CLAIMS

1. A method for 3-D printing a metal object having a density at least 95% that of pure metal, the method comprising:

forming a series of layers comprising the metal object, each layer formed from a metal filament, wherein forming each layer comprises:

forming a series of voxels from the metal filament via application of ultrasonic energy to a print tool in contact with the metal filament, wherein the print tool comprises a tungsten carbide bar having a thickness of between 2 mm and 3 mm and a length of between 12 mm and 25 mm,

wherein a portion of the print tool in contact with the metal filament vibrates with an amplitude of between 0.9 microns and 1.1 microns responsive to the ultrasonic energy,

wherein each voxel in the series of voxels is coupled via mass transport to adjacent voxels in the layer and to adjacent voxels in the prior layer,

wherein, during formation of a voxel, the temperature of the metal filament increases by less than 6 degrees Celsius,

wherein each voxel is formed via application of ultrasonic energy for a period of between 200 microseconds and 400 microseconds,

and

wherein the forming a series of voxels is conducted at room temperature and in ambient atmosphere.

2. The method of claim 1, wherein the metal filament comprises at least one of aluminum, titanium, gold, silver, copper, or a steel alloy.

3. The method of claim 1, further comprising varying an intensity of the applied ultrasonic energy between formation of voxels to alter the microstructure of the metal.

4. The method of claim 1, wherein the print tool is coupled to a piezoelectric crystal operative at between 40 kHz and 200 kHz.

5. The method of claim 1, wherein forming the series of voxels is conducted at 10 Newtons of force applied to the metal filament.

6. The method of claim 1, wherein the metal filament comprises grains, and wherein, responsive to the application of ultrasonic energy, the grains are deformed to cause sub-grain formation.

7. The method of claim 1, wherein the application of ultrasonic energy is conducted at a power density of at least 160 watts per square centimeter.

8. The method of claim 1, further comprising removing at least a portion of the metal object.

9. The method of claim 1, wherein the temperature increase of the metal filament within a voxel in the series of voxels arises from: (i) volumetric heat generation from plastic deformation of the metal filament, (ii) frictional heat generation from relative motion between the metal filament and a prior voxel, and (iii) cyclic shear deformation of the voxel in the metal filament axial direction.

10. A method for additive manufacturing, the method comprising:

contacting a first length of metal wire with a metal substrate;

inducing, via application of ultrasonic energy, materials flow and solid-state diffusion in the first length of metal wire in a first target area to bond a portion of the first target area to the metal substrate, wherein the ultrasonic energy is applied to the first length of metal wire via a print tool comprising a tungsten carbide bar having a thickness of between 2 mm and 3 mm and a length of between 12 mm and 25 mm; and

inducing, via application of ultrasonic energy, materials flow and solid-state diffusion in the first length of metal wire in a second target area at least partially overlapping the first target area to bond a portion of the second target area to the metal substrate,

wherein the materials flow and solid-state diffusion in the first length of metal wire in the first target area occurs with a temperature rise in the wire of less than 6 degrees Celsius.

11. The method of claim 10, further comprising:

contacting a second length of metal wire to the first target area and the second target area; and

inducing, via application of ultrasonic energy, materials flow and solid-state diffusion in the second length of metal wire in a third target area to bond a portion of the third target area to at least one of the first target area or the second target area.

12. The method of claim 10, wherein 10 Newtons of force is applied to the first length of metal wire during the inducing the materials flow and solid-state diffusion in the first length of metal wire.

13. The method of claim 10, wherein the source of the ultrasonic energy is a piezoelectric crystal operating at a frequency of about 60 kHz, and wherein the piezoelectric crystal and the print tool are coupled via a steel horn.

14. The method of claim 11, wherein the combined density of the first target area, the second target area, and the third target area exceeds 95% of the density of the pure metal.

15. The method of claim 10, wherein the portion of the first target area bonded to the substrate forms a voxel.

16. The method of claim 15, further comprising repeatedly forming a series of voxels to form a desired structure.

17. The method of claim 16, further comprising varying the amount of ultrasonic energy applied to a set of voxels in the series of voxels to control a microstructure of the metal grain in the desired structure.

18. The method of claim 10, wherein the metal comprises at least one of aluminum, titanium, gold, silver, copper, or a steel alloy.

19. The method of claim 10, wherein the method is performed at room temperature and in ambient atmosphere.

20. The method of claim 10, wherein, responsive to the ultrasonic energy, a free end of the print tool vibrates with an amplitude of between 0.9 microns and 1.1 microns.

21. The method of claim 10, wherein the ultrasonic energy is applied for a period of between 200 microseconds and 400 microseconds.

22. The method of claim 10, further comprising removing at least a portion of the first target area, the second target area, or the third area to form a desired structure.

23. An additive manufacturing system, the system comprising:

a print tool comprising a tungsten carbide bar having a thickness of between 2 mm and 3 mm and a length of between 12 mm and 25 mm;

an ultrasonic energy source;

a build plate, the print tool configured to guide a metal filament with respect to the build plate;

an x-axis motor;

a y-axis motor;

at least one z-axis motor, wherein each of the x-axis motor, the y-axis motor, and the at least one z-axis motor are operable to move the build plate with respect to the print tool; and

a printer control board in electronic communication with the x-axis motor, the y-axis motor, and the at least one z-axis motor, wherein the printer control board is operative to:

print, by a printing step, a plurality of voxels to form a formed object, the printing step comprising:

guide the metal filament to a voxel location and with respect to the build

plate;

hold, via at least one of the x-axis motor, the y-axis motor, or the at least one z-axis motor, the metal filament in place at the voxel location at a first pressure;

supply an ultrasonic energy through the print tool and into the metal filament by vibrating the print tool at the voxel location, wherein responsive to the ultrasonic energy, a portion of the print tool in contact with the metal filament vibrates with an amplitude of between 0.9 microns and 1.1 microns, and wherein responsive to the vibrating the print tool, a plastic strain, a frictional heat, and a cyclic shear deformation are induced in the metal filament such that a temperature rise is less than 6 degrees Celsius to form a voxel at the voxel location; and

control, by adjusting a magnitude of the ultrasonic energy that is input via the ultrasonic energy source during the printing step, a microstructure of the formed object.

24. The system of claim 23, wherein the ultrasonic energy source further comprises a piezoelectric crystal-based transducer.

25. The system of claim 24, wherein the supply of the ultrasonic energy through the print tool by the vibrating the print tool is performed by oscillating the piezoelectric crystal-based transducer at a frequency of about 60 kHz.

26. The system of claim 24, wherein the supply of the ultrasonic energy through the print tool by the vibrating the print tool is performed by oscillating at a frequency of between about 40 kHz and about 200 kHz.

27. The system of claim 23, wherein the print tool further delivers the ultrasonic energy to an interface between the metal filament and a metal surface coupled to the build plate.

28. The system of claim 27, wherein the metal filament comprises solid aluminum.

29. The system of claim 28, wherein the metal filament comprises a diameter of about 300

microns.

30. The system of claim 27, wherein the print tool steps down a length of the metal filament to form a solid metal road.

31. The system of claim 30, wherein the solid metal road is about 600 microns in width.

32. The system of claim 31, wherein the solid metal road is about 125 microns in height.

33. The system of claim 27, wherein the ultrasonic energy is used to shape the metal filament.

34. The system of claim 23, wherein responsive to the supply of the ultrasonic energy through the print tool by the vibrating the print tool, the metal filament is fused to a surface at room temperature and in ambient atmosphere.

35. The system of claim 23, wherein the printer control board is further operative to apply, via the print tool, 10 Newtons of force to the metal filament during the supply of the ultrasonic energy through the print tool by the vibrating the print tool.