METHOD FOR POWDERED METAL FORMING

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Filed Jan. 25, 1965, Ser. No. 427,665

13 Claims. (Cl. 75—214)

ABSTRACT OF THE DISCLOSURE

Broadly, the method of the disclosure consists of mixing the desired ratio of metal powders, pressing the mixture of metal powders to form a briquette, heating the briquette to the plastic condition of the metals, inserting the heated briquette in a die of a desired configuration, forming the heated briquette to the die configuration by striking same with a high energy rate means, and removing the formed article from the die. The apparatus for carrying out the method may be manually or automatically operated.

This invention relates to the forming of metal parts, particularly to the forming of parts utilizing metal powder, and more particularly to a method and apparatus for making three dimensional parts by high energy rate forming of metal powder.

It has heretofore been the usual practice to form three dimensional parts from stock by machining operations which involve the removal of a substantial amount of metal in the defining of geometrical features of the part. This procedure is not only wasteful of material but is also time consuming and accordingly, expensive.

High performance missiles, spacecraft and aircraft require the ultimate in structural part design and fabrication. Designers can envisage optimum systems and parts, but are forced by technological limitations to compromise their designs of parts and systems to compensate for producibility aspects.

This invention is directed to a process, and apparatus for carrying out the process, which forms precision metal alloy parts directly from metal powders by a high energy rate force and thus greatly advances the known technology. This process is capable of consistently and rapidly producing substantially finished, high quality parts of a wide variety of shapes and sizes, in one operation. This process is extremely economical. In addition to effecting a high production rate, the process is not limited by processing characteristics of exotic alloys. Because the raw material for parts produced by this process is low cost metal powder, new metal alloys may be formulated as required to meet the mechanical, physical and environmental performance requirements, beyond the present state of the art.

In the process of this invention metal powders are mixed to give the alloy desired, and compacted into a briquette. After compaction, the briquette is heated in a controlled atmosphere to the plastic range. This temperature is normally below the solidus. After the briquette is at the plastic range, it is formed in a die with high energy force. This may be done, if desirable, in the presence of an inert gas.

The high energy rate extrusion process of the present invention produces several unique results. The part is formed in the precise shape of the die with complete filling of the die. Flow lines are eliminated, resulting in a maximum longitudinal strength of the material with no reduction of strength in the transverse direction. The extrusion process also gives excellent grain refinement with superior metallurgical and physical properties.

The present process depends on the ability of a porous body (billet or briquette) of heated metal (metal powder) to be deformed by extrusion in a three dimensional die using a high energy rate forming apparatus. The high energy rate is necessary to minimize temperature loss during the process and to insure plasticity. Thus, the process produces a high density part from a low density metal powder billet.

An aerodynamic surface, such as a control surface of a missile, can be formed by the present invention by using only about half of the energy necessary to extrude the same shape from a bar of solid metal, thereby increasing the life of the tooling utilized. Additionally, articles formed from metal powders in accordance with this invention have a grain structure different than that of articles formed from solid metal. This is due to the high velocity of the individual particles being achieved with a small energy loss as compared with energy losses associated with handling a massive piece of solid metal, because the interstices between the powder particles offer voids for deformation and paths for flow and will accelerate as fast as the metal powder particles and be deformed only through deformation of the metal powder particles caused by back pressure. It has been determined that by a careful manipulation of energy rate application, proper control of the density of the preformed briquette, and control of the plasticity of the metal powder particles through temperature regulation, a nearly or completely dense body can be produced in a shaped die, the term dense inferring "specific gravity." The part thus produced requires a minimum of machining as a secondary operation. The tooling (apparatus) is not unnecessarily stressed which insures long life. The resulting parts have unusual properties being characterized primarily by small grain size. Thus, with the process of the invention, metallurgical compositions can be produced that are not possible to cast, etc.

Therefore, it is an object of this invention to provide a method and apparatus for forming metal parts.

Another object of the invention is to provide a method for forming parts from metal powders.

Another object of the invention is to provide a method for forming three dimensional parts from metal powders utilizing a high energy rate forming apparatus.

Another object of the invention is to provide a method for producing a high density part from a low density metal powder billet.

Another object of the invention is to provide a method of making three dimensional parts from metal powders wherein the parts have a substantially uniform fine grain structure.

Another object of the invention is to provide an apparatus for heating, transferring, and forming by high energy rate application, metal powders into substantially finished parts.

Other objects of the invention, not specifically set forth above, will become readily apparent from the following description and accompanying drawings wherein:

FIG. 1 is a plan view illustrating a three dimensional article produced by the invention;
FIG. 2 is a view taken on line 2—2 of FIG. 1;
FIG. 3 is a schematic view illustrating compaction of the powder metal briquette;
FIG. 4 is a schematic view illustrating heating and extruding of the briquette in a high energy rate forming apparatus; and
FIG. 5 is a view illustrating an embodiment of an apparatus for carrying out the method of the invention.

Referring now to the drawings, FIGS. 1 and 2 illustrate a three dimensional article formed in accordance with the invention, the article, for illustrative purposes only, being an aerodynamic surface 10 for an air vehicle or the like, which, prior to this invention as set forth above, had to be machined from stock material. Aerodynamic surface
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3. Comprises a butt or base portion 11 and a contoured apex 17. Body portion 12 additionally includes a flat surface 13 and 14. Surface 13 is inclined from a leading edge 15 rearwardly, with surface 14 being inclined from a trailing edge 16 forwardly to intersect with 13 to define an apex 17. Body portion 12 additionally includes a flat bottom surface 18 and an outward edge or lip 19 which is perpendicular with respect to the leading and trailing edges 15 and 16. Body portion 12 tapers as indicated at 20 from trailing edge 15 to butt portion 11. Also apex 17 curves rearwardly at and abouts the tapered area 20.

FIGS. 1 and 2 thus clearly illustrate the problems involved and the machining requirements to make articles such as aerodynamic surfaces 10 or other three dimensional articles by prior known methods. Such articles are quickly and economically made by the method and apparatus of this invention.

There are many known methods of producing metallic powders usable in the present invention. For example, when a steel such as SAE 4600 is melted and poured in thin streams by a cross jet of liquid, such as water, the liquid steel is broken into very small drops which solidify almost instantly because of their high surface area-to-mass ratio and the quenching effect of the jet. The particles made in this way are dried and annealed in a furnace containing a reducing atmosphere. The resulting powder contains very little oxide, is decarburized and each particle is, in effect, a very small solid ingot. The absence of carbon is important because the ferrite powder produced is sufficiently soft to mold into billets or briquettes at a comparatively low pressure. Many alloy steels can be made by this method. The size of the powder particles normally is directly related to the grain structure of the formed article.

An alloy powder, such as SAE 4600, for example, containing nickel and molybdenum, both of which will reduce easily is preferable because it can be made with a very low oxide content. A typical chemical analysis of this powder is as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.01</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.26</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.49</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.04</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.012</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.86</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The typical physical properties of this powder are as follows:

Sieve analysis, mesh percent:

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.2</td>
</tr>
<tr>
<td>100-140</td>
<td>12.5</td>
</tr>
<tr>
<td>140-200</td>
<td>24.1</td>
</tr>
<tr>
<td>200-325</td>
<td>35.7</td>
</tr>
<tr>
<td>325</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Approximate density: 3.21 gms./cc.

Flow (sec./50 gms.): 0.52

The above properties will vary, but not to any great extent.

The selected powder must be mixed to arrive at a suitable material for the alloy. Carbon, if lacking, must be added as well as a lubricant to allow the powder compact (billet) to be easily removed from the preform (billet) die. The constituents are weighed and placed in a mixing container. Using SAE 4600 metal powder, the following percentage proportions are exemplary:

<table>
<thead>
<tr>
<th>Powder Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE 4600 metal powder</td>
<td>99.3</td>
</tr>
<tr>
<td>Zinc stearate</td>
<td>0.5</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The mixing container can be, for example, placed on rollers and rolled at a speed which causes the powder to cascade. The powder is mixed with the additives until satisfactory homogeneity of the constituents is produced.

Other methods of mixing the powder, such as a twin shell dry blender, may be effectively utilized.

The billet or briquette 30 is produced in a die 31 with a bottom and a top punch 32 and 33, respectively, as schematically illustrated in FIG. 3. The diameter of the die 31 is determined by the size of the billet 30 required to form a specific article; thus various size dies or adjustable dies are required. The punches 32 and 33 have very close tolerances with respect to the internal diameter of the die 31. The punch and die assembly, as here illustrated by way of example only, is set up to provide double action pressing which produces a billet with a uniform density as possible. The density, for example, of SAE 4600 metal powder mixture, may be maintained at 6.2 to 6.4 gm./cc.

The steps in producing a billet or briquette 30 will vary depending on the equipment being utilized. Briefly, with a double punch and die assembly as illustrated in FIG. 3, the steps include:

1. Weighing the mixed powder;
2. Positioning the lower punch 32 in the die 31;
3. Placing the weighed powder in the die 31;
4. Leveling the powder;
5. Inserting the top punch 33;
6. Applying desired pressure, such as 20 tons/in.2 to the punches;
7. Removing the pressure;
8. Reapplying desired pressure, if required, to increase the density of the billet;
9. Removing the pressure;
10. Removing lower punch 32;
11. Applying pressure on the top punch 33 to eject the formed billet 30;
12. Clean the die 31 and punches 32 and 33.

The briquettes or billets are produced without heating sintering) since it is desirable to maintain interstices between the powder particles which offer voids for deformation and paths for flow of the particles. This produces the fine grain structure in the formed article.

With a billet or briquette 30 formed by pressing as described above or by other forming methods such as by an automatic tableting (billet) machine, the aerodynamic surface 10 or other three dimensional article is formed from the billet 30 in a high energy rate forming (H.E.R.F.) apparatus such as that commercially known as "Dynapak" and manufactured by the assignee of this application and described, for example, in U.S. Patents 2,925,803; 3,056,538 and 3,093,117. H.E.R.F. apparatus as defined herein is a forming apparatus which utilizes a high energy power source for driving the ram unit thereof at a high velocity rate. For example, the energy used to form the surface illustrated in FIGS. 1 and 2 is approximately 14,300 foot pounds applied to the heated metal powder billet at a velocity of 760 ft./sec. The larger the part being formed, the higher the required pressure, and higher pressures require higher velocities where the mass of the ram is constant. Thus, with various types of forming apparatus and/or various types of parts being formed, the energy will vary, and it is the energy applied over a certain period of time which produces the grain structure of the formed article. The velocity of the ram unit of the apparatus is important because of its being a square function as illustrated by the formulas \( E=V^2W/M \) in which:

\[ E = \text{energy} \]
\[ W = \text{weight} \]
\[ V = \text{velocity} \]
\[ G = \text{gravity} \]
\[ M = \text{mass} \]

The forming operation of a billet 30 into a three dimensional article such as aerodynamic surface 10 is illustrated in FIG. 4 and consists essentially of four operations; namely, heating the billet, transferring the heated billet to the die of the H.E.R.F. apparatus, forming the
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The interaction of gas and the large surface area, which is chemical in nature, is thus of the utmost importance. Atmospheres react in various ways with metals dependent on the chemical content of the gas and the position of the metal in the electro-motive series of elements. Aluminum, silicon, manganese, chromium all lie above hydrogen and therefore, produce very stable oxides. If these metals are a major constituent in an alloy such as 304 stainless steel (18% chromium) the formation of oxides should be avoided. If no oxygen is present in the protective atmosphere then very little oxide can be formed. Heating in a vacuum, dry inert gas, dry hydrogen, or dissociated anhydrous ammonia in a very tight system will result in a low oxide content billet such as is necessary for austenitic stainless steel or other chemically active alloys.

Endothermic atmospheres produced by reforming hydrocarbons and the oxygen in the air can be made to produce gas with a carbon potential. Endothermic gas is used as a means of controlling the carbon content in the surface of steel. The gas carbon potential is due to the presence of carbon monoxide and the amount of carbon monoxide may be changed by changing the mixture of gas and air fed to the heated catalytic chamber. The ratio between carbon monoxide, carbon dioxide, and water vapor is a constant for any single temperature and because the water vapor content is easily checked, it has become practice to describe the carbon monoxide content (carbon potential) as a dew point.

New systems of carbon dioxide measurement such as by infrared cells offer advantages over the prior known methods. Roughly the carbon potential is inversely proportional to the dew point and is proportional to the temperature and carbon content. The selection of carbon potential is dependent on temperature and carbon in the material. It is possible to carburize steel using endothermic atmosphere and possible to decarburize steel using an endothermic atmosphere; therefore the selection of the proper dew point is important and a variable. Endothermic atmospheres are not suitable for chemically active alloys because of their water vapor and carbon dioxide content and because they will carburize some alloys such as 18-8 stainless steel.

Exothermic atmospheres are simple products of combustion of hydrocarbon gas and air. Exogas is useful in protecting boron, iron, etc. at low temperatures. The easily reducible copper base alloys, with the exception of zinc containing brass, can be heated with confidence in these atmospheres.

Thus, variations in time, temperature and atmosphere depend on conditions pertinent to each system and can be solved only by experience and at best can be controlled accurately only by constant surveillance. As pointed out above, the variations in the heating process or operation are three. Following is a list of these variables and the values assigned them, by way of example only, for the production of an article such as aerodynamic surface 10 from SAE 4600 metal powder mixture:

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Exothermic 10°F. Dew Point.</th>
<th>Temperature</th>
<th>2300°F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>20 minutes in the furnace.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

During the heating cycle, several changes take place. The graphite goes into solution in the ferrite producing iron carbide which at the diffusion temperature also remains in solution. The zinc stearate is volatilized from the billet and no trace of zinc is found on spectrographic analysis of the finished article or part.

The billet 30, heated to the plastic state in furnace 40, is transferred as indicated by the arrows and legend in FIG. 4 to the lubricated and assembled tooling set up (H.E.R.F. apparatus) generally indicated at 41. Transfer time varies from 3 to 5 seconds, depending on the method of transfer utilized. Apparatus 41 as schematically illustrated in FIG. 4 comprises a receiver unit 42 for the heated billet 30, a power unit 43 having a ram 44 which moves
through receiver unit 42 into a die block 45. Die block 45 retains therein a split die 46 configured to define the shape of the formed article or part, block 45 including an aperture 47 which serves as an exhaust port thereby preventing an undesirable explosion in the die 46 due to the forces therein. If desired the die 46 may include an orifice 48 through which the billet material is extruded prior to its entry into die cavity 49. The heated billet 30 having been positioned adjacent die 46 and with the power unit 43 of the H.E.R.F. apparatus 41 set at a fire pressure, for example, at 400 p.s.i., with a back pressure, for example, of 100 p.s.i., the power unit is activated and the heated billet is forced at a high velocity into die cavity 49 by the rapid movement of ram 44, the billet thereby conforming to the configuration of die 46. The split die 46 is then removed from die block 45 and the formed article or part 10 is removed from the die. The average travel distance of ram 44 is approximately 7 inches. This distance will vary depending upon the high energy rate forming apparatus being used.

In tests conducted on articles such as aerodynamic surface 10 made from the above stated metal powder mixture and in accordance with the invention, final chemical analysis of the high energy rate formed article was as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.20</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.83</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.50</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.35</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.27</td>
</tr>
<tr>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Hardness tests were made of the thus formed aerodynamic surface 10 and the hardness averages about an RC 23, with near an RC 45 over the flat body portion 12 and about an RC 10 at the heavy butt portion 11.

The microstructure of samples of articles produced by this invention is unusual. The small particle size of the raw material, which is not consolidated until the end of the forming operation, results in a fine grain equiaxed structure. The variations in the movement of the metal during the extrusion process result in a variation in microstructure throughout the article produced. It has thus been shown that this invention will extrude low carbon steel from powders at very low forming (forming) pressures. The metalurgy involved is unusual but the fine grain structure in the blade or body portion of surface 10 and the unusually high hardness when even small amounts of carbon are added produces structural integrity. The uniformly high density and the absence of porosity in the blade indicate that the modules will be the same as steel produced by conventional methods. These novel results are due to the use of metal powders formed into an end article by a high energy rate forming apparatus, which due to the high rate at which the heated billet material is extruded, cannot be produced by any prior known process.

Referring now to FIG. 5, the embodiment of a mechanism for carrying out the forming process includes a high energy rate forming apparatus generally comprised of a hydraulic power supply unit 50, a power unit 51, a control console 52, and an induction heating power supply unit 53.

Power unit 51 includes a die support mechanism 54 mounted on support members 55 and a ram 56 movable along support members 55. Operatively mounted in die support members 55 is a tapered die holder or block 57 within which a split die 58 is positioned, die 58 being configured to define the shape of aerodynamic surface 10 or other three dimensional articles or parts. A die ejection cylinder 59 is operatively supported by mechanism 54 and functions to move split die 58 into or out of holder 56. Cylinder 59 is connected with a pressure source (not shown) through conduits 60 and 61.

Induction heating power supply unit 53 includes an atmosphere controlled heating tube or tunnel 62 for billets 30 having a loading chute 63 and a gate 64 controlled by an escapement mechanism 65, such as a solenoid. A loading ram or chute 65 is pivotally mounted adjacent gate 64 and is raised or lowered by means (not shown) through arm and lever mechanism 67. A billet inserting mechanism 68, such as a solenoid, is mounted on or inserted at proper sequence into heating tube or tunnel 62 and heated under controlled environment for the required time. When a billet 30 is heated, loading ramp 66 is lowered to the solid line position, escapement mechanism 65 is actuated to open gate 64 and allows a billet 30 to roll to the end of ramp 66 which is aligned with the opening in split die 58. Actuation of billet inserting mechanism 68 inserts heated billet 30 into die 58. Loading ramp 66 is retracted to the position shown in phantom. Power unit 51 is actuated, which fires ram 56 against billet 30 which extrudes the billet material to the configuration of die cavity. As described above, power unit 51 includes means for retracting ram 56 after firing. Die ejection cylinder 59 is actuated which causes split die 58 to move out of tapered block 57 and open. The extruded article is removed, the die lubricated and cylinder 59 retracted thereby securing split die 58 in tapered holder or block 57 and placing the apparatus in condition for repeating the cycle.

While not shown, the control functions of the FIG 5 mechanism may be electrically interlocked to provide rapid foolproof cycling or may be independently operated as shown.

It has been shown that the preforming and heating of a billet can be controlled to permit rather extensive and easy extrusion of relatively thick and thin sections by high energy rate forming apparatus. Another desirable feature of extruding a preformed powder metal billet herein provided is the ease of compounding new compositions to a high degree of reproducibility to provide the desired flexibility of modification of chemical composition, hardenability and physical properties, if changes in design conditions so demand. An additional feature of the present invention is revealed in the extremely fine grain structure that can be developed in the formed parts. It has been shown that practical theoretical density can be obtained following impact extrusion of relatively thick and thin sections using the high energy rate forming apparatus, thus providing substantially complete absence of residual porosity, this being accomplished by appropriate gating and venting of the die cavity.

Following impact extrusion, as indicated above, a very fine grain size is developed utilizing the present invention, resulting in a very fine structure in the as-extruded and cooled part. The grain size is extremely fine in the thinnest sections (0.012" thick) and yet much finer than usual for wrought steels in thicker section (0.250" thick). Such good toughness can be obtained in dense extruded sections.

Tests have shown that the alloy compositions that are common in conventional alloying techniques can be formed by the present invention. Thus, for example, it is possible to produce parts from 20% tungsten additions as easily as working with steel. However, tool and die materials, die lubricants, oxidation inhibitors in powdered metal mixtures, etc., present problems which have to be considered for the various types of powdered metal mixtures being formed.

Advantages of the forming method and apparatus of this invention are summarized as follows:

1. Low raw material cost in addition to very low forming costs.
Articles from a wide variety of alloy combinations can be produced.

Superior physical properties of the formed article with no directional characteristics.

Little or no machining of the formed article required.

Substantially no porosity in the formed article.

A wide variety of article shapes can be made with very high precision.

Makes possible a high production rate.

Although a specific embodiment of the apparatus for carrying out the inventive forming process has been illustrated and described and specific examples of materials and process conditions have been set forth as exemplifying the invention, modifications and changes will become apparent to those skilled in the art, and it is intended to cover in the appended claims all such modifications and changes as come within the true spirit and scope of the invention.

What we claim is:

1. A method for producing parts comprising the steps of forming a billet of predetermined powdered material, heating the formed billet to the plastic range thereof, positioning the heated billet in a die having a predetermined internal configuration, extruding the heated billet to conform with the internal die configuration by striking the billet with a high energy rate means, and removing the thus formed part from the die.

2. The method of forming briquettes made of powdered metals into three dimensional articles comprising the steps of heating the briquette under predetermined atmospheric and temperature conditions for a predetermined time, transferring the heated briquette to a die having an internal configuration for shaping the article to be formed, extruding the heated briquette to assume the internal configuration of the die by striking the briquette one time with a high energy rate forming apparatus capable of applying a predetermined amount of energy at a predetermined rate, and removing the formed article from the die.

3. The method defined in claim 2, wherein the atmospheric condition for heating the briquettes is a protective atmosphere for the type of metal powder of which the briquettes are constituted.

4. The method defined in claim 3, wherein the protective atmosphere is an endothermic dew point range of 7° to 13°F.

5. The method defined in claim 2, wherein the temperature condition for heating the briquettes is below the solidus temperature.

6. The method defined in claim 2, wherein the temperature condition for heating the briquettes is in the range from 2200°F to 2400°F.

7. The method defined in claim 2, wherein the heating time for the briquettes is sufficient for diffusion of the briquette material.

8. The method defined in claim 2, wherein the heating time for the briquettes is in the range from 15 to 25 minutes.

9. The method defined in claim 2, wherein the energy of the high energy rate forming apparatus is applied at a velocity above 700 feet per second.

10. The method defined in claim 2, wherein the briquette is composed essentially of carbon, silicon, manganese, sulfur, phosphorus, nickel, molybdenum and iron, and wherein the briquette is heated for a time period in the range from about 15 to 25 minutes to a temperature in the range between about 2200°F and about 2400°F under an endothermic dew point range of about 7°F to about 13°F.

11. The method defined in claim 10, wherein the heated briquette is extruded by the high energy rate forming apparatus being applied at a velocity above 700 feet per second.

12. The method defined in claim 2, wherein the heated briquette is extruded by the energy of the high energy rate forming apparatus being applied at a pressure in the range from about 300 p.s.i. to about 700 p.s.i. and at a velocity in the range from about 700 feet per second to about 900 feet per second.

13. The method defined in claim 2, wherein the briquette is selected from the group consisting of steel, copper, aluminum and stainless steel.

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