the peening or rolling tools. They also can increase the time and complexity for manufacturing a workpiece, and thus can be overly costly or impractical to utilize.

[0010] These methods also can increase waiting times between layers, which can negatively affect productivity and potentially limit fabrication freedom. Excessive cooling between layer deposition also can increase the temperature differential between layers and further exacerbate residual stress development. For the methods that physically work the deposited layer, contaminations from tooling also will be a concern since any contaminations can get enclosed between layers of the final product in an additive process.

[0011] Accordingly, there exists a need in this art for an economical method of performing direct metal deposition at a rate of metal deposition in an additive manufacturing system that yields metal products having reduced or minimized residual stress, or distortion, or both, than is achieved in traditional additive manufacturing processes. It would be desirable to provide DED processes that reduce the incidence of residual stresses or cracking in the DED manufactured object. It also would be desirable to provide DED processes that reduce the incidence of local distortion of the object being manufactured as additional metal layers are deposited.

Summary

[0011a] In an aspect, the present disclosure refers to a support structure for a substrate, the support structure comprising: a first side comprising: two or more cavities separated by one or more stiffening member; and a rim having a flat surface around a perimeter of the first side; a second side opposite of the first side, the second side having a curved surface and comprising knurls or corrugations; and a ceramic coating disposed on the knurls or corrugations.

[0011b] In another aspect, the present disclosure refers to a directed energy deposition method for producing a metal workpiece, comprising: pre-bending a substrate of a metal material with thermal energy by forming a plurality of melting tracks on a first surface of the substrate using a melting tool to produce a pre-bent substrate; using the support structure of the above aspect to support the pre-bent substrate, and securing the pre-bent

substrate and the support structure supporting the pre-bent substrate to a jig using a plurality of clamps; and forming the metal workpiece on a second surface of the substrate by an additive manufacturing process that comprises melting a metal feedstock to deposit a layer of molten metal on the second surface of the substrate to form a base material and deposits subsequent layers of molten metal on the base material to form the workpiece, wherein the second surface of the substrate is opposite the first surface of the substrate.

[0011c] In another aspect, the present disclosure refers to a system for directed energy deposition, comprising: a jig for securing a pre-bent substrate; a support structure of the above aspect to be positioned between the jig and when the pre-bent substrate is secured to the jig; clamps for securing the pre-bent substrate to the jig; one or more melting tools comprising a DED thermal source to melt a source of metal into metallic molten material that is deposited on a surface of a base material; a gas jet device to direct a cooling gas to impinge upon the as-solidified material adjacent to a liquid-solid boundary of the liquid molten pool to influence temperature gradients; a supply of the cooling gas; and an actuator for positioning and moving the base material relative to the melting tool and the gas jet device.

[0012] Accordingly, examples provided herein are directed to production of workpieces having reduced or minimized residual stress, or distortion, or both using additive manufacturing processes that substantially obviates one or more of the problems due to limitations and disadvantages of the related art. As embodied and broadly described, provided are devices, systems and methods to reduce or minimize residual stress or distortion or both during metal additive manufacturing to achieve products with improved material quality. DED manufactured products having these reductions in residual stress or distortion demonstrate increased strength, fatigue resistance, and durability. The devices, system and methods provided can increase throughput and yield of DED formed products, and yield workpieces within specified tolerances.

[0013] Because the methods provided herein can reduce or eliminate residual stress or distortion or both, the methods can be used to fabricate DED

CLAIMS

1. A support structure for a substrate, the support structure comprising:

a first side comprising:

two or more cavities separated by one or more stiffening member; and

a rim having a flat surface around a perimeter of the first side;

a second side opposite of the first side, the second side having a curved surface and comprising knurls or corrugations; and

a ceramic coating disposed on the knurls or corrugations.

2. The support structure of claim 1, wherein the stiffening member maintains mold rigidity or provides mold deformation resistance or both.

3. The support structure of claim 1 or 2, further comprising a non-magnetic metal.

4. The support structure of any one of claims 1 to 3 further comprising a metal having a melting point of 1350 °C or greater.

5. The support structure of claim 3 or 4, wherein the metal comprises an austenitic stainless steel.

6. The support structure of claim 5, wherein the austenitic stainless steel comprises carbon, chromium, copper, manganese, molybdenum, nickel, nitrogen, phosphorus, silicon or a combination of any two or more thereof.

7. The support structure of claim 5, wherein the austenitic stainless steel comprises at least 18 % chromium.

8. The support structure of claim 5, wherein the austenitic stainless steel is a 300 series stainless steel.

9. The support structure of claim 5, wherein the austenitic stainless steel comprises a 304 stainless steel, a 309 stainless steel, a 310 stainless steel, a 316 stainless steel, a 318 stainless steel, a 321 stainless steel or a 330 stainless steel.

10. The support structure of any one of claims 1 to 9, wherein the ceramic coating comprises zirconium dioxide, zirconium dioxide stabilized by addition of yttrium oxide, yttrium aluminium oxide, alkaline earth metal silicates, ZrV_2O_7 , $Mg_3(VO_4)_2$ or a combination thereof.

11. The support structure of any one of claims 1 to 10, wherein the ceramic coating comprises ZrO_2 $8Y_2O_3$.

12. The support structure of any one of claims 1 to 11, wherein the ceramic coating has a thickness of 0.1 mm to about 5 mm.

13. The support structure of any one of claims 1 to 12, further comprising a nominal mold deflection of from about 3 mm to about 35 mm.

14. The support structure of any one of claims 1 to 13, further comprising a bond coat onto which the ceramic coating is applied.

15. A directed energy deposition method for producing a metal workpiece, comprising:

pre-bending a substrate of a metal material with thermal energy by forming a plurality of melting tracks on a first surface of the substrate using a melting tool to produce a pre-bent substrate;

using the support structure of any one of claims 1 to 14 to support the pre-bent substrate, and securing the pre-bent substrate and the support structure supporting the pre-bent substrate to a jig using a plurality of clamps; and

forming the metal workpiece on a second surface of the substrate by an additive manufacturing process that comprises melting a metal feedstock to deposit a layer of molten metal on the second surface of the substrate to form a base

material and deposits subsequent layers of molten metal on the base material to form the workpiece,

wherein the second surface of the substrate is opposite the first surface of the substrate.

16. The method of claim 15, wherein the metal feedstock is a metal in the form of a powder, a wire, or a combination thereof.

17. The method of claim 15 or 16, further comprising pre-heating the pre-bent substrate prior to forming the metal workpiece while secured to the jig to a temperature of about 400 °C to about 900 °C by applying thermal energy to the second side of the substrate.

18. The method of any one of claims 15 to 17, wherein the pre-bending the substrate comprises inducing thermal gradients in the substrate.

19. The method of any one of claims 15 to 18, wherein the melting tool comprises a thermal source selected from among a laser beam, an electron beam, a plasma arc, a gas tungsten arc, a gas metal arc and any combination thereof.

20. The method of any one of claims 15 to 19, wherein during the pre-bending the first surface of the substrate, an area of application of thermal energy reaches a temperature that is a melting point of the metal material, or a temperature from about 5 °C to about 50 °C less than or greater than the melting point of the metal material.

21. The method of any one of claims 15 to 20, wherein during the pre-bending of the first surface of the substrate, formation of the melting tracks results in formation of tensile stress at a centerline of each of the melting tracks and formation of a compressive stress in an area away from the centerline of each of melting tracks upon cooling of the substrate.

22. The method of claim 21, wherein the tensile stress at the centerline of the melting track is within about 10 % of a yield strength of the substrate.

23. The method of claim 21, wherein the tensile stress at the centerline of the melting track exceeds the magnitude of a yield strength of the substrate.

24. The method of any one of claims 15 to 23, wherein the pre-bending step further comprises directing a cooling gas toward the melting tracks using a gas jet device to accelerate cooling of the melting track.

25. The method of claim 24, wherein directing the cooling gas toward the melting tracks forms a thermal gradient in the substrate, and imparts a residual stress in the substrate upon cooling.

26. The method of claim 24 or 25, wherein the gas jet device directs the cooling gas toward of the melting tracks at a rate from about 50 L/min to about 500 L/min.

27. The method of any one of claims 24 to 26, wherein the cooling gas is applied in a constant stream, or applied intermittently, or applied in a pulsed flow.

28. The method of any one of claims 24 to 26, wherein the cooling gas comprises an inert gas selected from among argon, helium, neon, xenon, krypton and combinations thereof.

29. The method of any one of claims 24 to 28, wherein the cooling gas is applied at a temperature 100 °C or less.

30. The method of any one of claims 24 to 29, wherein the cooling gas is applied at a temperature of 25 °C or less.

31. The method of any one of claims 24 to 30, wherein the gas jet device produces a turbulent flow of the cooling gas, a laminar flow of the cooling gas, or a combination of a turbulent flow and laminar flow of the cooling gas.

32. The method of any one of claims 24 to 31, wherein the gas jet device comprises a plurality of nozzles, the nozzles directing the cooling gas in a direction away from the thermal source of the melting tool, and at least one nozzle directing the cooling gas to an as-solidified metal of the melting track.

33. The method of any one of claims 15 to 32, wherein the melting tracks are produced equidistant from each other.

34. The method of any one of claims 15 to 33, wherein the distance between the melting tracks is from about 10 mm to about 60 mm.

35. The method of any one of claims 15 to 34, further comprising:

determining a centerline of each wall of a preform that is to be formed on the second surface of the substrate; and

positioning the melting tracks on the first surface of the substrate from about 10 mm to about 20 mm away from the centerlines of the majority of walls of the preform to be formed on the second surface of the substrate.

36. The method of any one of claims 15 to 35, further comprising forming a majority of the melting lines on the first surface at one or more locations other than those corresponding to one or more areas occupied by of one or more walls of the workpiece to be formed on the second side of the substrate.

37. The method of any one of claims 15 to 36, wherein the pre-bending forms a pre-bent substrate having a uniform elasto-plastic bend.

38. The method of any one of claims 15 to 37, further comprising pre-bending of the substrate while the substrate is clamped to a jig and thermally insulated from the jig.

39. The method of any one of claims 15 to 38, wherein one or more clamps comprises an insulating coating on each surface that comes into contact with the pre-bent substrate.

40. The method of claim 39, wherein the insulating coating comprises a ceramic material, a silicon carbide, a silicon nitride, a boron carbide or a combination thereof.

41. The method of claim 40, wherein the ceramic material comprises an alumina, a zirconia, titanium oxide, an alkaline earth metal silicate, an aluminium titanate, a zirconium dioxide, a zirconium dioxide stabilized by addition of yttrium oxide, a yttrium aluminium oxide, ZrV_2O_7, $Mg_3(VO_4)_2$ or a combination thereof.

42. The method of claim 40 or 41, wherein the thickness of the insulating coating is from 0.1 mm to 5 mm.

43. The method of any one of claims 39 to 42, wherein the clamps comprise a knurling pattern or corrugation on a surface in contact with the pre-bent substrate.

44. The method of any one of claims 39 to 43, further comprising tightening the clamps to bring the pre-bent substrate into full contact with the underlying support structure.

45. The method of claim 44, wherein each of the clamps is tightened to a torque of from about 10 N•m to about 100 N•m.

46. The method of any one of claims 39 to 45, wherein the clamps are positioned so that the clamps meet at a start or an end of a wall of the workpiece being produced.

47. The method of any one of claims 15 to 46, wherein the pre-heating of the pre-bent substrate is done using one or more melting tools comprising a DED thermal source under conditions that:

a) form melting tracks but do not melt the surface of the pre-bent substrate; or

b) form melting tracks and melt the surface of the pre-bent substrate at the melting tracks.

48. The method of claim 46, further comprising positioning the melting tool at a standoff position greater than a standoff position used for forming the workpiece.

49. The method of claim 48, further comprising pre-heating the pre-bent substrate comprising a first short edge and an opposite second short edge and a first long edge and an opposite second long edge prior to DED deposition to form a workpiece, the pre-heating comprising:

a) positioning a melting tool comprising a DED thermal source at the first short edge and within about 10 mm to about 60 mm of the first long edge of the pre-bent substrate secured to the jig;

b) applying the thermal energy form the DED thermal source of the melting tool across the surface of the pre-bent substrate starting at the first short edge and across the surface to the second opposite short edge to form a first line of energy application to the surface;

c) repositioning the DED thermal source of the melting tool to the first short edge and displaced a distance of about 10 mm to about 60 mm from the first line of energy application and toward the second long edge; and

d) repeating steps b) and c) until lines of energy application are applied across the surface of the pre-bent substrate to a position from about 10 mm to about 60 mm from the second opposite long edge.

50. The method of claim 48 or 49, further comprising pre-heating the pre-bent substrate prior to DED deposition to form a workpiece, by applying thermal energy to a frontside of the substrate using a heating device.

51. The method of claim 50, wherein the heating device comprises an infrared heater, an inductive heater, a resistive heater, or combinations thereof.

52. The method of claim 50, wherein the heating device comprises a conductor-in-conduit heat source, a heater strip, a resistive heating strip, an infrared heater, a Positive Thermal Coefficient ceramic heater, a thick film ceramic heater, a resistance wire heater, a resistance ribbon heating device, an infrared heater, an induction heater or a combination thereof.

53. The method of any one of claims 15 to 52, wherein the pre-heating raises the temperature of the pre-bent substrate to a temperature of about 350 °C to about 650 °C.

54. The method of any one of claims 16 to 53, where the forming of the metal workpiece comprises:

providing the metal feedstock in the form of a wire;

using a single melting tool to heat and melt the wire such that molten metallic material is deposited onto an area of the substrate to form a base material;

moving the base material relative to a position of the melting tool in a predetermined pattern such that the successive deposits of molten metallic material onto the base material solidifies and forms the three-dimensional object.

55. The method of any one of claims 16 to 53, where the forming of the metal workpiece comprises:

a) providing the metal feedstock in the form of a wire;

b) using a first melting tool to heat at least a portion of a surface of the substrate to form a preheated area on the substrate;

c) using a second melting tool to heat and melt the wire such that molten metallic material is deposited onto the preheated area to form a base material;

d) moving the base material relative to a position of the first melting tool and second melting tool in a predetermined pattern;

e) using the first melting tool to heat at least a portion of a surface of the base material to form a preheated area on the base material and depositing molten metallic material produced by the second melting tool melting the metallic material onto the preheated area on the base material; and

f) repeating steps d) and e) such that the successive deposits of molten metallic material onto the preheated areas on the base material solidifies and forms the three-dimensional object.

56. The method of claim 54 or 55, further comprising:

using a gas jet device to direct a cooling gas across a surface of the molten metallic material, or to impinge on a surface of the molten metallic material, or to impinge upon a surface of a solidified material adjacent to a liquid-solid boundary of the molten metallic material, or any combination thereof; and

moving the base material relative to the position of the melting tool(s) and the gas jet in a predetermined pattern such that the successive deposits of molten metallic material solidifies and forms the three-dimensional object.

57. The method of claim 54 or 55, wherein:

the first melting tool comprises a PTA torch, a laser device, an electron beam device, or any combination thereof; and

the second melting tool comprises a PTA torch, a laser device, a coaxial powder feed nozzle laser system, an electron beam device, or any combination thereof.

58. The method of claim 57, wherein:

the first melting tool comprises a first PTA torch and the second melting tool comprises a second PTA torch; or

the first melting tool comprises laser device and the second melting tool comprises a PTA torch; or

the first melting tool comprises a PTA torch and the second melting tool comprises a laser device; or

the first melting tool comprises a laser device and the second melting tool comprises a coaxial powder feed nozzle laser system; or

the first melting tool comprises a PTA and the second melting tool comprises a torch coaxial powder feed nozzle laser system; or

the first melting tool comprises a PTA torch and the second melting tool comprises an electron beam device; or

the first melting tool comprises an electron beam device and the second melting tool comprises a PTA torch; or

the first melting tool comprises an electron beam device and the second melting tool comprises a laser device; or

the first melting tool comprises laser device and the second melting tool comprises an electron beam device.

59. The method of claim 58, wherein when the second melting tool comprises a PTA torch, the PTA torch is electrically connected to a direct current power source such that an electrode of the PTA torch becomes the cathode and the metallic material is a consumable electrode that becomes the anode.

60. The method of any one of claims 15 to 59, wherein each of pre-bending the substrate, pre-heating the pre-bent substrate, and forming the metal workpiece is performed within a closed chamber containing an inert atmosphere.

61. The method of claim 60, wherein the inert atmosphere comprises argon, neon, xenon, krypton, helium or a combination thereof.

62. A system for directed energy deposition, comprising:

a jig for securing a pre-bent substrate;

a support structure of any one of claims 1 to 14 to be positioned between the jig and when the pre-bent substrate is secured to the jig;

clamps for securing the pre-bent substrate to the jig;

one or more melting tools comprising a DED thermal source to melt a source of metal into metallic molten material that is deposited on a surface of a base material;

a gas jet device to direct a cooling gas to impinge upon the as-solidified material adjacent to a liquid-solid boundary of the liquid molten pool to influence temperature gradients;

a supply of the cooling gas; and

an actuator for positioning and moving the base material relative to the melting tool and the gas jet device.