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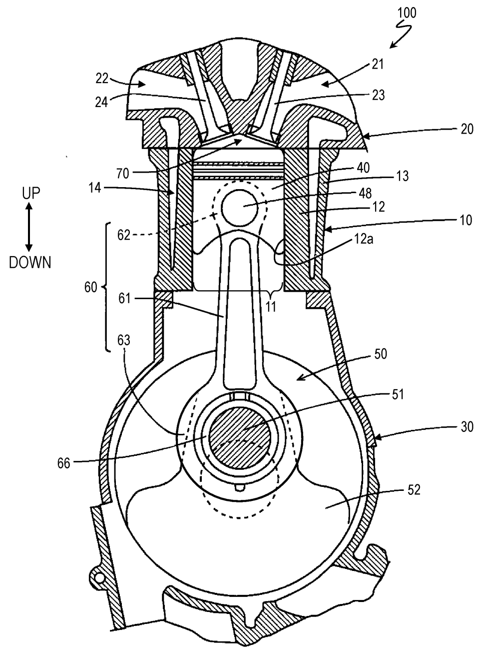
(54) INTERNAL COMBUSTION ENGINE AND TRANSPORTATION DEVICE

(57) An internal combustion engine **(100)** includes a piston **(40)** formed of an aluminum alloy; and a cylinder block **(10)** including a cylinder wall **12** including a sliding surface **(12a),** along which the piston is slidable. The cylinder block is formed of an aluminum alloy containing silicon, and includes a plurality of primary-crystal silicon grains **(2)** at the sliding surface. The sliding surface has a ten-point average surface roughness Rz_{JIS} of 0.5 μm or smaller, and the plurality of primary-crystal silicon grains at the sliding surface have a crushing ratio of 200 or lower.

FIG.1



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Description

TECHNICAL FIELD

[0001] The present disclosure relates to an internal combustion engine, and specifically to an internal combustion engine including a cylinder block formed of an aluminum alloy containing silicon, and also relates to a transportation vehicle including such an internal combustion engine.

BACKGROUND ART

[0002] Recently, for the purpose of reducing the weight of an internal combustion engine, an aluminum alloy has been used more and more widely to form cylinder blocks. Cylinder blocks are required to have a high wear resistance. Therefore, an aluminum alloy containing a high content of silicon, namely, an aluminum-silicon-based alloy having a hyper eutectic composition is considered promising as an aluminum alloy for cylinder blocks. In a cylinder block formed of an aluminum-silicon-based alloy, silicon crystal grains located at a sliding surface contribute to improvement in the wear resistance. Such a cylinder block formed of an aluminum-silicon-based alloy is disclosed in, for example, Patent Document No. 1.

[0003] In order to improve the wear resistance or the seizure resistance of the cylinder block, a mesh-like groove referred to as a cross hatch is generally formed in a surface of a cylinder wall defining a cylinder bore. Oil (lubricant oil) is retained in the cross hatch, and thus a state where the cylinder wall and a piston skirt or a piston ring operate smoothly with respect to each other may be kept. This may suppress wear and seizure.

CITATION LIST

PATENT LITERATURE

[0004] Patent Document No. 1: WO2004/002658

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0005] However, projected and recessed portions caused at the surface of the cylinder wall during the formation of the cross hatch prevents an oil film to be formed uniformly. This partially ruptures the oil film and thus increases the friction resistance. In addition, the oil retained in the cross hatch remains in the surface of the cylinder wall without being scraped off, and is exposed to high temperature combustion gas to evaporate or combust and thus is discharged as exhaust gas. This increases the consumption amount of the oil, which progressively deteriorates performance of a catalyst.

[0006] An embodiment of the present invention made in light of the above-described problems has an object of, in an internal combustion engine including a cylinder block formed of an aluminum alloy containing silicon, decreasing the friction resistance of a cylinder wall and the consumption amount of oil while providing a certain level of seizure resistance with certainty.

SOLUTION TO PROBLEM

[0007] This specification discloses the internal combustion engine and the transportation vehicle described in the following items.

[Item 1]

An internal combustion engine, including:

a piston formed of an aluminum alloy; and
a cylinder block including a cylinder wall including a sliding surface, along which the piston is slidable;
wherein the cylinder block is formed of an aluminum alloy containing silicon, and includes a plurality of primary-crystal silicon grains at the sliding surface;
wherein the sliding surface has a ten-point average surface roughness Rz_{JIS} of 0.5 μm or smaller, and
wherein the plurality of primary-crystal silicon grains at the sliding surface have a crushing ratio of 200 or lower.

[0008] In the engine according to an embodiment of the present invention, the ten-point average surface roughness

Rz_{JIS} of the sliding surface of the cylinder wall is 0.5 μm or smaller. Namely, the sliding surface has projected and recessed portions that are sufficiently small to cause the sliding surface to be considered as being mirror-finished. Therefore, a uniform oil film is formed at the sliding surface, which may decrease the friction resistance. This may decrease the sliding loss and improve the fuel efficiency. In addition, oil (lubricant oil) remaining in the surface of the cylinder wall is decreased in the amount as a result of being scraped off by a piston ring. This decreases the consumption amount of the oil and suppresses deterioration in performance of a catalyst. Furthermore, the small size of the projected and recessed portions at the sliding surface decreases aggressiveness of the cylinder wall to other members (aggressiveness to piston rings and a piston skirt).

[0009] There is a concern that when the surface roughness of the sliding surface is decreased, the amount of the oil retained in the sliding surface may be decreased and thus the seizure resistance may be decreased. However, in the engine according to an embodiment of the present invention, the primary-crystal silicon grains, which are highly hard, are present at the sliding surface. Therefore, the surface pressure applied to an alloy substrate (matrix) is decreased, and thus a sufficient level of seizure resistance may be guaranteed. A groove such as a cross hatch is not necessary, and thus the oil may be prevented from escaping into the groove. Therefore, the oil film has a higher pressure and a fluid lubrication state is preferably realized. This also guarantees a certain level of seizure resistance.

[0010] In the engine according to an embodiment of the present invention, the crushing ratio of the primary-crystal silicon grains at the sliding surface of the cylinder wall is 200 or lower. Therefore, a large number of the primary-crystal silicon grains that are not crushed (that may be considered "healthy") are exposed at the sliding surface. This also decreases the aggressiveness to the other members. In addition, the contact load with the piston skirt and the piston rings is dispersed in the exposed healthy primary-crystal silicon grains, which improves the seizure resistance and the wear resistance of the cylinder wall.

[Item 2]

[0011] The internal combustion engine of item 1, wherein the sliding surface has an arithmetic average roughness Ra that is smaller than 0.05 μm.

[0012] In the case where the arithmetic average roughness Ra of the sliding surface of the cylinder wall is smaller than 0.05 μm, the projected and recessed portions at the sliding surface are small. Therefore, a uniform oil film is formed at the sliding surface, which may decrease the friction resistance. This may decrease the sliding loss and improve the fuel efficiency. In addition, the oil remaining in the surface of the cylinder wall is decreased in the amount as a result of being scraped off by the piston ring. This decreases the consumption amount of the oil and suppresses deterioration in performance of a catalyst. Furthermore, the small size of the projected and recessed portions at the sliding surface decreases the aggressiveness of the cylinder wall to the other members (aggressiveness to the piston rings and the piston skirt).

[Item 3]

[0013] The internal combustion engine of item 1 or 2, wherein the plurality of primary-crystal silicon grains have an area size occupying a ratio of 8% or higher of an area size of the sliding surface.

[0014] In the case where the ratio of the area size occupied by the primary-crystal silicon grains with respect to the area size of the sliding surface is 8% or higher, the surface pressure applied to the alloy substrate is decreased, which improves the seizure resistance and the wear resistance.

[Item 4]

[0015] The internal combustion engine of any one of items 1 through 3, wherein where the sliding surface is divided into a plurality of grids each having a size of 0.1 mm × 0.1 mm and the ratio of the number of grids where no primary-crystal silicon grain is present with respect to the total number of the grids is referred to as a "blank ratio", the blank ratio is 55.5% or lower.

[0016] The "blank ratio" is an index indicating how the primary-crystal silicon grains are dispersed. A lower blank ratio indicates that the primary-crystal silicon grains are better dispersed. In the case where the blank ratio of the sliding surface is 55.5% or lower, the surface pressure applied to the alloy substrate is sufficiently decreased. Therefore, the seizure resistance and the wear resistance are improved.

[Item 5]

[0017] The internal combustion engine of any one of items 1 through 4, wherein the cylinder block is formed of an aluminum alloy containing silicon at a content of 15% by mass or higher and 25% by mass or lower.

[0018] From the point of view of sufficiently improving the wear resistance and the strength of the cylinder block, the aluminum alloy as the material of the cylinder block preferably contains silicon at a content of 15% by mass or higher and 25% by mass or lower. In the case where the silicon content is 15% by mass or higher, a sufficiently large amount of the primary-crystal silicon grains may be deposited, which may sufficiently improve the wear resistance of the cylinder block. In the case where the silicon content is 25% by mass or lower, the strength of the cylinder block may be kept sufficiently high.

[Item 6]

[0019] The internal combustion engine of any one of items 1 through 5, wherein the plurality of primary-crystal silicon grains have an average grain diameter of 8 μm or longer and 50 μm or shorter.
[0020] The primary-crystal silicon grains have an average grain diameter in the range of 8 μm or longer and 50 μm or shorter. In this case, the wear resistance of the cylinder block may be further improved.
[0021] In the case where the average grain diameter of the primary-crystal silicon grains is longer than 50 μm, the number of the primary-crystal silicon grains per unit area size of the sliding surface is small. Therefore, a large load is applied to each of the primary-crystal silicon grains while the engine is operated, and the primary-crystal silicon grains may possibly be crushed. The crushed pieces of the primary-crystal silicon grains act undesirably as polishing particles, which causes a risk that the sliding surface is significantly worn.
[0022] In the case where the average grain diameter of the primary-crystal silicon grains is shorter than 8 μm, merely a small part of the primary-crystal silicon grains is embedded in the matrix. Therefore, the primary-crystal silicon grains easily fall while the engine is operated. The primary-crystal silicon grains that have fallen act undesirably as polishing particles, which causes a risk that the sliding surface is significantly worn.
[0023] By contrast, in the case where the average grain diameter of the primary-crystal silicon grains is 8 μm or longer and 50 μm or shorter, the primary-crystal silicon grains are present in a sufficient number per unit area size of the sliding surface. Therefore, the load applied to each of the primary-crystal silicon grains while the engine is operated is relatively small, which suppresses the crushing of the primary-crystal silicon grains. Since the part of the primary-crystal silicon grains that is embedded in the matrix is sufficiently large, the fall of the primary-crystal silicon grains is suppressed. Therefore, the wear of the sliding surface by the primary-crystal silicon grains that have fallen is suppressed.

[Item 7]

[0024] The internal combustion engine of any one of items 1 through 6,

wherein the piston includes a piston main body and a plurality of piston rings attached to an outer circumferential portion of the piston main body, and
wherein each of the plurality of piston rings includes a diamond-like carbon layer on an outer circumferential portion thereof.

[0025] In the case where each of the plurality of piston rings includes the diamond-like carbon layer on the outer circumferential portion thereof, the cylinder wall may be prevented with more certainty from being scuffed by the piston rings.

[Item 8]

[0026] The internal combustion engine of any one of items 1 through 7,

wherein the piston includes a piston head and a piston skirt extending from an outer circumferential portion of the piston head, and
wherein the piston skirt includes a resin layer or a plating layer formed on at least a part of an outer circumferential surface thereof.

[0027] In the case where the piston skirt includes the resin layer or the plating layer formed on at least a part of the outer circumferential surface thereof, the wear resistance and the seizure resistance of the piston may be improved.

[Item 9]

[0028] A transportation vehicle, comprising the internal combustion engine of any one of items 1 through 8.
[0029] The internal combustion engine according to an embodiment of the present invention is preferably usable in

any of various types of transportation vehicles.

ADVANTAGEOUS EFFECTS OF INVENTION

[0030] According to an embodiment of the present invention, in an internal combustion engine including a cylinder block formed of an aluminum alloy containing silicon, the friction resistance of a cylinder wall and the consumption amount of oil may be decreased while a certain level of seizure resistance is provided with certainty.

BRIEF DESCRIPTION OF DRAWINGS

[0031]

FIG. **1** is a cross-sectional view schematically showing an engine (internal combustion engine) **100** according to an embodiment of the present invention.
FIG. **2** is a side view schematically showing a piston **40** included in the engine **100.**
FIG. **3** is a perspective view schematically showing a cylinder block **10** included in the engine **100.**
FIG. **4** is a cross-sectional view schematically showing a sliding surface **12a** of a cylinder wall **12** and the vicinity thereof.
FIG. **5** shows an example of image of the sliding surface **12a.**
FIG. **6** is a view provided to illustrate the definition of a blank ratio of the sliding surface **12a.**
FIG. **7** is a cross-sectional view schematically showing a piston ring **42** of the piston **40.**
FIG. **8** is a cross-sectional view schematically showing a piston skirt **44** of the piston **40.**
FIG. **9** is a flowchart showing production steps of the cylinder block **10.**
FIG. **10** is a flowchart showing production steps of the cylinder block **10.**
FIG. **11** is a graph showing the relationship between the grit size of the whetstone and the crushing ratio of the primary-crystal silicon grains.
FIG. **12** is a graph showing a roughness curve of a sliding surface in comparative example 1.
FIG. **13** is a graph showing a roughness curve of the sliding surface **12a** in example 1.
FIG. **14** is a graph showing the consumption amount of oil measured by an extraction method in each of comparative example 1 and example 1.
FIG. **15A** is a schematic view showing how oil **OL** is scraped off by a piston ring **42** at a sliding surface **12a'** of a cylinder wall **12'** included in an engine in comparative example 1.
FIG. **15B** is a schematic view showing how oil **OL** is scraped off by the piston ring **42** at the sliding surface **12a** of the cylinder wall **12** included in the engine in example 1.
FIG. **16** is a graph showing results of measurement of the friction mean effective pressure (FMEP) in each of examples 2 through 5.
FIG. **17** is a graph showing FMEP decreasing ratios in each of examples 2 and 3 at rotation rates of the engine of 4400 rpm, 4800 rpm and 5200 rpm.
FIG. **18** is a graph showing results of measurement of the FMEP performed in repetition in example 6.
FIG. **19** is a graph showing results of measurement of the FMEP performed in repetition in comparative example 2.
FIG. **20** is a graph showing a change in the height of wear of a barrel-type test piece along time in an SRV test performed in each of example 7 and comparative example 3.
FIG. **21** is a graph showing a change in the height of wear of a cylinder test piece along time in an SRV test performed in each of example 7 and comparative example 3.
FIG. **22** is a graph showing the time period from the start of operation of the engine until seizure of the piston and the cylinder occurs in each of example 7 and comparative example 3.
FIG. **23** is a side view schematically showing an automatic two-wheeled vehicle **300** including the engine **100.**

DESCRIPTION OF EMBODIMENTS

[0032] Hereinafter, an embodiment of the present invention will be described with reference to the drawings. While a water-cooled engine will be described as an example below, the engine according to an embodiment of the present invention is not limited to being of a water-cooled type and may be of an air-cooled type. While a single-cylinder engine will be described as an example below, there is no specific limitation on the number of the cylinders in the engine.

[Structure of the engine]

[0033] FIG. **1** shows an engine (internal combustion engine) **100** according to an embodiment of the present invention.

FIG. **1** is a cross-sectional view schematically showing the engine **100.**

[0034] As shown in FIG. **1,** the engine **100** includes a cylinder block **10,** a cylinder head **20,** and a crankcase **30.** The engine **100** further includes a piston **40,** a crankshaft **50,** and a con rod (connecting rod) **60.** The following description will be made with settings that a direction from the cylinder block **10** toward the cylinder head **20** is an "upward direction" and a direction from the cylinder block **10** toward the crankcase **30** is a "downward direction".

[0035] The cylinder block (may also be referred to as a "cylinder body") **10** includes a cylinder wall **12** and an outer wall **13.** The cylinder wall **12** is formed to define a cylinder bore **11.** The outer wall **13** surrounds the cylinder wall **12** and forms an outer enclosure of the cylinder block **10.** A water jacket **14** holding cooling water is provided between the cylinder wall **12** and the outer wall **13.**

[0036] The cylinder head **20** is provided above the cylinder block **10.** The cylinder head **20** defines a combustion chamber **70** together with the cylinder wall **12** and the piston **40.** The cylinder head **20** includes an intake port **21,** through which fuel is to be introduced into the combustion chamber **70,** and an exhaust port **22,** through which exhaust gas is to be discharged from the combustion chamber **70.** An intake valve **23** is provided in the intake port **21,** and an exhaust valve **24** is provided in the exhaust port **22.**

[0037] The crankcase **30** is provided below the cylinder block **10.** Namely, the crankcase **30** is located so as to be on the side opposite to the cylinder head **20** with the cylinder block **10** being located therebetween. The crankcase **30** may be separate from, or may be integrally formed with, the cylinder block **10.**

[0038] The piston **40** is accommodated in the cylinder bore **11.** In this embodiment, no cylinder sleeve is fit into the cylinder bore **11.** Therefore, the piston **40** moves up and down in a reciprocating manner in the cylinder bore **11** while being in contact with an inner circumferential surface (cylinder bore **11**-side surface) **12a** of the cylinder wall **12.** Namely, the inner circumferential surface **12a** of the cylinder wall **12** is a sliding surface along which the piston **40** is slidable.

[0039] The crankshaft **50** is accommodated in the crankcase **30.** The crankshaft **50** includes a crankpin **51** and a crank arm **52.**

[0040] The con rod **60** includes a rod main body **61** having a rod-like shape, a small end portion **62** provided at one end of the rod main body **61,** and a large end portion **63** provided at the other end of the rod main body **61.** The con rod **60** connects the piston **40** and the crankshaft **50** to each other. Specifically, a piston pin **48** of the piston **40** is inserted into a through-hole (piston pin hole) of the small end portion **62,** and the crankpin **51** of the crankshaft **50** is inserted into a through-hole (crankpin hole) of the large end portion **63.** This structure connects the piston **40** and the crankshaft **50** to each other. A bearing **66** is provided between an inner circumferential surface of the large end portion **63** and the crankpin **51.**

[0041] FIG. **2** is a side view schematically showing the piston **40** of the engine **100.** In this embodiment, the piston **40** (more specifically, a piston main body **41** described below) is formed of an aluminum alloy. The piston **40** may be formed by forging or casting. As shown in FIG. **2,** the piston **40** includes the piston main body **41** and a plurality of piston rings **42.** The piston main body **41** includes a piston head **43** and a piston skirt **44.**

[0042] The piston head **43** is located at a top end of the piston **40.** Ring grooves holding the piston rings **42** are formed in an outer circumferential portion of the piston head **43.** The piston skirt **44** extends downward from the outer circumferential portion of the piston head **43.**

[0043] The piston rings **42** are attached to an outer circumferential portion of the piston main body **41,** more specifically, to the outer circumferential portion of the piston head **43.** In this embodiment, the piston **40** includes three piston rings **42.** The number of the piston rings **42** is not limited to three. Among the three piston rings **42,** the piston rings at a top position and at a central position (a top ring and a second ring) **42a** and **42b,** for example, are compression rings that keep the combustion chamber **70** in an airtight state. The piston ring at a bottom position (third ring) **42c** is an oil ring that scrapes off extra oil attached to the cylinder wall **12.** The piston rings **42** are formed of a metal material (e.g., steel).

[0044] FIG. **3** is a perspective view schematically showing the cylinder block **10** of the engine **100.** As described above, the cylinder block **10** includes the cylinder wall **12** including the sliding surface **12a,** and the outer wall **13.** The water jacket **14** is provided between the cylinder wall **12** and the outer wall **13.** In this embodiment, the cylinder block **10** is formed of an aluminum alloy containing silicon. More specifically, the cylinder block **10** is formed of an aluminum-silicon-based alloy having a hyper eutectic composition.

[0045] FIG. **4** is a cross-sectional view schematically showing the sliding surface **12a** of the cylinder wall **12** and the vicinity thereof. As shown in FIG. **4,** the cylinder wall **12** of the cylinder block **10** includes an aluminum-containing solid-solution matrix (alloy substrate) **1** and a plurality of primary-crystal silicon grains **2** dispersed in the matrix **1.** Some of the primary-crystal silicon grains **2** are exposed to the sliding surface **12a.** Namely, the cylinder block **10** includes the primary-crystal silicon grains **2** at the sliding surface **12a.**

[0046] Although not shown, the cylinder wall **12** further includes a plurality of eutectic silicon grains dispersed in the matrix **1.** Therefore, the cylinder block **10** may further include the eutectic silicon grains at the sliding surface **12a.** When a molten aluminum-silicon-based alloy having a hyper eutectic composition is cooled, relatively large silicon crystal grains are deposited first and then relatively small silicon crystal grains are deposited. The relatively large silicon crystal grains are the "primary-crystal silicon grains", and the relatively small silicon crystal grains are the "eutectic silicon grains".

[0047] In this embodiment, the cylinder block **10** is formed such that the sliding surface **12a** has a ten-point average surface roughness Rz_{JIS} in a predetermined range. Specifically, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** is 0.5 μm or smaller in generally the entirety of the sliding surface **12a.**

[0048] As represented by the following expression, the ten-point average surface roughness Rz_{JIS} is of a certain reference length of a profile curve, and is a difference between an average value of elevations of the highest peak through the fifth highest peak R1, R3, R5, R7 and R9, and an average value of elevations of the lowest trough through the fifth lowest trough R2, R4, R6, R8 and R10. The ten-point average surface roughness Rz_{JIS} may be measured by use of a surface roughness meter (e.g., Surfcom 1400D produced by Tokyo Seimitsu Co., Ltd.).

[Expression 1]

$$Rz_{JIS} = \{(R1+R2+R3+R4+R5) - (R2+R4+R6+R8+R10)\}/5$$

[0049] In this embodiment, the cylinder block **10** is formed such that the primary-crystal silicon grains **2** at the sliding surface **12a** are crushed at a crushing ratio in a predetermined range. Specifically, the crushing ratio of the primary-crystal silicon grains **2** at the sliding surface **12a** is 200 or lower in generally the entirety of the sliding surface **12a.** The crushing ratio of the primary-crystal silicon grains **2** is a ratio, represented by percentage, of the area size of the crushed part of the primary-crystal silicon grains **2** with respect to the area size of the primary-crystal silicon grains **2** at the sliding surface **12a.** A specific method for measuring the crushing ratio will be described below.

[0050] As described above, in the engine **100** in this embodiment, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** of the cylinder wall **12** is 0.5 μm or smaller. Namely, the sliding surface **12a** has projected and recessed portions that are sufficiently small to cause the sliding surface **12a** to be considered as being mirror-finished. Therefore, a uniform oil film is formed at the sliding surface **12a,** which may decrease the friction resistance. This may decrease the sliding loss and improve the fuel efficiency. In addition, oil (lubricant oil) remaining in the surface of the cylinder wall **12** is decreased in the amount as a result of being scraped off by the piston ring **42.** This decreases the consumption amount of the oil and suppresses deterioration in performance of a catalyst. Furthermore, the small size of the projected and recessed portions at the sliding surface **12a** decreases aggressiveness of the cylinder wall **12** to other members (aggressiveness to the piston rings **42** and the piston skirt **44).** From the point of view of further enhancing the above-described effects, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** is more preferably 0.3 μm or smaller.

[0051] There is a concern that when the surface roughness of the sliding surface **12a** is decreased, the amount of the oil retained in the sliding surface **12a** may be decreased and thus the seizure resistance may be decreased. However, in the engine **100** in this embodiment, the primary-crystal silicon grains **2,** which are highly hard, are present at the sliding surface **12a.** Therefore, the surface pressure applied to the alloy substrate (matrix) **1** is decreased, and thus a sufficient level of seizure resistance may be guaranteed. A groove such as a cross hatch is not necessary, and thus the oil may be prevented from escaping into the groove. Therefore, the oil film has a higher pressure and a fluid lubrication state is preferably realized. This also guarantees a certain level of seizure resistance.

[0052] In the engine **100** in this embodiment, the crushing ratio of the primary-crystal silicon grains **2** at the sliding surface **12a** of the cylinder wall **12** is 200 or lower. Therefore, a large number of the primary-crystal silicon grains **2** that are not crushed (that may be considered "healthy") are exposed at the sliding surface **12a.** This also decreases the aggressiveness to the other members. In addition, the contact load with the piston skirt **44** and the piston rings **42** is dispersed in the exposed healthy primary-crystal silicon grains **2,** which improves the seizure resistance and the wear resistance of the cylinder wall **12.**

[0053] The crushing ratio of the primary-crystal silicon grains **2** may be measured as follows, for example.

[0054] First, an image of the sliding surface **12a** is captured by use of a bore scope. FIG. **5** shows an example of the image of the sliding surface **12a.** As shown in FIG. **5,** crushed parts **2a** of the primary-crystal silicon grains **2** and non-crushed parts **2b** of the primary-crystal silicon grains **2** are present at the sliding surface **12a.** Next, an area size **S1** of the crushed parts **2a** of the primary-crystal silicon grains **2** is found by binarization using image analysis software. The crushed parts **2a** have a black external appearance, and thus may be distinguished by binarization from the non-crushed parts **2b** and the alloy substrate **1.** Next, an area size **S2** of the primary-crystal silicon grains **2** (including both of the crushed parts **2a** and the non-crushed parts **2b)** is found by binarization using the image analysis software. Then, the crushing ratio of the primary-crystal silicon grains **2** is calculated based on the following expression from the found area sizes **S1** and **S2.**

$$\text{Crushing ratio [\%] of the primary-crystal silicon grains} = (S1/S2) \times 100$$

[0055] The surface roughness of the sliding surface **12a** of the cylinder wall **12** may also be represented by, for example, an arithmetic average roughness Ra. In this embodiment, the sliding surface **12a** has an arithmetic average roughness Ra that is, for example, lower than 0.05 μm.

[0056] From the point of view of the seizure resistance and the wear resistance, the ratio of the area size occupied by the primary-crystal silicon grains **2** with respect to the area size of the sliding surface **12a** is preferably 8% or higher. In the case where the ratio of the area size occupied by the primary-crystal silicon grains **2** with respect to the area size of the sliding surface **12a** is 8% or higher, the surface pressure applied to the alloy substrate **1** is decreased, which improves the seizure resistance and the wear resistance.

[0057] The ratio of the area size occupied by the primary-crystal silicon grains **2** with respect to the area size of the sliding surface **12a** may be measured as follows, for example. First, an image of the sliding surface **12a** is captured by use of the bore scope. Next, the area size **S2** of the primary-crystal silicon grains **2** is found by binarization using the image analysis software. Then, the ratio of the area size occupied by the primary-crystal silicon grains **2** may be calculated based on the following expression from the found area size **S2** and an area size **S3** of the entire viewing field for measurement.

$$\text{Ratio [\%] of the area size occupied by the primary-crystal silicon grains with respect to the area size of the sliding surface} = (S2/S3) \times 100$$

[0058] The sliding surface **12a** may also be evaluated by a "blank ratio". FIG. **6** is a view provided to illustrate the definition of the "blank ratio". As shown in FIG. **6,** the sliding surface **12a** is divided into a plurality of grids **Sq** each having a size of 0.1 mm × 0.1 mm. These grids **Sq** naturally include grids **Sq1,** where the primary-crystal silicon grains **2** are present, and grids **Sq2,** where the primary-crystal silicon grains **2** are not present. The "blank ratio" is the ratio (percentage) of the number of the grids **Sq2** with no primary-crystal silicon grains **2** with respect to the total number of the grids **Sq.**

[0059] The "blank ratio" may be considered as an index indicating how the primary-crystal silicon grains **2** are dispersed. A lower blank ratio indicates that the primary-crystal silicon grains **2** are better dispersed. In the case where the blank ratio of the sliding surface **12a** is 55.5% or lower, the surface pressure applied to the alloy substrate **1** is sufficiently decreased. Therefore, the seizure resistance and the wear resistance are improved.

[0060] From the point of view of sufficiently improving the wear resistance and the strength of the cylinder block **10,** the aluminum alloy as the material of the cylinder block **10** preferably contains silicon at a content of 15% by mass or higher and 25% by mass or lower. In the case where the silicon content is 15% by mass or higher, a sufficiently large amount of the primary-crystal silicon grains **2** may be deposited, which may sufficiently improve the wear resistance of the cylinder block **10.** In the case where the silicon content is 25% by mass or lower, the strength of the cylinder block **10** may be kept sufficiently high.

[0061] The primary-crystal silicon grains **2** have an average grain diameter in the range of 8 μm or longer and 50 μm or shorter. In this case, the wear resistance of the cylinder block **10** may be further improved. In the case where the average grain diameter of the primary-crystal silicon grains **2** is longer than 50 μm, the number of the primary-crystal silicon grains **2** per unit area size of the sliding surface **12a** is small. Therefore, a large load is applied to each of the primary-crystal silicon grains **2** while the engine **100** is operated, and the primary-crystal silicon grains **2** may possibly be crushed. The crushed pieces of the primary-crystal silicon grains **2** act undesirably as polishing particles, which causes a risk that the sliding surface **12a** is significantly worn. In the case where the average grain diameter of the primary-crystal silicon grains **2** is shorter than 8 μm, merely a small part of the primary-crystal silicon grains **2** is embedded in the matrix **1.** Therefore, the primary-crystal silicon grains **2** easily fall while the engine **100** is operated. The primary-crystal silicon grains **2** that have fallen act undesirably as polishing particles, which causes a risk that the sliding surface **12a** is significantly worn.

[0062] By contrast, in the case where the average grain diameter of the primary-crystal silicon grains **2** is 8 μm or longer and 50 μm or shorter (more preferably 12 μm or longer and 50 μm or shorter), the primary-crystal silicon grains **2** are present in a sufficient number per unit area size of the sliding surface **12a.** Therefore, the load applied to each of the primary-crystal silicon grains **2** while the engine **100** is operated is relatively small, which suppresses the crushing of the primary-crystal silicon grains **2.** Since the part of the primary-crystal silicon grains **2** that is embedded in the matrix

1 is sufficiently large, the fall of the primary-crystal silicon grains **2** is suppressed. Therefore, the wear of the sliding surface **12a** by the primary-crystal silicon grains **2** that have fallen is suppressed.

[0063] The eutectic silicon grains have an average grain diameter shorter than that of the primary-crystal silicon grains **2.** The average grain diameter of the eutectic silicon grains is, for example, 7.5 μm or shorter.

[0064] The average grain diameters of the primary-crystal silicon grains **2** and the eutectic silicon grains may be measured as follows by image processing performed on an image of the sliding surface **12a.** First, a diameter (equivalent diameter) of each of the silicon crystal grains with an assumption that the silicon crystal grains are of a true circle is calculated based on an area size of each silicon crystal grain obtained by the image processing. As a result, the number (frequency) and the diameters of the silicon crystal grains are specified. Tiny crystal grains each having a diameter shorter than 1 μm are not counted as silicon crystal grains. Based on the calculated number (frequency) and the calculated diameters of the silicon crystal grains, a grain size distribution of the silicon crystal grains is obtained. The obtained grain size distribution (histogram) includes two peaks. The grain size distribution is divided into two regions with the threshold being a diameter of a portion forming a trough between the two peaks. The region corresponding to longer diameters is set as the grain size distribution of the primary-crystal silicon grains, and the region corresponding to shorter diameters is set as the grain size distribution of the eutectic silicon grains. Based on each of the grain size distributions, the average crystal diameter of the primary-crystal silicon grains and the average crystal diameter of the eutectic silicon grains may be calculated.

[0065] FIG. **7** is a cross-sectional view showing an example of structure of the piston ring **42** of the piston **40.** In the example shown in FIG. **7,** a diamond-like carbon layer (hereinafter, referred to as a "DLC layer") **42D** is formed on an outer circumferential portion (outer circumferential surface) of the piston ring **42.** The outer circumferential portion of the piston ring **42** is a portion to be in contact with the cylinder wall **12.** The piston ring **42** does not need to include the DLC layer **42D.** However, the DLC layer **42D** formed on the outer circumferential surface of each of the piston rings **42** may prevent, with more certainty, the cylinder wall **12** from being scuffed by the piston rings **42.**

[0066] The DLC layer **42D** is preferably formed by a deposition method (e.g., a CVD method or a PVD method) . The DLC layer **42D** may have any composition or a thickness with no specific limitation. From the point of view of preventing the scuffing with more certainty, the thickness of the DLC layer **42D** is preferably 2 μm or greater. From the point of view of the adhesiveness, the thickness of the DLC layer **42D** is preferably 20 μm or less.

[0067] FIG. **8** is a cross-sectional view showing an example of structure of the piston skirt **44.** In the example shown in FIG. **8,** the piston skirt **44** includes a resin layer **rl** formed on at least a part of an outer circumferential surface thereof. The resin layer **rl** is provided on a substrate **bl** formed of an aluminum alloy.

[0068] The resin layer **rl** includes, for example, a polymer matrix and solid lubricant particles dispersed in the polymer matrix. As a material of the polymer matrix, thermosetting polyamideimide, for example, is preferably usable. Needless to say, the material of the polymer matrix is not limited to this. As the solid lubricant particles, any of various known types of solid lubricant particles may be used. For example, graphite particles and molybdenum disulfide particles are preferably usable. The resin layer **rl** may be formed by, for example, applying a liquid resin material to the piston skirt **44** by a spray method or any of various printing methods (a screen printing method, a pad printing method or the like).

[0069] In the case where the piston skirt **44** includes the resin layer **rl** formed on at least a part of the outer circumferential surface thereof, the wear resistance and the seizure resistance of the piston **40** may be improved.

[0070] The piston skirt **44** may include a plating layer (e.g., iron-plating layer) instead of the resin layer **rl.** Also in the case where the piston skirt **44** includes the plating layer formed on at least a part of the outer circumferential surface thereof, the wear resistance and the seizure resistance of the piston **40** may be improved. The piston skirt **44** may not need to include either the resin layer **rl** or the plating layer.

[Method for producing the cylinder block]

[0071] With reference to FIG. **9** and FIG. **10,** a method for producing the cylinder block **10** included in the engine **100** according to this embodiment will be described. FIG. 9 and FIG. **10** are flowcharts showing production steps of the cylinder block **10.**

[0072] First, a molded body formed of an aluminum alloy containing silicon is prepared (step **ST1).** This molded body includes primary-crystal silicon grains and eutectic silicon grains at, and in the vicinity of, a surface thereof. The step **ST1** of preparing the molded body includes, for example, steps **ST1a** through **ST1e** shown in FIG. **10.**

[0073] First, an aluminum alloy containing silicon is prepared (step **ST1a).** For the reasons described above, the content of silicon in the aluminum alloy is preferably 15% by mass or higher and 25% by mass or lower. The aluminum alloy contains aluminum at a content of, for example, 73.4% by mass or higher and 79.6% by mass or lower. The aluminum alloy may contain copper. In this case, the aluminum alloy contains copper at a content of, for example, 2.0% by mass or higher and 5.0% by mass or lower.

[0074] Next, the prepared aluminum alloy is heated in a melting furnace to be melted and thus a molten aluminum alloy is formed (step **ST1b).** About 100 ppm by mass of phosphorus may be incorporated into the pre-melting aluminum alloy or the molten aluminum alloy. In the case where the aluminum alloy contains phosphorus at a content of 50 ppm by mass or higher and 200 ppm by mass or lower, increase in the size of the silicon crystal grains may be suppressed. Therefore, the silicon crystal grains may be dispersed uniformly in the alloy. The aluminum alloy may contain calcium at a content of 0.01% by mass or lower. In this manner, the effect provided by phosphorus that the size of the silicon crystal grains is decreased to an extremely minute level is guaranteed, and thus a metal tissue having a high wear resistance may be provided. Namely, it is preferred that the aluminum alloy contains phosphorus at a content of 50 ppm by mass or higher and 200 ppm by mass or lower and calcium at a content of 0.01% by mass or lower.

[0075] Next, the molten aluminum alloy is used to perform casting (specifically, high-pressure dis-casting) (step **ST1c).** Namely, the molten aluminum alloy is cooled in a casting mold to form a molded body. In this step, a portion to be the sliding surface **12a** of the cylinder wall **12** is cooled at a high cooling rate (e.g., 4°C/second or higher and 50°C/second or lower). In this manner, a molded body including the silicon crystal grains, contributing to the wear resistance, at, and in the vicinity of, a surface thereof is obtained. The casting step **ST1c** may be performed by use of a casting device disclosed in, for example, WO2004/002658.

[0076] Next, the molded body removed from the casting mold is subjected to one of heat treatments referred to as "T5", "T6" and "T7" (step **ST1d).** According to the T5 treatment, the molded body is, immediately after being removed from the casting mold, for example, washed with water or the like to be quenched, then is subjected to artificial aging at a predetermined temperature for a predetermined time period in order to improve the mechanical properties thereof and to stabilize the size thereof, and then is cooled with air. According to the T6 treatment, the molded body is, after being removed from the casting mold, subjected to a solution treatment at a predetermined temperature for a predetermined time period, then is cooled with water, then is subjected to artificial aging at a predetermined temperature for a predetermined time period, and then is cooled with air. According to the T7 treatment, the molded body is subjected to artificial aging more excessively than according to the T6 treatment. The T7 treatment may stabilize the size more than the T6 treatment, but results in a lower hardness than the T6 treatment.

[0077] Next, the molded body is subjected to predetermined mechanical processing (step **ST1e).** Specifically, a surface of the molded body to be in contact with the cylinder head **20** or the crankcase **30** is, for example, shaved.

[0078] After the molded body is prepared as described above, an inner circumferential surface of a portion, of the molded body, to become the cylinder wall is subjected to a first honing process (referred to as a "rough honing process") (step **ST2).** Specifically, the inner circumferential surface is polished with a whetstone having a relatively small number of grit size (e.g., #600 diamond whetstone).

[0079] Then, the inner circumferential surface is subjected to a second honing process (referred to as a "finish honing process") (step **ST3).** Specifically, the inner circumferential surface is polished with a whetstone having a larger number of grit size than used in the rough honing process (e.g., with a #3000 diamond whetstone). The rough honing process and the finish honing process may be performed by use of a honing device disclosed in, for example, Japanese Laid-Open Patent Publication No. 2004-268179.

[0080] In this manner, the cylinder block **10** may be obtained. The number of times of honing process is not limited to two as described above. The grit size of the whetstone to be used in the honing processes may be adjusted to control the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a.** A whetstone having a relatively large number of grit size may be used in the final honing process among the plurality of honing processes, so that the ten-point average surface roughness Rz_{JIS} is decreased to 0.5 μm or smaller. It has been found out by the studies made by the present inventors that in the case where a whetstone having a grit size of #3000 or a larger number is used in the final honing process, the crushing ratio of the primary-crystal silicon grains **2** at the sliding surface **12a** may be decreased to 200 or lower.

[0081] FIG. **11** is a graph showing results of an investigation on the relationship between the grit size of the whetstone and the crushing ratio of the primary-crystal silicon grains. For this investigation, the first honing process was performed with a #600 diamond whetstone, and then the second honing process was performed with a diamond whetstone having a predetermined grit size so as to obtain a polishing depth of 4 μm. After this, the crushing ratio of the primary-crystal silicon grains was measured. In FIG. **11,** the horizontal axis represents the grit size of the whetstone used in the second honing process, and the vertical axis represents the crushing ratio of the primary-crystal silicon grains. It is seen from FIG. **11** that in the case where the grit size of the whetstone is #3000 or of a larger number, the crushing ratio of the primary-crystal silicon grains may be decreased to 200 or lower.

[Results of the investigations of the effects]

[0082] First, a sample of the engine **100** according to an embodiment of the present invention was produced (example 1), and the effect of decreasing the consumption amount of oil thereof was compared with that of an engine in comparative example 1. The results of the investigation will be described. The cylinder block **10** of the engine **100** in example 1 was produced by the method described above. For producing a cylinder block in comparative example 1, two honing processes were performed. Specifically, a rough honing process was performed for the purpose of forming oil grooves, and a finish honing process was performed for the purpose of forming a plateau portion between the oil grooves.

[0083] FIG. **12** shows a roughness curve of a sliding surface in comparative example 1, and FIG. **13** shows a roughness curve of the sliding surface **12a** in example 1. From a comparison between FIG. **12** and FIG. **13,** it is seen that the surface roughness of the sliding surface **12a** in example 1 is smaller than the surface roughness of the sliding surface in comparative example 1. The ten-point average surface roughness Rz_{JIS} of the sliding surface in comparative example 1 was 3.05 μm, whereas the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** in example 1 was 0.25 μm. The crushing ratio of the primary-crystal silicon grains 2 at the sliding surface **12a** in example 1 was 200 or lower.

[0084] FIG. **14** shows the consumption amount of oil measured by an extraction method in each of comparative example 1 and example 1. As can be seen from FIG. **14,** the consumption amount of the oil was smaller by 21% in example 1 than in comparative example 1.

[0085] FIG. **15A** is a schematic view showing how oil **OL** is scraped off by a piston ring **42** at a sliding surface **12a'** of a cylinder wall **12'** included in the engine in comparative example 1. In comparative example 1, the surface roughness (ten-point average surface roughness Rz_{JIS}) of the sliding surface **12a'** is relatively large, and therefore, the oil **OL** remains in a large amount in the sliding surface **12a'** without being scraped off by the piston ring **42.** The remaining oil **OL** is exposed to flame **FL** to evaporate or combust. Therefore, in the case where the amount of the remaining oil **OL** is large, the consumption amount of the oil is large.

[0086] FIG. **15B** is a schematic view showing how oil **OL** is scraped off by the piston ring **42** at the sliding surface **12a** of the cylinder wall **12** included in the engine **100** in example 1. In example 1, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** is as small as 0.25 μm. It is considered that this decreases the amount of the oil **OL** remaining in the sliding surface **12** and thus decreases the consumption amount of the oil.

[0087] Now, results of an investigation on the effect of decreasing the friction resistance (friction loss) will be described. Regarding examples 2, 3, 4 and 5, in which the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** was respectively 0.224 μm, 0.334 μm, 0.403 μm and 0.496 μm, the friction mean effective pressure (FMEP) was measured by a floating liner method. In all of examples 2, 3, 4 and 5, the crushing ratio of the primary-crystal silicon grains **2** was 6 to 70. The FMEP is a value obtained by dividing the friction work per cycle by the piston stroke volume, and a higher FMEP indicates a larger friction force. FIG. **16** shows results of measurement of the FMEP. The FMEPs shown FIG. **16** are each an average value of the FMEPs at rotation rates of the engine of 4400 rpm, 4800 rpm and 5200 rpm. FIG. **16** also shows an FMEP of the engine in comparative example 1 (120.1 kPa) with the one-dot chain line.

[0088] It is seen from FIG. **16** that as the ten-point average surface roughness Rz_{JIS} is smaller, the FMEP is lower, and that in the case where the ten-point average surface roughness Rz_{JIS} is 0.5 μm or lower as in examples 2 through 5, an FMEP lower than the FMEP in comparative example 1 is obtained.

[0089] FIG. **17** shows FMEP decreasing ratios in each of examples 2 and 3 at rotation rates of the engine of 4400 rpm, 4800 rpm and 5200 rpm. It is seen from FIG. **17** that the effect of decreasing the FMEP tends to be greater on the lower side of the rotation rate.

[0090] Now, results of an investigation on the continuity of the effect of decreasing the friction loss will be described. In example 6, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** was 0.214 μm, and the crushing ratio of the primary-crystal silicon grains **2** was 200 or lower. FIG. **18** shows results of measurement of the FMEP performed in repetition in example 6. In comparative example 2, the ten-point average surface roughness Rz_{JIS} of the sliding surface was 0.563 μm (after being measured nine times) . FIG. **19** shows results of measurement of the FMEP performed in repetition in comparative example 2.

[0091] As can be seen from FIG. **18** and FIG. **19,** when the measurement was performed for comparison at the same timings (with the same number of times of measurement), the FMEPs were lower by 10% or greater in example 6 than in comparative example 2 at all the timings. For example, at the first measurement, the FMEP was lower by 17% in example 6 than in comparative example 2. Even at the tenth measurement, in which the effect of decreasing the FMEP was minimum, example 6 exhibited an effect of decreasing the FMEP by 10% or greater (specifically 10.3%) .

[0092] Now, results of an investigation on the aggressiveness of the cylinder wall to the other members and on the wear resistance of the cylinder wall will be described. For this investigation, a vibration friction wear test (SRV test) was performed on a barrel-type test piece mimicking the piston skirt and on a cylinder test piece cut from the cylinder wall. The SRV test was performed for example 7, in which the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** was 0.124 to 0.237 μm (0.162 μm on average) and the crushing ratio of the primary-crystal silicon grains **2** was 150, and also for comparative example 3, in which the ten-point average surface roughness Rz_{JIS} of the sliding surface was 1.6 to 3.2 μm. The SRV test was performed with the barrel-type test piece being slid at a constant load in a temperature of oil of 130°C (immersed in the oil), and the heights of wear of the barrel-type test piece and the cylinder test piece were measured.

[0093] FIG. **20** shows changes in the height of wear of the barrel-type test piece along time. It is seen from FIG. **20** that the height of wear of the barrel-type test piece is lower in example 7 than in comparative example 3. At 60 minutes after the start of the test, the height of wear was lower by 69% in example 7 than in comparative example 3. As can be seen, it has been confirmed that the aggressiveness of the cylinder wall **12** to the other members is decreased in example

7.

[0094] FIG. **21** shows changes in the height of wear of the cylinder test piece along time. It is seen from FIG. **21** that the height of wear of the cylinder test piece is lower in example 7 than in comparative example 3. As can be seen, it has been confirmed that the wear resistance of the cylinder wall **12** is improved in example 7.

[0095] In example 7 and comparative example 3, the engine was operated under the conditions promoting seizure of the cylinder and the piston, and the time period from the start of the operation until the seizure occurred was measured. FIG. **22** shows results of measurement of the time period from the start of the operation until the seizure occurred.

[0096] As shown in FIG. **22,** the time period until the seizure occurred was about 6.5 times longer in example 7 than in comparative example 3. It has been confirmed that the seizure resistance of the cylinder wall **12** is improved in example 7.

[Transportation vehicle]

[0097] The engine **100** according to an embodiment of the present invention is preferably usable for various types of transportation vehicles. FIG. **23** shows an example of automatic two-wheeled vehicle including the engine **100** according to an embodiment of the present invention.

[0098] In an automatic two-wheeled vehicle **300** shown in FIG. **23,** a head pipe **302** is provided at a front end of a main body frame **301.** A front fork **303** is attached to the head pipe **302** so as to be swingable in a left-right direction of the vehicle. A front wheel **304** is rotatably supported at a bottom end of the front fork **303.**

[0099] A seat rail **306** is attached so as to extend rearward from a top portion of a rear end of the main body frame **301.** A fuel tank **307** is provided on the main body frame **301,** and a main seat **308a** and a tandem seat **308b** are provided on the seat rail **306.**

[0100] A rear arm **309** extending rearward is attached to the rear end of the main body frame **301.** A rear wheel **310** is rotatably supported at a rear end of the rear arm **309.**

[0101] The engine **100** is held on a central portion of the main body frame **301.** A radiator **311** is provided to the front of the engine **100.** An exhaust pipe **312** is connected to an exhaust port of the engine **100,** and a muffler **313** is attached to a rear end of the exhaust pipe **312.**

[0102] A transmission **315** is coupled with the engine **100.** A drive sprocket **317** is attached to an output shaft **316** of the transmission **315.** The drive sprocket **317** is coupled with a rear wheel sprocket **319** of the rear wheel **310** via a chain **318.** The transmission **315** and the chain **318** act as a transmission mechanism that transmits power generated by the engine **100** to the driving wheel.

[0103] The automatic two-wheeled vehicle **300** includes the engine **100** according to an embodiment of the present invention, and therefore, obtains effects of, for example, improving the fuel efficiency, decreasing the consumption amount of oil, and suppressing deterioration in performance of a catalyst.

[0104] In this embodiment, the automatic two-wheeled vehicle is shown as an example of the transportation vehicle. The engine according to an embodiment of the present invention is not limited to being used for an automatic two-wheeled vehicle, and is also preferably usable for any other transportation vehicle such as an automatic four-wheeled vehicle, an automatic three-wheeled vehicle, a seacraft or the like.

[0105] As described above, the internal combustion engine **100** according to an embodiment of the present invention includes the piston **40** formed of an aluminum alloy; and the cylinder block **10** including the cylinder wall **12** including the sliding surface **12a,** along which the piston **40** is slidable. The cylinder block **10** is formed of an aluminum alloy containing silicon, and includes the plurality of primary-crystal silicon grains **2** at the sliding surface **12a.** The sliding surface **12a** has a ten-point average surface roughness Rz_{JIS} of 0.5 μm or smaller, and the plurality of primary-crystal silicon grains **2** at the sliding surface **12a** have a crushing ratio of 200 or lower.

[0106] In the engine **100** according to an embodiment of the present invention, the ten-point average surface roughness Rz_{JIS} of the sliding surface **12a** of the cylinder wall **12** is 0.5 μm or smaller. Namely, the sliding surface **12a** has the projected and recessed portions that are sufficiently small to cause the sliding surface **12a** to be considered as being mirror-finished. Therefore, a uniform oil film is formed at the sliding surface **12a,** which may decrease the friction resistance. This may decrease the sliding loss and improve the fuel efficiency. In addition, the oil (lubricant oil) remaining in the surface of the cylinder wall **12** is decreased in the amount as a result of being scraped off by the piston ring **42.** This decreases the consumption amount of the oil and suppresses deterioration in performance of a catalyst. Furthermore, the small size of the projected and recessed portions at the sliding surface **12a** decreases the aggressiveness of the cylinder wall **12** to the other members (aggressiveness to the piston rings **42** and the piston skirt **44)** .

[0107] There is a concern that when the surface roughness of the sliding surface **12a** is decreased, the amount of the oil retained in the sliding surface **12a** may be decreased and thus the seizure resistance may be decreased. However, in the engine **100** according to an embodiment of the present invention, the primary-crystal silicon grains **2,** which are highly hard, are present at the sliding surface **12a.** Therefore, the surface pressure applied to the alloy substrate (matrix) **1** is decreased, and thus a sufficient level of seizure resistance may be guaranteed. A groove such as a cross hatch is not necessary, and thus the oil may be prevented from escaping into the groove. Therefore, the oil film has a higher pressure and a fluid lubrication state is preferably realized. This also guarantees a certain level of seizure resistance.

[0108] In the engine **100** according to an embodiment of the present invention, the crushing ratio of the primary-crystal silicon grains **2** at the sliding surface **12a** of the cylinder wall **12** is 200 or lower. Therefore, a large number of the primary-crystal silicon grains **2** that are not crushed (that may be considered "healthy") are exposed at the sliding surface **12a.** This also decreases the aggressiveness to the other members. In addition, the contact load with the piston skirt **44** and the piston rings **42** is dispersed in the exposed healthy primary-crystal silicon grains **2,** which improves the seizure resistance and the wear resistance of the cylinder wall **12.**

[0109] In an embodiment, the sliding surface **12a** has an arithmetic average roughness Ra that is smaller than 0.05 μm.

[0110] In the case where the arithmetic average roughness Ra of the sliding surface **12a** of the cylinder wall **12** is smaller than 0.05 μm, the projected and recessed portions at the sliding surface **12a** are small. Therefore, a uniform oil film is formed at the sliding surface **12a,** which may decrease the friction resistance. This may decrease the sliding loss and improve the fuel efficiency. In addition, the oil remaining in the surface of the cylinder wall **12** is decreased in the amount as a result of being scraped off by the piston ring **42.** This decreases the consumption amount of the oil and suppresses deterioration in performance of a catalyst. Furthermore, the small size of the projected and recessed portions at the sliding surface **12a** decreases the aggressiveness of the cylinder wall **12** to the other members (aggressiveness to the piston rings **42** and the piston skirt **44)** .

[0111] In an embodiment, the plurality of primary-crystal silicon grains **2** have an area size occupying a ratio of 8% or higher of an area size of the sliding surface.

[0112] In the case where the ratio of the area size occupied by the primary-crystal silicon grains **2** with respect to the area size of the sliding surface **12a** is 8% or higher, the surface pressure applied to the alloy substrate **1** is decreased, which improves the seizure resistance and the wear resistance.

[0113] In an embodiment, where the sliding surface **12a** is divided into a plurality of grids **Sq** each having a size of 0.1 mm × 0.1 mm and the ratio of the number of grids **Sq** where no primary-crystal silicon grain **2** is present with respect to the total number of the grids **Sq** is referred to as a "blank ratio", the blank ratio is 55.5% or lower.

[0114] The "blank ratio" is an index indicating how the primary-crystal silicon grains **2** are dispersed. A lower blank ratio indicates that the primary-crystal silicon grains **2** are better dispersed. In the case where the blank ratio of the sliding surface **12a** is 55.5% or lower, the surface pressure applied to the alloy substrate **1** is sufficiently decreased. Therefore, the seizure resistance and the wear resistance are improved.

[0115] In an embodiment, the cylinder block **10** is formed of an aluminum alloy containing silicon at a content of 15% by mass or higher and 25% by mass or lower.

[0116] From the point of view of sufficiently improving the wear resistance and the strength of the cylinder block **10,** the aluminum alloy as the material of the cylinder block **10** preferably contains silicon at a content of 15% by mass or higher and 25% by mass or lower. In the case where the silicon content is 15% by mass or higher, a sufficiently large amount of the primary-crystal silicon grains **2** may be deposited, which may sufficiently improve the wear resistance of the cylinder block **10.** In the case where the silicon content is 25% by mass or lower, the strength of the cylinder block **10** may be kept sufficiently high.

[0117] In an embodiment, the plurality of primary-crystal silicon grains **2** have an average grain diameter of 8 μm or longer and 50 μm or shorter.

[0118] The primary-crystal silicon grains **2** have an average grain diameter in the range of 8 μm or longer and 50 μm or shorter. In this case, the wear resistance of the cylinder block **10** may be further improved.

[0119] In the case where the average grain diameter of the primary-crystal silicon grains **2** is longer than 50 μm, the number of the primary-crystal silicon grains 2 per unit area size of the sliding surface **12a** is small. Therefore, a large load is applied to each of the primary-crystal silicon grains **2** while the engine **100** is operated, and the primary-crystal silicon grains **2** may possibly be crushed. The crushed pieces of the primary-crystal silicon grains **2** act undesirably as polishing particles, which causes a risk that the sliding surface **12a** is significantly worn.

[0120] In the case where the average grain diameter of the primary-crystal silicon grains **2** is shorter than 8 μm, merely a small part of the primary-crystal silicon grains **2** is embedded in the matrix **1.** Therefore, the primary-crystal silicon grains **2** easily fall while the engine **100** is operated. The primary-crystal silicon grains **2** that have fallen act undesirably as polishing particles, which causes a risk that the sliding surface **12a** is significantly worn.

[0121] By contrast, in the case where the average grain diameter of the primary-crystal silicon grains **2** is 8 μm or longer and 50 μm or shorter, the primary-crystal silicon grains **2** are present in a sufficient number per unit area size of the sliding surface **12a.** Therefore, the load applied to each of the primary-crystal silicon grains **2** while the engine **100** is operated is relatively small, which suppresses the crushing of the primary-crystal silicon grains **2.** Since the part of the primary-crystal silicon grains **2** that is embedded in the matrix **1** is sufficiently large, the fall of the primary-crystal silicon grains **2** is suppressed. Therefore, the wear of the sliding surface **12a** by the primary-crystal silicon grains 2 that have fallen is suppressed.

[0122] In an embodiment, the piston **40** includes the piston main body **41** and the plurality of piston rings **42** attached to the outer circumferential portion of the piston main body **42,** and each of the plurality of piston rings **42** includes the diamond-like carbon layer **DLC** on the outer circumferential portion thereof.

[0123] In the case where each of the plurality of piston rings **42** includes the diamond-like carbon layer **DLC** on the outer circumferential portion thereof, the cylinder wall **12** may be prevented with more certainty from being scuffed by the piston rings **42.**

[0124] In an embodiment, the piston **40** includes the piston head **43** and the piston skirt **44** extending from the outer circumferential portion of the piston head **43,** and the piston skirt **44** includes the resin layer **rl** or the plating layer formed on at least a part of the outer circumferential surface thereof.

[0125] In the case where the piston skirt **44** includes the resin layer **rl** or the plating layer formed on at least a part of the outer circumferential surface thereof, the wear resistance and the seizure resistance of the piston **40** may be improved.

[0126] The transportation vehicle according to an embodiment of the present invention includes the internal combustion engine **100** having any of the above-described structures.

[0127] The internal combustion engine **100** according to an embodiment of the present invention is preferably usable in any of various types of transportation vehicles.

INDUSTRIAL APPLICABILITY

[0128] According to an embodiment of the present invention, in an internal combustion engine including a cylinder block formed of an aluminum alloy containing silicon, the friction resistance of a cylinder wall and the consumption amount of oil may be decreased while a certain level of seizure resistance is provided with certainty. The internal combustion engine according to an embodiment of the present invention is preferably usable in any of various types of transportation vehicles including an automatic two-wheeled vehicle.

REFERENCE SIGNS LIST

[0129] **1:** matrix (alloy substrate); 2: primary-crystal silicon grain; **2a:** crushed part of the primary-crystal silicon grain; **2b:** non-crushed part of the primary-crystal silicon grain; **10:** cylinder block; **11:** cylinder bore; **12:** cylinder wall; **12a:** sliding surface (inner circumferential surface of the cylinder wall); **13:** outer wall; **14:** water jacket; **20:** cylinder head; **21:** intake port; **22:** exhaust port; **23:** intake valve; **24:** exhaust valve; **30:** crankcase; **40:** piston; **41:** piston main body; **42:** piston ring; **42a:** top ring; **42b:** second ring; **42c:** third ring; **42D:** diamond-like carbon layer; **43:** piston head; **44:** piston skirt; **48:** piston pin; **50:** crankshaft; **51:** crankpin; **52:** crank arm; **60:** con rod; **61:** rod main body; **62:** small end portion; **63:** large end portion; **70:** combustion chamber; **100:** engine (internal combustion engine); **300:** automatic two-wheeled vehicle; **Sq:** grid; **Sq1:** grid where the primary-crystal silicon grains are present; **Sq2:** grid where the primary-crystal silicon grains are not present; **bl:** substrate; **rl:** resin layer

Claims

1. An internal combustion engine, comprising:

   a piston formed of an aluminum alloy; and
   a cylinder block including a cylinder wall including a sliding surface, along which the piston is slidable;
   wherein the cylinder block is formed of an aluminum alloy containing silicon, and includes a plurality of primary-crystal silicon grains at the sliding surface;
   wherein the sliding surface has a ten-point average surface roughness Rz_{JIS} of 0.5 μm or smaller, and
   wherein the plurality of primary-crystal silicon grains at the sliding surface have a crushing ratio of 200 or lower.

2. The internal combustion engine of claim 1, wherein the sliding surface has an arithmetic average roughness Ra that is smaller than 0.05 μm.

3. The internal combustion engine of claim 1 or 2, wherein the plurality of primary-crystal silicon grains have an area size occupying a ratio of 8% or higher of an area size of the sliding surface.

4. The internal combustion engine of any one of claims 1 through 3, wherein where the sliding surface is divided into a plurality of grids each having a size of 0.1 mm $\times$ 0.1 mm and the ratio of the number of grids where no primary-crystal silicon grain is present with respect to the total number of the grids is referred to as a "blank ratio", the blank ratio is 55.5% or lower.

5. The internal combustion engine of any one of claims 1 through 4, wherein the cylinder block is formed of an aluminum alloy containing silicon at a content of 15% by mass or higher and 25% by mass or lower.

6. The internal combustion engine of any one of claims 1 through 5, wherein the plurality of primary-crystal silicon grains have an average grain diameter of 8 μm or longer and 50 μm or shorter.

7. The internal combustion engine of any one of claims 1 through 6,

wherein the piston includes a piston main body and a plurality of piston rings attached to an outer circumferential portion of the piston main body, and
wherein each of the plurality of piston rings includes a diamond-like carbon layer on an outer circumferential portion thereof.

8. The internal combustion engine of any one of claims 1 through 7,

wherein the piston includes a piston head and a piston skirt extending from an outer circumferential portion of the piston head, and
wherein the piston skirt includes a resin layer or a plating layer formed on at least a part of an outer circumferential surface thereof.

9. A transportation vehicle, comprising the internal combustion engine of any one of claims 1 through 8.

FIG.1

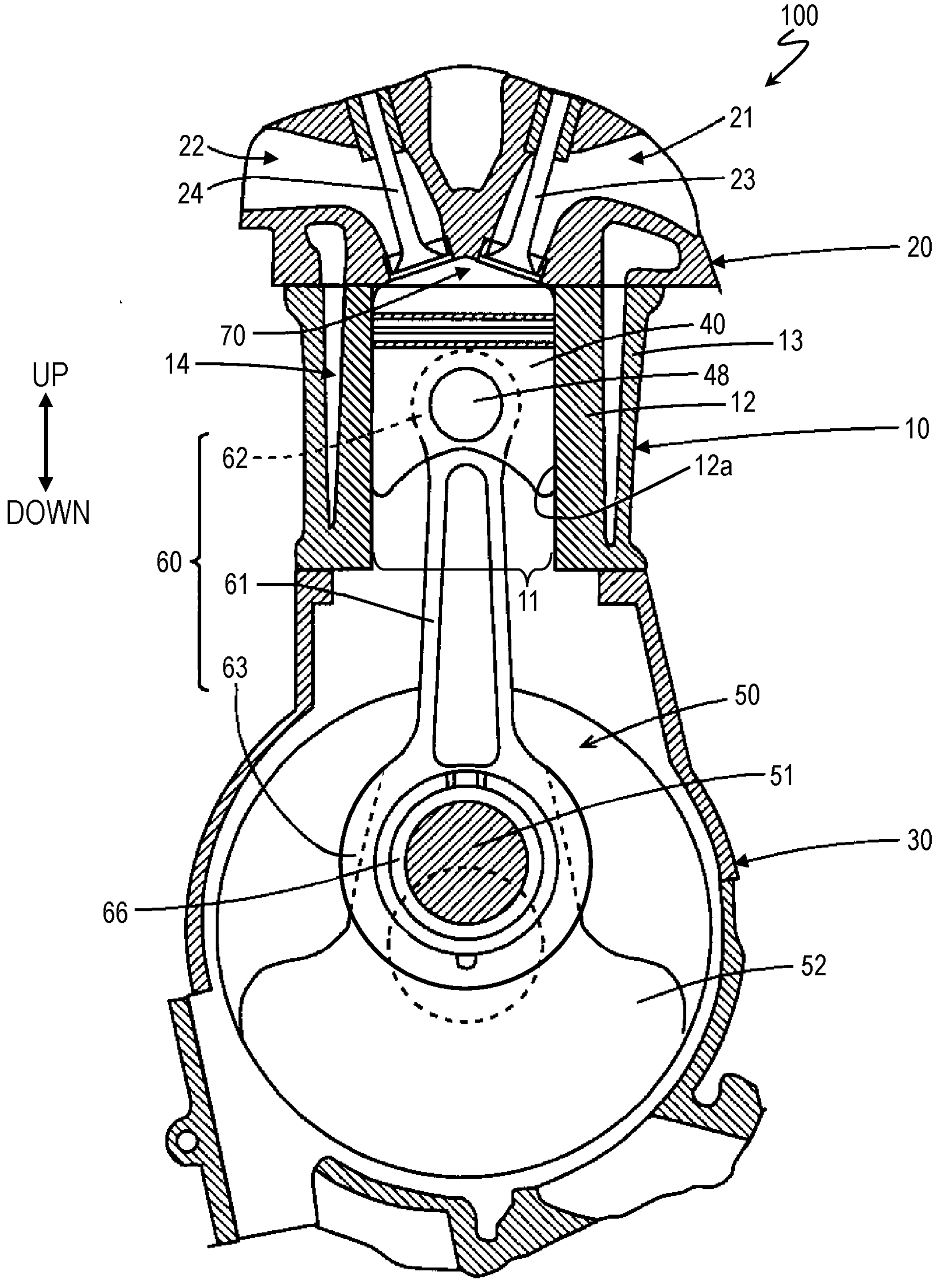

100
21
22
23
24
20
70
40
13
14
48
UP
12
10
62
12a
DOWN
60
61
11
63
50
51
30
66
52

FIG.2

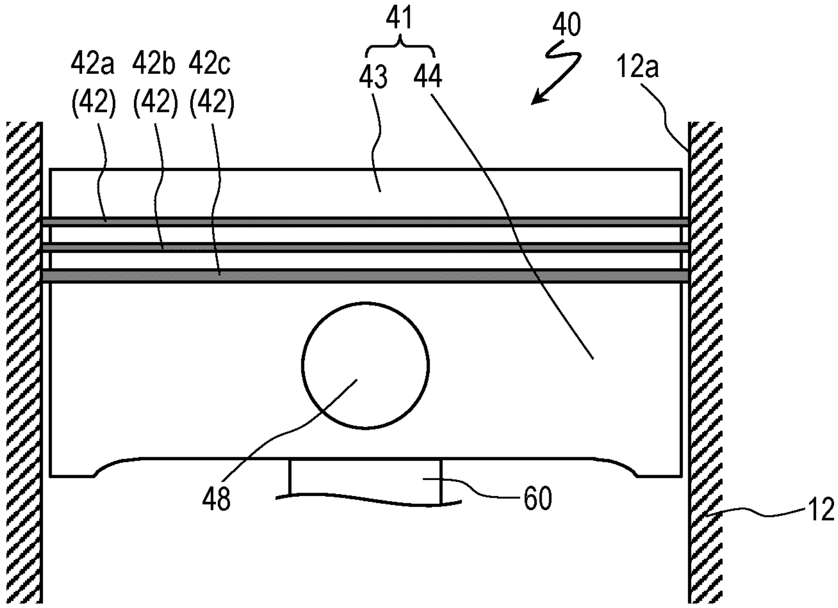


FIG.3

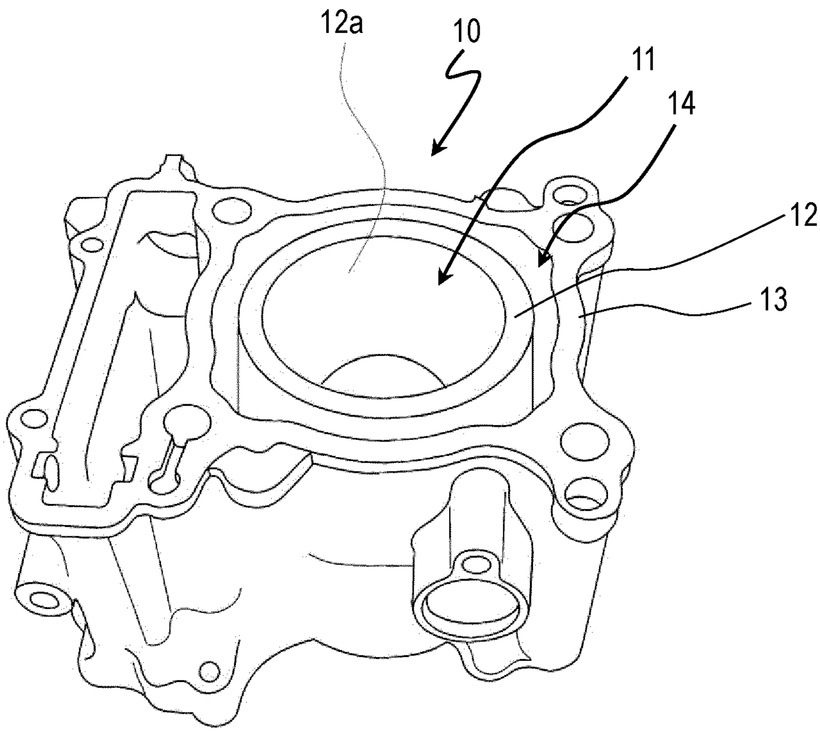


FIG.4

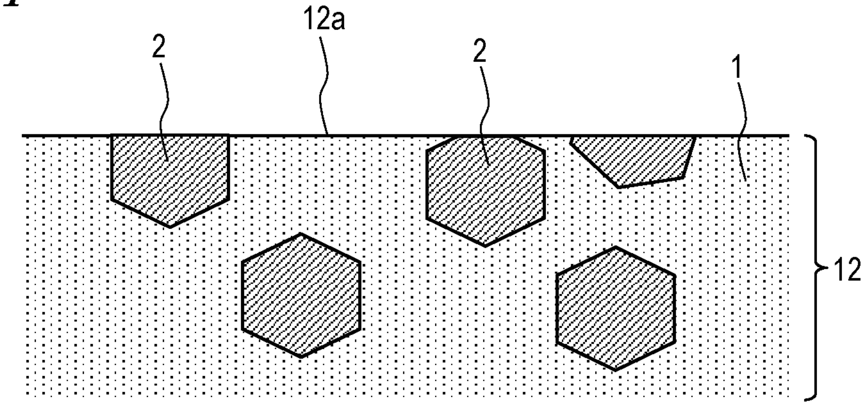


FIG.5

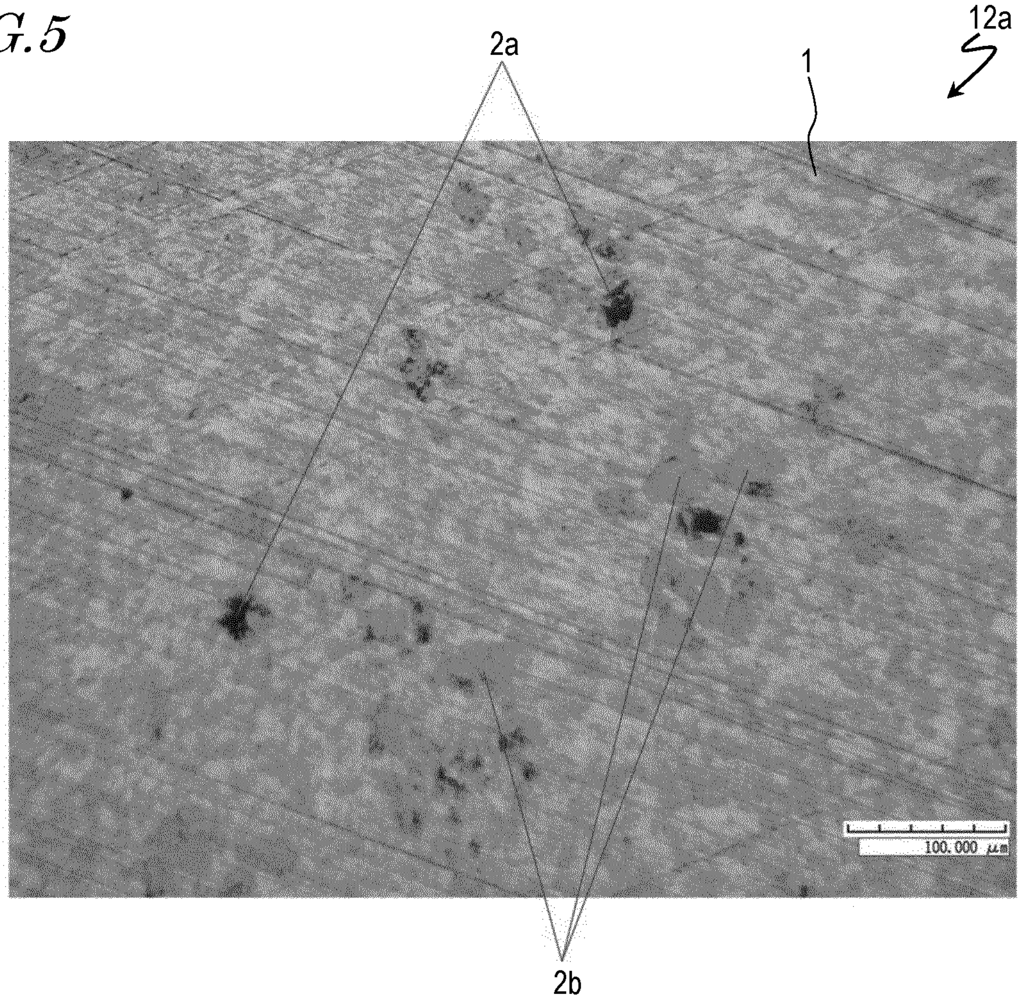


FIG.6

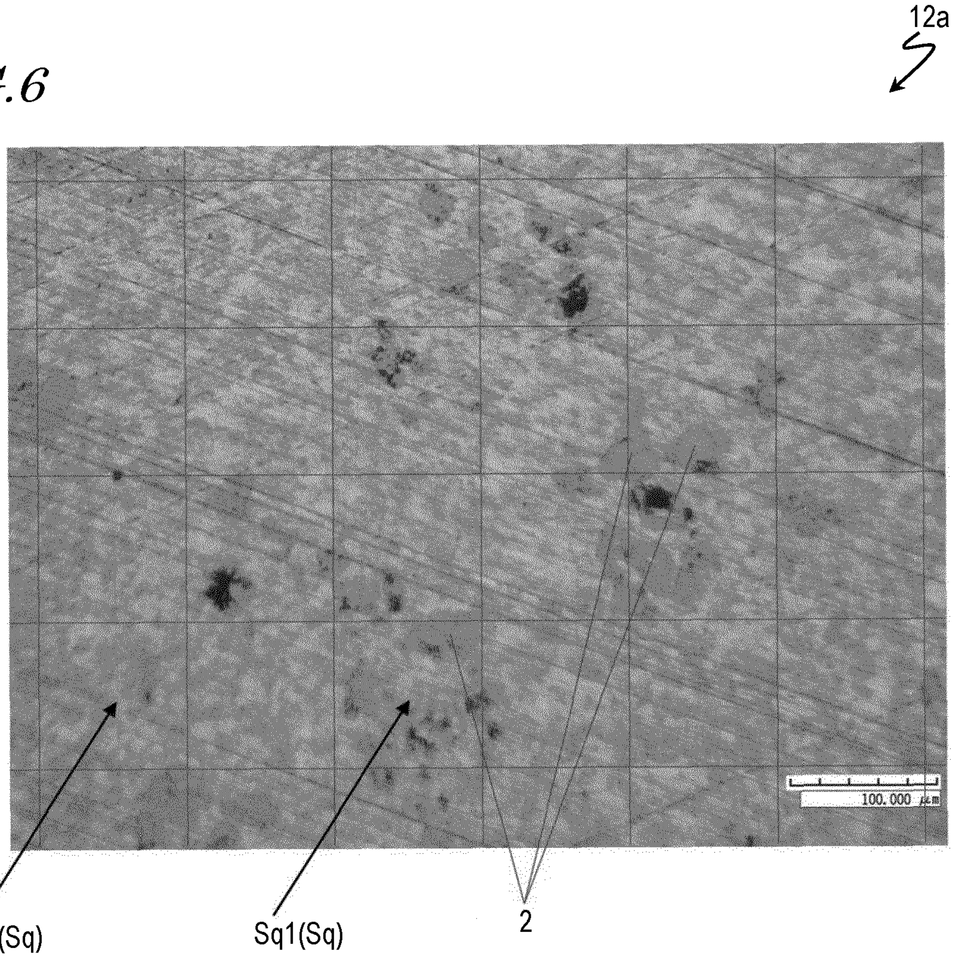


FIG.7

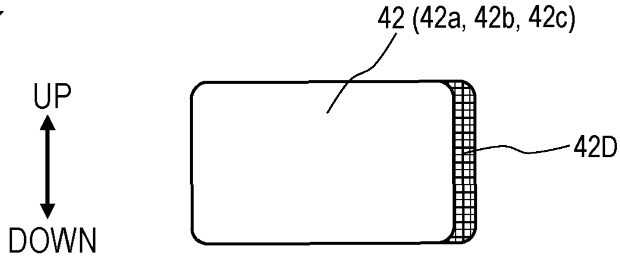


FIG.8

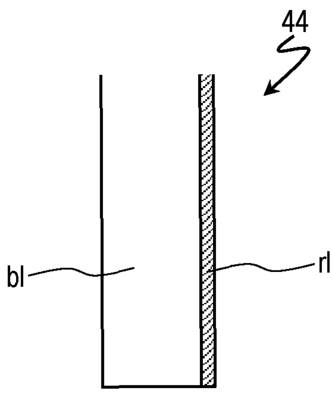


FIG.9

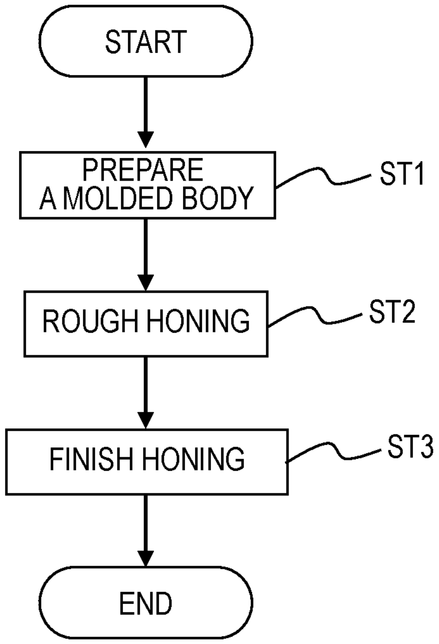

START
PREPARE A MOLDED BODY
ST1
ROUGH HONING
ST2
FINISH HONING
ST3
END

FIG.10

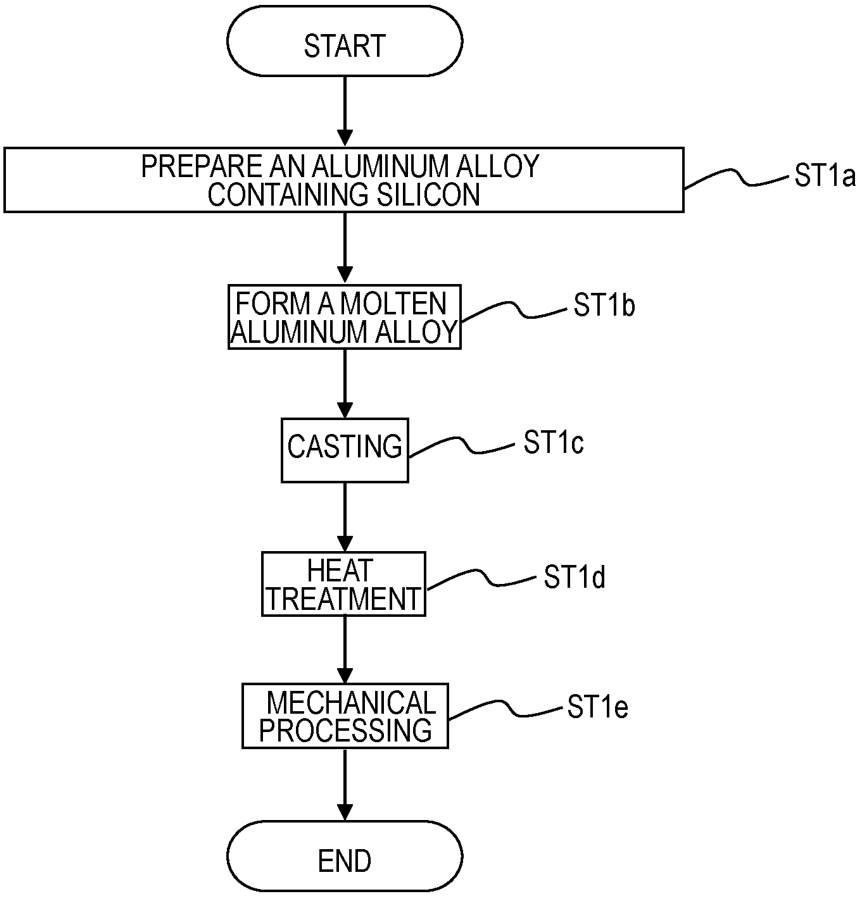

START
PREPARE AN ALUMINUM ALLOY CONTAINING SILICON
ST1a
FORM A MOLTEN ALUMINUM ALLOY
ST1b
CASTING
ST1c
HEAT TREATMENT
ST1d
MECHANICAL PROCESSING
ST1e
END

FIG. 11

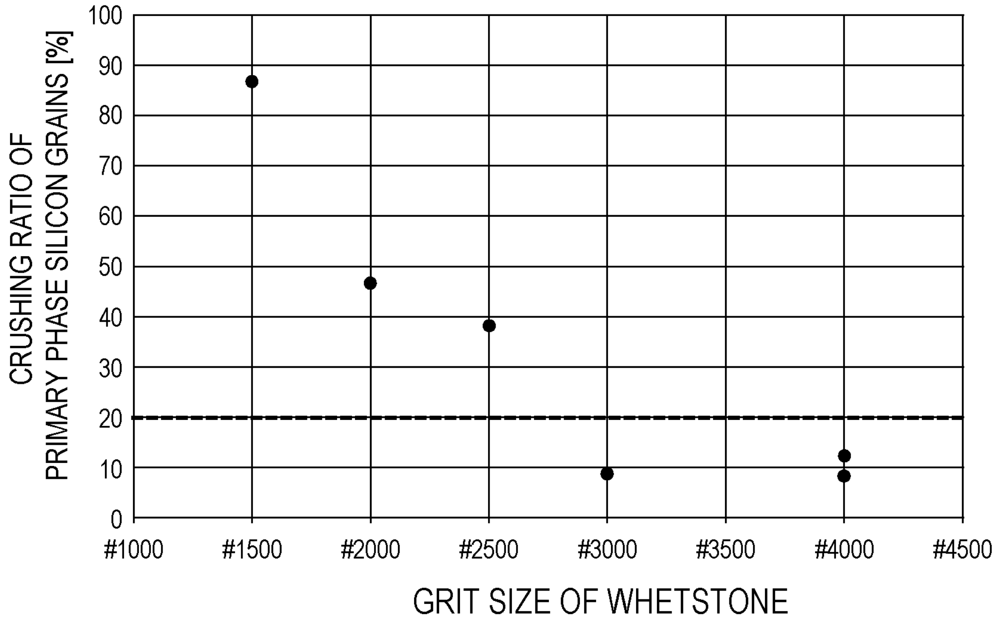


FIG. 12

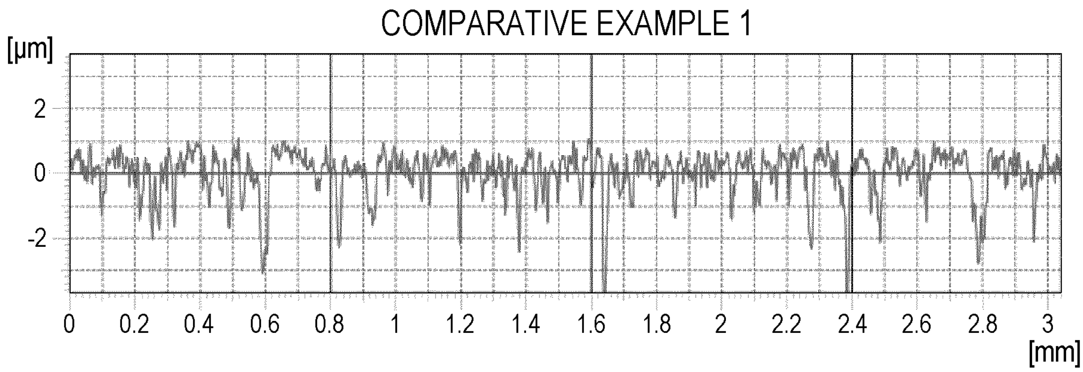


FIG. 13

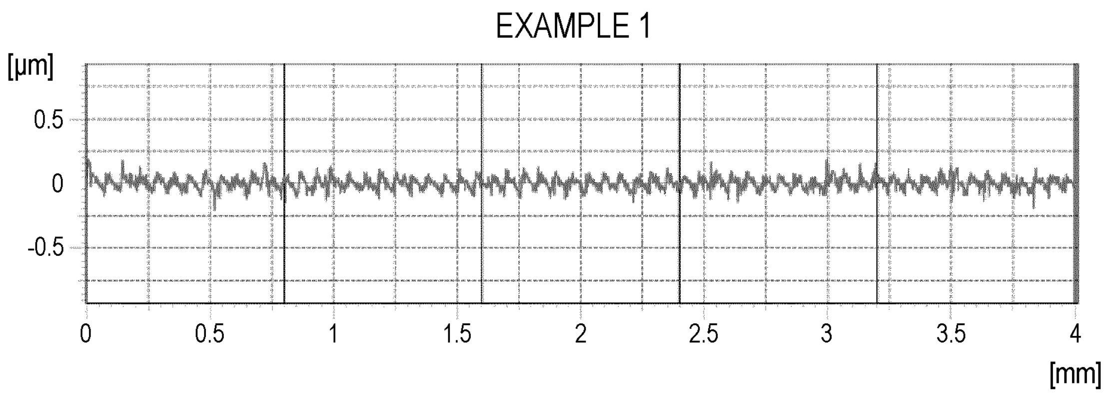


FIG.14

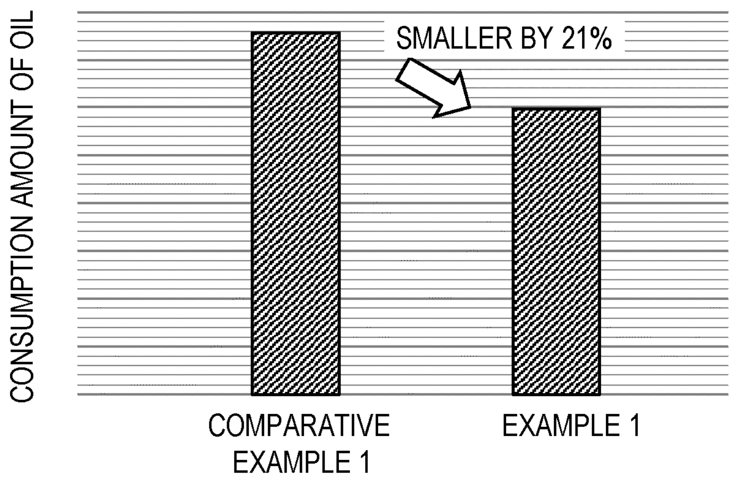


FIG.15A

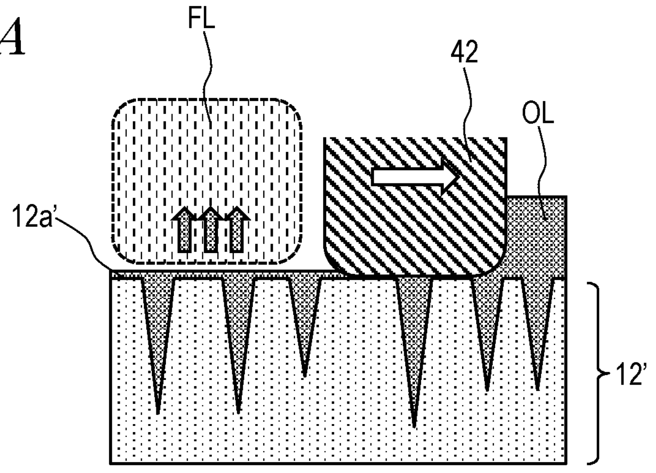


FIG.15B

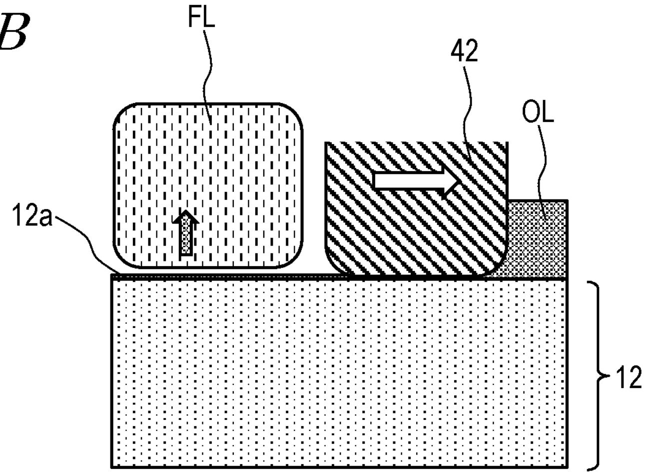


FIG.16

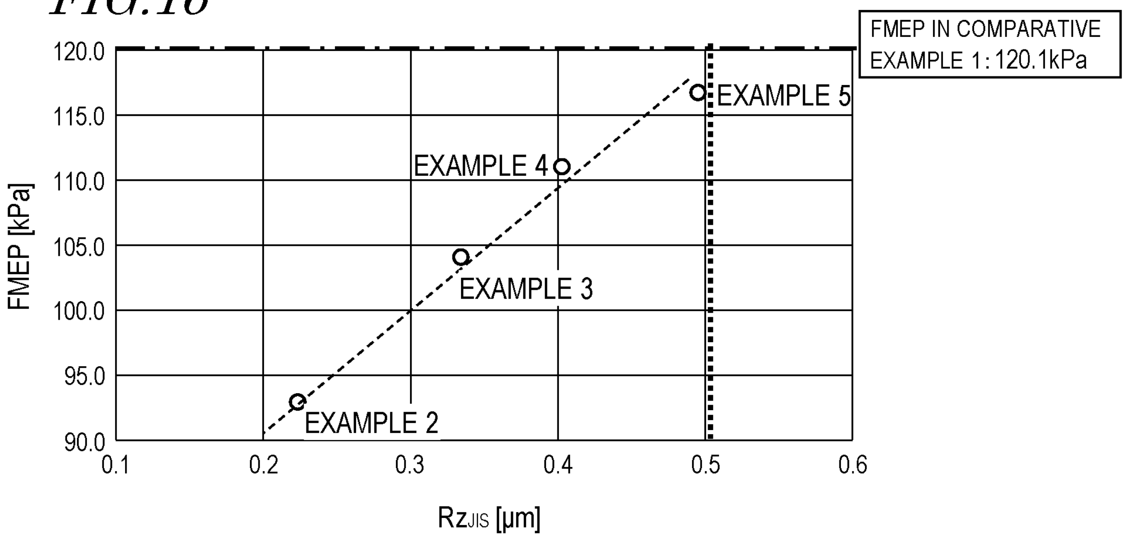


FIG.17

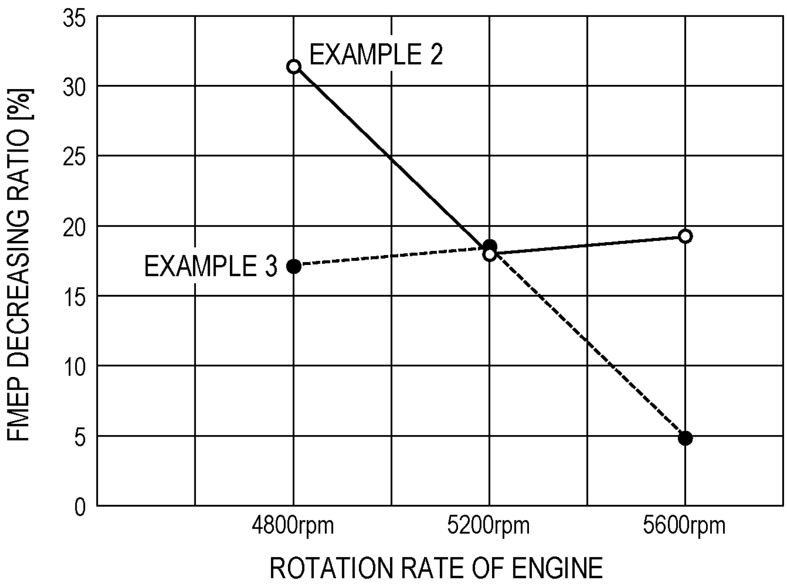


FIG.18

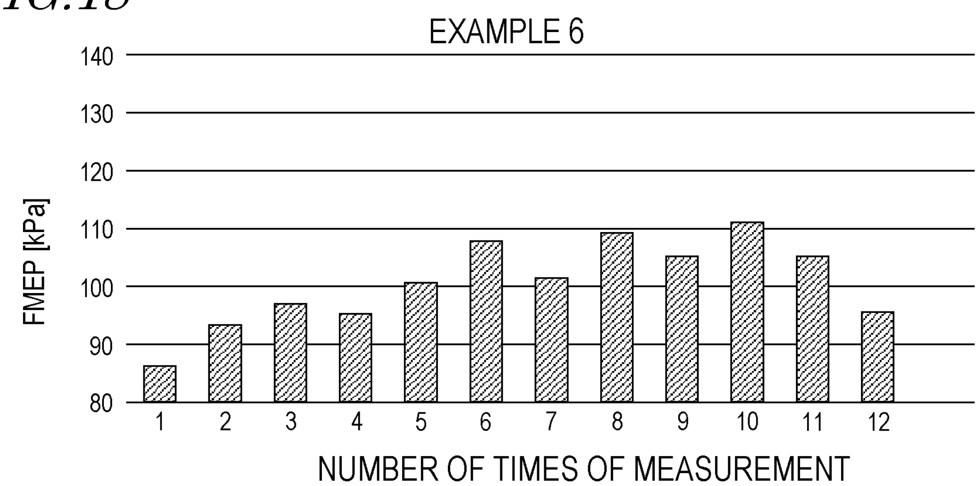


FIG.19

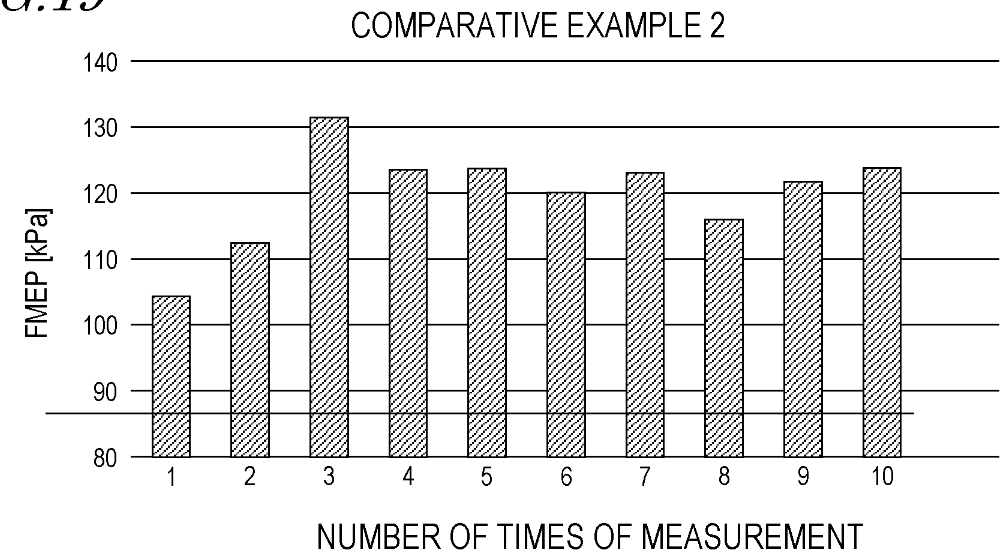


FIG.20

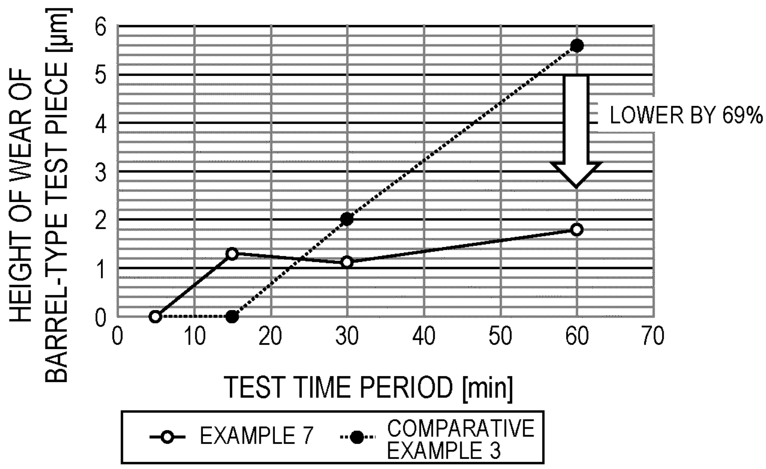


FIG.21

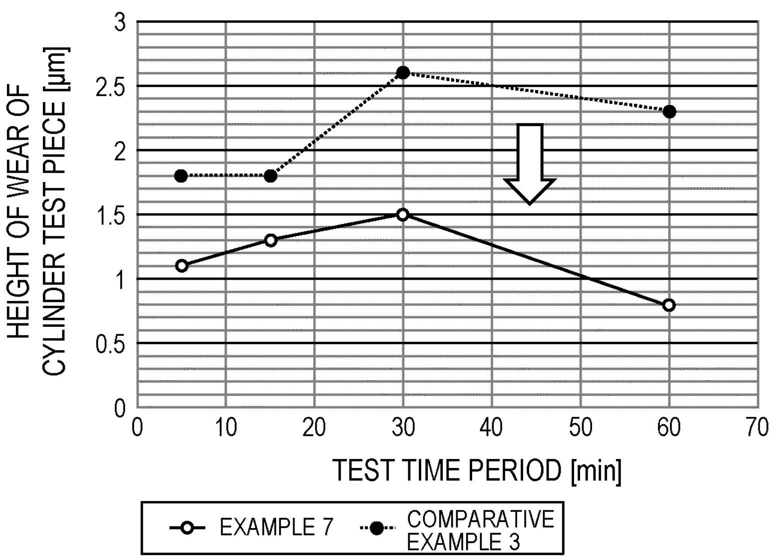
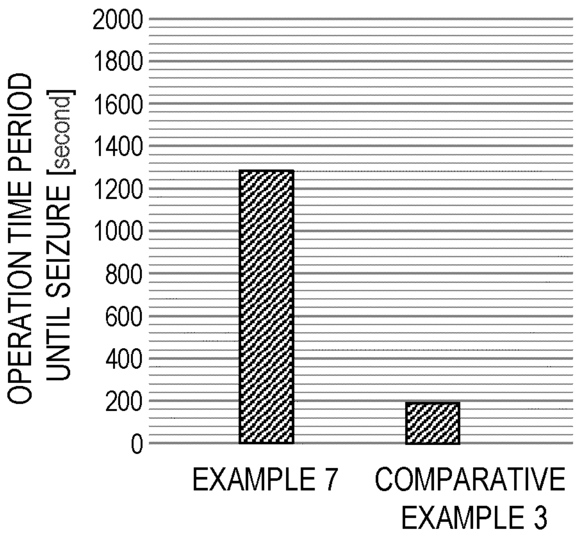


FIG.22


OPERATION TIME PERIOD UNTIL SEIZURE [second]
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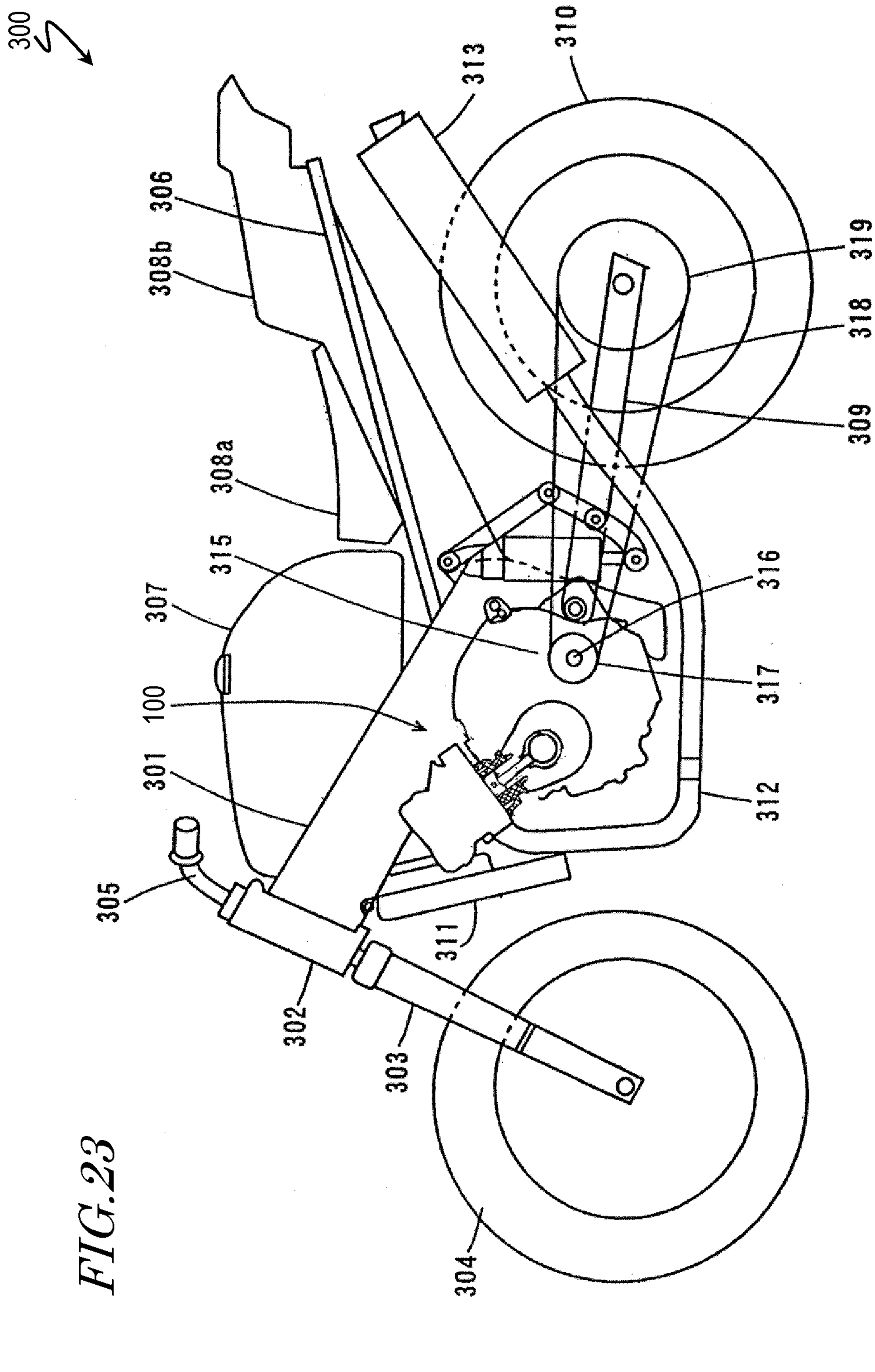
1800
1600
1400
1200
1000
800
600
400
200
0
EXAMPLE 7
COMPARATIVE EXAMPLE 3

FIG.23


300
310
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308a
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304

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2021/045976

A. CLASSIFICATION OF SUBJECT MATTER

F02F 1/00(2006.01)i
FI: F02F1/00 C

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F02F1/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2022
Registered utility model specifications of Japan 1996-2022
Published registered utility model applications of Japan 1994-2022

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 1-253553 A (HONDA MOTOR CO LTD) 09 October 1989 (1989-10-09) p. 2, upper right column, lines 3-8, p. 3, upper left column, line 8 to p. 3, lower left column, line 3, p. 3, lower right column, line 16 to p. 4, upper left column, line 17, p. 4, upper right column, line 16 to p. 5, lower left column, line 11, fig. 3	1-9
Y	JP 2002-221077 A (NISSAN MOTOR CO LTD) 09 August 2002 (2002-08-09) paragraphs [0006], [0013], [0018]-[0025]	1-9
Y	JP 7-88711 A (TOSHIBA TUNGALOY CO LTD) 04 April 1995 (1995-04-04) paragraphs [0005], [0007], [0011], [0018]	1-9
Y	JP 10-331970 A (NISSAN MOTOR CO LTD) 15 December 1998 (1998-12-15) column "abstract", claims 1-6, paragraphs [0022]-[0024], fig. 2-3	3-4
Y	JP 2003-13163 A (TOYOTA MOTOR CORP) 15 January 2003 (2003-01-15) claim 11, paragraphs [0026]-[0027], [0047]-[0051], [0087]	7

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2022	**01 February 2022**

Name and mailing address of the ISA/JP	Authorized officer
Japan Patent Office (ISA/JP) **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2021/045976

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
JP 1-253553 A	09 October 1989	(Family: none)	
JP 2002-221077 A	09 August 2002	(Family: none)	
JP 7-88711 A	04 April 1995	(Family: none)	
JP 10-331970 A	15 December 1998	(Family: none)	
JP 2003-13163 A	15 January 2003	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- WO 2004002658 A **[0004] [0075]**
- JP 2004268179 A **[0079]**