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(54) **METHOD OF DIRECTLY MAKING RAPID PROTOTYPE TOOLING HAVING FREE-FORM SHAPE**

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(52) **U.S. Cl.** **427/191**; 427/201; 427/205; 419/5; 419/6; 419/8

(58) **Field of Search** 364/468.04; 427/191, 427/201, 205; 419/5, 6, 8

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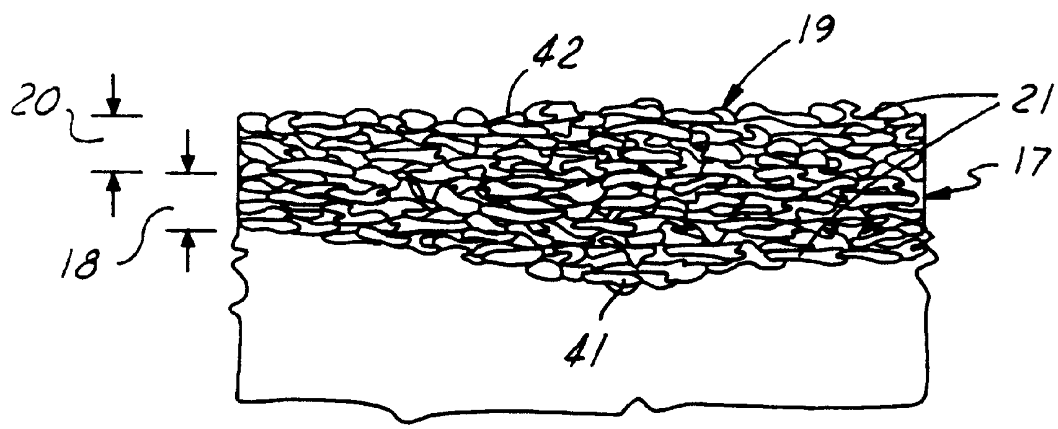
(57) **ABSTRACT**

A method and apparatus for directly making rapid prototype tooling from a computer model having a free-form shape. The method steps comprise essentially: (a) machining a soft metal tooling base so as to contour at least one free-form surface in conformity with the computer model; (b) cold-gas dynamic spraying the contoured surface to form superimposed impact welded metal particle layers, the layers consisting of at least one thermal management under-layer comprising primarily copper, and at least an outer wear resistant layer comprising primarily tool steel.

11 Claims, 3 Drawing Sheets



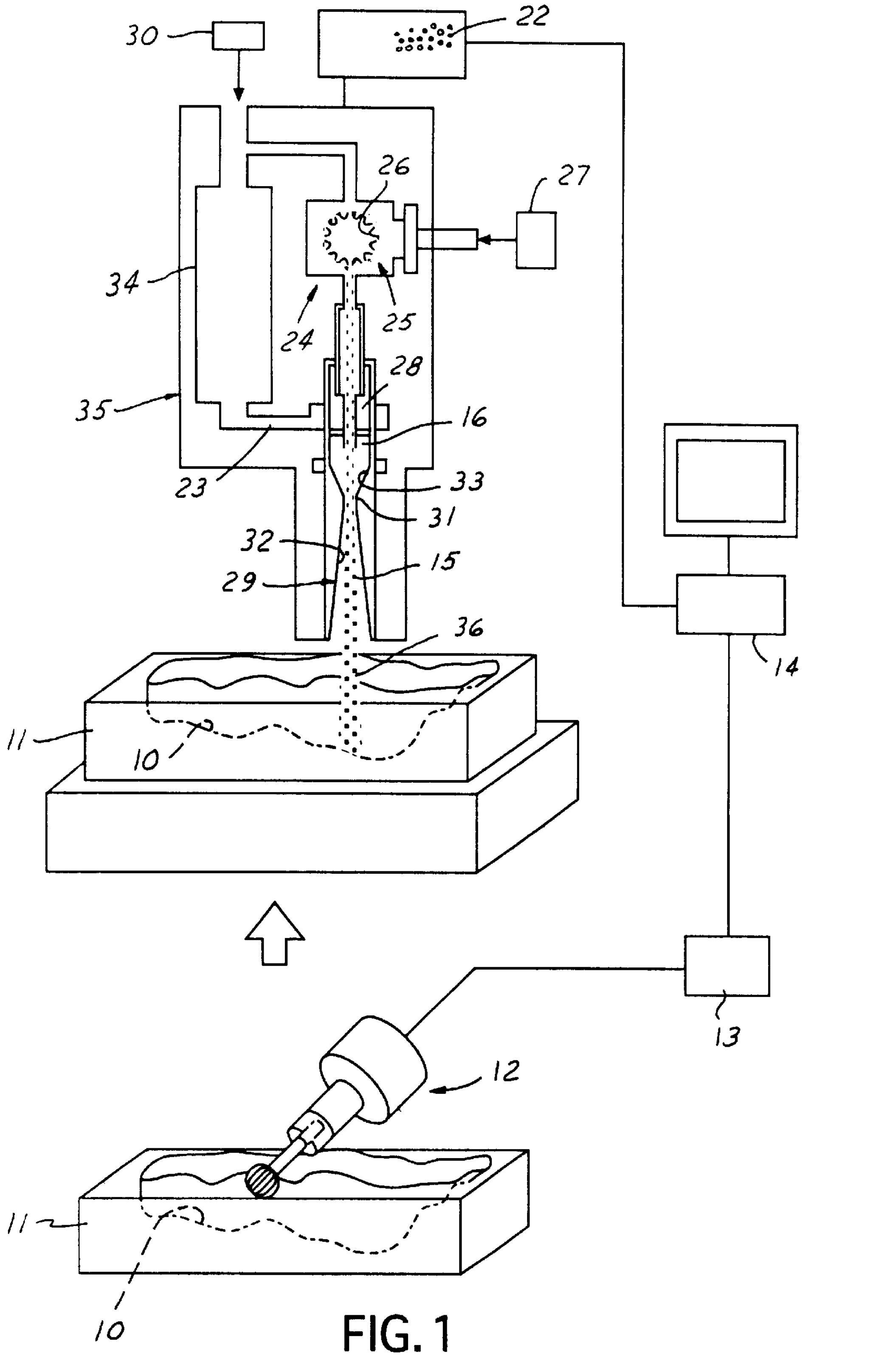


FIG. 1

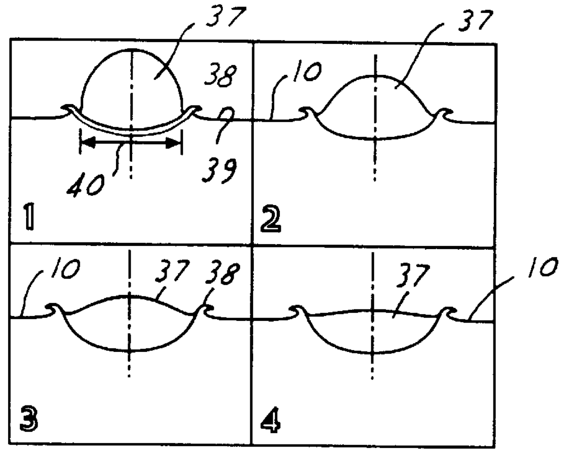


FIG. 2

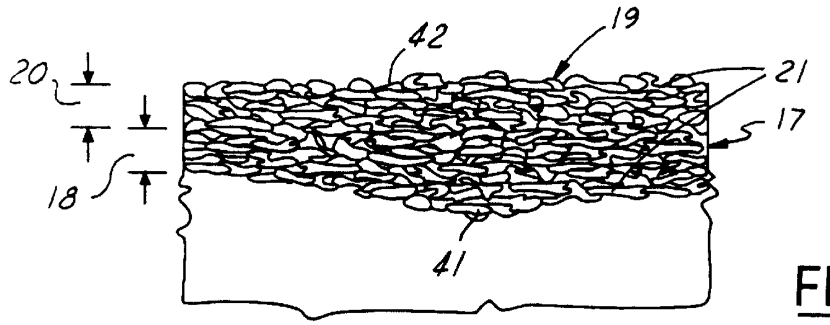


FIG. 3

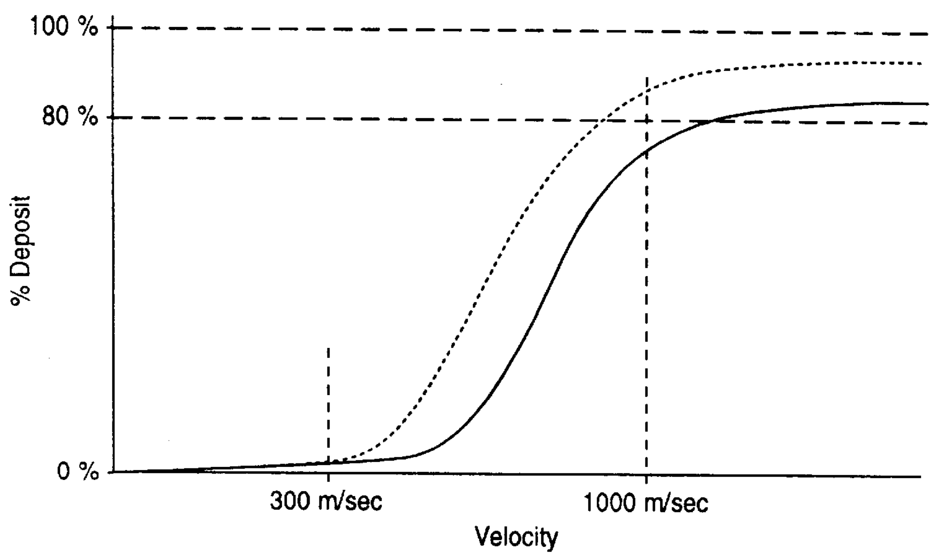


FIG. 4

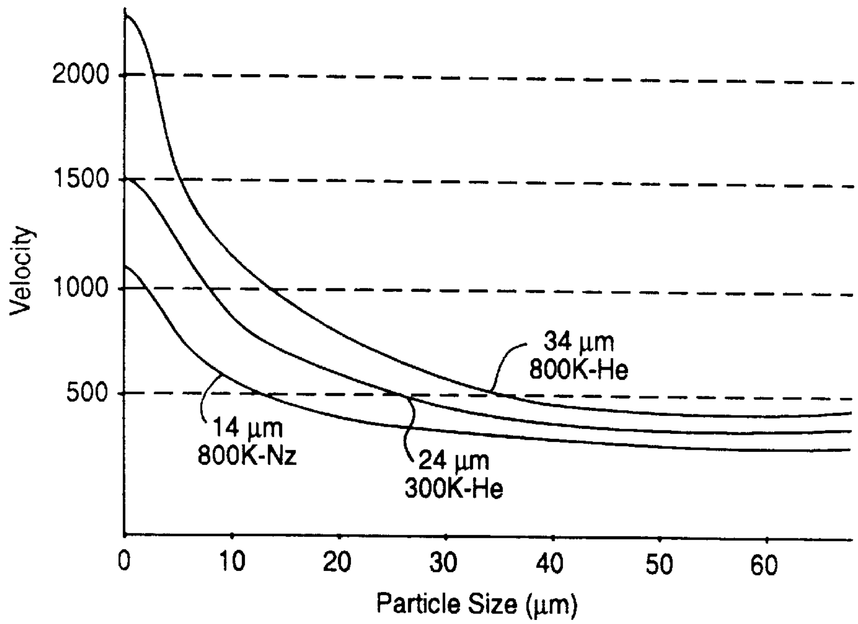


FIG. 5

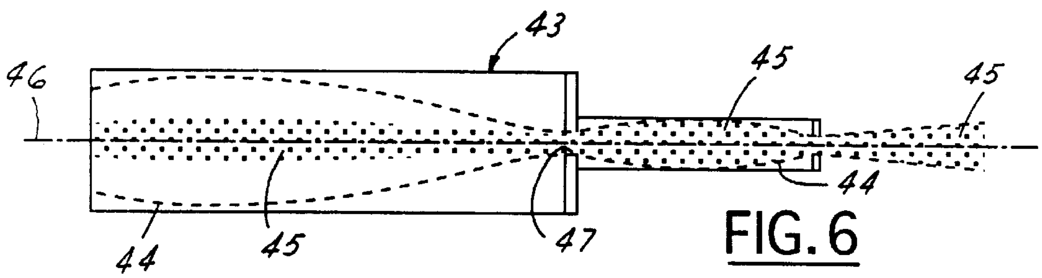


FIG. 6

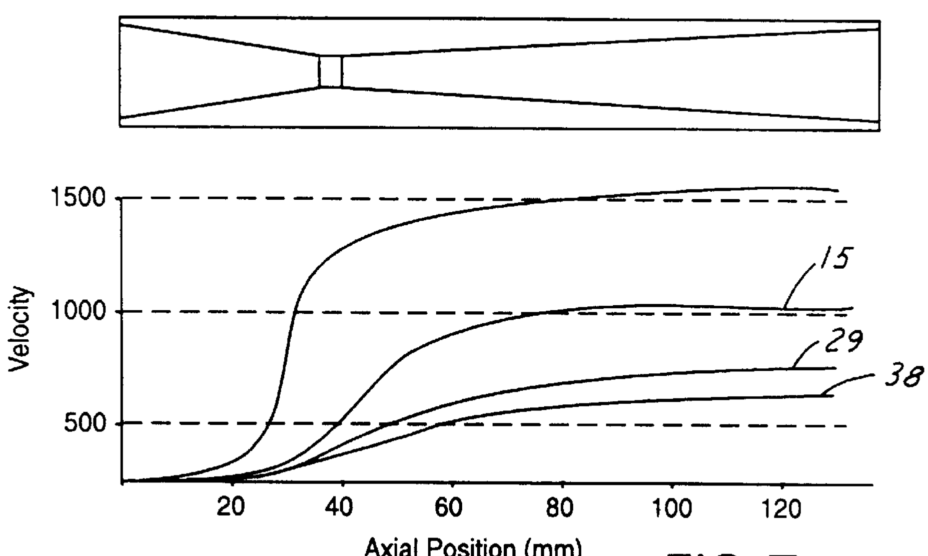


FIG. 7

METHOD OF DIRECTLY MAKING RAPID PROTOTYPE TOOLING HAVING FREE-FORM SHAPE

BACKGROUND OF THE INVENTION

1. Technical Field

This invention relates to technology for making rapid free-form tooling and more particularly to making such tooling more wear resistant with a technique that does not require melting of metal but does follow a computer model of the tooling.

2. Discussion of the Prior Art

Direct fabrication of near-net shapes in metal, from a computer model, typically involves melting and solidification, which can cause high residual stresses, undesirable phases, poor microstructures, rough surface finish, warpage and other problems. Several prior art technologies can fabricate near-net shapes of metal and do so directly or indirectly from a computer model. One such technology is to use a laser that builds up a part by laying down successive small laser-welded beads in a computer-controlled pattern. Another technique uses directed light fabrication, others selective laser sintering. Yet others have used thermal spray deposition to build up a part by spraying molten metal droplets onto any work-piece surface, using computer-controlled masking and/or intermediate machining operations to control the pattern of the deposited material for the successive sprayed layers. Still another approach is investment casting of a part using a wax or polymeric mold pattern that is created with a computer-based process such as stereo-lithography. Although such technologies have a potential to cut time and costs for rapid prototyping, there are inherent difficulties that have hindered widespread application of such prior technological methods. All of these prior technologies involve melting and solidification. Each new layer starts out molten, solidifies, and must eventually cool to room temperature. In addition to simple dimensional changes, the resulting thermal contraction can produce significant residual stresses in the completed part and may even cause thin parts to warp. Moreover, undesirable phases or microstructures may be formed, especially at interfaces between dissimilar metals.

SUMMARY OF THE INVENTION

An object of this invention is to provide more wear resistant rapid tooling by uniquely selecting a soft metal as a tooling base and adding thereto welded layers of a thermally conductive metal and a wear resistant metal, such addition not requiring the melting of any such metals during fabrication.

The invention, in one aspect, that meets the above object, is a method of directly making rapid prototype tooling from a computer model having a free-form shape, comprising: (a) machining a soft metal tooling base so as to contour at least one free-form surface in conformity with the computer model; (b) cold-gas dynamic spraying the contoured surface to form superimposed impact-welded metal particle layers, the layers consisting of at least one thermal management under-layer comprising primarily copper, and at least an outer wear resistant layer comprising at least primarily tool steel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic view of apparatus used to carry out certain essential steps of the inventive method;

FIG. **2** is a series of enlarged schematic elevational views of a metal particle as it impacts and bonds with the contoured surface of the tooling base according to this invention;

FIG. **3** is an enlarged schematic sectional view of particles deposited in layers by the cold-gas dynamic spraying step of this invention;

FIG. **4** is a graphical illustration showing variation of mean velocity as a function of deposition efficiency for different metal particles as propelled by the supersonic nozzle;

FIG. **5** is a graphical illustration of velocity, within the supersonic nozzle, as a function of particle size;

FIG. **6** is an illustration of one type of aerodynamic focusing element used with the apparatus of this invention; and

FIG. **7** is a graphical illustration depicting the degree of particle acceleration in the supersonic nozzle as a function of axial position within the nozzle.

DETAILED DESCRIPTION AND BEST MODE

As shown in FIG. **1**, the first step of the process is to machine a free-form contoured surface **10** into a "tooling" base constituted of a soft machineable metal, such as aluminum. Machining **12**, such as by milling, grinding or boring, controlled by an NC module **13**, is carried out to conform with a computer software model of the part in computer **14**; such machining brings the contoured surface **10** of the base to near-net shape relative to the model, allowing parts to be made from such tooling. "Tooling" is used herein to mean dies or patterns that are used repeatedly to replicate a part or other configuration by forging or casting metal against the tooling. Aluminum is preferably selected for the tooling base because: (i) it is easily machined with speed and with little effort, and (ii) it absorbs mechanical and thermal shock better than steel. Other equivalent soft metals that can be used in place of aluminum may be selected from the group comprising: copper, zinc and aluminum alloys.

Also referring to FIG. **1**, a second step of the process comprises using a relatively cold gas **16** to supersonically blow powder particles **15** (having a particle size in the range of 10–50 microns) against the free-form contoured aluminum surface **10** with sufficient kinetic energy and velocity (500–1500 m/s), and in an un-melted condition, to cause plastic deformation and consolidation of the particles **15** upon impact with the surface **10** by a phenomenon analogous to explosive welding. Such cold-gas spraying eliminates undesirable influences, characteristic of the prior art, such as grain growth induced stresses, and existence of oxidation phases in the metal particles. The process allows higher deposition rates and reduces the fabrication cycle time to 1/10 that of known direct rapid tooling technologies, while allowing code-posit of dissimilar metal particles without alloying or dilution.

Different powder metal particles are applied in sequence; first, a thermal management layer **17** is deposited, in a thickness **18** of 3–10 mm, and then a wear resistant layer **19** is deposited in a thickness **20** of 5–15 microns to complete a coating **21**. The thermal management layer **17** must rapidly conduct heat between the wear resistant layer and the aluminum base to carry away heat generated during use of the tooling and thereby decrease cycle time when using such tooling.

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layer particle splats **41** are covered by wear resistant particle splats **42**. Such "splats" in the cold-sprayed deposit show sharp angular boundaries, with no apparent evidence of localized melting, even at much higher magnifications.

If the spray of particles is concentrated to a smaller diameter, even greater detail and accuracy can be obtained in achieving a uniform wear resistant coating. To this end an aerodynamic focusing element **43** can be used upstream of the supersonic nozzle and performs essentially as a means of slowing down the particle-laden gas stream through a flow constriction as illustrated in FIG. **6**. As the gas **44**, carrying the solid particles **45**, converges toward the centerline **46** upstream of the constriction **47**, particles are accelerated toward the centerline axis by the radially inward component of the flow. As the gas decelerates radially, inertia causes the solid particles to continue to move toward the centerline. The expansion of the flow as it exits the constriction **47** is more gradual, and the particles are not strongly accelerated away from the centerline. The net result is that particles downstream of the aerodynamic focusing constriction occupy a streamline closer to the centerline than the streamline they occupied upstream of the aerodynamic constriction. The degree of focusing is determined by how much closer to the centerline is the final particle. Depending upon factors such as the flow velocity, the diameter of the constriction, gas viscosity and mass density, particle size, and the initial radial position of the solid particle, different degrees of focusing will occur. This subcritical velocity focusing can be further improved by using multiple constrictions in series, as shown in FIG. **6**, to progressively move the particles closer to the central axis **46**. Thus, with the aerodynamically focused powder stream and with the supersonic nozzle held at an angle, with respect to a perpendicular to the local surface, of about 0°, maximum impact and control can be obtained.

To enhance coating effectiveness as a continuous coherent and well bonded wear-resistant coating, the particles of copper and tool steel may be blended as a transient gradient between the thermal management layer of copper and the wear resistant layer of tool steel. Smaller steel particles (less than 5 microns) nest more readily with the larger copper particles (10–45 microns) to avoid any possible inter-splat boundaries to enhance the integrity of the coating.

While the best mode and viable alternatives for carrying out the invention have been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and variations for the practicing the invention as defined by the following claims.

What is claimed is:

1. Method of directly making a wear resistant article from a computer model having a free-form shape, comprising:

(a) machining a soft metal article base so as to contour at least one free-form surface conforming essentially to said computer model; and;

(b) cold-gas dynamic spraying the contoured surface to form superimposed impact-welded metal particle layers thereon, the layers consisting of at least one thermal management under-layer comprising primarily cooper, and at least one outer wear-resistant layer comprising primarily tool steel.

2. The method as in claim **1**, in which spraying of step (b) is carried out to attain a critical velocity of impact in the range of 550–1000 m/sec.

3. The method as in claim **1**, in which said soft metal is selected from the group consisting of copper, zinc and aluminum alloys.

4. The method as in claim **1**, in which said soft metal is aluminum or an aluminum alloy.

5. The method as in claim **1**, in which said under layer is deposited in a thickness of 3–10 mm and said outer layer in a thickness of at least 5–15 mm.

6. The method as in claim **1**, in which in step (b) said metal particles for the thermal management layer are selected from the group consisting of copper and copper alloys, and said wear resistant metal particles are selected from tool steel compositions.

7. The method as in claim **1**, in which in step (b) said cold-gas spraying is carried out by use of helium or a helium mixture as a propellant, which propellant is heated to the temperature range of 250–500° C.

8. The method as in claim **1**, in which the size range of said copper particles is 5–44 microns and the size range of the wear resistant particles is 1–50 microns.

9. The method as in claim **1**, in which in step (b) said spraying is carried out by use of a supersonic nozzle and that employs gas to propel the particles in a stream, and in which the copper and wear resistant particles are blended together in the spraying stream when changing from one layer to the other to create a mixed intermediate zone interfacing the layers.

10. The method as in claim **1**, in which in step (b) said spraying additionally uses apparatus to aerodynamically focus the stream of particles immediately upstream of entering the supersonic nozzle to provide a more focused stream for impacting the contoured surface of the base.

11. A method of king a wear-resistant article from a computer model having a free-formed shape, said method comprising:

machining an article base to form a contoured surface conforming essentially to the computer model, said article being made of a soft metal; and

cold gas dynamically spaying metal particles in an un-melted condition to form superimposed impacts-welded metal particle layers on the contoured surface, the layers consisting of at least one thermal management under-layer comprising essentially copper, and at least one outer wear-resistant layer comprising primarily tool steel.

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