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 curved clamping mold, 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.

[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 curved clamping mold of the above aspect as an underlying support structure to support the pre-bent substrate, and securing the pre-bent

substrate and the curved clamping mold 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 curved clamping mold 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

formed components of a medium to large size (*e.g.*, up to 3 m), which cannot easily be produced using conventional additive manufacturing processes. In addition, because of the reduction or elimination of the typical large amounts of residual stress, distortion or a combination thereof in conventional DED metal structure, manufactured metal structures can be produced that are geometrically within tolerances and specifications.

[0014] Because residual stress and distortion often can be seen as key barriers for mainstream acceptance of DED technologies for metals, particularly in safety-critical applications, the devices, systems and methods provided herein that can minimize residual stress or distortion can open new markets or engender wider acceptance of DED produced components. Devices, systems and methods provided herein also can result in effective control over residual stress and distortion in DED metal structures so that material utilization efficiencies of both substrate and DED material can be improved. These improvements in material utilization, in conjunction with production of DED produced products within tolerances, can result in less waste and reworking, which can significantly reduce DED manufacturing costs.

[0015] Provided in an example are methods for DED manufacturing that include pre-bending a metallic substrate to form a plastically pre-bent substrate prior to DED of single-sided metallic structures. Also provided are methods for DED manufacturing that include pre-bending a metallic substrate to form a plastically pre-bent substrate and pre-heating the pre-bent substrate prior to DED of metallic structures. Also provided is an apparatus for manufacturing components having reduced residual stress and distortion by DED. The apparatus can be used with conventional DED energy supply sources used to melt a metal powder and/or wire feedstock. The apparatus includes a curved clamping mold as an underlying support structure for a plastically pre-bent substrate. Also provided are systems using conventional DED energy supply sources modified using CAD-CAM program instructions that when executed cause the DED process to follow the shape of the underlying curved clamping mold.

[0016] Provided in an example are methods for DED manufacturing that minimize or prevent distortion in a DED manufactured product. This can increase the efficiency of the manufacturing process, such as by minimizing waste of substrate and the

amount of deposited material that must be used. In particular, because the highest thermally induced stress fields can be introduced in the first deposited layers, and the distortion effect can particularly be seen in the substrate, methods provided herein can conserve substrate material sacrificed or lost in conventional additive manufacturing processes. The methods can result in improved material utilization efficiencies of both substrate and DED material compared to conventional methods. Methods provided herein can provide effective control over residual stress and distortion in DED structures. This can lead to reducing material waste, buy-to-fly or BTF ratios can be driven close to unity. Reducing material waste, as well as reducing or eliminating rework time, can significantly reduce cost of manufacture.

[0017] Provided in an example is a curved clamping mold. The curved clamping mold includes a first side that includes two or more cavities separated by one or more than one 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 including knurls or corrugations. The curved clamping mold can include a ceramic coating. The stiffening member can maintain mold rigidity or can provide mold deformation resistance or both. The curved clamping mold can include or be made out of a non-magnetic metal. The curved clamping mold can include or be made out of a metal having a melting point of 1350°C or greater. The curved clamping mold can include or be made out of a metal that is or includes an austenitic stainless steel. The austenitic stainless steel can include carbon, chromium, copper, manganese, molybdenum, nickel, nitrogen, phosphorus, silicon or a combination of any two or more thereof. The austenitic stainless steel can include at least 18% chromium. The austenitic stainless steel can be a 300 series stainless steel. The austenitic stainless steel can include 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 or a combination thereof.

[0018] The ceramic coating of the curved clamping mold can be applied to any one or more surfaces. The ceramic coating can include 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. The ceramic coating can include ZrO_2 $8Y_2O_3$. The ceramic coating can have a thickness of 0.1 mm to about 5 mm. The curved clamping mold can include a nominal mold

deflection of from about 3 mm to about 35 mm. The curved clamping mold can include a bond coat onto which the ceramic coating is applied. The bond coat can be between a surface of the curved clamping mold and the ceramic coating.

[0019] Also provided in an example is a directed energy deposition method for producing a metal workpiece. The method can include 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 first melting tool to produce a pre-bent substrate; using the curved clamping mold described herein as an underlying support structure to support the pre-bent substrate when it is secured to a jig, and securing the pre-bent substrate and the curved clamping mold supporting the pre-bent substrate to the jig using a plurality of clamps. After the pre-bent substrate and the curved clamping mold are secured to the jig, the method includes forming the metal workpiece on a second surface of the substrate by an additive manufacturing process that can a) 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; or b) deposit a layer of metal powder and melts the metal powder on the second surface of the substrate to form a base material, and deposits subsequent layers of metal powder and melts the powder on the base material to form the workpiece, where the second surface of the substrate is opposite the first surface of the substrate. The method can include pre-heating the pre-bent substrate 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. The pre-bending the substrate can include inducing thermal gradients in the substrate. In the methods, a melting tool that includes 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 can be used. During the pre-bending the first surface of the substrate, an area of application of thermal energy can reach 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. During the pre-bending of the first surface of the substrate, formation of the melting tracks can result 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. The tensile stress at the centerline of

second PTA torch. The first melting tool can include laser device and the second melting tool can include a PTA torch. The first melting tool can include a PTA torch and the second melting tool can include a laser device. The first melting tool can include a coaxial powder feed nozzle laser system and the second melting tool can include a laser device. The first melting tool can include a coaxial powder feed nozzle laser system and the second melting tool can include a PTA torch. The first melting tool can include a PTA torch and the second melting tool can include an electron beam device. The first melting tool can include an electron beam device and the second melting tool can include a PTA torch. The first melting tool can include an electron beam device and the second melting tool can include a laser device. The first melting tool can include laser device and the second melting tool can include an electron beam device. When the second melting tool includes a PTA torch, the PTA torch can be electrically connected to a direct current power source such that an electrode of the PTA torch becomes the cathode and the metallic material can be a consumable electrode that becomes the anode.

[0028] In the methods provided herein, every step of the methods, including each of pre-bending the substrate, pre-heating the pre-bent substrate, and forming the metal workpiece, can be performed within a closed chamber containing an inert atmosphere. The inert atmosphere can include argon, neon, xenon, krypton, helium or a combination thereof.

[0029] Also provided in an example is a system for directed energy deposition. The system can include a jig for securing a pre-bent substrate; a curved clamping mold as described herein to be positioned between the jig and when the pre-bent substrate is secured to the jig; insulated 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 the liquid-solid boundary of the liquid molten pool, or any combination thereof; 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.

[0030] Additional features and advantages of the embodiments described herein will be set forth in the description which follows, and in part will be apparent from the description, or may be learned by practice of the invention. The objectives