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(54) **FRICTION WELDING**

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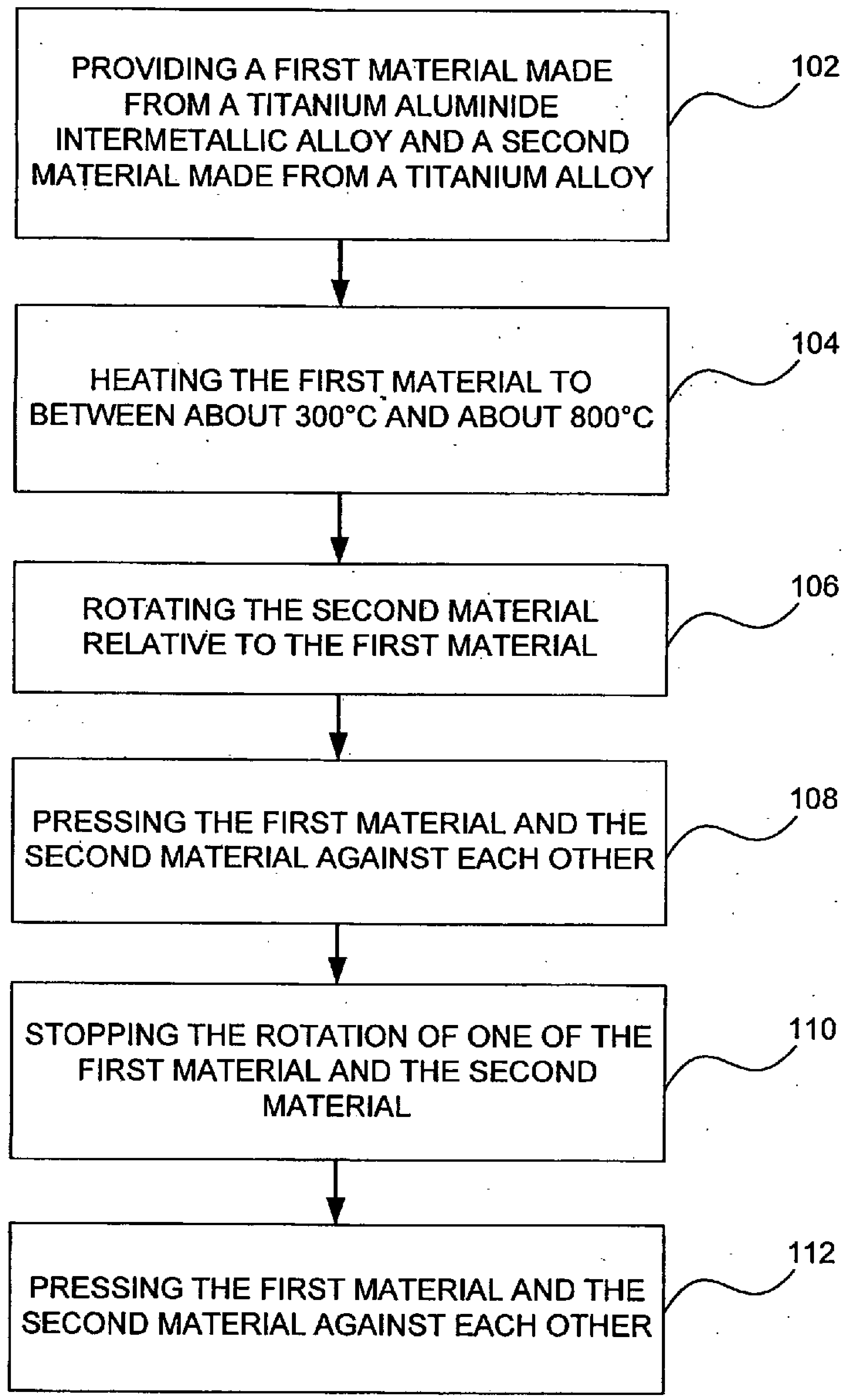
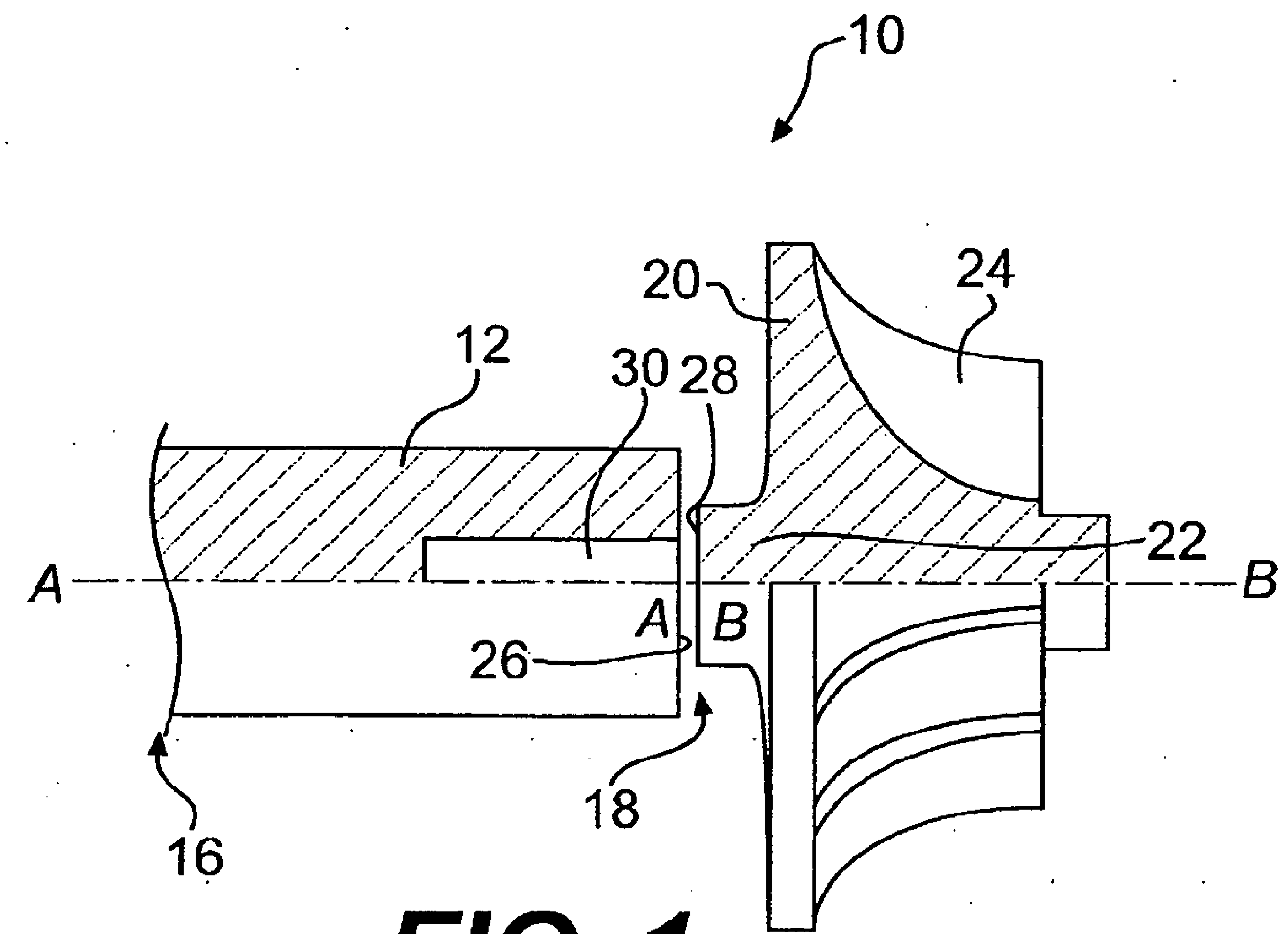
(57) **ABSTRACT**

A method of bonding two materials by friction welding method. A first material may be made from a titanium aluminide intermetallic alloy and a second material may be made from a titanium alloy. The first material may be heated to a temperature between about 300° C. and about 800° C. The second material may be rotated relative to the first material. The first material and the second material may be pressed against each other while one of the first material, and the second material is rotated. The rotation of one of the first material and the second material may be stopped, and the first material and the second material may be pressed against each other after the rotation of one of the first material and the second material is stopped.




10
20
24
12
30
28
22
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26
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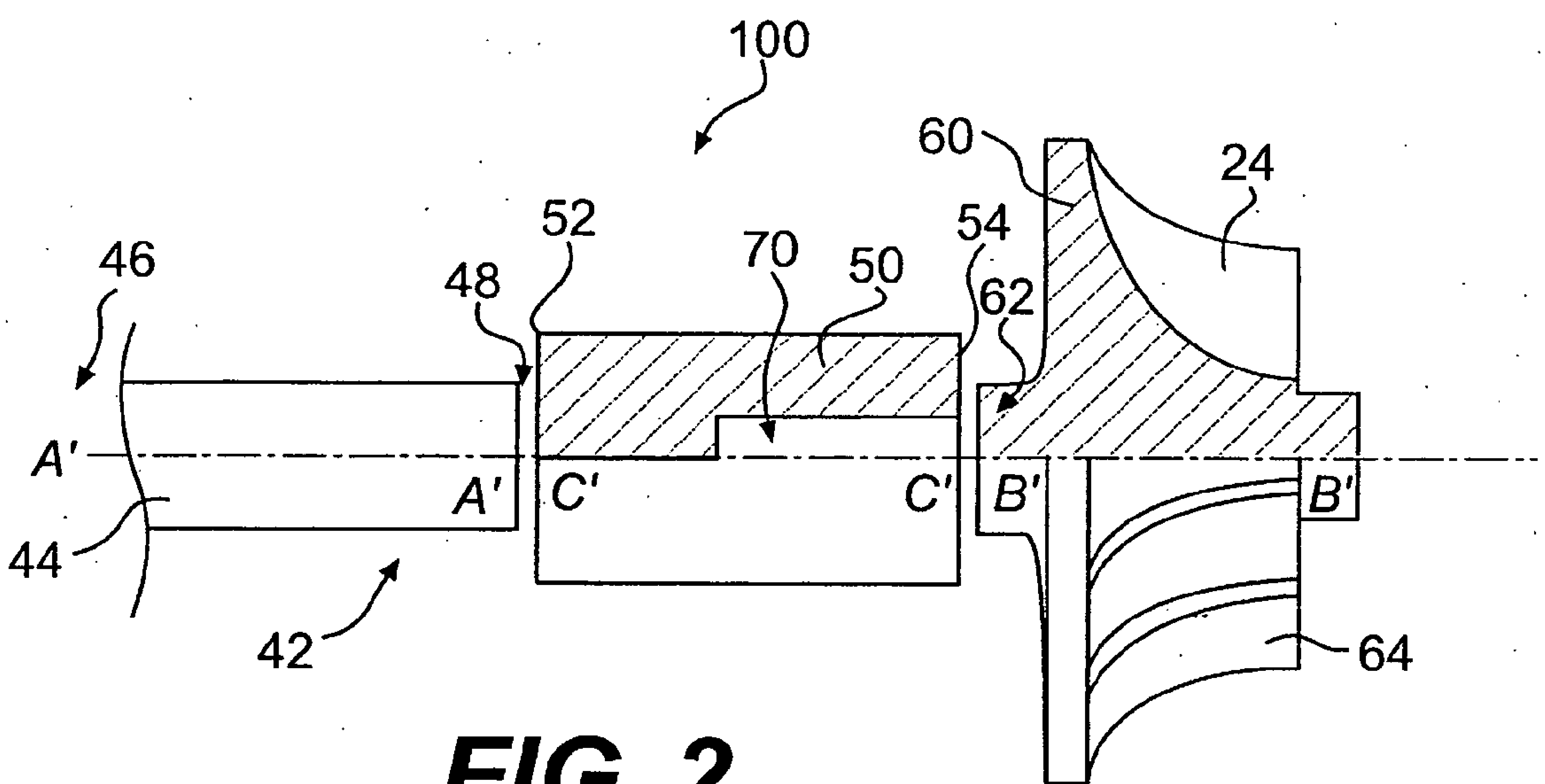
16

FIG. 1


100
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24
52
70
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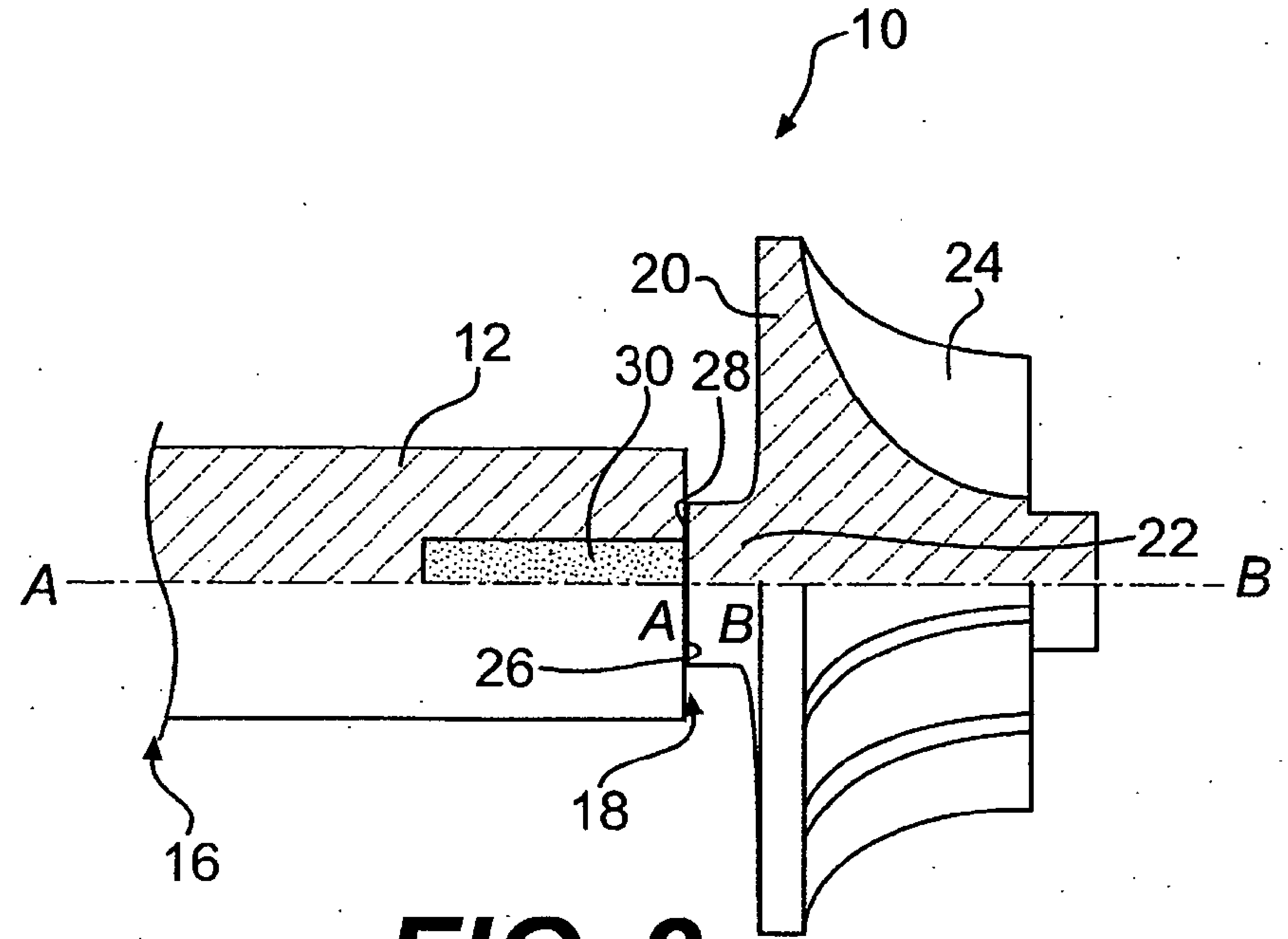
B'
44
42
64

FIG. 2


10
20
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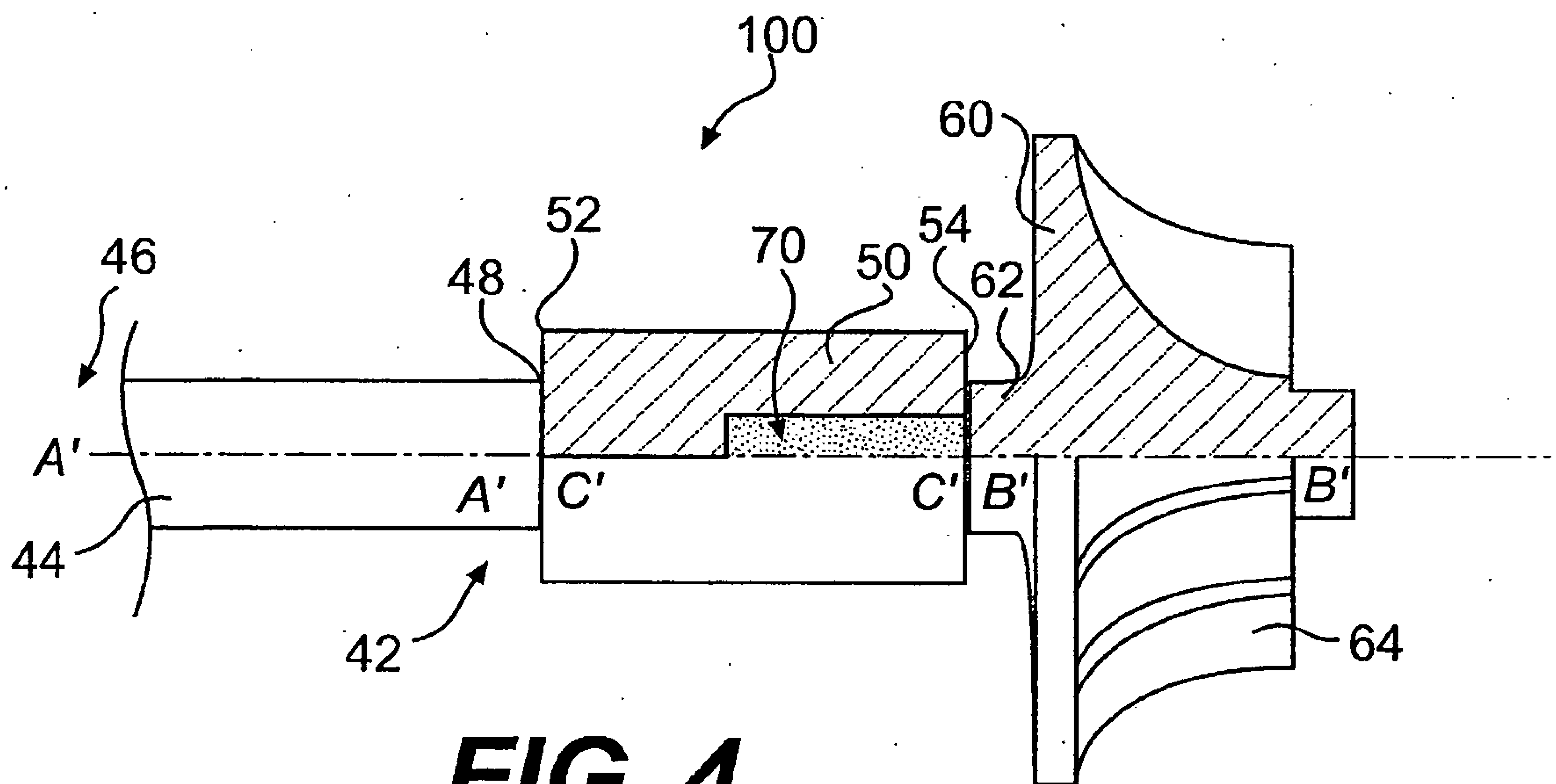
16

FIG. 3


100
60
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46
48
70
50
62
A'
A'
C'
C'
B'
B'
44
42
64

FIG. 4

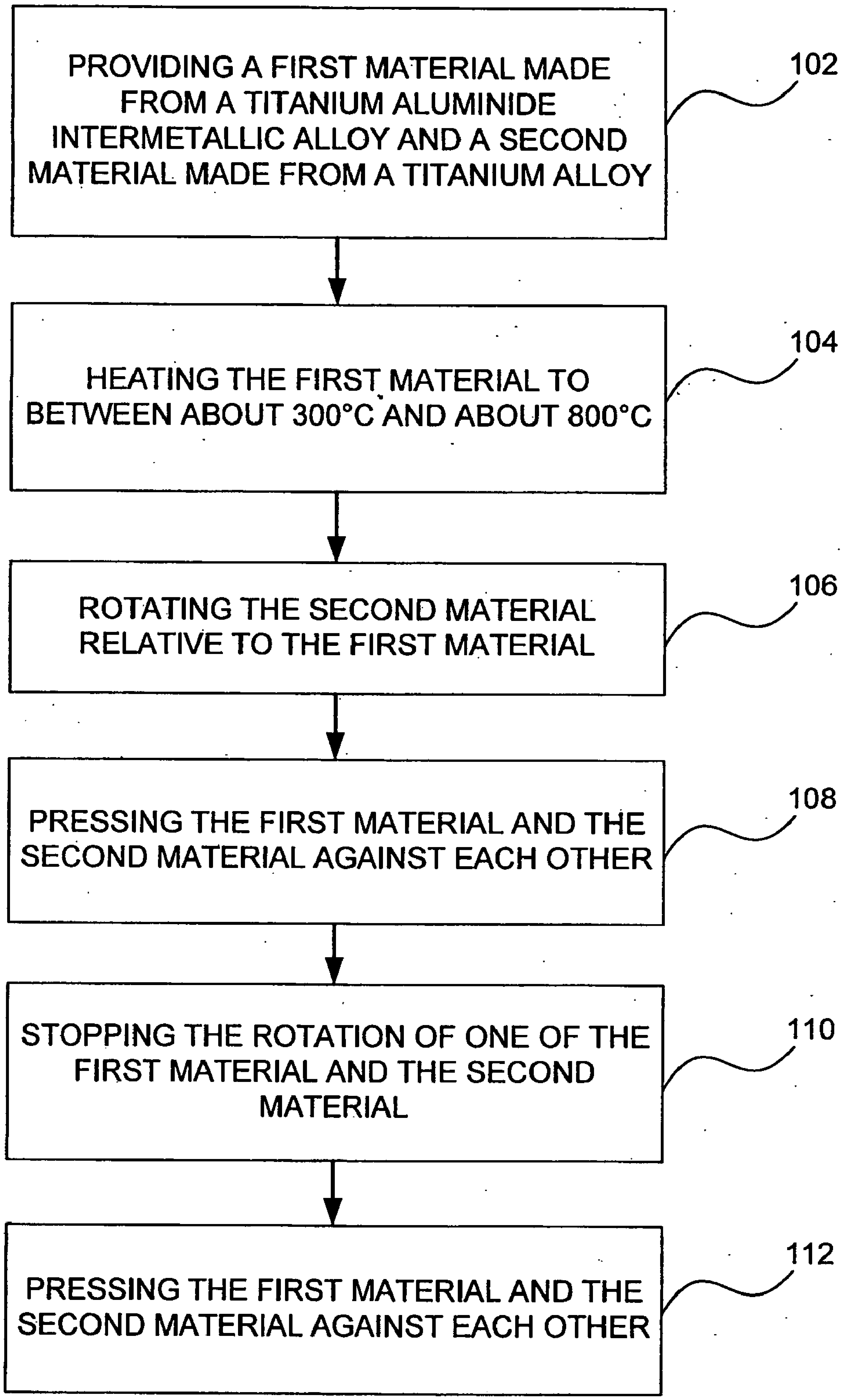
PROVIDING A FIRST MATERIAL MADE FROM A TITANIUM ALUMINIDE INTERMETALLIC ALLOY AND A SECOND MATERIAL MADE FROM A TITANIUM ALLOY
102
HEATING THE FIRST MATERIAL TO BETWEEN ABOUT 300°C AND ABOUT 800°C
104
ROTATING THE SECOND MATERIAL RELATIVE TO THE FIRST MATERIAL
106
PRESSING THE FIRST MATERIAL AND THE SECOND MATERIAL AGAINST EACH OTHER
108
STOPPING THE ROTATION OF ONE OF THE FIRST MATERIAL AND THE SECOND MATERIAL
110
PRESSING THE FIRST MATERIAL AND THE SECOND MATERIAL AGAINST EACH OTHER
112

FIG. 5

FRICTION WELDING

U.S. GOVERNMENT RIGHTS

[0001] This invention was made with government support under the terms of Contract No. DE-AC05-00OR22725 awarded by the Department of Energy. The government may have certain rights in this invention.

TECHNICAL FIELD

[0002] The present disclosure relates generally to a method of bonding different materials, and more particularly, to a method of bonding different materials by friction welding.

BACKGROUND

[0003] Titanium aluminide intermetallic alloys possess a favorable combination of low density and high temperature capabilities, and thus have emerged as potential high temperature materials to replace super-alloys in many applications, e.g. turbines and valves. The use of titanium aluminide intermetallic alloys, however, depends on the resolution of a critical issue, namely, integrating a titanium aluminide intermetallic alloy component successfully to its application system by bonding titanium aluminide intermetallic alloy to itself or a different material. Bonding titanium aluminide intermetallic alloys is challenging mainly because of three reasons: high local thermal stress involved with bonding process, formation of brittle intermetallic phases at the bonding interface, and inherent low room temperature ductility of titanium aluminide intermetallic alloys. Because of these reasons, the titanium aluminide intermetallic alloy components and the bonding interface are prone to crack during or after the bonding process and usually associated with inferior joint properties. In some applications, because of specific geometry or large component size of the titanium aluminide intermetallic alloy components, the local thermal stresses can become extremely high and therefore render the bonding process even more challenging. For example, in turbine rotor applications, the bonding interface is fairly close to turbine backface, and the geometry of the turbine hub changes rapidly. This rapid changing in geometry, in addition to the large thermal mass of turbine wheel, may cause a steep temperature gradient, and therefore, may cause large thermal stress which may exceed the strength of the titanium aluminide intermetallic alloy in the vicinity of the bonding interface. In valve applications, the geometry change may be relative gradual as compared to turbine. However, in large size valves (for example, more than four inches (10.16 cm) in valve head diameter), the temperature change across the joining interface of the valve during bonding process may cause additional thermal stresses.

[0004] One method of bonding titanium aluminide intermetallic alloy components and titanium (Ti) alloy is described in Japanese Patent Publication No. 1990/02160188 (the '188 publication) to Misao et al. The '188 publication describes a specific set of parameters for joining titanium aluminide intermetallic alloy and Ti alloy by friction welding. The friction welding method with specific set of parameters can help to reduce the formation of intermetallic phases at the joining interface. The method may not be capable of providing acceptable joint properties for joining components with relatively large size, e.g., large size valves, or joining components with special geometry shapes, e.g., turbine wheels, which may experience large thermal and stress changes during bonding process.

[0005] Another method of joining titanium aluminide intermetallic alloy and Ti alloy is described in U.S. Patent Publication No. 2003/0015570 (now U.S. Pat. No. 6,691,910) (the '910 patent) to Hirose et al. The '910 patent describes a method of joining a valve stem made of Ti alloy with a valve head made of titanium aluminide intermetallic alloy to form a poppet valve by friction welding. This '910 patent discloses a method of reducing the plastic deformation (burrs) of Ti alloy. The '910 patent uses an induction unit for in-situ heating the titanium aluminide intermetallic alloy component to 900-1100° C. during the welding process to reduce the burrs of Ti alloy. When the titanium aluminide intermetallic alloy component is heated beyond 900° C., the strength of titanium aluminide intermetallic alloy may decrease significantly, and therefore, may cause damage to the titanium aluminide intermetallic alloy component. Heating titanium aluminide component, which may increase the burrs from the titanium aluminide generated from the friction welding process, however, may not reduce the burrs from titanium alloy. Moreover, to avoid oxidation, thermal stress and other possible detrimental effects to the titanium aluminide intermetallic alloy component, heating the titanium aluminide intermetallic alloy component to 900-1100° C. has to be performed in a complicated manner, which may increase the cost. Furthermore, the induction heating method in '910 patent might not be applicable in some applications, e.g. turbine wheels, due to the turbine wheels' special geometry.

[0006] Nevertheless, although the methods of the '188 publication and '910 patent may be used to join the Ti alloy with the titanium aluminide intermetallic alloy, they may have been only successful on components with relatively small scale and relatively simple geometry shape, e.g., small size valves having gradual geometry contour changes.

[0007] The disclosed system is directed to overcoming one or more of the problems set forth above.

SUMMARY OF THE INVENTION

[0008] In one aspect, the present disclosure is directed to a method of bonding two materials. A first material may be made from a titanium aluminide intermetallic alloy and a second material may be made from a titanium alloy. The first material may be heated to a temperature between about 300° C. and about 800° C. The second material may be rotated relative to the first material. The first material and the second material may be pressed against each other while one of the first material and the second material is rotated. The rotation of one of the first material and the second material may be stopped, and the first material and the second material may be pressed against each other after the rotation of one of the first material and the second material is stopped.

[0009] In another aspect, the present disclosure is directed to a method of producing a turbine rotor assembly. A turbine rotor wheel made from a titanium aluminide intermetallic compound is heated to a predetermined temperature. A turbine rotor shaft is rotated relative to the turbine rotor wheel. The turbine rotor shaft is pressed against the turbine rotor wheel while the turbine rotor shaft is rotated. The rotation of the turbine rotor shaft may be stopped and the turbine rotor shaft is pressed against the turbine rotor wheel after the rotation of the turbine rotor shaft is stopped.

[0010] In yet another aspect, the present disclosure is directed to an assembly made by a friction welding process. The assembly includes a first material and a second material. At least one of the first material and the second material may include a cavity at an end of at least one of the first material and the second material to be coupled to the other material. The cavity may be at least partially filled with at least one of the first material and the second material as a result of the friction welding process.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a partial section view of an exemplary disclosed turbine rotor assembly according to one embodiment of the invention;

[0012] FIG. **2** is a partial section view of an exemplary disclosed turbine rotor assembly according to another embodiment of the invention;

[0013] FIG. **3** is a partial section view of the exemplary disclosed turbine rotor assembly of FIG. **1** after friction welding;

[0014] FIG. **4** is a partial section view of the exemplary disclosed turbine rotor assembly of FIG. **2** after friction welding; and

[0015] FIG. **5** is a flow chart illustrating an exemplary disclosed method according to one embodiment of the invention.

DETAILED DESCRIPTION

[0016] FIG. **1** illustrates a first exemplary turbine rotor assembly **10**. The turbine rotor assembly **10** may be used in a turbocharger in an internal combustion engine to increase engine power and efficiency. The internal combustion engine may be any type of engine, for example, a diesel engine, a gasoline engine or a gaseous-fuel-driven engine. The internal combustion engine may be associated with a fixed or mobile machine. Such machines may include, for example, an earth moving machine such as an excavator, a dozer, a loader, a backhoe loader, a motor grader, a dump truck, any other earth moving machines or a ship.

[0017] As shown in FIG. **1**, the turbine rotor assembly **10** may include a rotor shaft **12** extending along a central axis A between a first end **16** and a second end **18**, and a turbine rotor wheel **20** joined to the second end **18** of the rotor shaft **12**. FIG. **1** shows a longitudinal partial cross-sectional view of the rotor shaft **12** and the turbine rotor wheel **20** prior to the two members being joined together to form the turbine rotor assembly **10**. The turbine rotor wheel **20** may include a hub portion **22** extending along a central axis B and a plurality of vanes **24** extending radially and outwardly from the hub portion **22**. The second end **18** of the rotor shaft **12** may include an end surface **26**. The hub portion **22** may include an end surface **28**.

[0018] In one embodiment, the rotor shaft **12** may be made from a titanium alloy, for example, alpha and near alpha alloys, alpha-beta alloys, or unalloyed titanium. Some examples of the alpha-beta alloys may include Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-6Al-2Sn-4Zr-6Mo, etc. The turbine rotor wheel **20** may be made from a titanium aluminide intermetallic alloy. Titanium aluminide intermetallic alloys may include TiAl or Ti_3Al intermetallic compound-based alloys, for example, Ti-45Al-2Nb-2Cr, Ti-47Al-2Nb-2Cr, or Ti-48Al-2Nb-0.7Cr-0.3Si, etc. Titanium aluminide intermetallic compound-based alloys may be solid state solutions that may have Nb, Cr, Si or other solute atoms randomly distributed in the solvent, namely, titanium aluminide intermetallic compound, in which Ti and Al atoms may form a long-range ordered crystal structure. The rotor shaft **12** may be made from a titanium (Ti) alloy. Ti alloys may be solid solutions that have Al, V, and other solute atoms randomly distributed in the Ti solvent. The rotor shaft **12** may define a cavity **30** extending along the central axis A at the second end **18**. In one embodiment, the cavity **30** may have a circular cross-section. The cavity **30** may employ any other configuration.

[0019] As shown in FIG. **3**, the hub portion **22** of the turbine rotor wheel **20** may be coaxially aligned with the rotor shaft **12**, and the end surface **28** of the hub portion **22** may be bonded to the end surface **26** of the rotor shaft **12** by a rotary friction welding process, which will be described in detail below. During the rotary friction welding process, the end surface **28** and the end surface **26** may plastically deform and some material may flow into the cavity **30**.

[0020] FIG. **2** shows another embodiment **100** of the turbine rotor assembly. The turbine rotor assembly **100** may include a rotor shaft **42**, which may include a first section **44** and a second section **50**, and a turbine rotor wheel **60**. The first section **44** may be a shaft portion extending along a central axis A' between a first end **46** and a second end **48**. The second section **50** may be an intermediate portion **50** extending along a central axis C' between a first end **52** and a second end **54**. FIG. **2** shows the shaft portion **44**, the intermediate portion **50**, and the turbine rotor wheel **60** prior to these members being joined together to form the turbine rotor assembly **100**. The turbine rotor wheel **60** may include a hub portion **62** extending along a central axis B' and a plurality of vanes **64** extending radially and outwardly from the hub portion **62**.

[0021] The hub portion **62**, the intermediate portion **50**, and the shaft portion **44** may be coaxially aligned. The hub portion **62** of the turbine rotor wheel **60** may be bonded to the second end **54** of the intermediate portion **50**, and the first end **52** of the intermediate portion **50** may be coupled to the second end **48** of the shaft portion **44**.

[0022] In one embodiment, the shaft portion **44** may be made from a metal, for example, steel. The intermediate portion **50** may be made from a titanium alloy, for example, alpha and near alpha alloys, alpha-beta alloys, or unalloyed titanium. Some examples of the alpha-beta alloys may include Ti-6Al-4V, Ti-6Al-6V-2Sn, and Ti-6Al-2Sn-4Zr-6Mo, etc. The turbine rotor wheel **60** may be made from a titanium aluminide intermetallic alloy, for example, Ti-45Al-2Nb-2Cr, Ti-47Al-2Nb-2Cr, or Ti-48Al-2Nb-0.7Cr-0.3Si, etc. The intermediate portion **50** may define a cavity **70** extending along the central axis C' at the second end **54** of the intermediate portion **50**. Similar to, the above-described embodiment shown in FIG. **1**, the cavity **70** may employ different configurations.

[0023] As shown in FIG. **4**, the turbine rotor wheel **60** may be bonded to the second end **54** of the intermediate portion **50** by a friction welding process which will be described in detail below. During the friction welding process, the hub portion **62** and the second end **54** may plastically deform and some material may flow into the cavity **70**. The intermediate portion **50** may be coupled to the shaft portion **44** by thread, welding, brazing, or other mechanisms. The welding process of intermediate portion **50** to the shaft portion **44** may include friction welding, laser welding, electron beam welding (EBW) (which is a fusion bonding process that produces a weld by impinging a beam of high energy electrons to heat the welding joint), or other welding methods.

INDUSTRIAL APPLICABILITY

[0024] The disclosed friction welding method may be used to bond a material made from a titanium aluminide intermetallic alloy to another material that may be made from a titanium alloy. Particularly, the disclosed friction welding method may be used to bond a TiAl turbine rotor wheel to a turbine rotor shaft to form a turbine rotor assembly used in, for example, a turbocharger. The turbocharger can be used in an engine system to improve transient response and thermal efficiency of the engine.

[0025] Bonding processes that involves very high temperatures may produce large temperature gradient near the bonding region and may cause high local thermal stresses in the joining region. TiAl intermetallic materials have limited ductility, and therefore, are prone to crack during or after the bonding process. In some applications, e.g. turbine wheel, the high local thermal stress near the joining region could be further enhanced because of specific component geometry or large component size, which poses a great challenge to the joining process. Preheating the TiAl intermetallic material to a predetermined temperature, e.g. 600° C., combined with the specified set of welding conditions as described in this disclosure, can decrease thermal stresses and, therefore, avoid cracking. In addition, the specified set of welding conditions with preheating as disclosed in this disclosure can minimize excessive diffusion/reaction, reduce the formation of brittle intermetallic phases at the interface and therefore, produce superior joining properties. The disclosed friction welding method can be used in turbine applications as well as large valve applications (for example, more than four inches (10.16 cm) in valve head diameter), where high local thermal stresses may be encountered because of special geometry or larger size.

[0026] An exemplary welding process for bonding a turbine rotor wheel **20** to a rotor shaft **12** to form a turbine rotor assembly **10** as shown in FIG. **5** is described in detail below. At step **102**, a first material made from a titanium aluminide intermetallic alloy and a second material made from a titanium alloy are provided. In an exemplary embodiment, the first material may be the turbine rotor wheel **20** made from the titanium aluminide intermetallic alloy, and the second material may be a section of a turbine rotor shaft **12**, for example, an intermediate portion **50**. At step **104**, the TiAl turbine rotor wheel **20** may be preheated to a predetermined temperature, for example, at least about 300° C. In one embodiment, the TiAl turbine rotor wheel **20** may be preheated to a temperature in a range from about 300° C. to about 800° C. In another embodiment, the TiAl turbine rotor wheel **20** may be preheated to a temperature in a range from about 400° C. to about 650° C. Then, the TiAl turbine rotor wheel **20** and the rotor shaft **12** may be bonded by a rotary friction welding process.

[0027] The rotary friction welding may include two stages, a friction stage at steps **106**, **108**, and **110** and a forging stage at step **112**. In the friction stage at the step **106**, the rotor shaft **12** may be held by a chuck in a rotating machine, and the turbine rotor wheel **20** may be held by a chuck in a machine that may hold the turbine rotor wheel **20** in a stationary manner and that may linearly move the turbine rotor wheel **20** along the central axis. The hub portion **22** of the turbine rotor wheel **20** and the rotor shaft **12** may be coaxially aligned, with the hub portion **22** facing the second end **18** of the rotor shaft **12**. While the rotor shaft **12** held by the rotating chuck is rotated at a high speed, the turbine rotor wheel **20** held by the chuck may be moved toward the rotor shaft **12**, and the hub portion **22** of the turbine rotor wheel **20** may be pressed onto the second end **18** of the rotor shaft **12** at a predetermined friction pressure for a predetermined time duration at the step **108**. The time duration may also be expressed in burn-off distance which may vary with the alloy used.

[0028] In one embodiment, in the friction stage, the rotor shaft **12** may be rotated at a predetermined rotational speed, for example, 800 revolutions per minute (rpm). The rotational speed may also correspond to a linear speed between about 0.3 m/s and about 5 m/s at the outer circumference of the hub portion **22**. The turbine rotor wheel **20** and the rotor shaft **12** may be pressed against each other at a predetermined pressure, for example, about 10 megapascal (MPa) to 200 MPa for a predetermined time, for example, about 5 to 60 seconds. In another embodiment, the friction stage may include two sub-stages. In the first sub-stage, the turbine rotor wheel **20** and the rotor shaft **12** may be pressed against each other by a first predetermined pressure, for example, about 20 MPa to 60 MPa for about 5 to 30 seconds. In the second sub-stage, the turbine rotor wheel **20** and the rotor shaft **12** may pressed against each other by a second predetermined pressure of about 50 MPa to 200 MPa for about 0.5 to 5 seconds. The pressure and time may be different according to the size, weight and shape of the turbine rotor wheel **20** and the preheat temperature of the turbine rotor wheel **20** before the rotary friction welding process. The rotating chuck may be then rapidly braked to stop the rotation of the rotor shaft **12** at step **110**.

[0029] The forging stage may start after the rotation of the rotor shaft **12** is stopped. In the forging stage at the step **112**, the two end surfaces **26** and **28** may be pressed against each other firmly by a predetermined forge pressure, for example, at least about 200 MPa, for a predetermined time duration depends on component size, for example, about 5 to 60 seconds.

[0030] In the friction stage, the friction between the end surfaces **26** and **28** may generate heat, and the end surface **28** of the hub portion **22** of the turbine rotor wheel **20** and the end surface **26** of the second end **18** of the rotor shaft **12** may plastically deform. In both the friction stage and the forge stage, materials from the hub portion **22** and the second end **18** may flow into the cavity **30** and at least partially fill the cavity **30**. The cavity **30** may help to reduce the probability of thermal cracking because the temperature gradient in radial direction may be reduced as the center part generally has a low linear speed and therefore may be heated up slower by friction than the outer circumference. The cavity **30** may also increase joint properties because it may reduce the thickness of diffusion/reaction layer, which can minimize the formation of intermetallic phases. The arrangement of the cavity **30** may also reduce burrs generated at the outer circumference of the rotor shaft **12** and the hub portion **22** during the process of welding the second end **18** of the rotor shaft **12** with the hub portion **22** of the turbine rotor wheel **20**, and therefore, it may also reduce the mechanical work needed to remove the burrs afterwards.

[0031] In one embodiment, the bonded portion of the turbine rotor assembly **10** may be provided with a post-weld heat treatment to release stress generated in the friction welding process in the bonded portion. For example, the bonded portion of the turbine rotor assembly **10** may be heated to a predetermined temperature, for example, about 400° C., to release stress generated during the friction welding process.

[0032] The exemplary turbine rotor assembly **100** as shown in FIG. **2** can be formed by a welding process described in detail below. The hub portion **62** of the TiAl turbine rotor wheel **60** may be preheated to a predetermined temperature at the step **104**, for example, at least about 300° C. In one embodiment, the TiAl turbine rotor wheel **60** may be preheated to a temperature in a range from about 300° C. to about 800° C. In another embodiment, the TiAl turbine rotor wheel **60** may be preheated to a temperature in a range from about 400° C. to about 650° C. Then, the TiAl turbine rotor wheel **60** and the intermediate portion **50** may be bonded by a rotary friction welding process, which can be similar or identical to the process of bonding the TiAl turbine rotor wheel **20** to the rotor shaft **12** as described above from the step **106** to the step **112**. In one embodiment, after the TiAl turbine rotor wheel **60** is bonded to the intermediate portion **50**, the first end **52** of the intermediate portion **50** may be then coupled to the second end **48** of the shaft portion **44**. In another embodiment, the intermediate portion **50** may be bonded to the shaft portion **44** first, and then the intermediate portion **50** is bonded to the turbine rotor wheel **60**. The intermediate portion **50** may be coupled to the shaft portion **44** by thread, welding, brazing, or other mechanisms. The welding process for bonding the intermediate portion **50** to the shaft portion **44** may include friction welding, laser welding, electron beam welding (EBW), or other welding methods.

[0033] Several advantages over the prior art may be associated with the method of bonding a first material made from a titanium aluminide intermetallic alloy to a second material made from a titanium alloy by friction welding described in the subject application. It can be used successfully on turbine applications as well as large-scale valve applications. The arrangement may avoid cracking in the joint or in the titanium aluminide intermetallic alloy component caused by excessive local thermal stress. The disclosed method may also provide successful friction welding on applications with special geometry. The method may utilize specified sets of welding conditions as disclosed above designed to work with preheating to minimize the formation of brittle intermetallic phases in order to provide superior joint quality. It may also avoid damaging the titanium aluminide intermetallic alloy component, increase operation robustness and reduce production cost by limiting the preheating temperature to a predetermined temperature range, for example, below about 800° C. Furthermore, the arrangement of the cavity at the end of the rotor shaft or the intermediate portion to be bonded to the turbine rotor wheel may increase joint properties effectively and may reduce the mechanical work needed to remove burrs generated in welding the turbine rotor wheel with the rotor shaft.

[0034] It will be apparent to those skilled in the art that various modifications and variations can be made to the friction welding method. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosed friction welding method. It is intended that the specification and examples be considered as exemplary only, with a true scope being indicated by the following claims and their equivalents.

What is claimed is:

1. A method of bonding two materials comprising:

providing a first material made from a titanium aluminide intermetallic alloy and a second material made from a titanium alloy;

heating the first material to a temperature between about 300° C. and about 800° C.;

rotating the second material relative to the first material;

pressing the first material and the second material against each other while rotating one of the first material and the second material;

stopping the rotation of one of the first material and the second material; and

pressing the first material and the second material against each other after stopping the rotation of one of the first material and the second material.

2. The method of claim **1**, wherein the temperature is between about 400° C. and 650° C.

3. The method of claim **1**, wherein pressing the first material and the second material against each other while rotating one of the first material and the second material includes pressing the first material and the second material against each other at a pressure of about 10 MPa to 200 MPa for about 5 to 60 seconds.

4. The method of claim **1**, wherein pressing the first material and the second material against each other while rotating one of the first material and the second material includes:

pressing the first material and the second material against each other at a first pressure for a first time period; and

pressing the first material and the second material against each other at a second pressure for a second time period, the second pressure being different from the first pressure.

5. The method of claim **4**, wherein the first pressure is about 20 MPa to 60 MPa, and the first time period is about 5 to 30 seconds, and the second pressure is about 50 MPa to 200 MPa, and the second time period is about 0.5 to 5 seconds.

6. The method of claim **1**, wherein pressing the first material and the second material against each other after stopping the rotation of one of the first material and the second material includes pressing the first material and the second material against each other at a pressure of about 200 MPa or greater for about 5 to 60 seconds after stopping the rotation of one of the first material and the second material.

7. The method of claim **1**, wherein providing a second material made from a titanium alloy includes providing a second material having a cavity at an end of the second material.

8. The method of claim **1**, wherein providing a first material made from a titanium aluminide intermetallic alloy includes providing a turbine rotor wheel made from the titanium aluminide intermetallic alloy, and wherein providing a second material made from a titanium alloy includes providing a rotor shaft made from the titanium alloy.

9. The method of claim **1**, wherein providing a first material made from a titanium aluminide intermetallic alloy includes providing a turbine rotor wheel made from the titanium aluminide intermetallic alloy, and wherein providing a second material made from a titanium alloy includes providing a section of a turbine rotor shaft, and wherein the section is made from the titanium alloy.

10. The method of claim **1**, wherein providing a first material made from a titanium aluminide intermetallic alloy includes providing a valve head having a diameter of about four inches (10.16 cm) or greater.

11. A method of producing a turbine rotor assembly comprising:

heating a turbine rotor wheel to a temperature between about 300° C. and about 800° C., wherein the turbine rotor wheel is made from a titanium aluminide intermetallic alloy;

rotating a turbine rotor shaft relative to the turbine rotor wheel;

pressing the turbine rotor shaft against the turbine rotor wheel while rotating the turbine rotor shaft;

stopping the rotation of the turbine rotor shaft; and

pressing the turbine rotor shaft against the turbine rotor wheel after stopping the rotation of the turbine rotor shaft.

12. The method of claim **11**, wherein the turbine rotor shaft is made from a titanium alloy.

13. The method of claim **12**, wherein the turbine rotor shaft includes a cavity at an end to be bonded to the turbine rotor wheel.

14. The method of claim **11**, wherein the turbine rotor shaft includes a section to be bonded to the turbine rotor wheel, the section being made from a titanium alloy.

15. The method of claim **14**, wherein the section of the turbine rotor shaft includes a cavity at an end to be bonded to the turbine rotor wheel.

16. The method of claim **11**, wherein the temperature is between about 400° C. and 650° C.

17. The method of claim **11**, wherein pressing the turbine rotor shaft against the turbine rotor wheel while rotating the turbine rotor shaft includes pressing the turbine rotor shaft and the turbine rotor wheel against each other at a pressure of about 10 MPa to 200 MPa for about 5 to 60 seconds.

18. An assembly made by a friction welding process comprising:

a first material; and

a second material,

wherein at least one of the first material and the second material includes a cavity at an end of the at least one of the first material and the second material to be coupled to the other material, the cavity being at least partially filled with at least one of the first material and the second material as a result of the friction welding process.

19. The assembly of claim **18**, wherein the first material includes a turbine rotor wheel made from a titanium aluminide intermetallic alloy.

20. The assembly of claim **18**, wherein the second material includes a turbine rotor shaft having at least a section made from a titanium alloy.

* * * * *