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[54] HOT FORMING OF TITANIUM AND TITANIUM ALLOYS

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[58] **Field of Search** 72/342, 364, 700; 148/11.5

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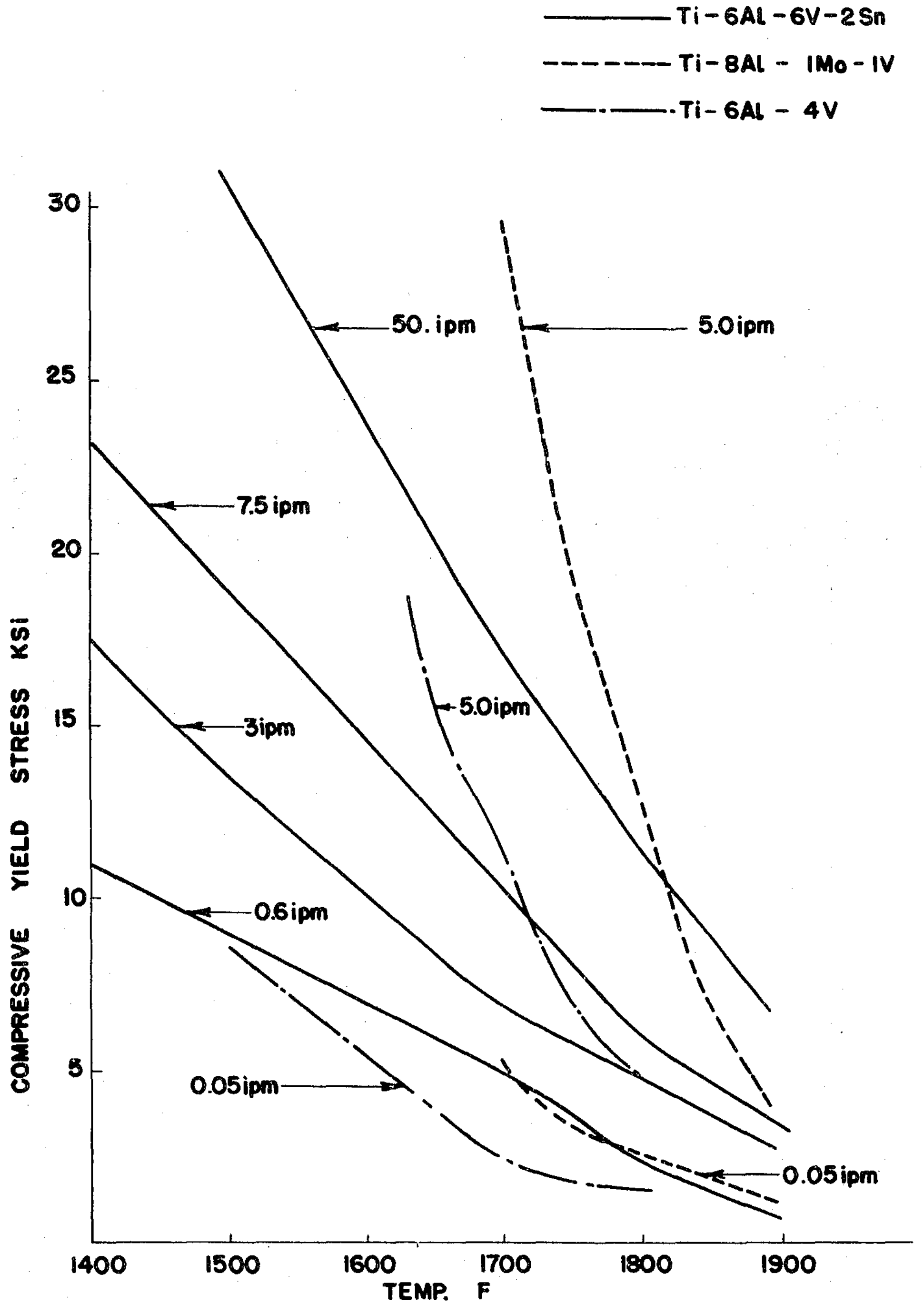
[57] **ABSTRACT**

A method for bulk deformation of titanium and titanium alloys employing elevated temperatures for the billet and the dies. The method permits single step forging from a billet or preform to a final shape without the necessity of further machining.

11 Claims, 1 Drawing Figure



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HOT FORMING OF TITANIUM AND TITANIUM ALLOYS

The present invention relates to the forming of titanium and titanium alloys. More particularly it relates to an improved method for the bulk plastic deformation of titanium and titanium alloys utilizing elevated deforming temperatures in dies that are heated to or close to the workpiece temperature.

Titanium and titanium alloys are becoming popular in the design of structures requiring a high strength-to-weight ratio. As used herein titanium alloys are defined to mean the structural alloys of titanium. Typical alloy compositions of this class normally include additions of aluminum and may also contain additions of one or more alloying agents such as tin, zirconium, molybdenum, vanadium, silicon, chromium, manganese and iron. Whenever used hereinafter the term "titanium alloys" is understood to also include industrially pure titanium. Titanium alloys find particular application in the field of aircraft and missile design, though other applications are continually being found where the advantageous properties of titanium alloys are beneficial. While it is already known that several important end uses exist for titanium alloys, there remains serious difficulty in the bulk deformation of these materials to their final shape for an intended use. As used herein the term "bulk deformation" means the forming of a finished product from an ingot, billet, slug or preform as opposed to bending or drawing sheet material.

A commercial forming process for titanium alloys should permit economical forming of the alloy into a desired shape while retaining desirable physical properties. Inherently such a process must retain in the alloy the microcrystalline structure necessary for attaining high strength-to-weight ratio. The chief difficulty in the known processes for the bulk deformation of titanium alloys has been in overcoming the very high compressive yield strength of titanium alloys which makes them extremely difficult to form into thin-forged webs and ribs and other configurations requiring extensive flow of material in the die.

The problem is complicated by the lack of availability of die materials suitable for forming materials having yield strengths in excess of 150,000 p.s.i., which is typical of titanium alloys. To limit the loading of the die and assure filling of the cavity, commercial bulk deformation of titanium alloys is presently accomplished by multistep forging employing a series of progressive dies, each set of which produces part of the required deformation. The several dies must be designed and fabricated to perform the forging in steps beginning with the initial billet and ending with a finished product. The workpiece must be transferred to successive dies as many as five or six times to reach its final shape. The cost is high in terms of die cost and time expended. The result is high costs of manufacturing for an already expensive metal. Die materials for present commercial forming methods are usually selected from the so-called hot-working die steels which possess adequate strength only at temperatures of 1,000° F. or below. For this reason forging proceeds with a substantial temperature gradient between the titanium alloy and the die, and cooling of the workpiece limits the deformation that can be attained in a single operation.

It is an object of the present invention to provide a method for deforming titanium and titanium alloys.

It is a further object of the present invention to provide an improved method of forging titanium and titanium alloys.

These and other objects of the invention are more particularly set forth in the following detailed description and in the drawing which is a plot of compressive yield strength as a function of temperature and press speed for several alloys.

The present invention relates to a method of forming titanium alloys at elevated temperatures. The process is performed by heating the workpiece to a temperature above 1,400° F. and heating the dies to the same or a slightly lower temperature. For simplicity, this process will be referred to herein as isothermal forming. The speed of the press is selected at from 0 to about 100 inches per minute depending on the alloy composition and the forming temperature. Titanium alloys are strain rate sensitive materials. That is, for any substantial deformation at elevated temperatures, the yield strength of the alloy is dependent on the rate of deformation. The higher the rate of deformation, the higher the yield strength. For the particular alloy employed, the temperature and press speed are selected so that the resultant yield strength does not exceed approximately one-third of the yield strength of the die material at the same temperature. A strength differential of this magnitude assures that the die material will not deform even when complex workpiece configurations are to be formed. It is by a proper selection of the above-named parameters that bulk deformation of titanium alloys is possible by isothermal forming, using a single die of commercially available material. The particular temperature selected and the particular press speed employed is keyed to the properties of the specific alloy being formed. The difficulty of forming is a function of the particular alloy being worked beginning with industrially pure titanium at the easiest end of the spectrum and extending to the alloys most difficult to work, such as Ti–8Al–1Mo–1V.

As stated above titanium alloys exhibit a sensitivity to strain rate wherein the yield strength increases with strain rate. The drawing shows this property for three typical titanium alloys at several temperatures and pressing rates. The curves illustrate to a limited extent the variety of strain rate sensitivity exhibited by different alloys of titanium. The curves are labeled in inches per minute of press travel rather than actual strain rate because in forming complex shapes the strain rate varies throughout the forging. The values used to plot the curves were obtained by axially compressing alloy cylinders 1 inch in diameter and 2 inches long. The values plotted are for the compressive yield strengths at which plastic deformation begins.

The solid lines represent commercial Ti–6Al–6V–2Sn alloy compressed at press speeds ranging from 0.6 to 50 inches per minute of head travel. This alloy is representative of a titanium alloy which can be worked at a wide variety of pressing speeds and virtually throughout the temperature range from about 1,400° to about 1,950° F. without excessive die pressures.

The dash lines represent commercial Ti–8Al–1Mo–1V alloy. The press speeds range only from 0.05 to 5.0 inches per minute, yet the strain rate sensitivity of this alloy is much more pronounced. Also, for this alloy the practical temperature range is at the upper end of the 1,400° to 1,950° F. temperature range. At a pressing speed of 5 inches per minute the yield strength ranges from 4,000 p.s.i. at 1,900° F. up to 30,000 p.s.i. at 1,700° F. Ti–8Al–1Mo–1V represents alloys which are at the difficult to work end of the spectrum in the context of the present invention. These alloys should be deformed at temperatures above 1,700° F. or at extremely low-strain rates, or both, depending on the die material employed. In addition, high pressing speeds such as 50 inches per minute appear to be impractical at any temperature for this alloy, and working this alloy below 1,700° F. appears feasible only at pressing speeds of the order of about 0.1 inch per minute or less. Even the curve for 0.05 inches per minute displays a marked increase in stress between 1,750° and 1,700° F.

The dot-dash lines represent Ti–6Al–4V alloy deformed at two press speeds. As can be seen this alloy remains relatively easy to work between 1,500° and 1,800° F. so long as the pressing speed is low. When the pressing speed is raised to just 5 inches per minute, the stress-temperature relationship becomes similar to, if not as extreme as that of Ti–8Al–1Mo–1 V alloy.

It should be pointed out that the data of the drawing present approximate figures for yield strength which is the stress at which plastic deformation begins. The forging pressures necessary to fill an intricate die with these alloys are considerably higher than the yield strength values illustrated. However, the relationship between the various alloys illustrated in the drawing holds approximately true for the respective final forging pressures. For this reason the yield strength of the titanium alloy as stated earlier should not be more than one-third of the yield strength of the die material at the temperature and speed selected thus providing a factor of 3 for final die-filling pressure without destroying the dies.

As stated earlier, the values in the drawing are expressed in terms of speed of press head travel rather than actual strain rate because the actual strain rate in a complex three-dimensional shape varies from point to point for a constant press speed and is a function of the press head speed, the shape of the original billet and the final shape. Lowering the strain rate throughout the material lowers the final forging pressure on the die faces. In some cases it may be desirable to deform at a constant total press force and allow the deforming body to select its own optimum strain rate. The need for such a measure is dependent on the alloy and the temperature involved. Obviously, the pressing could also be carried out in multiple steps if desired using the single set of dies and partial forging in each step.

A temperature range of between about 1,400° and about 1,950° F. is preferred for several reasons. As mentioned earlier, the temperature at which titanium alloys are formed has a relationship to the microcrystalline structure and consequently to the mechanical properties of the finished product. Titanium alloys exhibit a change in crystal structure at some temperature from hexagonal to body-centered cubic. This temperature is called the beta transus and is a well-defined property of each alloy. The beta transus temperatures for most known alloys range from about 1,500° to 1,900° F. For example, the beta transus temperatures for Ti–6Al–6V–2 Sn, Ti–8Al–1Mo–1V and Ti–6Al–4V are approximately 1,735°, 1,900° and 1,830° F., respectively. Forming alloys above the beta transus results in a final product which retains the body-centered cubic microcrystalline structure and possesses different properties than are provided by forming below the beta transus. The desirability of forming above or below the beta transus depends therefore on the desired properties for the specific application. Accordingly, the temperature for each application is selected based on the specific alloy employed and the microcrystalline structure desired.

Referring now to the die materials employed, it is common to most metals and alloys to exhibit some decrease in strength with an increase in temperature. The rate of decrease is not linear over wide temperature ranges and varies greatly between materials. By selecting a temperature range in which commercially available materials such as nickel and cobalt base superalloys exhibit sufficient high-temperature strength relative to the hot strength of titanium alloys, bulk deformation of titanium alloys may be accomplished without significant deformation of the dies. Temperatures below about 1,400° F. are not generally desirable because the yield strength of titanium alloys may reach or exceed that of the nickel and cobalt alloys die material. Examples of representative die materials which exhibit adequate compressive yield strengths at the desired temperatures are given in table I.

TABLE I

0.2% Compressive Yield Strength of Die Materials—(k.s.i.)

Air Melted and Cast

Trade name	1400° F.	1600° F.	1800° F.	1900° F.
Inconel 713C	104	92	46	21
IN 100	116	118	71	45
MAR-M200	113	117	73	51
Udimet 700	40	60	31	16
X-40	43	43	25	16
F-484	53	51	43	37

Vacuum Melted and Cast

Trade name	1400° F.	1600° F.	1800° F.	1900° F.
Inconel 713C	119	130	49	N.A.*
IN 100	115	117	84	N.A.
MAR-M200	115	114	66	N.A.
Udimet 700	90	100	48	N.A.

*N.A.—Not available

The values set forth in table I are for the standard definition of yield strength measured at 0.2 percent deformation in compression, and are presented by way of example of alloys some of which are clearly suitable for use as dies in the isothermal deformation of titanium alloys under the proper conditions. It should be noted, however, that not every die material listed is suitable for the highest yield strength alloys of titanium; rather the particular die material should be selected based on the material to be deformed. It will be apparent to one skilled in the art that there are other alloys which might be utilized as die materials, particularly for the easiest to work titanium alloys and pure titanium.

As in any forming process, the primary objective in selecting the material for the forming tool or die is to avoid plastic deformation which would destroy the dies. Therefore the die pressures are to be kept below the yield strength of the die material selected so that only elastic deformation occurs.

The alloys listed in table I are themselves difficult to form into finished shapes. They are difficult to machine; however, dies of these materials may be produced by commercial processes such as precision casting so that costs of die manufacture are minimized.

Temperatures below 1,400° F. have been excluded for reasons which are apparent from a consideration of the drawing and table I. The yield strength and hardness for most titanium alloys increases rapidly with decrease in temperature. The increase is more rapid than the corresponding increases for the superalloy die materials. For example, at 1,000° F., Ti–8Al–1Mo–1V exhibits a yield strength of 60,000 lbs. p.s.i. at low-strain rates. Therefore since the forging pressure necessary to fill an intricate die at the lowest strain rate would be approximately three times the yield strength, the die material would be subjected to a pressure of 180,000 p.s.i. during forging at 1,000° F. This value is substantially above even the room temperature properties of known alloys such as those in table I. In addition, the yield strength of the typical titanium alloy increases to values exceeding 100,000 p.s.i. at room temperature.

Temperatures between about 1,950° F. and the melting point of the various titanium alloys are of limited practical interest because deforming at these higher temperatures causes the titanium alloy to undergo crystal growth so that structural properties deteriorate. While there appears to be no fixed cutoff where this crystal growth becomes too damaging to structural properties, such growth is limited to a negligible amount if forging temperatures are within about 50° F. above the beta transus for the particular alloy. Accordingly, even when the deformation is performed above the beta transus range of any titanium alloy it is preferred not to exceed the beta transus by any more than 50° F. to avoid the resultant crystal growth and loss in strength or certain other mechanical properties.

Although it is possible to perform the process of the present invention by heating the billet and the dies substantially above 1,400° F. and forging while both are cooling, much better control of properties and die wear is achieved by continued heating of the dies during forging so that the operation is performed isothermally at the selected temperature. Several conventional heating methods may be employed. It is preferred, however, that the heating be done by means external to the dies such as induction heating coils. The billet or preform is preheated to the same as or slightly higher temperature than the dies.

Lubrication during the forging operation promotes die filling. Several hot forging lubrication techniques, such as a combination of glass and graphite, are suitable and prevent both adhesion to the die and oxidation of the billet. As in any forging operation excessive lubricant accumulation prevents complete die filling and should be avoided.

The present invention may be better understood by reference to the following specific examples which show the relationship of temperature and pressing speed.

EXAMPLE I

A scaled down airplane nosewheel was prepared from a preform of Ti–6Al–6V–2Sn. The preform was in the form of an annular ring having an outside diameter of 7.27 inches, an inside diameter of 2.40 inches and a thickness of 0.54 inches. The preform weighed 3.25 pounds and was coated with a glass lubricant prior to forming. The preform was heated in a furnace of 1,800° F. Suitable dies of IN 100 were inserted in a press and were heated to 1,800° F. by external induction heating coils surrounding the dies. The preform was inserted between the dies and was pressed at a pressing speed of 0.1 inches per minute to a final forging load of 250 tons. The forging was completed in a single step to form a finished nosewheel. The forging had a plan area of 37 square inches. The final forging pressure was 13,500 p.s.i.

EXAMPLE II

A preform having the same composition and dimensions as example I was heated to 1,700° F. and was inserted into the same set of dies which were also preheated to 1,700° F. Pressing was effected at 0.1 inches per minute. At this temperature a forging load of 300 tons was required to close the dies resulting in a final forging pressure of 16,200 p.s.i.

EXAMPLE III

A preform having the same composition and dimensions as example I was heated to 1,600° F. and was inserted into the same set of dies which were also preheated to 1,600° F. Pressing was again effected at 0.1 inches per minute. At this temperature a forging load of 350 tons was required to close the dies resulting in a final forging pressure of 18,900 p.s.i.

EXAMPLE IV

A pair of dies weighing 150 pounds each was formed of IN 100 to define a die cavity having an intricate form including corners, thin webs and flanges. A billet in the form of a rectangular block of Ti–6Al–6V–2Sn weighing 2.1 pounds and having dimensions of 2.75 inches by 3 inches by 1.52 inches was heated in a furnace to 1,800° F. The dies were also heated to 1,800° F. by induction heating coils surrounding the dies. The billet was coated with glass lubricant before forging, was inserted between the dies and was pressed at 1,800° F. at a press speed of 3 inches per minute. Pressing was continued at a constant speed until the die cavity closed at a forging load of 250 tons. Complete die filling was achieved. The plan area of the finished forging was 10.5 square inches giving a final forging pressure of 47,600 p.s.i.

The final form of the forging was generally of a rectangular shape and included four sidewalls roughly one-fourth inch in thickness and 2½ inches high with a central web spanning the rectangular opening approximately half the distance from the bottom to the top of the rectangular walls. The shape was designed for maximum material displacement during the forging operation.

EXAMPLE V

A billet having the same dimensions and composition as that of example IV was heated to 1,700° F. and inserted between the same set of dies as in example IV. The dies were preheated to 1,700° F. and pressing was effected at 3 inches per minute to die closure. The resulting shape was identical to that of example IV and required a forging load of 325 tons resulting in a final forging pressure of 61,800 p.s.i.

EXAMPLE VI

A billet of the same composition and dimensions as in the example IV was heated to 1,800° F. and inserted into the same set of dies. The dies were preheated to 1,800° F. Pressing was effected at 0.1 inches per minute to die closure. The resulting shape was identical to that of example IV and required a forging load of 75 tons for die closure resulting in a final forging pressure of 14,300 p.s.i.

EXAMPLE VII

A larger set of dies defining a die cavity of the same shape as that of example IV and having scaled up dimensions was formed from IN 100. A billet of Ti–6Al–6V–2Sn in the form of a block having dimensions of 4.06 inches by 2.81 inches by 1.89 inches and weighing 3.6 pounds was heated to 1,800° F. The dies were also heated to 1,800° F. as in example IV. The billet was coated with glass lubricant and inserted between the dies. Pressing was effected at 3 inches per minute to die closure with a forging load of 350 tons required for die closure. The plan area of the final forged form was 15.5 square inches resulting in a final forging pressure of 45,200 p.s.i.

The foregoing examples illustrate the principle of the invention described and claimed herein. In examples I to III the only variable is the temperature and the effect on the forging pressure is evident. Examples IV and V show the effect of increased pressing speed at the temperatures illustrated in examples I and II. Example VI differs from example I only in the shape. The values for forging pressure are quite close indicating for given temperature and press speed the final forging pressure can be predicted regardless of the shape of the forging. Example VII is similar to example IV and illustrates that the forging pressure is not appreciably affected by the size of the forging.

While the present invention has been described with reference to a forging operation, it applies equally to the extrusion of titanium and titanium alloys. In the extrusion process the die is manufactured of superalloy and the billet of material is placed in a container and forced through the die. In the application of the present invention both the billet and the die are heated above 1,400° F. and are maintained at the desired temperature during the extrusion by conventional heating means compared to present processes of extrusion, pressures can be substantially reduced because much slower extrusion speeds can be selected in the absence of cooling thus taking advantage of the strain rate sensitivity of the alloy.

The present invention provides a new process for forming finished parts of titanium and titanium alloys either above or below the beta transus with a minimum of difficulty and process steps. The result is better products at a great savings in time and cost.

Various changes and modifications of the present invention will occur to those skilled in the art without deviating from the spirit or scope of the invention which features are defined in the following claims.

What is claimed is:

1. A method of forging titanium and titanium alloys comprising the steps of:
   without first preworking of a workpiece to change the grain size thereof heating a workpiece to a temperature within the range of between about 1,400° and about 1,950° F.,
   heating a forging device to a temperature within the range of between about 1,400° and about 1,950° F.,
   inserting said workpiece into said forging device exposed to the ambient atmosphere,
   forging in the ambient atmosphere said heated workpiece while maintaining said forging device and said workpiece within said temperature range, and
   controlling the forging speed such that the highest pressure exerted does not exceed the yield strength of said forging device at the temperature employed.

2. The method defined in claim 1 wherein said forging is accomplished at a substantially constant temperature.

3. The method defined in claim 1 wherein said forging is conducted in a superalloy die.

4. The method defined in claim [illegible] wherein said forging speed is selected so that the yield strength of the titanium alloy does not exceed one-third of the yield strength of the forging device.

5. The method defined in claim **1** wherein said forging is accomplished in a single step and produces a finished shape.

6. A method for forging complex three-dimensional shapes with strain rate sensitive titanium alloys comprising the steps of:

without first preworking a billet to change the grain size thereof heating an alloy billet and heating a single set of forging dies to a temperature above 1,400° F.,

forging said alloy billet to fill completely a complex shaped three-dimensional die cavity to a finished shape in a single set of heated dies while maintaining said temperature, and

maintaining a sufficiently low die speed that the final forging pressure does not exceed the yield strength of said set of dies.

7. The method defined in claim **6** wherein said final forging pressure does not exceed 100,000 p.s.i.

8. The method defined in claim **6** wherein the die speed does not exceed 10 inches per minute.

9. The method defined in claim **6** wherein the die speed varies from 0 to 10 inches per minute during the forging process.

10. The method defined in claim **6** including the further steps of coating said alloy billet with a material to prevent oxidation of the billet and to serve as a lubricant to prevent adhesion of the billet to the die and wherein said forging takes place in the ambient atmosphere.

11. The method defined in claim **10** wherein a thin coating comprised of glass and graphite is applied to said billet to provide the lubrication and to prevent oxidation without providing such an accumulation as would prevent complete filling of the complex shape of the die by the billet.

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