsequent forming processes after attaining the roughly-shaped metal workpiece.

[0079] Method 70 further includes performing 14 a first heat-treating process on the roughly-shaped metal workpiece to transition the roughly-shaped metal workpiece from an annealed condition comprising at least one friction stir weld to produce a first hardened condition, with the roughly-shaped metal workpiece comprising at least one friction stir weld. When the metal workpiece is aluminum or an aluminum alloy, the first hardened condition is the T4 condition.

[0080] The method 70 further includes performing 72 at least one age-hardening process on the roughly-shaped metal workpiece in the first hardened condition. When the metal workpiece is aluminum or an aluminum alloy and the first hardened condition is the T4 condition, the age-hardening process can be a natural aging process to age the metal workpiece to a stable condition.

[0081] The method 70 further includes forming 16 the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is

in the first hardened condition. The shaped metal workpiece is one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece. An example of the shaped metal workpiece is the metal workpiece 114b, 114c, 114d, 114e, and 120 as shown in figures. 11B, 11C, 11D, 11E, and FIG 12, which is described in more detail below. According to aspects of the present disclosure of the invention, in step 16 the forming processes used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece includes subjecting the metal sheet to super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes, and combinations thereof.

[0082] Method 70 further includes performing 18 a second heat-treating process on the shaped workpiece to transition the shaped metal workpiece from the first hardened condition to produce a second hardened condition. When the metal workpiece is aluminum or an aluminum alloy, the second hardened condition is the T6 condition.

[0083] The method 70 further includes performing 74 at least one age-hardening process on the shaped metal workpiece in the second-hardened hardened condition. When the metal workpiece is aluminum or an aluminum alloy and the second hardened condition is the T6 condition, the age-hardening process can be an artificial aging process to age the metal workpiece to achieve precipitation hardening.

[0084] At least one forming process can be performed while the metal is in the second hardened condition. However, all of the forming processes on the roughly-shaped workpiece (e.g., forming the roughly-shaped metal workpiece into the shaped metal workpiece) may be completed while the metal is in the first hardened condition.

[0085] Figures 8A, 8B, and 8C show a series in progression of exemplary drawings illustrating how a workpiece may be formed during an explosive forming process that can be used in the forming processes 16, 24, 36, 37, 42, and 52. According to explosive forming assembly 80a, a tank 82 contains an amount of water 83. A die 84 defines a cavity 85 and a vacuum line 87 extends from the cavity 85 through the die 84 to a vacuum (not shown). Workpiece 86a is held in position in the die 84 via a hold-down ring or other retaining device (not shown). An explosive charge 88 is shown suspended in the water 83 via a charge detonation line 89, with charge detonation line 19a connected to a detonator (not shown). As shown in figure 8B, the charge 88 (shown in figure 8A) has been detonated in explosive forming assembly 80b creating a shock wave "A" emanating from a gas bubble "B", with the shock wave "A" causing the deformation of the workpiece 86b into cavity 85 until the workpiece 86c is driven against (e.g., immediately proximate to and in contact with) the inner surface of die 84 as shown in figure 8C.

[0086] Consistent with particular aspects of the present disclosure of the invention, figure 9 is a perspective drawing of a metal workpiece 90 in an annealed con-

dition and, for the purpose of the present disclosure, in a roughly-shaped condition or state. As shown in figure 9, workpiece 90 has been shaped into a substantially frusto-conical shape. Friction stir welds 92 are shown in workpiece 90, and are introduced into the metal workpiece before, after and/or during the forming of the metal workpiece into the roughly-shaped condition. While friction stir welds are shown, the present disclosure of the invention contemplates any welds that collectively can be referred to as "fly-away" welds as described herein. As shown, workpiece 90 is a metal workpiece that is preferably made from aluminum or an aluminum alloy or alloys. Workpiece 90 can be shaped into the frusto-conical orientation by forming processes, including forming processes such as rolling or other physical shaping means suitable to physically transform and shape a metal from a first, or initial, orientation (e.g., a metal sheet) to a subsequent roughly-shaped orientation, such as shown in figure 9.

[0087] Consistent with particular aspects of the present disclosure of the invention, figure 10 is a perspective view of a forming station 100. As shown in figure 10, workpiece 90 is introduced into forming block 102 that has a forming block cavity 104. The forming station 100 is non-specific as to any particular forming process that can be used to shape metal workpieces. Representative forming processes include forming processes used to transform a roughly-shaped metal workpiece into the shaped (i.e., near-finally-shaped or finally-shaped) metal workpiece such as super-plastic processes, super-plastic/diffusion bond processes, form-die processes, explosive-forming processes (such as the process shown in figures 8A-8C), and combinations thereof, and include a forming block or die against which, by a force, a metal workpiece can be driven to achieve a predetermined shape.

[0088] Consistent with particular aspects of the present disclosure of the invention, figures 11A, 11B, 11C, 11D, and 11E are cross-sectional side views showing a section of a workpiece within forming blocks, and showing the progressive forming and shaping of a workpiece from a roughly-shaped workpiece 90 as shown in figures 9 and 10 into a near-finally and/or finally-shaped workpiece.

[0089] Figure 11A shows a cross-sectional side view of forming block 102 taken across line "A" of forming block 102 as shown in figure 10. figure 11A, in step 110a, shows cross-section of roughly-shaped metal workpiece 90 resting within the cavity of forming block 112a (a cross-section of forming block 102 taken along line "A" as shown in figure 10). After workpiece 90 has been exposed to at least one forming process, figure 11B shows step 110b, wherein roughly-shaped metal workpiece 90 is now shown as 114b having been shaped such that the roughly-shaped metal workpiece rests substantially proximate to the wall 113a of cavity 115. The roughly-shaped workpiece 90 is thus transformed into shaped workpiece 114b. Shaped workpiece 114c is shown as

having been further shaped as compared to the shaped workpiece 114b shown in figure 11B.

[0090] As shown in figure 11C, shaped workpiece 114b has been further shaped into workpiece 114c by trimming workpiece end 114c' of workpiece 114c. Figure 11D shows a second forming block 112b having a wall 113b with a contour that is different from the contour of wall 113a of forming block 112a. The wall 113b defines a cavity of the second forming block 112b. In this way, forming block 112b has a different cavity configuration as compared to the cavity of forming block 112a. As shown in step 110c, the workpiece 114c has now been subjected to a further forming process and further shaped into a workpiece configuration shown as workpiece 114d. Figure 11E shows step 110e wherein workpiece 114d has been further shaped by a further forming process followed by a trimming operation to shape workpiece end 114e' of workpiece 114e. According to aspects of the present disclosure of the invention, workpieces 90, 114b, and 114c can be considered to be a roughly-shaped workpiece, while workpieces 114d and 114e are shown to be a nearly-finally shaped workpiece. In further aspects, workpieces 114d and/or 114e may be considered to be finally-shaped workpieces, depending upon the desired and predetermined configuration of the workpiece according to the final workpiece configuration needed in use. According to further aspects (not shown) additional forming steps may be used, requiring additional forming blocks, if desired.

[0091] Figure 12 is a perspective view of a nacelle lip-skin according to an aspect of the present disclosure of the invention. As shown in figure 12, a lipskin 120 is fabricated according to methods disclosed herein, and ready for installation to an aircraft engine nacelle 132 on an aircraft 130 as shown in figure 13.

[0092] According to aspects of the present disclosure of the invention, the forming processes are conducted while the metal workpiece is in the first hardened condition. The present disclosure of the invention further contemplates aspects where some of the forming processes may be conducted while the metal workpiece is in the second hardened condition. However, such forming of the workpiece in the second hardened condition will be finished forming and shaping; in some cases modifying the metal workpiece less than about 3% of the forming conducted on the metal workpiece as compared with the forming conducted on the workpiece when the workpiece is in conditions other than the second hardened condition. The present disclosure of the invention therefore contemplates forming the metal workpiece via forming processes conducted: 1) in the annealed and first hardened conditions; 2) in the annealed and in either the first hardened or second hardened conditions; and 3) in the annealed and both the first hardened and second hardened conditions.

[0093] According to aspects of the present disclosure of the invention, friction stir welds that are incurred in the metal workpieces produced according to the methods

presented herein are retained in the near-finally-shaped and/or finally-shaped metal workpieces. In other words, the friction stir weld(s) made in the metal workpieces are not removed in finishing steps. As a result, the need for couplers or other reinforcing component parts (e.g. rivets, fasteners, etc.) is obviated according to aspects of the present disclosure of the invention.

[0094] Aspects of the present disclosure of the invention may, of course, be carried out in other ways than those specifically set forth herein without departing from essential characteristics of the aspects presented herein. The present aspects are to be considered in all respects as illustrative and not restrictive, and all changes coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

Claims

1. A method for making a heat-treated structure formed of metal, such as an engine nacelle for an aircraft, the method comprising:

performing a first heat-treating process on a roughly-shaped metal workpiece in an annealed condition to transition the roughly-shaped metal workpiece from the annealed condition into a first hardened condition, the roughly-shaped metal workpiece in the annealed condition comprising at least one friction stir weld;
forming the roughly-shaped metal workpiece into a shaped metal workpiece while the roughly-shaped metal workpiece is in the first hardened condition, the shaped metal workpiece comprising one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece; and
performing a second heat-treating process on the shaped metal workpiece to transition the shaped metal workpiece from the first hardened condition to a second hardened condition.

2. The method according to claim 1, comprising forming the second hardened metal workpiece into a shaped metal workpiece, said shaped metal workpiece being in one of a near-finally-shaped metal workpiece or a finally-shaped metal workpiece.
3. The method according to claim 2, wherein the shaped metal workpiece is, or comprises, a near-finally-shaped metal workpiece, the method further comprising:
forming the near-finally-shaped metal workpiece into the finally-shaped metal workpiece while the near-finally-shaped metal workpiece is in the second hardened condition.
4. The method according to claim 2 or 3, wherein the shaped metal workpiece comprises a finally-shaped

metal workpiece, the method further comprising using one or more forming processes to shape the roughly-shaped metal workpiece into the finally-shaped metal workpiece, preferably wherein the forming process is selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.

5. The method according to any of the preceding claims, wherein, before the step of performing the first heat-treating process on the roughly-shaped metal workpiece, a metal sheet is formed into the roughly-shaped metal workpiece while the metal sheet is in the annealed condition, preferably wherein the step of forming a metal sheet comprises rolling the metal sheet into the roughly-shaped metal workpiece.
6. The method according to claim 5, wherein the metal sheet is in an annealed condition, and is formed into the roughly-shaped metal workpiece by a process selected from the group consisting of: a super-plastic forming process; a super-plastic/diffusion bond forming process; a form-die forming process; an explosion forming process; and combinations thereof.
7. The method according to any of the preceding claims, wherein the roughly-shaped workpiece is a conical-shaped metal workpiece or a frusto-conical-shaped metal workpiece.
8. The method according to any of the preceding claims, wherein the at least one of the steps of performing the first heat-treating process and performing the second heat-treating process further comprise: performing at least one age-hardening process on the roughly-shaped metal workpiece in the first and/or second hardened condition.
9. The method according to claim 8, wherein the age-hardening process is a natural aging process when the roughly-shaped metal is in the first hardened condition and wherein the age-hardening process is an artificial aging process when the roughly shaped metal is in the second hardened condition.
10. The method according to any of the preceding claims, wherein the first hardened condition comprises a first age-hardened condition, and the second hardened condition comprises a second age-hardened condition.
11. The method according to any of the preceding claims, wherein the step of performing the first and/or second heat-treating process further comprises so-

lution heat-treating the metal.

12. The method according any one of the preceding claims, wherein performing the first heat-treating process comprises performing a T-4 heat-treating process on the roughly-shaped metal workpiece and/or , wherein performing the second heat-treating process comprises performing a T-6 heat-treating process.
13. A metal structure obtainable according to the method of any of the preceding claims, preferably wherein the metal comprises aluminium or an aluminium alloy, more preferably wherein the structure is annularly-shaped, even more preferably wherein the metal structure is a lipskin for use in a nacelle for an aircraft.
14. A nacelle, for use on an aircraft, the nacelle comprising a lipskin comprising at least one friction stir weld.
15. An aircraft comprising a nacelle according to claim 13 or 14.

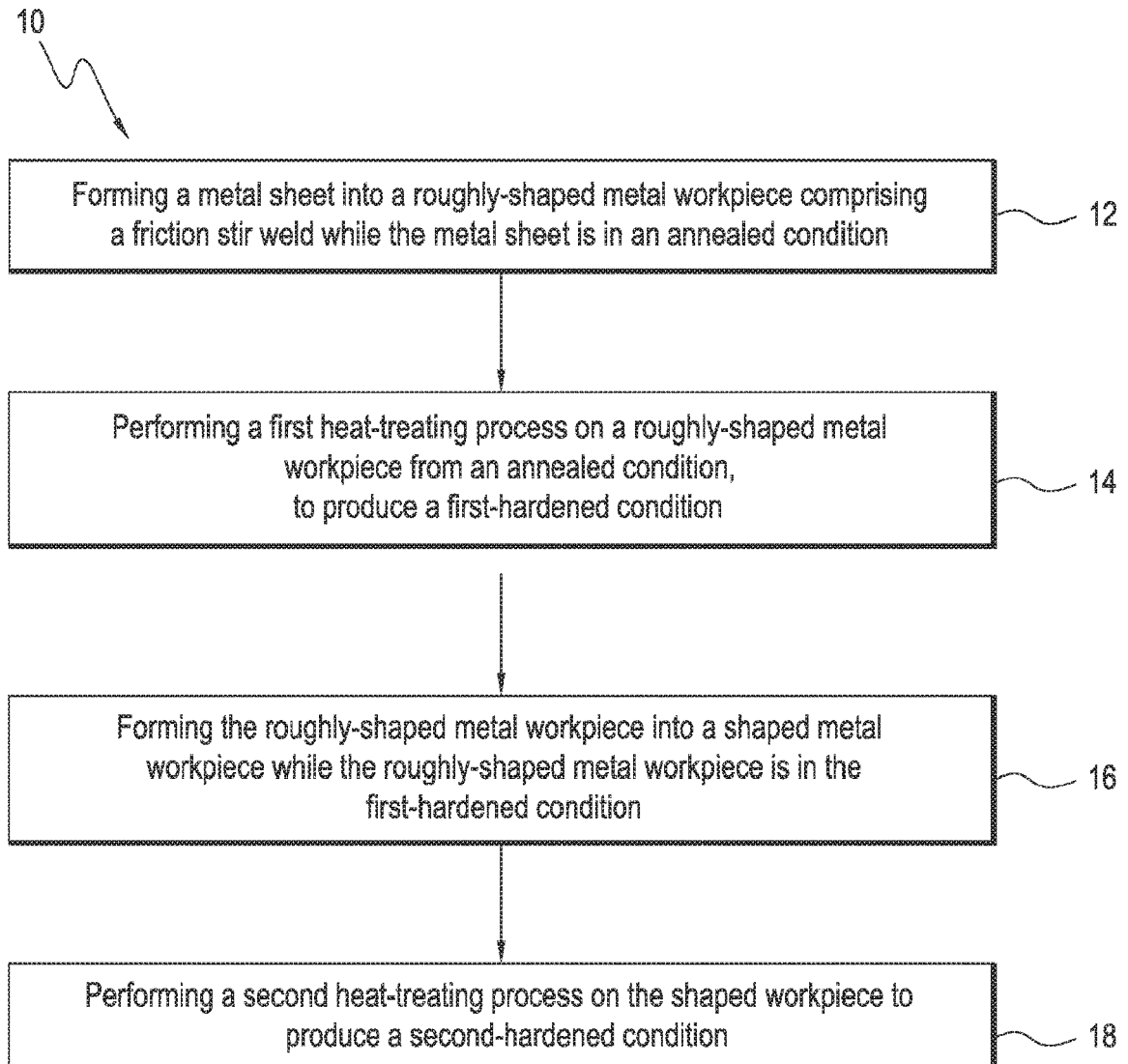


FIG. 1

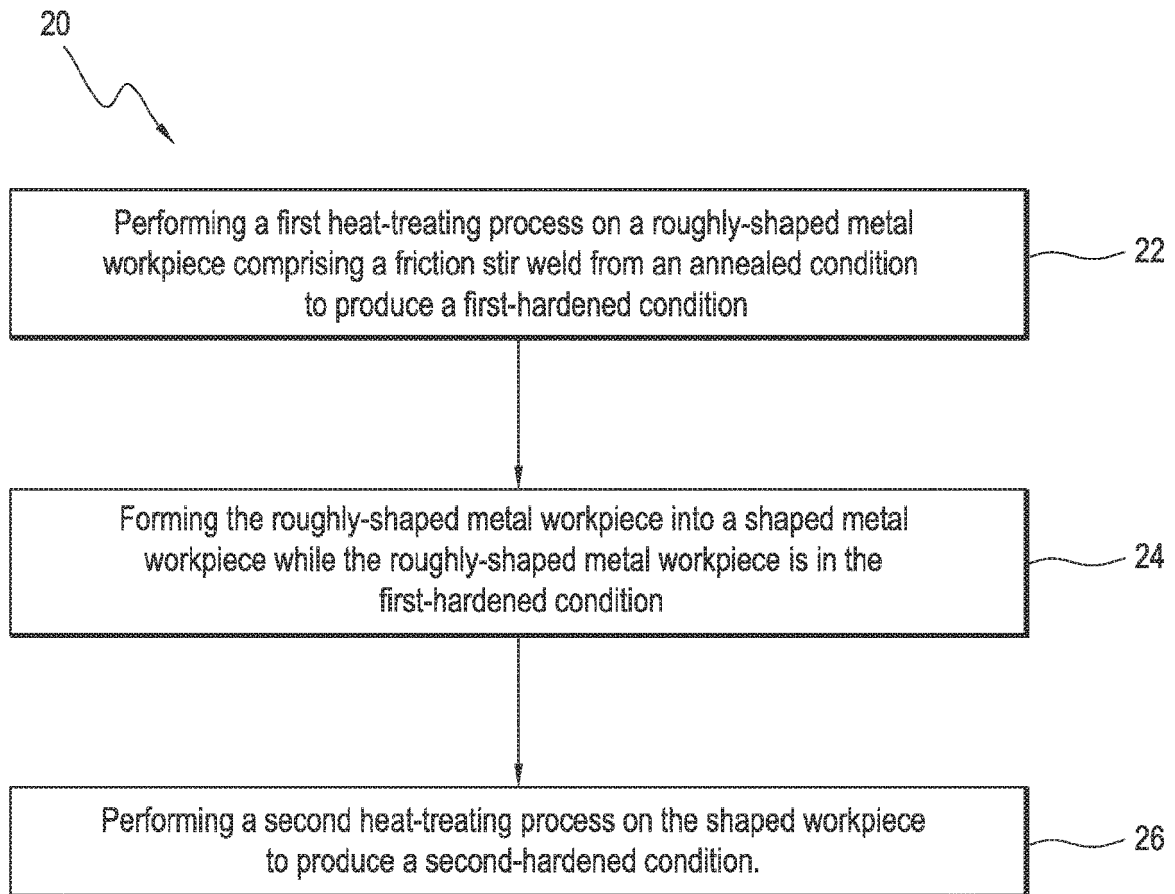


FIG. 2

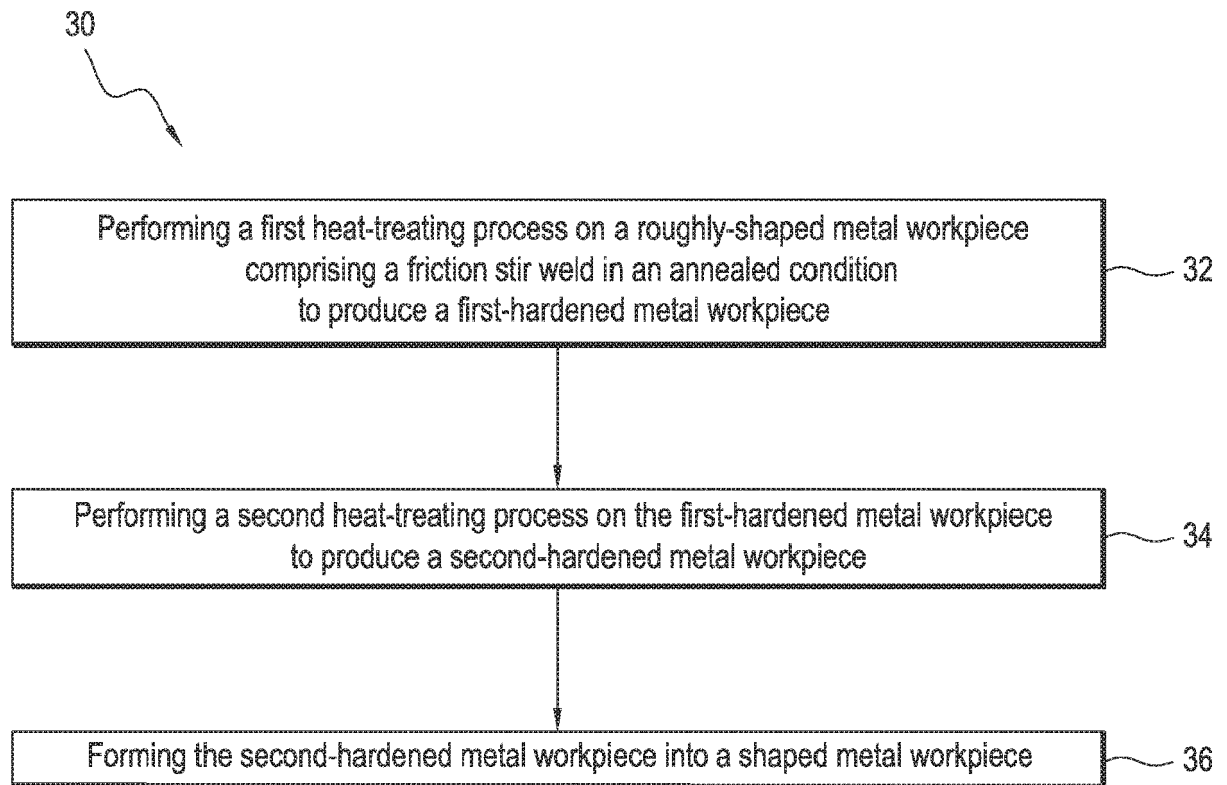


FIG. 3

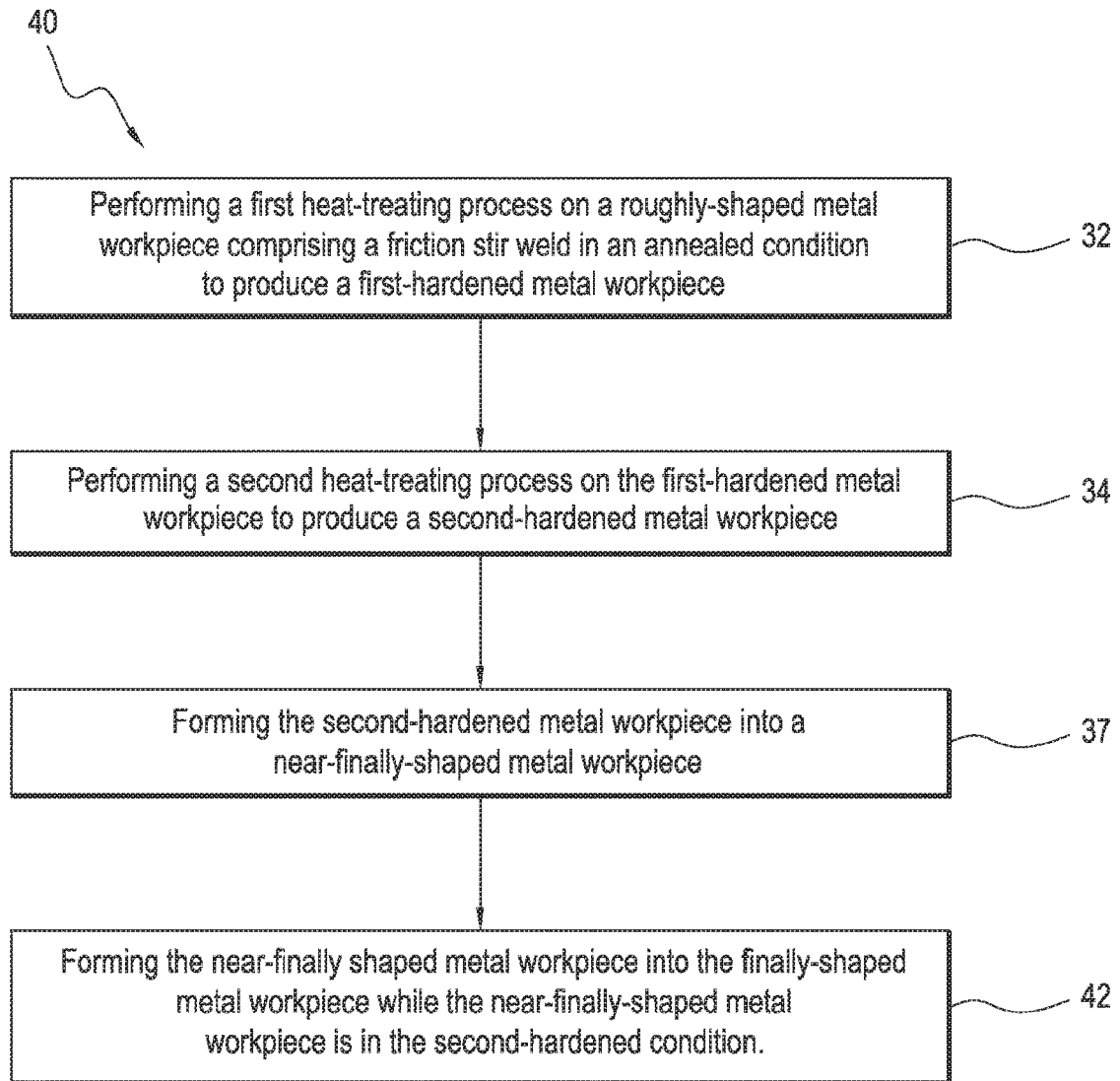


FIG. 4

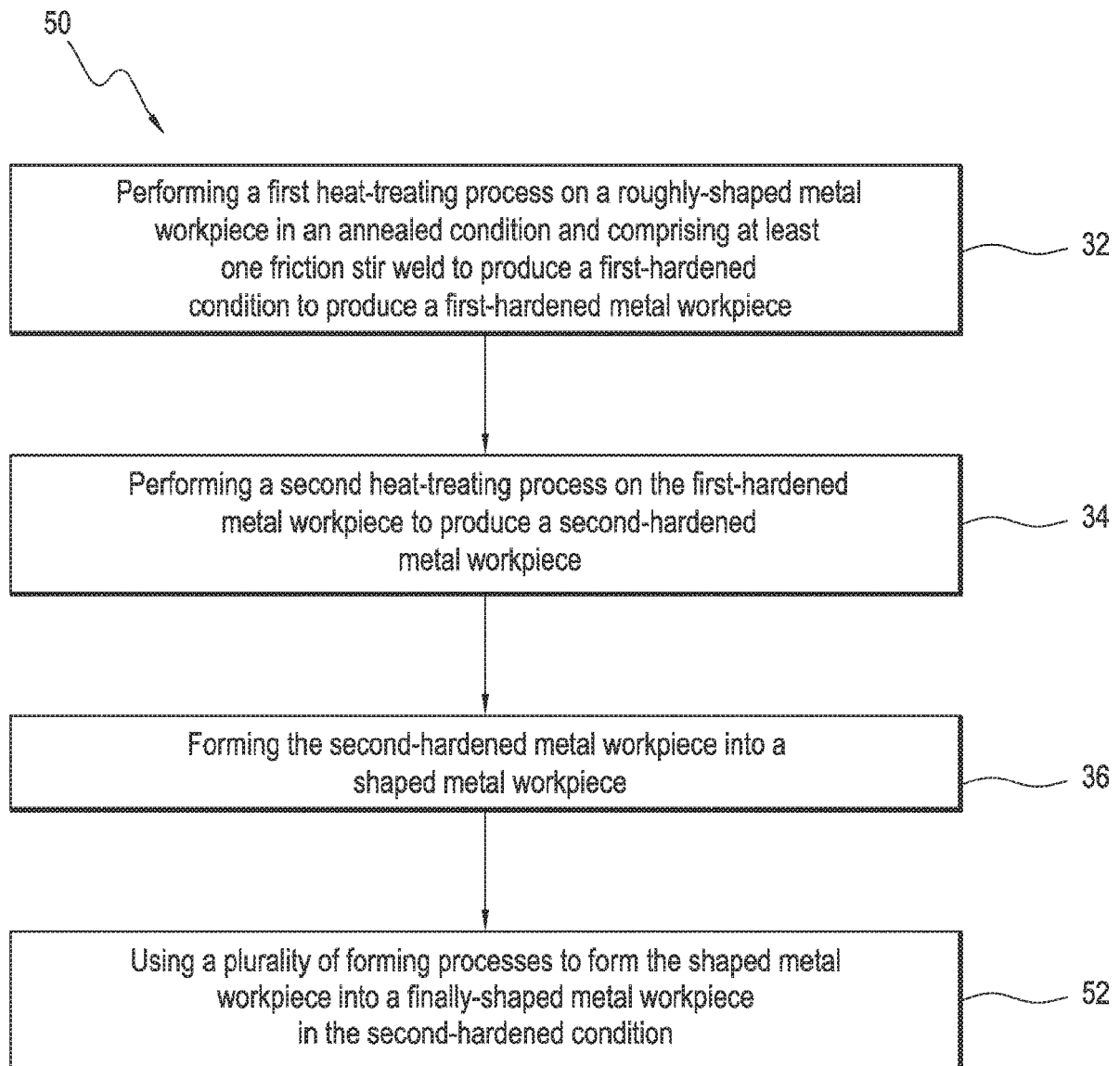


FIG. 5

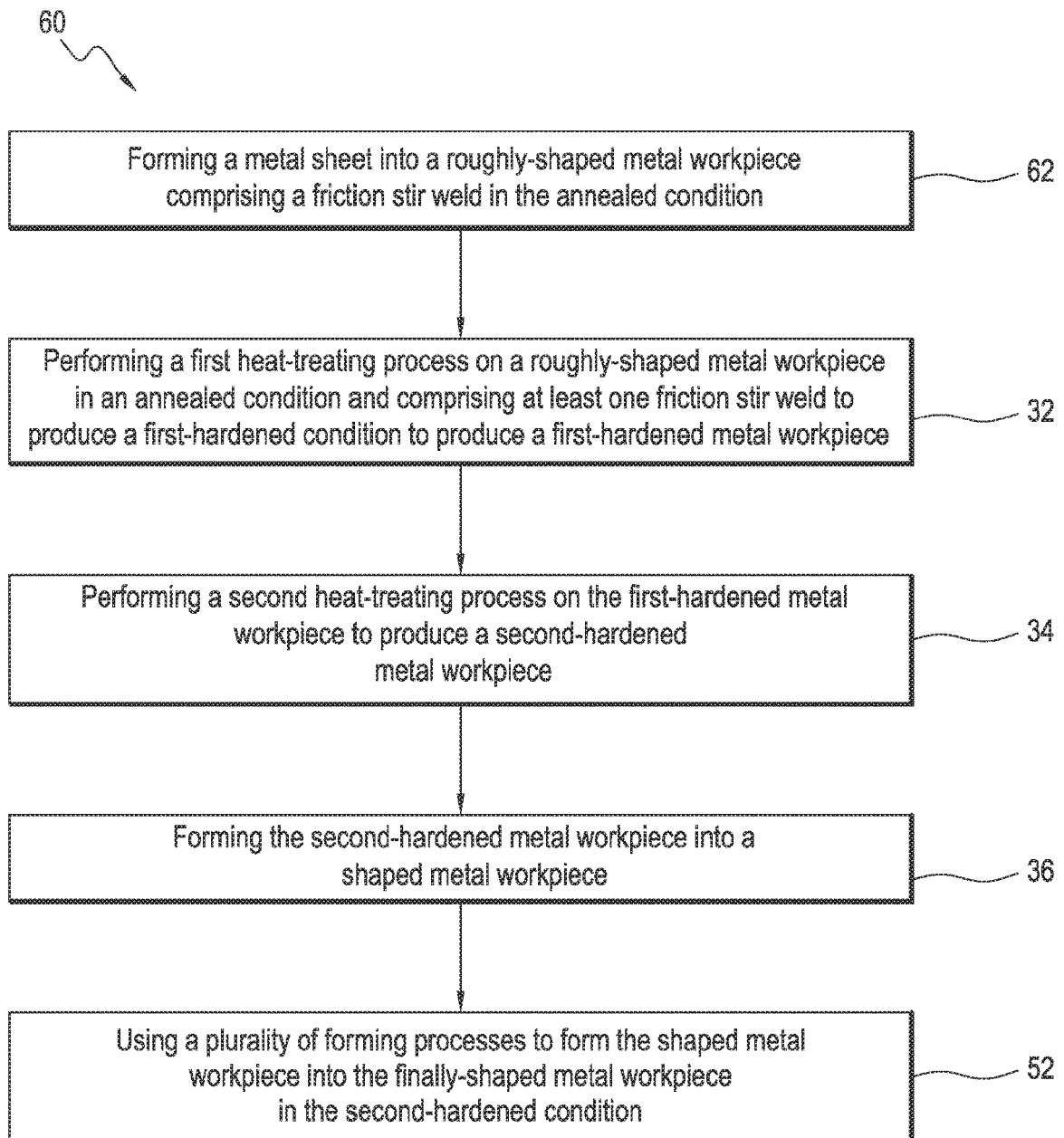


FIG. 6

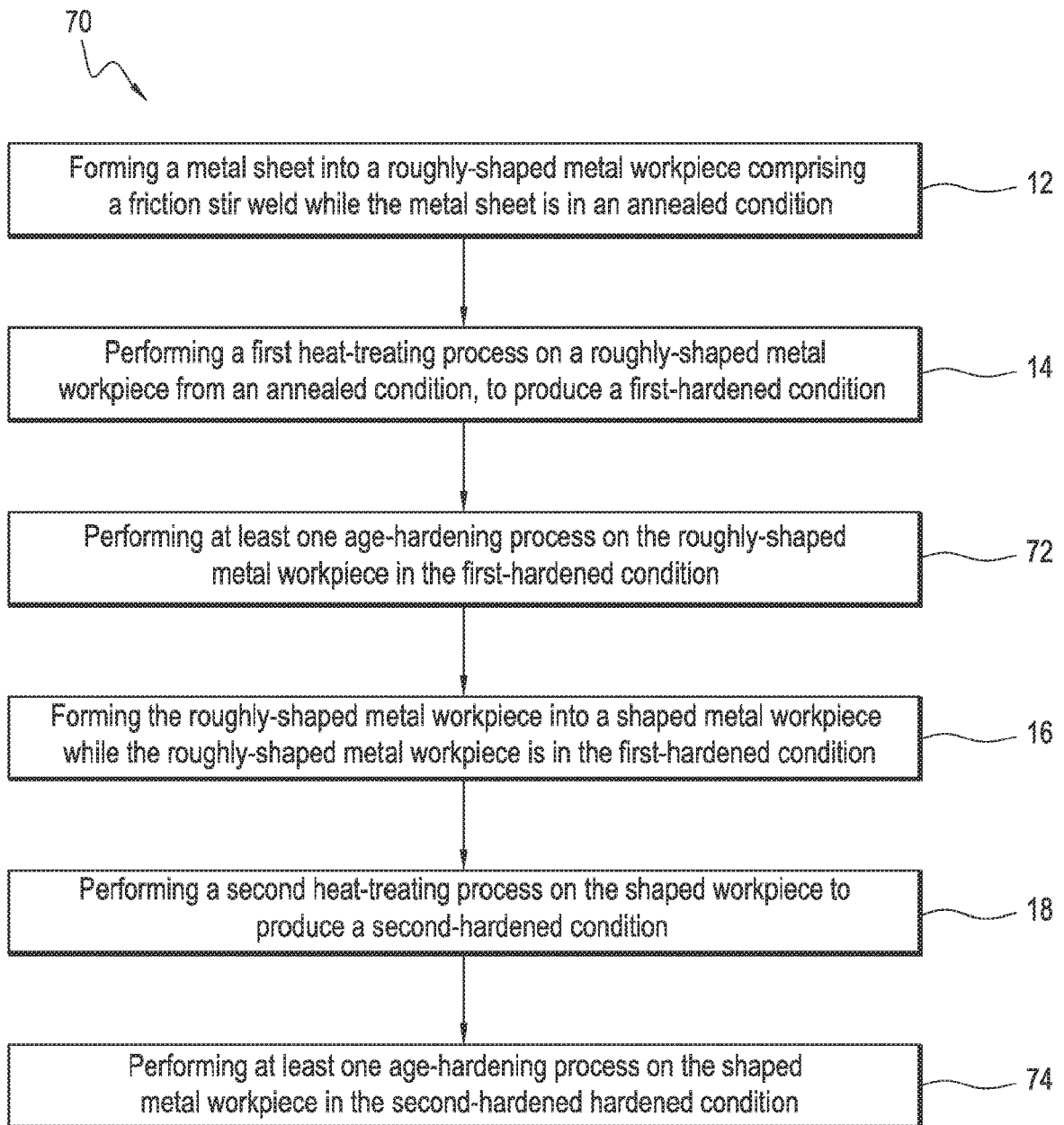


FIG. 7

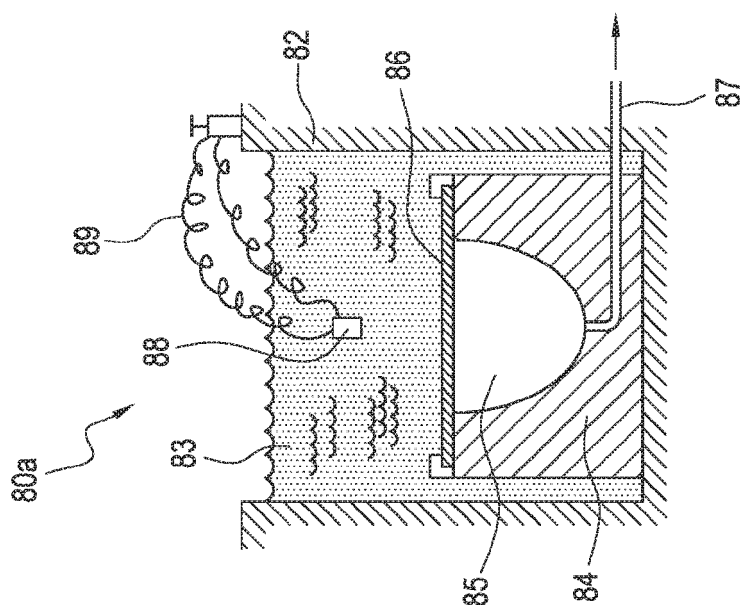


FIG. 8A

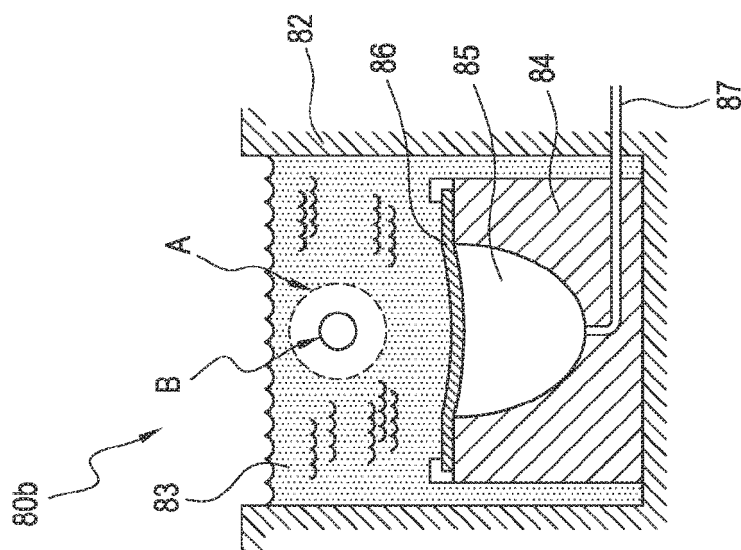


FIG. 8B

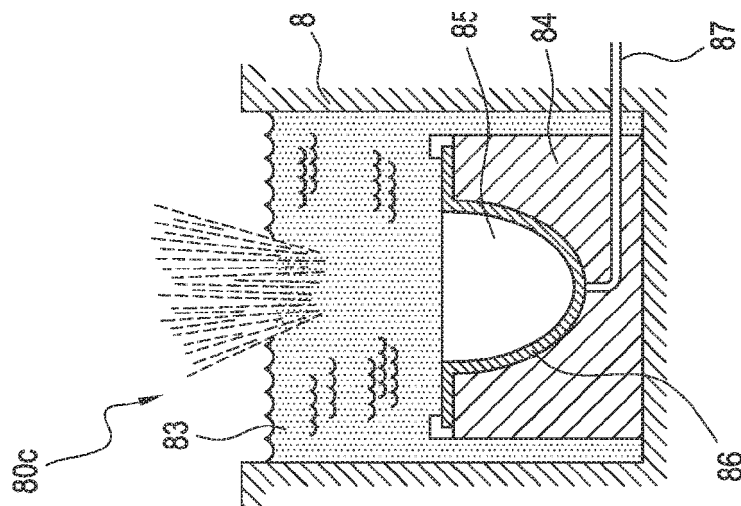


FIG. 8C

FIG. 9

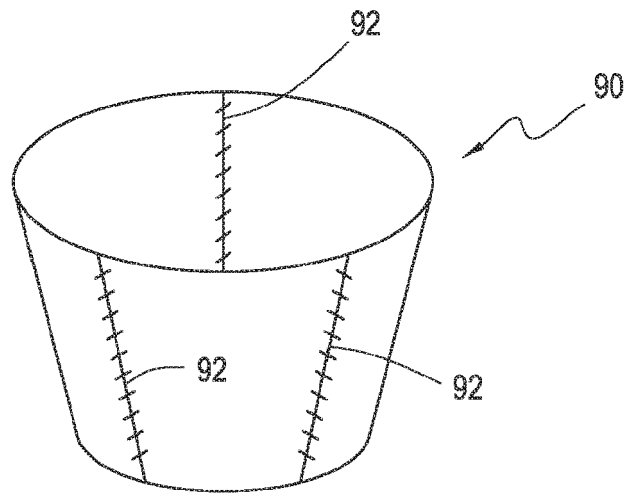
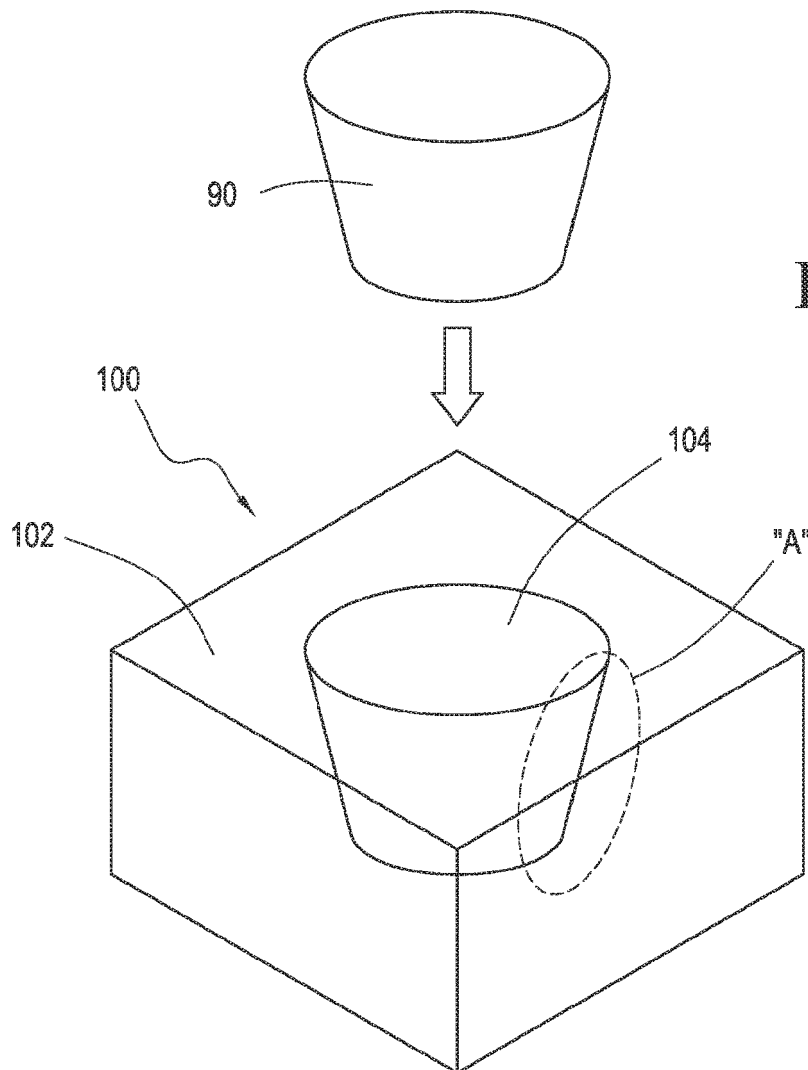


FIG. 10



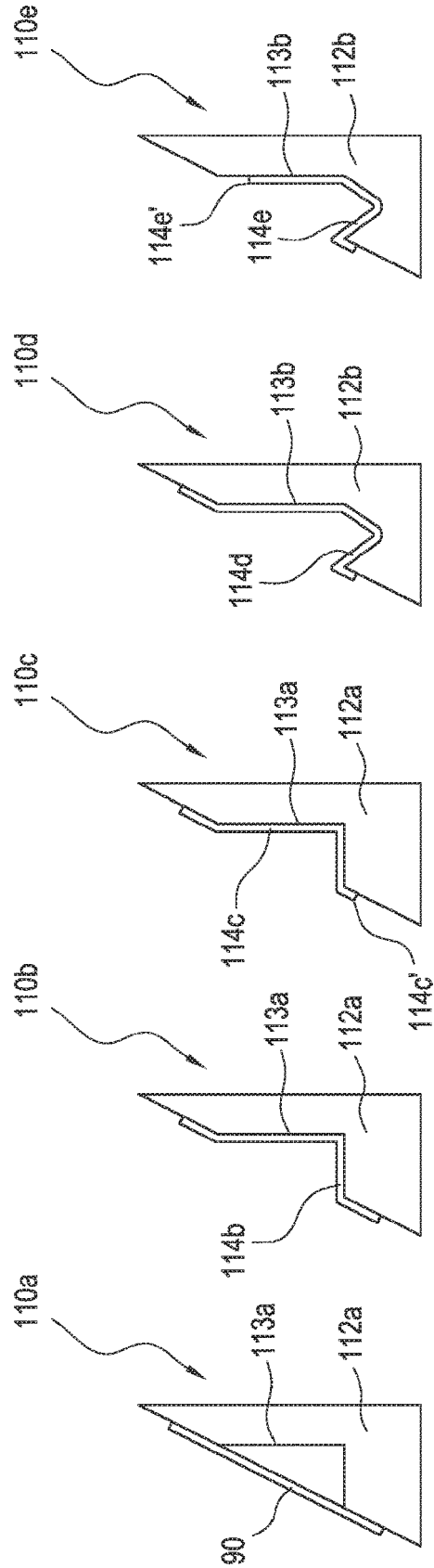


FIG. 11A FIG. 11B FIG. 11C FIG. 11D FIG. 11E

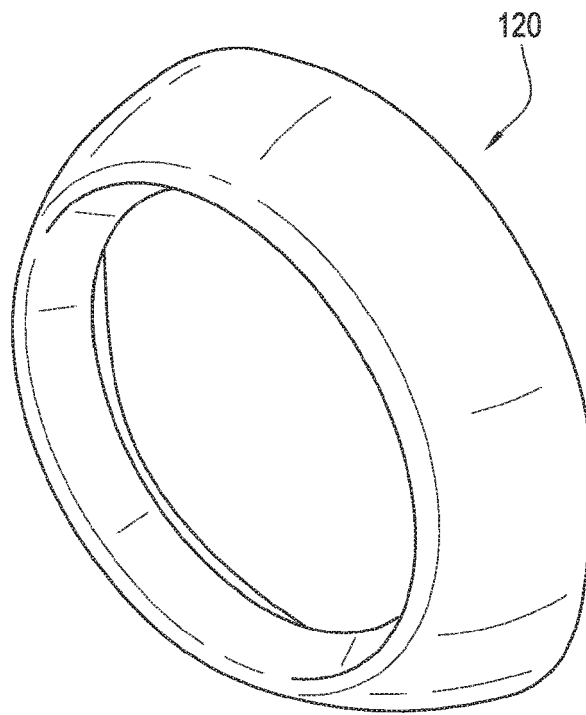


FIG. 12

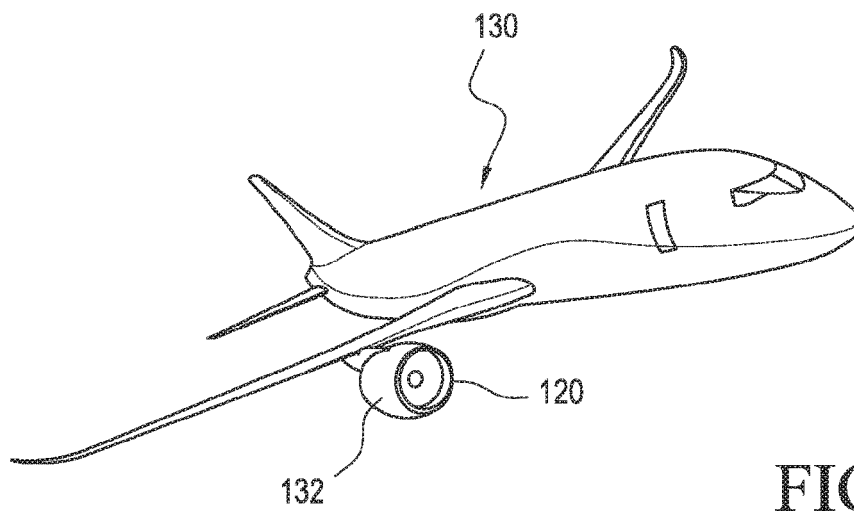


FIG. 13



EUROPEAN SEARCH REPORT

Application Number
EP 18 17 3837

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	YUAN S J ET AL: "Formability and microstructural stability of friction stir welded Al alloy tube during subsequent spinning and post weld heat treatment", MATERIALS SCIENCE AND ENGINEERING: A, vol. 558, 19 August 2012 (2012-08-19), pages 586-591, XP028938841, ISSN: 0921-5093, DOI: 10.1016/J.MSEA.2012.08.056	1-12	INV. C22F1/04
Y	* p.587: "2. Experimental procedure" *	13-15	
Y	N.N.: "Custom Machines Create Engine Lip Skins on Boeing Aircraft", 1 December 2016 (2016-12-01), XP055487595, Retrieved from the Internet: URL:https://www.techbriefs.com/component/content/article/tb/features/application-briefs/26069 [retrieved on 2018-06-25] * page 1 - page 2 *	13-15	
X	US 8 323 427 B1 (SLATTERY KEVIN T [US] ET AL) 4 December 2012 (2012-12-04) * fig. 12 with c. 6, l. 41ff *	1,8-10	TECHNICAL FIELDS SEARCHED (IPC) C22F
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 25 June 2018	Examiner Radeck, Stephanie
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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25-06-2018

10	Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82