

Sept. 6, 1966

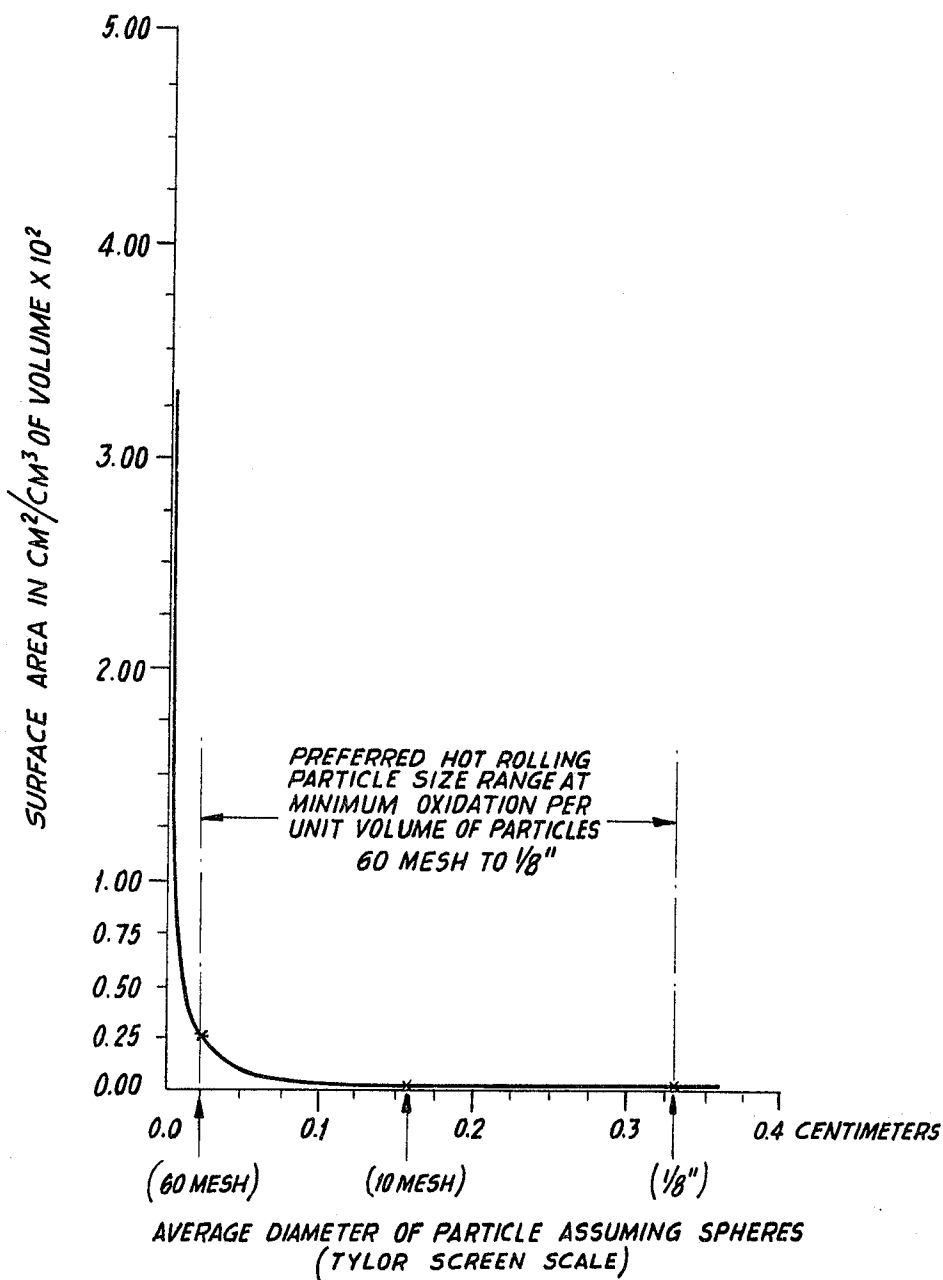
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3,270,409

PRODUCTION OF FLAT SHAPES BY THE HOT ROLLING OF METAL POWDERS

Filed Feb. 19, 1963

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

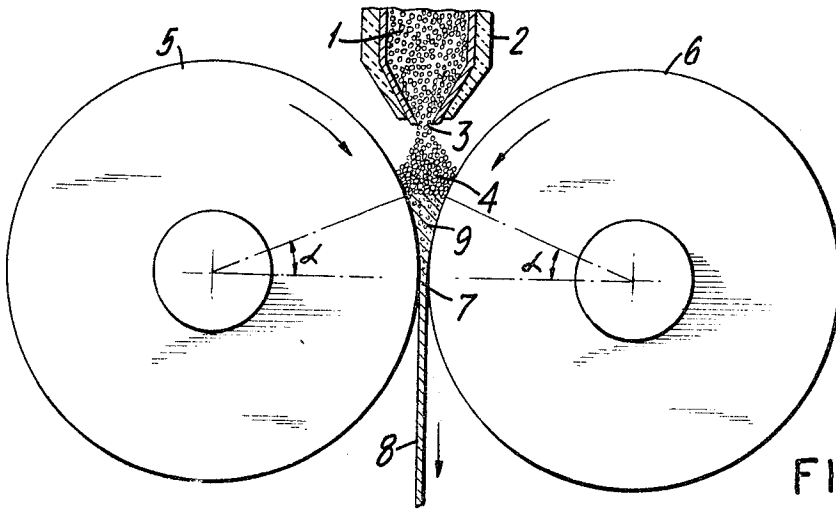


FIG. 2

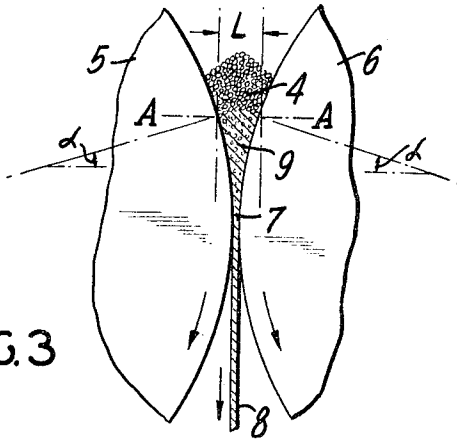


FIG. 3

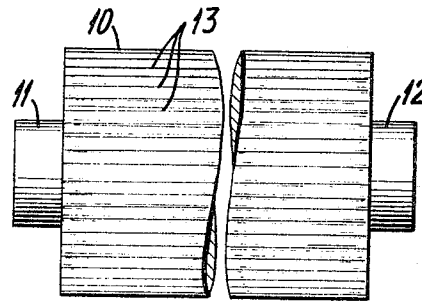


FIG. 4

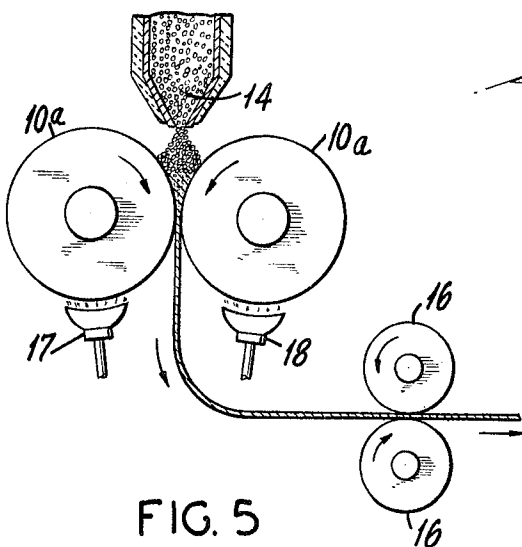


FIG. 5

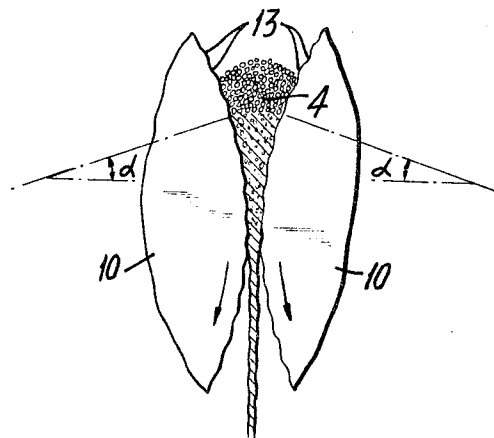


FIG. 4a

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3,270,409

PRODUCTION OF FLAT SHAPES BY THE HOT ROLLING OF METAL POWDERS

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This invention relates to a process for the production of flat metal shapes by the continuous hot rolling of metal powder and, in particular, to the continuous production of hot rolled strip or sheet from heated coarse metal powders.

The production of wrought flat metal shapes by conventional methods generally involves melting, casting and rolling. Depending on the kind of metal or alloys being produced, serious manufacturing difficulties may arise due to segregation of both metallic and non-metallic constituents occurring in the ingot, piping, cold shuts, preferred orientation of the grains and large grain size differences in the ingot which adversely affect forging and the like. This applies particularly to high strength alloys in which segregation of certain of the elements can lead to difficulties in forging, rolling and other working operations. With regard to complex alloys, the composition in the molten state is generally homogeneous but becomes heterogeneous both on a grain size basis and on a long range scale upon casting due to temperature-solubility laws, wherein the composition in the as-cast structure is non-uniform. The casting heredity of such alloys is seldom easy to control, particularly in some of the super-alloys, stainless steel, and certain of the less ductile alloys containing refractory metal, for example, chromium-base alloys, and because of this, such alloys are difficult to process. The direct powder rolling of metal powders into strip or sheet is not faced with such heredity problems for the reason that the metal can be provided with a fairly uniform composition and with fine grains, preferably directly from the melt.

It is known that metal powder can be converted to wrought metal sheet or strip by feeding the metal powder at room temperature into the nip of parallel spaced rolls, the powder being fed either horizontally where the rolls are supported one above the other in a vertical plane, or being fed vertically by gravity to the rolls where the rolls are supported side by side in a horizontal plane. Generally, in powder metal rolling, the rolls are in contact and roll "spring-back" relied upon in producing strip or sheet of the desired gage. As the metal powder passes between the rolls, it is subjected to a rolling pressure sufficient to cause the particles of metal to interlock and cohere, and the resulting green shape is then subjected to a sintering treatment in order to further densify the shape, increase its strength and ductility, and, if necessary, is further rolled, either hot or cold to effect further reduction thereof for densification and properties.

One of the disadvantages of producing strip or sheet by the cold rolling of metal powders is that there is a limitation in the maximum thickness of the final material that can be produced. In order to insure a cold rolled strip of sufficient green strength for further processing, fine powders are required, for example powders not exceeding 325 mesh in size. Fine powders are preferred over coarse in that they provide more interparticle contact points and, therefore, sinter more easily, especially after compaction. However, with fine powders there is a limit to the width of the gap between rolls that can be employed and hence the maximum size thickness strip

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that can be produced, depending on the amount of spring-back in the rolls. In addition, there is a limit as to the degree of densification that can be obtained by cold rolling.

Generally, fine powders which display good green strength when compacted have a fairly low apparent density. It is not uncommon, for instance, to have fine metal powders whose apparent density is less than 30% of its absolute density. For example, carbonyl nickel powder of about 3 microns in size may have a bulk or apparent density as low as about one gram per cubic centimeter (about 89% porosity) as against the absolute density for nickel of about 8.9 grams/cc. The degree to which such powder may be compacted by the rolls will depend upon the extent of the gripping zone of the rolls, which is the zone at which the working portions of the rolls begin to grip the powder and feed it through the gap. As this is determined by the angle of friction, which is generally low for polished rolls, the degree to which the powder may be compressed (i.e., compaction ratio) is to some extent related to the volume of metal powder occupying the gripping zone above the nip of the rolls and its maximum cross section. To increase the density of the nickel powder to about five times its apparent density, that is from one gram/cc. to 5 grams/cc., would require compacting the powder to about one-fifth of the volume occupying the gripping zone (a compaction ratio of 5 to 1). The extent to which this can be done to produce a variety of thicknesses of product will depend upon the roll size, since the greater the roll diameter, the greater will be the volume of metal powder occupying the gripping zone and the greater the maximum width of its cross section, everything else being equal. According to U.S. Patent 3,034,173, when carbonyl nickel powder is cold rolled into a strip through 8 inch rolls, the maximum thickness of strip obtainable is generally about 0.035 inch. The width of strip is limited to ranges of about 4 to 6 inches and rolling speeds to about 10 to 30 feet per minute. For a 20 inch mill, the maximum thickness is of the order of about 0.1 inch, whereas to produce a ¼ inch strip, a diameter roll of about 5 feet would be required, which is not at all economical. It must be remembered that, even then, the strip produced is of very low density and must be sintered and further processed by cold working to full density.

It would be desirable if a method could be provided for producing metal strip of varying thicknesses up to 0.2" using conventional roll sizes, e.g., roll sizes ranging from about 8 to about 16 inches in diameter, whereby to make available intermediate strip sizes from which other size products can be produced by further mill processing. The utilization of metal powder of higher apparent density, e.g., an apparent density of about 50% of the absolute density, would appear to offer one approach to the problem since less compaction would be required to produce a higher density and thicker product. Unfortunately, such powders usually do not have very good green strength and, when cold compacted, do not produce material capable of being handled in subsequent working operations.

Hot rolling has been considered but avoided because of the difficulty encountered in protecting fine powders, e.g., —325 mesh powders, from oxidation. Because of the fineness of powder, oxidation tends to proceed rapidly and, in the case of some metals, exothermically to the extent of completely burning up. Further, such powders in the hot condition tend to stick together and interfere with uniform feeding of the particles to the nip of the

rolls. Moreover, because of the high surface area of the particles, air tends to be entrained during compression, whereby full densification is not assured and in addition, depending upon fabrication temperatures, blisters tend to form.

I have now discovered a method of continuously hot rolling metal powders into flat metal shapes of thickness and density greater than that obtainable by prior cold rolling techniques.

It is an object of my invention to provide a method for producing flat metal shapes of substantially full density by hot rolling metal powders characterized by a relatively high apparent density.

Another object is to provide a powder rolling method wherein heated metal powder of a particular morphology is employed to produce flat wrought metal product of substantially full density.

It is a further object of my invention to provide a method of continuously hot rolling metal powders of compositions which are normally difficult to process.

These and other objects will more clearly appear from the following disclosure and the accompanying drawing, wherein:

FIG. 1 shows the relation of surface area per cubic centimeter of powder and its effect on the oxidation of the powder;

FIG. 2 depicts the gravimetric feeding of coarse metal powder to the nip of a pair of rolls;

FIG. 3 is a partial enlargement of FIG. 2 at the nip of the rolls showing in more detail the positioning of the unworked and the partially worked powder at and near the gripping zone of rolls;

FIGS. 4 and 4a depict a roll with a roughened surface for increasing the amount of the gripping zone; and

FIG. 5 shows the working process as carried out with a tandem arrangement of rolls.

In carrying out my hot rolling process, I contemplate the use of coarse metal particles having a relatively high apparent density, for example, apparent densities at least about 40% of true density, and generally in excess of about 45% of true density. For my purpose, I prefer to use metal powders having apparent densities in the neighborhood of about 50% and above of true density.

To insure powder of the foregoing characteristics, the particle size will generally exceed 100 mesh in size and range up to about $\frac{1}{8}$ " in average diameter. Preferably, the average size of the powder will range from about 60 mesh to about $\frac{1}{4}$ inch average diameter.

The morphology of the powder is important. The coarse powder should be spheroidal-like in shape, be relatively smooth and substantially free from sharp projections. By spheroidal, I mean a particle which is solid and dense and characterized by curved surfaces. Such particles may have a spherical contour, preferably imperfect spheres, or globules, or have a general ellipsoidal shape, or be shaped like a tear drop, or even be partially cylindrical, so long as the particles do not have sharp corners or projections which might interfere with its flowability. Particles in which the curved surfaces appear to be slightly flat are advantageous in that they tend to be gripped more readily by the surface of the rolls in the gripping zone, particularly particles having a superficial oxide coating. The spheroidal particles referred to above have good packing density and generally exhibit apparent densities in excess of about 45% and in the neighborhood of about 50% and above of true density.

Powders of the foregoing type are those produced by solidification from a liquid melt, such as powders produced by atomization, wherein a thin stream of the molten metal passing through an orifice is dispersed into liquid particles with high velocity jets of air or steam and the particles quenched at the moment of contact with the air. Any oxidation which takes place is limited only to the surface of the particles and is generally very thin. Because the particles are subjected to quick cooling, their composition

is homogeneous and segregation practically non-existent. Also because of the low surface to volume ratio which is inherent in coarse spheroidal-like particles, the amount of oxygen absorbed is generally very low. This will be apparent by referring to FIG. 1 which shows the relation between surface area per unit volume of powder and the average particle size of the powder. The extent to which a particle will oxidize is proportional to the area exposed. It will be noted that for coarse particle sizes in the range of 60 mesh to $\frac{1}{4}$ inch average diameter, the degree of oxidation would be substantially lower than for finer particles below 100 mesh, e.g., 325 mesh powder or finer.

Another method for producing powder from a liquid bath involves pouring the melt on a rotating surface, the cooling being accomplished by water. By employing a high speed disc, ellipsoidal or banana shaped particles are obtainable having a high apparent density.

Powders produced from the liquid melt by ultrasonic disintegration are particularly adaptable to my hot rolling process in that the coarse particles produced by this method have a fairly uniform size and shape. This method comprises passing a molten stream of metal into a pulse cavity in a die wherein high energy gas in rapid bursts in opposing directions atomizes the metal. Liquid metal is readily sheared, and at high rates of energy application acquires a measure of viscosity or stiffness which facilitates disintegration. By controlling the rate of metal pour through the pulse cavity, particles of the desired size are produced. The amount of superheat in the metal will in turn determine the shape of the powders. High superheat will allow for slower solidification, permitting particles to become more spherical.

Since the ultrasonic pulse can be generated as, for example, argon gas, this would permit a maximum degree of protection to the atomized powder against oxidation, nitrogen solution, etc. Further, the solidification and cooling of the coarse powder particles may also take place in the same argon atmosphere to give optimum efficiency to the process.

In feeding metal powder to the nip of the rolls, it is important that the powder have good flowability so that the powder continually flows freely into the gripping zone of the rolls. The point at which the rolls begin to grip the free flowing powder is dependent upon the angle of friction between the volume of powder above the gap and the rolls. Because of the morphology of the powder, its apparent density and the fact that the rolling is conducted hot, the angle of friction is greater than that which would prevail in cold rolling and, therefore, the degree of compaction will be greater, taking into account the increased plasticity of the heated powder. In the hot rolling of carbon steels produced by conventional casting and forging operations, the coefficient of friction may range from about 0.2 to 0.4 over temperatures ranging from 400° C. to 900° C., as opposed to cold rolling in which the coefficient of friction is substantially below 0.2 and ranges up to 0.15 for rough rolls. The use of cast iron rolls may be advantageous in that hot rolling friction is increased to about 50% of the normal values.

Stating it broadly, my invention comprises gravimetrically feeding hot coarse metal powder of melting point above 1100° C. and of spheroidal shape and relatively high apparent density to the nip of the rolls at a temperature above the minimum recrystallization temperature of the metal, continuously maintaining a reservoir of the hot metal powder against the gripping zone of the rolls above the nip such that the cross-sectional width of the reservoir of powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap to provide a compaction ratio sufficient to substantially completely densify the metal, and continuously hot consolidating the coarse metal powder into a wrought metal sheet or strip.

By "effective roll gap" is meant the amount of gap

which prevails between the rolls at the moment the metal passing therethrough is being compressed. For example, depending upon the characteristics and temperature of the hot metal powder being rolled and the gage thickness desired in the product issuing from the rolls, the rolls may be set at zero, that is touching each other, wherein the "effective roll gap" is the gap that exists during rolling as a result of roll spring-back. Or, again depending upon the characteristics and temperature of the powder, the initial roll setting may be such as to provide a gap of say 0.05" which, after spring-back, may result in an effective roll gap of, let us say, 0.075". The amount of reduction will depend upon the cross sectional width of metal at the beginning of the gripping zone between the rolls and the amount of effective roll gap. For powders having an apparent density of at least 40% of true density, the compaction ratio should be at least 2.5 to 1 as determined by the ratio of the cross-sectional width of the metal at the beginning of the gripping zone to the width of the effective roll gap.

Referring to FIG. 2, I show hot coarse metal powder being fed from hopper 1 which may be the discharge end of a furnace or suitable means for continuous, controlled atmosphere heating of the powder. The powder is preferably maintained under non-oxidizing conditions until it is fed to the nip of the rolls. The amount maintained against the roll is at least sufficient to provide a reservoir for continuously feeding powder into the gripping zone of the rolls. To minimize loss of heat to the surroundings, the hopper has an insulation 2 surrounding it of, for example, asbestos. Preferably, the hopper should be long in the direction of flow of the metal powder.

The powder having a relatively high apparent density and being free flowing passes through the tapered discharge orifices or spout of the hopper at 3 to maintain a reservoir 4 of free flowing metal powder against rolls 5 and 6. The metal powder continually feeds gravimetrically, with or without the aid of a vibratory device depending on the characteristics of the powder, into reservoir 4 and from there into the gripping zone defined by the angle of friction α as shown. The metal powder is gradually compressed together into a wedge which is drawn downward by the rolls and further compressed and passes through the effective roll gap at 7 and emerges as a highly densified hot rolled band 8. This is depicted more clearly in FIG. 3 which shows reservoir 4 of free flowing metal powder feeding into gripping zone 9 the upper limit of which is defined by the angle of friction α where the metal is gradually compressed until it reaches the full pressure of the rolls at the gap 7. The manner in which the powder continuously feeds into the zone is akin to continuous casting except here the consolidation is achieved in the solid state.

The hot metal powder begins to be effectively compressed at the cross-sectional bridge indicated by the line A—A where the rolls begin to grip the powder. The width L of the cross section of the bridge is about 2.67 times the width of the effective roll gap. For an absolute roll gap of about 0.05 inch, this would provide sufficient volume of powder in the gripping zone, the width L at the bridge being about 0.2 inch. Allowing for roll spring-back, the hot rolled strip emerging from the roll may be 20 or more thousands greater than the absolute width of the gap, for example, in the neighborhood of about 0.075 inch. With the compression starting at a cross-sectional width of about 0.2 inch at the beginning of the gripping zone, the final strip will emerge reduced about 2.67 times (0.2 divided by 0.075), which would be sufficient to substantially completely densify the powder having an apparent density ranging from about 40% to 50% of true density.

Where a situation arises requiring an initial roll gap, it may be difficult to start the continuous rolling process

due to powder falling through the gap. This can be avoided by starting the rolling process with the rolls touching each other and then as the rolling is underway, gradually separating the rolls to the desired setting, such that the new roll setting coupled with the amount of spring back results in the desired effective roll gap.

An advantage of using coarse powder is that while the apparent density is generally high, the size of the pores is large and allows the interstitial air to leave the powder as it is being compressed, the air passing through the free flowing reservoir 4 of powder directly above it, the reservoir being in a viable state and continually moving downward into the gripping zone as hot rolled metal is continuously discharged from the rolls.

As has been stated hereinbefore, the cross-sectional width of the gripping zone will generally be greater in the case of coarse spheroidal particles having a superficial oxide coating than with common clean particles. Whereas oxide stringers in conventionally produced sheet material have a deleterious affect on the physical properties, small amounts of oxides introduced into the metal by powder metal rolling is generally not deleterious, as such oxides do not form stringers and are generally uniformly distributed throughout the metal as an ultra-finely divided phase. In the case of spheroidal metal powders which tend to form a refractory oxide coating, e.g. stainless steel or certain of the nickel-base alloys which contain aluminum and titanium as age-hardening elements, such oxides as a fine dispersion tend to confer beneficial strength properties on the final product, to increase the recrystallization temperature of the final product and minimize parasitic grain growth.

The gripping zone can also be increased by using a rough ground roll. Since, in general, the fabrication of hot rolled strip would be in the production of fully dense intermediate products for subsequent hot and/or cold working, rolls of various surface roughness may be used to increase the cross sectional width of the powder drawn into the gripping zone. Such rolls may be prepared by grinding shallow furrows into the roll longitudinally across the surface parallel to the longitudinal axis. The valley of the furrows may be 0.003 to 0.01 inch below the surface of the rolls and about 1/4 inch apart. FIGS. 4 and 4a show such a roll 10 having necks 11 and 12 and shallow furrows 13 ground into the surface radially equidistant from each other. Such a roll may be employed in the tandem set-up shown in FIG. 5 wherein hot coarse metal powder is fed to rolls 10 surface roughened as shown in FIGS. 4 and 4a and the hot densified strip 15 emerging from the rolls immediately thereafter passed through another set of rolls 16 having a smooth polish where it is further reduced. Water sprays 17, 18 or other cooling means may be employed to keep the rolls from overheating. Whether a single pass through the rolls is used or an arrangement in tandem as shown in FIG. 5, my invention makes possible the production of a substantially fully dense hot rolled metal product in a single continuous metallurgical operation.

By maintaining the temperature of the particles at above the minimum recrystallization temperature, the tendency of the powder to become stressed is greatly minimized. Under such conditions the particles are easily welded together, even where superficial oxide films are present, the films being easily ruptured by interparticle contact during compaction by the rolls. The temperature of the particles will vary according to the metal and alloys being rolled. Generally, the homologous hot working temperature above the recrystallization temperature will fall within the range of about 40% of the absolute melting point to about 80% of its absolute melting point. The ratio of the minimum recrystallization temperature of a pure metal to its melting point is about 0.35. Alloying, however, tends to lower the melting point and increases the recrystallization temperature and, therefore, generally speaking the homologous working temperature

will exceed 40% of the absolute melting point and preferably range from about 50% to 80% of the absolute melting point.

Examples of working temperatures of several alloys and steels are given as follows:

Type Metal	Min. Recryst. Temp., °C.	Melting Point °C.	Hot Rolling Temp., °C.	T (Rolling) Tabs. M.P.
304 S.S. ¹	650	1,420	800	0.64
430 S.S. ²	800	1,480	700	0.55
Low Carbon Steel (0.15% C)	485	1,480	700	0.55
Low Carbon Steel (0.15% C)	485	1,480	600	0.50
Nimonic 90 ³	800	1,400	900	0.70

¹ 304 S.S.—18–20% Cr, 8–11% Ni, 0.08% C (max.), 1.0% Si (max.), 2.0% Mn (max.), balance Fe.

² 430 S.S.—14–18% Cr, 0.25% C (max.), 1.0% Si (max.), 1.0% Mn (max.), balance Fe.

³ Nimonic 90—20% Cr, 18% Co, 5% Fe (max.), 0.1% C (max.), 2.5% Ti, 1.5% Al, 1% Si (max.), 1% Mn (max.), balance Ni.

As illustrative of the invention, the following example is given:

Example 1

Stainless steel powder (Type 304) of minus 10 mesh and substantially all on 60 mesh is provided of spheroidal shape produced by ultrasonic disintegration having an apparent density of about 45% of its true density. The powder is heated to about 800° C. in a radiant tube furnace by gravity drop from a hopper which controls the rate of feed. The time of fall counter to a recirculated CO/CO₂ atmosphere of a slightly reducing composition, permits the powder to reach 800° C. at the bottom of the furnace. The powder is not permitted to build up at the bottom of the furnace to minimize any tendency for sticking and agglomeration, and is also continuously discharged onto the roll surfaces. Control of the hopper feed into the preheat furnace, control of the discharge out of the furnace, and roll speed will provide adequate flexibility to permit uninterrupted processing. The hopper is situated directly above a pair of compacting rolls of about 12 inches in diameter separated by a gap of about 0.05 to 0.06 inch in order to produce a hot rolled strip in the neighborhood of about 0.09 to 0.1 inch. The rotation of the rolls is set to provide a strip speed emerging from the rolls falling within the range of about 100 to 300 feet per minute. The powder is fed at a rate to the rolls to maintain a reservoir of powder at the rolls sufficient to keep the gripping zone filled. The strip has a very thin oxide coating which can be removed prior to any subsequent cold rolling operation. As has been stated hereinbefore, the rolls may start off in contact with each other and then gradually separated to an effective gap to give a strip of about 0.09 to 0.1 inch thick.

Strip or sheet material produced in accordance with the foregoing example will generally have good density at the edges thereof. Widths of about 24 inches may be produced, although the width may range from about 4' to 60". After hot rolling the strip from the powder, the strip may be further hot rolled at 800° C. to thinner gages, or, after pickling, cold rolled to finish size and annealed to desired temper.

Example 2

An 80/20 nickel-chromium alloy is provided similar in size to the stainless steel powder of Example 1 produced by ultrasonic disintegration and having an apparent density of about 40% of its true density. The powder is heated as in Example 1 to a temperature of about 850° C. under substantially the same conditions and then continuously fed through a hopper situated directly above a pair of compacting rolls of about the same diameter and separated by a roll gap of about 0.05 inch to produce a hot rolled strip in the neighborhood of about 0.08 inch. The rolls are rotated at a speed to provide

a strip speed emerging from the rolls of about 200 feet per minute. The powder is controllably fed to the rolls to maintain a reservoir of powder at the rolls sufficient to keep the gripping zone continually filled. The strip produced is annealed by heating it to a temperature of about 900° C. in a continuous annealing furnace according to conventional practice and thereafter pickled to remove the oxide and then subjected to a series of cold working and annealing operations to produce fine gage material.

Example 3

A low carbon steel powder (0.1% C) of substantially spheroidal shape is provided of particle size in excess of 100 mesh and ranging up to about 10 mesh having an apparent density in the neighborhood of about 50% of true density. The powder is continuously heated to a temperature of about 700° C. in a reducing atmosphere of partially combusted hydrocarbon gas having a ratio of CO/CO₂ and a little hydrogen sufficient to prevent the formation of FeO. Heating to 700° C. is preferred in order to keep the powder in the alpha ferrite region as the powder rolls easier when fed to the rolls than when the powder is in the austenitic state. The powder is fed from the hopper to the rolls while being maintained at the preferred temperature. As a preferred embodiment, a protective curtain of burning natural gas is provided between the hopper and the rolls in order to avoid the formation of FeO about the particles.

Rolls of 12" diameter are employed set at a roll gap of about 0.07" to produce a flat shape having a thickness in the neighborhood of about 0.1". The roll is provided with a surface finish such that the coefficient of friction with the powder in contact with it is at least 0.12. The powder is fed into the nip of the rolls at a dimension parallel to the roll axis corresponding to the production of sheet material of about 48" wide. As the hot sheet emerges from between the rolls, water is sprayed on it to minimize oxidation and decarburization. The rolls are rotated at a speed corresponding to about 150 surface feet per minute.

The hot rolled sheet is thereafter pickled and subjected to one or more stages of cold rolling and annealing until the desired size is produced. The product produced by this process has a very fine grain structure, good ductility and a yield greater than that normally obtained when producing similar products from a conventionally cast and forged ingot.

Example 4

A nickel base alloy comprising 15% Cr, 28% Co, 3% Mo, 3% Al, 2% Ti, 0.13% C and the balance substantially nickel of substantially spheroidal shape is provided of particle size in the range of about minus 10 mesh to plus 60 mesh having an apparent density at least about 40% of true density. The powder is continuously heated to a temperature of about 900° C. in a cracked ammonia atmosphere. Some fine oxide remains because Al₂O₃, TiO₂ and Cr₂O₃ do not reduce when the powder is heated 900° C. However, such oxides are advantageous in conferring beneficial physical properties to the final wrought product at high temperature.

The heated powder is fed continuously from the hopper to the rolls while being maintained at the indicated temperature. Because of the oxide coating, the coefficient of friction will be higher than with the usual powder metals. The powder is fed to a pair of rolls having a rough finish, whereby to assure a coefficient of friction in the order of about 0.15 and above.

Rolls of 12" diameter are employed set at a roll gap of about 0.03" to produce a flat shape or sheet about 36" wide having a thickness in the neighborhood of about 0.09". Because such complex alloys resist working more than the more simple compositions, the roll spring-back will be greater. Hence, a smaller roll gap would be used in arriving at a sheet product of desired

gage. In order to insure a sheet of substantially full density, without further preheat, the rolling is conducted in tandem as shown in the embodiment of FIG. 5. The last set of rolls would be preferably 6 inches in diameter with back-up rolls as is commonly employed in the art to obtain the desired final gage. The rolls are set to rotate at a speed corresponding to about 100 surface feet per minute.

The hot rolled sheet produced by the foregoing method is thereafter annealed at about 1050° C. to 1100° C., pickled and then subjected to further hot or cold rolling, with or without further annealing, to the desired size. The product produced by this process has a very fine and uniform grain structure, finely dispersed carbides, good ductility and a yield greater than that normally obtained when producing similar products from a conventionally cast and forged ingot.

The method of hot consolidating coarse metal powders as described hereinbefore enables the production of flat articles, such as strip or sheet, of gage sizes larger than is normally obtained by cold rolling and sintering of metal powders. By utilizing dense metal powder of substantially spheroidal characteristics, preferably having an apparent density of at least about 40% of true density, and of particle sizes in excess of 100 mesh, my invention enables the hot rolling of such powders into wrought metal shapes of a variety of gages. To insure densification of the powder into the desired product, the cross-sectional width of the gripping zone formed between the powder and the surface of the roll at the region where the rolls begin to grip the powder should be such relative to the effective roll gap as to provide a compaction ratio of at least 2.5 to 1 and, preferably, 4 to 1. As a further embodiment, it is preferred that the rolls have a surface characteristic (e.g., surface finish) such that the gripping angle in the gripping zone corresponds to a coefficient of friction of over 0.1 and, preferably, at least about 0.15. By correlating such factors as powder morphology, particle size, powder density, surface characteristic of the rolls, rolling temperature, etc., optimum processing conditions can be determined for each type of metal or alloy treated.

It will be apparent that my invention is applicable to the hot rolling of a variety of metals and alloy compositions. Generally speaking, my invention is applicable to metals having a melting point above 1100° C. Among such metals are included coarse metal powders of iron, the SAE steels and such iron-base alloys as 64% iron and 36% nickel; 31% nickel, 4 to 6% cobalt, and the balance iron; 54% iron and 46% nickel; 90% iron and 10% molybdenum or tungsten; 53% iron, 25% nickel, 16% chromium and 6% molybdenum; 74% iron, 18% chromium and 8% nickel; 86% iron and 14% chromium; 82% iron and 18% chromium; 73% iron and 27% chromium and other iron-base alloys, such as tool steels, for example, one containing 1% C, 6% Mo, 6% W, 1% Cr and the balance Fe.

Coarse nickel powders may also be employed, as well as such nickel-base alloys as 80% nickel and 20% chromium; 80% nickel, 14% chromium and 6% iron; 7% iron, 1% columbium, 2.5% titanium, 0.7% aluminum and the balance nickel; 28% cobalt, 15% chromium, 3% molybdenum, 3% aluminum, 2% titanium, 0.13% carbon, and the balance substantially nickel; 13.5% cobalt, 20% chromium, 4% molybdenum, 3% aluminum, 3% titanium and the balance substantially nickel; 58% nickel, 15% chromium, 17% molybdenum, 5% tungsten and 5% iron; and 95% nickel, 4.5% aluminum and 0.5% manganese; and other nickel-base alloys.

Cobalt-base alloys may likewise be processed in accordance with the invention. Among such alloys are included 27% Cr, 6% Mo and the balance Co. Complex alloys containing cobalt are likewise contemplated, such as an alloy comprising 20% Cr, 20% Co, 20% Ni, 4% W, 4% Mo, 4% Cb, and the balance Fe.

It is apparent from the foregoing that the iron group metals Fe, Ni and Co and Fe-base, Ni-base and Co-base alloys are amenable to processing by my invention.

Generally speaking, the invention is applicable to those metals of melting point above 1100° C. which in the form of spheroids at 100 mesh and larger are sufficiently ductile such that they can be flattened out when subjected to hammering or other flattening operation. Such powders are easily consolidated by hot rolling in accordance with the invention.

Although the present invention has been described in conjunction with preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention as those skilled in the art will readily understand. Such modifications and variations are considered to be within the purview and scope of the invention and the appended claims.

What is claimed is:

1. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder of melting point above 1100° C. to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of the metal and having a shape which insures free flowability and a relatively high apparent density at said temperature, continuously maintaining a reservoir of the free flowing hot metal powder against the metal drawn into the gripping zone of the rolls sufficient to continuously feed metal into the gripping zone, the surface characteristics of the rolls relative to the metal powder being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, such that the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap to provide a compaction ratio for effectively densifying the metal, and continuously hot rolling the metal powder into a wrought metal shape.

2. The method of claim 1 wherein the coarse metal powder has a particle shape selected from the group consisting of spheres, imperfect spheres, ellipsoids, tear drops and partial cylinders.

3. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder of melting point above 1100° C. to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of the metal and having a shape which insures free flowability and an apparent density of at least 40% of true density at said temperature, continuously maintaining a reservoir of the free flowing hot metal powder against the metal drawn into the gripping zone of the rolls sufficient to continuously feed metal into the gripping zone, the surface characteristics of the rolls relative to the metal powder being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, such that the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap to provide a compaction ratio of at least 2.5 to 1 for effectively densifying the metal, and continuously hot rolling the metal powder into a wrought metal shape.

4. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder of melting point above 1100° C. exceeding 100 mesh in size and having a substantially spheroidal shape and an apparent density of at least about 40% of true density to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of

the metal, continuously maintaining a reservoir of the free flowing hot metal powder against the metal in the gripping zone of the rolls sufficient to continuously feed metal in the gripping zone, the surface characteristics of the rolls being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, wherein the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap so as to provide a compaction ratio of at least about 2.5 to 1 for densifying the metal, and continuously hot rolling the metal powder into a wrought metal shape.

5. The method of claim 4 wherein the average particle size of the metal powder ranges from about 60 mesh to about one-eighth inch.

6. The method of claim 4 wherein the temperature of the powder being worked above its minimum recrystallization temperature falls within the range of about 40% to 80% of its absolute melting point.

7. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder of melting point above 1100° C. selected from the group consisting of Fe, Ni, Co, Fe-base, Ni-base and Co-base alloys and having a substantially spheroidal shape and an apparent density of at least 40% of true density to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of the metal, continuously maintaining a reservoir of the free flowing hot metal powder against the metal drawn into the gripping zone of the rolls sufficient to continuously feed metal into the gripping zone, the surface characteristics of the rolls relative to the metal powder being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, such that the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap to provide a compaction ratio of at least 2.5 to 1 for effectively densifying the metal, and continuously hot rolling the metal powder into a wrought metal shape.

8. The method of claim 7 wherein the average particle size of the metal powder ranges from about 100 mesh to one-eighth inch and wherein the temperature of the metal powder above its minimum recrystallization temperature falls within the range of about 40% to 80% of its absolute melting temperature.

9. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder of an average size exceeding 100 mesh, having a melting point above 1100° C., a substantially spheroidal shape and an apparent density of at least about 40% of true density to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of the metal, said metal powder being characterized by a thin refractory oxide coating, continuously maintaining a reservoir of the free flowing hot metal powder against the metal drawn into the gripping zone of the rolls, the surface characteristics of the rolls relative to the metal powder being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, such that the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap whereby to provide a compaction ratio of at least about 2.5 to 1, densifying the metal and continuously hot rolling the metal powder into a wrought metal shape characterized by a fine dispersion of refractory oxide therethrough.

10. The method of claim 9 wherein the temperature of the powder above the minimum recrystallization temperature falls within the range of about 40% to 80% of its absolute melting point.

11. A method for continuously hot consolidating metal powders into wrought elongated flat shapes which comprises continuously gravimetrically feeding free flowing hot coarse metal powder selected from the group consisting of Fe, Ni, Co, Fe-base, Ni-base or Co-base alloys of melting point above 1100° C. exceeding 100 mesh in size and having a substantially spheroidal shape and apparent density of at least about 40% of true density to the nip of a pair of rolls having an effective roll gap, said powder being fed at a temperature above the minimum recrystallization temperature of the metal, continuously maintaining a reservoir of the free flowing hot metal powder against the metal in the gripping zone of the rolls sufficient to continuously feed metal in the gripping zone, the surface characteristics of the rolls being such as to provide a gripping angle with the metal corresponding to a coefficient of friction of at least 0.1, wherein the cross-sectional width of the reservoir of the powder across the rolls at which the gripping zone begins is at least sufficient relative to the effective roll gap so as to provide a compaction ratio of at least about 2.5 to 1 for densifying the metal, and continuously hot rolling the metal powder into a wrought metal shape.

12. The method of claim 11 wherein the average particle size of the powder ranges from about 60 mesh to one-eighth inch and wherein the temperature of the powder above its minimum recrystallization temperature falls within the range of about 40% to 80% of its absolute melting point.

13. A method for continuously hot consolidating metal powders into elongated flat shapes which comprises, providing free flowing coarse workable metal powders of average size ranging from about 60 mesh to one-eighth inch of substantially spheroidal configuration of apparent density at least about 40% true density characterized by a melting point of above 1100° C. and by relatively large contacting surfaces for consolidation by a pair of metal rolls, bringing said free flowing metal powder to the nip of the rolls at a temperature above the minimum recrystallization temperature of the metal falling within the range of about 40% to 80% of its absolute melting point, maintaining a continuous feed of the coarse metal powder to the rolls having an effective roll gap so that a reservoir of metal powder is continuously maintained at said relatively high packing density against at least the gripping zone of the rolls above the gap such that the cross-sectional width of the reservoir between the rolls at least at the point at which the rolls begin to frictionally grip the metal powder and compress it is more than 2.5 times the width of the effective roll gap such that the gripping angle corresponds to a coefficient of friction of over 0.1, and continuously hot consolidating the coarse metal powder into wrought flat elongated metal shapes.

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