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(54) **Title**: HIGH TEMPERATURE SEAL SYSTEM

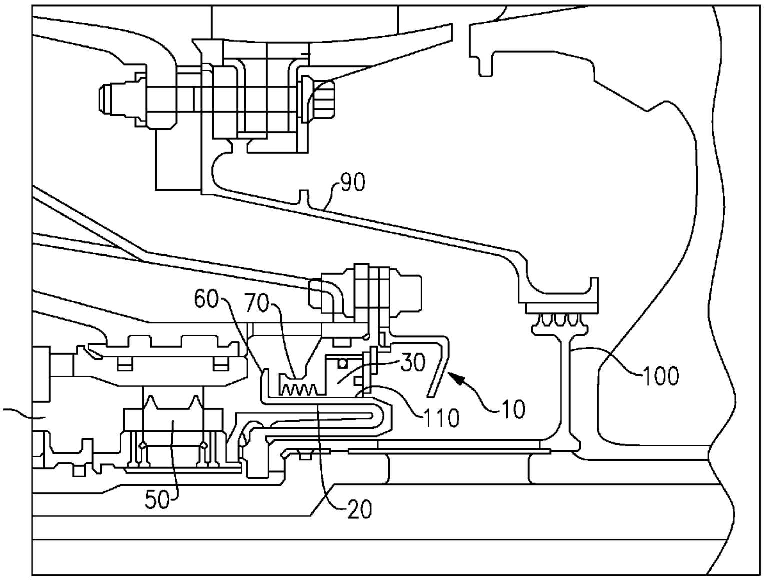

FIG.1

(57) **Abstract**: A hydrodynamic sealing system for use in an oxidizing environment includes a rotor and a sealing stator. The stator includes a solid lubricant or a surface treatment and the rotor is hardened or the stator is hardened and the rotor includes the solid lubricant or the surface treatment. The stator

[Continued on next page]

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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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is located proximate to the rotor to provide a seal. The stator and the rotor are robust at extreme temperatures above 700 degrees Fahrenheit (F) such that at least one of the stator and the rotor have a wear rate and a surface roughness sufficient to maintain an operating gap between the stator and rotor.

HIGH TEMPERATURE SEAL SYSTEM

GOVERNMENT RIGHTS STATEMENT

[0001] This invention was made with U.S. Government support under FA8650-09-D-2922 0002 awarded by (AFRL – WPAFB). The U.S. Government has certain rights in the invention.

BACKGROUND

[0002] This disclosure relates, in general, to materials and applications for use in extreme temperature environments.

[0003] There are a number of high temperature environments where elements that employ carbon based elements are unable to sustain operation. Typical carbon based elements suffer some serious degradation about and above 700 degrees Fahrenheit (F).

[0004] More specifically, sliding components such as linear or reciprocating applications including piston and rotor devices with components that are required are increasingly being required to operate in extreme environments.

[0005] In one example, hydrodynamic face seals and hydrodynamic circumferential seals are sealing technologies that minimize lubrication oil leakage. Hydrodynamic seals offer an attractive solution since they operate primarily in a non-contacting manner, thus increasing seal life and reliability in a compact axial space while maintaining tight seal clearances. Both hydrodynamic face seals as well as hydrodynamic circumferential seals rely on the development of a pressure profile between a rotating and static sealing surface to generate an operating gap as small as possible. A good surface finish must be maintained on the rotating and static sealing surfaces in order to preserve the required pressure profile. Although the hydrodynamic seals are non-contacting during the bulk of operation, they are subject to sliding contact during spin-up and shutdown of the rotor. To minimize wear and heat checking throughout contact operation, and consequently maintain a highly effective hydrodynamic seal, the seal components are generally made out of materials that exhibit excellent friction and wear characteristics.

[0006] Traditional hydrodynamic seals, typically made from carbon, are not suitable for operation at temperatures such as those exceeding 700 degrees Fahrenheit (F) due to the onset of severe, degrading oxidation at such temperatures. One example of such severe, degrading oxidizing conditions occurs in a gas turbine sump of a high mach turbo aircraft engine. Once the seals deteriorate the entire sump can fail.

[0007] In another application, an engine with pistons operating in a linear fashion employ rings and seals that have the same problems as noted herein.

[0008] Thus, there is a need for systems and methods for operations which allow for increased temperature operation while maintaining integrity and performance.

SUMMARY

[0009] The present system provides, in one aspect, a sealing system for use in an oxidizing environment which includes a rotor and a sealing stator. The stator includes a solid lubricant or a surface treatment and the rotor is hardened or the stator is hardened and the rotor includes the solid lubricant or the surface treatment. The stator is located proximate to the rotor to provide a seal. The stator and the rotor are robust at extreme temperatures above 700 degrees Fahrenheit (F) such that at least one of the stator and the rotor have a wear rate and a surface roughness sufficient to maintain an operating gap between the stator and rotor.

[0010] The present system provides, in one aspect, a sliding system for use in an oxidizing environment which includes a sliding portion and a sealing portion. The sealing portion includes a solid lubricant or a surface treatment and the sliding portion is hardened or the sliding portion includes the solid lubricant or the surface treatment and the sealing portion is hardened. The sealing portion is located proximate to the sliding portion to provide a seal. The sealing portion and the sliding portion are robust at temperatures above 700 degrees Fahrenheit (F) such that at least one of the sealing portion and the sliding portion have a wear rate and a surface roughness sufficient to maintain an operating gap between the sealing portion and the sliding portion.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] These and other features, aspects, and advantages of the present system will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0012] FIG. 1 is a side cross-sectional view of a hydrodynamic sealing system in accordance with an embodiment of the present system;

[0013] FIG. 2 is an enlarged view of a portion of the system of FIG. 1;

[0014] FIG. 3 is a schematic of the operation of a hydrodynamic face seal in accordance with an embodiment;

[0015] FIG. 4 depicts a disc-on-ring test apparatus;

[0016] FIG. 5 is a table listing materials utilized in stators and rotors for testing according to the apparatus of FIG. 4;

[0017] FIG. 6 is a plot of pre-test and post-test surface roughness for the rotor and stators of FIG. 5;

[0018] FIG. 7 is a plot of pre-test and post-test weight change for the rotors and stators of FIG. 5;

[0019] FIG. 8 is a plot of average torque during tests for the materials in FIG. 5;

[0020] FIG. 9 lists tabular data for the tests according to the apparatus of FIG. 4 and materials of FIG. 5;

[0021] FIG. 10 is a table of stators and rotors tested under Phase II testing;

[0022] FIG. 11 is a plot of pre-test and post-test surface roughness for the rotors and stators of FIG. 10;

[0023] FIG.12 is a plot of pre-test and post-test weight change for the rotors and stators of FIG. 10;

[0024] FIG. 13 is a plot of average torque during the tests of the stators and rotors of FIG. 10;

[0025] FIG. 14 is a table of results of the tests of the stators and rotors of FIG. 10;

[0026] FIG. 15 is a top view of a piston and cylinder in accordance with an embodiment of the present system; and

[0027] FIG. 16 is a side cross-sectional view of the system of FIG. 15.

DETAILED DESCRIPTION

[0028] In accordance with the principles of the present systems and methods for operating in extreme conditions are provided. One example is a coating or parent material that permits operation in the extreme environments, particularly for sliding elements.

[0029] In one example the sealing system provides a tight seal and maintains a small gap with low wear and surface roughness in a high temperature environment.

[0030] In an exemplary embodiment depicted in FIG. 1, a hydrodynamic sealing system 10 includes a rotor 20 coated with a hard coating and a seal 30 composed of a solid lubricant (e.g., Boronized Inconel 718) that is robust at temperatures exceeding 700 degrees Fahrenheit. In one example the temperature range goes up to about 1200 degrees Fahrenheit (F)). “Robust” is defined herein as having a wear rate and surface roughness sufficient to maintain an operating gap between the stator and rotor of about 0.0002 inches.

[0031] Hydrodynamic face seals, usually referred to as Dry Gas Seals in industries such as the Oil and Gas industry, consist of a rotating ring, known as a seat or rotor (e.g. rotor 20), and a stationary ring, known as the face or stator (e.g., seal 30). In one example the surface finish of each face seal is on the order of 0.1 μm. In a further example the geometry of the rotor includes radial grooves 200 that extend from the center of the seal face to the outer diameter as depicted in FIG. 3. The purpose of these grooves is to cut into the operating fluid (typically a gaseous hydrocarbon or dry nitrogen) while rotating and consequently build up hydrodynamic pressure toward a radially inner portion 210 of the grooves to separate the two seal faces. When in operation, hydrodynamic seal portions may be separated (e.g., by an operating gap), and when separated, the seat (e.g. rotor 20) rides on a cushion of gas over the face (e.g., seal 30) as depicted in FIG. 3. As indicated above, the seal portions may contact each other during start-up and shut down of a particular rotor. According to one example, the grooves of the seat are about 6 μm deep and the face - seat gap is about 3 μm.

[0032] System 10 is an advanced hydrodynamic seal that is robust in an oxidizing environment at extreme temperatures, for example greater than 700 degrees Fahrenheit (F) and in one example up to about 1200 degrees Fahrenheit (F). Such a sealing system could be used in sumps (e.g., a sump 40) of a High Mach Turbo Aircraft Engine as depicted in FIGS. 1-2, for example. Sump 40 may include a bearing 50, a seal oil slinger 60, seal windback threads 70, and a seal housing 80. A stationary seal 90 and a rotating labyrinth seal 100 are also depicted. An operating gap 110 is present between seal 30 and rotor 20. Seal 30 may include a surface treatment, such as Boronized Inconel 718 that is robust over 1000 degrees Fahrenheit (F) and at temperatures up to at least 1200 degrees Fahrenheit (F). The suitable operation of a hydrodynamic seal requires a sealing surface that maintains a low surface roughness throughout operation. The combination of a hard rotor coating (e.g., having a hardness Rockwell value of HRC 70 or more) and a seal component which includes an appropriate surface treatment (e.g., Boronized Inconel 718) results in a low coefficient of friction, a low wear rate, and the ability to retain an acceptable surface finish throughout operation. In another example, the rotor could include a surface treated material as described while the seal component could have a hard coating or may be otherwise hardened such that it has a hardness Rockwell value of HRC 70 or more.

[0033] As described herein, traditional hydrodynamic seals, typically made from carbon, are not suitable for operation at temperatures over 700 degrees Fahrenheit (F) due to the onset of severe, degrading oxidation, which leads to catastrophic failure of the seal a. Manufacturing the hydrodynamic seal out of a solid lubricant that is robust at high temperatures rather than carbon allows the operating temperature to reach at least 1200 degrees Fahrenheit (F).

[0034] In one example, forward, mid, and aft sumps of a High Mach Turbo Aircraft Engines reach extreme temperatures of 1000 degrees Fahrenheit (F) to about 1200 degrees Fahrenheit (F) when approaching the transition stage to a ramjet at Mach 3. Such extreme temperatures are well beyond the current design experience of hydrodynamic seal manufacturers. As described, current seals fabricated from carbon are subject to accelerated oxidation at temperatures exceeding 700 degrees F.

[0035] Various substrates and coatings for sump seals (e.g., sumps for High Mach Turbo Aircraft Engines) were investigated for operating at 1200° degrees Fahrenheit (F). Parameters for hydrodynamic seals to be used in this environment include, for example: wear resistance at 1200 degrees Fahrenheit (F), low coefficient of friction and low heat generation at sliding interface. As described herein, severe, degrading oxidation typically occurs at temperatures exceeding 700 degrees Fahrenheit (F) in traditional carbon seals. It is desirable that materials used in such seals survive at ranges of at least 700 degrees Fahrenheit (F), 1000 degrees Fahrenheit (F) and 1200 degrees Fahrenheit (F) to provide low leakage and are insensitive to an oil environment. The simulated testing predicted steady-state leakage (performance) based on operating regime, predicted thermal distortion and impact on performance, and characterized the effect of surface roughness on performance.

[0036] High temperature material testing was performed on a sliding wear test rig as depicted in Fig. 4 including a rotor disk 130 and a stator ring 140 having a gap 150 therebetween. The sliding wear test rig was designed for ring-on-disc testing, where the rotor is rotating and the stator (seal) is stationary. This testing mimics the actual conditions (e.g., the temperature and speed) which occurs in a high temperature (e.g., up to 1200 degrees F) environment, such as a sump seal in a High Mach Turbo Aircraft Engine, during the start up and shut down of the engine, i.e., before or after the hydrodynamic lift occurs.

[0037] The seal in one example (the static stator of test setup) consisted of the materials listed in FIG. 5. To mimic the material combination found in traditional hydrodynamic and carbon seals, a WC-Co coated Inconel 718 disc was tested against M-45 electrographite. To achieve the 1200 degree Fahrenheit (F) operating temperature, a CrC-NiCr rotor coating (oxidation resistant up to 1650 degrees Fahrenheit (F)) replaced the presently used WC-Co coating (oxidation resistant up to 1000 degrees Fahrenheit (F)). FIG. 5 summarizes the materials tested in Task 3 and Task 4.

[0038] The testing was separated into two phases (Phase 1 and Phase 2). The first phase of testing was used to identify potential seal material candidates. Phase 2 testing was performed at multiple isotherms throughout the operating range of the component. Phase 1 testing was run at a linear speed of 275 ft/s (at the outer diameter of the test sample). The temperature at the sliding interface was 1000 degrees Fahrenheit (F). Throughout the test, the contact pressure was held at 3.5 psi, which is the typical contact pressure as specified by traditional seal vendors. The second phase of testing was also conducted at 275 ft/s at isotherms of 72 degrees Fahrenheit (F), 400 degrees Fahrenheit (F), 600 degrees Fahrenheit (F), 800 degrees Fahrenheit (F), 1000 degrees Fahrenheit (F), and 1200 degrees Fahrenheit (F).

[0039] The characteristics evaluated in identifying successful material candidates were: 1) low coefficient of friction; 2) good wear resistance (quantified by surface roughness degradation and type of wear debris); and 3) low heat generation at the sliding interface. These characteristics would combine to produce an appropriate operating gap (e.g., 0.0002 in.) between a rotor and stator at the indicated temperatures for the lifetime of the seal. Accordingly, the specific test metrics to compare material performance were: 1) coefficient of friction data; 2) profilometry, to evaluate surface finish degradation as caused by wear and oxidation; 3) temperature levels at the sliding interface; and 4) mass loss (to evaluate wear).

[0040] Several materials were tested under Phase 1 conditions, i.e., a chamber temperature at 1000 degrees Fahrenheit (F), a maximum surface speed at 275 ft/s, a load at the wearing surface at 3.5 psi, and a test duration of 1 hour. FIG. 6 is a plot of the pre-test and post-test surface roughness (in micro inches R_a) for Test 1 – Test 10 for the rotor and stators. FIG. 7 is a plot of the pre-test and post-test weight change for the rotor and stators, and FIG. 8 is a plot of the average torque during each of the tests. FIG. 9 lists the tabular data from the tests.

[0041] Test 1 is the baseline test of the M-45 Electrographite stator versus a WC-Co rotor (current state of the art material combination). While the performance of this material combination was superior during the 1-hour wear test, the electrographite stator material oxidizes rapidly and is not suitable for long-term operation at the desired temperature.

[0042] The Test 2 material combination was not able to survive the operating conditions. The selected SiC material provides excellent wear characteristics; however, it did not provide a low coefficient of friction and the temperature of the stator increased rapidly. After 2 minutes, the thermal shock caused the brittle SiC stator to shatter into multiple pieces.

[0043] The Test 3 material combination of ESK Ekastic T Silicon Nitride and the CrCNiCr coated rotor provided the best test results from the non-baseline material combinations. The torque (friction) level for Test 3 is very similar to the Test 1 levels and the weight loss value for Test 3 is better than the Test 1 value. Phase 1 results from this material combination are very promising and it was selected to be tested under the Phase 2 operating conditions.

[0044] The stator materials for Test 4 and Test 5 were partially composed of hexagonal boron nitride. This material has a low coefficient of friction (e.g., less than 0.2 above 1000 degrees Fahrenheit (F) while graphite's coefficient of friction increases dramatically (e.g., over 0.8) above this temperature. Despite the promising high temperature friction data for these materials, the Test 4 and Test 5 material combinations did not perform well under the Phase 1 test conditions. These materials were not selected for Phase 2 testing.

[0045] The Test 6 material combination of the Tribaloy T-800 coating and the CrC-NiCr coated rotor provided marginally successful results regarding surface roughness and weight loss. The torque (friction) level for Test 6 was higher than the remainder of the Task 4 coatings tested and was not selected for Phase 2 testing.

[0046] The Test 7 material combination of Boronized Inconel and the CrC-NiCr coated rotor provided marginally successful results regarding surface roughness considering the stator roughness increased more than desired. Despite this, the torque (friction) level for Test 7 was lower than the baseline torque from Test 1 (carbon graphite). This low torque level from this material combination is very promising and it was selected for Phase 2 testing.

[0047] The Test 8 material combination of an Alcrona coated stator and the CrC-NiCr coated rotor provided marginally successful results regarding surface roughness, weight loss, and torque. This material combination was not selected for Phase 2 testing.

[0048] The Test 9 material combination of NASA PS304 coated stator and the CrC-NiCr coated rotor provided excellent results regarding surface roughness and marginal results for weight loss. The torque (friction) level for Test 9 was lower than the baseline torque from Test 1 (carbon graphite). This low torque level and low roughness change for this material combination was selected for Phase 2 testing.

[0049] The Test 10 material combination of TiAl Alloy coated stator and the CrC-NiCr coated rotor provided marginally successful results regarding surface roughness, weight loss, and torque. This material combination was not selected for Phase 2 testing.

[0050] The material combinations presented in FIG. 10 were tested under Phase 2 Conditions, i.e., with a chamber temperature varied up to 1200 degrees Fahrenheit

(F), a maximum surface speed at 275 ft/s, a load at the wearing surface at 3.5 psi, and a test duration of 1 hour. FIG. 11 is a plot of the pre-test and post-test surface roughness for the rotor and stators, FIG. 12 is a plot of the pre-test and post test weight change for the rotor and stators, and FIG. 13 is a plot of the average torque during each of the tests. FIG. 14 presents the tabular data relative to tests 11, 12, 13 and 11a.

[0051] The Test 11 material combination of Boronized Inconel stator and the CrC-NiCr coated rotor was able to survive the full test matrix for Phase 2. The surface roughness and weight change experienced by the specimens are similar to what was measured during Phase 1. The average torque measured at the 1000 degrees Fahrenheit (F) isotherm was 0.57in-lb which is much higher than the average torque measured at this same isotherm in Phase 1 testing (0.13in-lb). This offset may have been due to variations in the testing rig after a re-build thereof.

[0052] The material combinations tested in Test 12 and Test 13 did not survive the test past the 72 degrees Fahrenheit (F) isotherm. Both tests were stopped due to an excessive run out in the test rig shaft. To ensure these failures were due to material performance and not due to the re-build of the test rig the Test 11 material combination was re-tested as Test 11A. The data collected from 11A compared very well to data from Test 11. This agreement confirms that the test rig did not contribute to the Test 12 and Test 13 failures.

[0053] Based the Phase 2 test results, Boronized Inconel 718 and CrC-NiCr coated Inconel 718 are appropriate for the stator or seal (e.g., seal 30) and rotor (e.g., rotor 20), respectively. In particular, the average torque was lower than the other materials in test 11A, while the increase in roughness for Boronized Inconel 718 was the least of the other stators listed in FIG. 14. Thus, these materials used as discussed provided high temperature compatibility, good wear characteristics (gradual, as opposed to catastrophic), and the ability to maintain a good surface finish. Other appropriate materials for the stator include hexagonal boron nitride, and NASA PS304 coated Inconel 718. The quality of the NASA PS304 coating in the phase 2 testing was marginal due to the small geometry of the test stators which is believed to have contributed to the marginal result for weight loss in the phase 2 testing. The data from phase 1 shows this material to be appropriate for use as a stator (e.g., seal 30). Based on the available high temperature coefficient of friction data, hexagonal boron nitride appears to also to be a suitable replacement for carbon graphite for seals (e.g., seal 30) in high temperature applications. For example, a seal or stator could be completely made of a binder embedded with a solid lubricant, such as hexagonal boron nitride. The materials included in a stator of a hydrodynamic seal should allow the maintenance of an appropriate operating gap (e.g., up to 0.0002 in.) at an operating temperature of up to 1200 degrees Fahrenheit (F) (e.g., of a high temperature aircraft engine as described above). Further, the material choices for the rotors and stators could be reversed in each particular situation such that the stator material is used on the rotor and the material from the rotor could be used on the stator.

[0054] In another example depicted in FIGS. 15 and 16, a sliding element 100 (e.g., a piston of an engine) may be moveable relative to a sealing portion 110 (e.g., an inner cylinder wall of an engine) which are separated by a gap 120. As described above relative to system 10, these elements may be utilized in extreme temperature environments such that the sliding and/or sealing element may be formed of the materials described above and may have a wear rate and surface roughness sufficient to maintain an operating gap between the sliding element and sealing element of about 0.0002 inches. For example, the sliding element may be formed of, or may be coated with, CrC-NiCr while the sealing element may include Boronized Inconel 718, hexagonal boron nitride or NASA PS304 coated Inconel 718, for example. Alternatively, these material choices of the sealing element versus the sliding element may be reversed.

[0055] It will be understood by one of ordinary skill in the art that the materials described as being appropriate for sliding interfaces (such as linear or rotary) which are to be subjected to extreme environments, such as temperatures above 700 degrees Fahrenheit (F), about 1000 degrees Fahrenheit (F), about 1200 degrees Fahrenheit (F) and above 1200 degrees Fahrenheit (F), while having low leakage, and insensitivity to an oil environment, low wear resistance, low coefficient of friction and low heat generation at a sliding interface.

[0056] It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments (and/or aspects thereof) may be used in combination with each other. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the various embodiments without departing from their scope. While the dimensions and types of materials described herein are intended to define the parameters of the various embodiments, they are by no means limiting and are merely exemplary. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the various embodiments should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. Further, the limitations of the following claims are not written in means-plus-function format and are not intended to be interpreted based on 35 U.S.C. § 112, sixth paragraph, unless and until such claim limitations expressly use the phrase “means for” followed by a statement of function void of further structure. It is to be understood that not necessarily all such objects or advantages described above may be achieved in accordance with any particular embodiment. Thus, for example, those skilled in the art will recognize that the systems and techniques described herein may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other objects or advantages as may be taught or suggested herein.

[0057] While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

[0058] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

Claims:

1. A sealing system for use in an oxidizing environment, said system comprising:

a rotor and a sealing stator;

one of said stator comprising a solid lubricant or a surface treatment with said rotor being hardened and said rotor comprising said solid lubricant or said surface treatment with said stator being hardened; and

said stator located proximate said rotor to provide a seal, said rotor and said stator being robust at temperatures above 700 degrees Fahrenheit such that at least one of said stator and said rotor have a wear rate and a surface roughness sufficient to maintain an operating gap between said stator and said rotor.

2. The sealing system wherein the operating gap is about 0.0002 inches.

3. The system of claim 1 wherein said rotor consists of CrC-NiCr Coated Inconel 718.

4. The system of claim 1 wherein said stator comprises Boronized Inconel 718.

5. The system of claim 1 wherein said stator comprises hot pressed Hexagonal boron nitride.

6. The system of claim 1 wherein said stator comprises NASA PS304 Coated Inconel 718.

7. The system of claim 1 wherein said rotor and said stator comprise a high temperature hydrodynamic lift seal.

8. The system of claim 1 wherein said rotor and said stator comprise a sump seal for an aircraft engine.

9. The system of claim 1 wherein a roughness of said stator is less than 12 micro inches Ra when subjected to a load of about 3.5 psi for about an hour at a temperature of up to about 1200 degrees Fahrenheit.

10. The system of claim 1 wherein said stator comprises a surface roughness of less than about 2.0 micro inches Ra.

11. The system of claim 1 wherein said stator is robust at temperatures up to about 1200 degrees Fahrenheit.

12. The system of claim 1 wherein said stator is robust at temperatures up to about 1000 degrees Fahrenheit.

13. The system of claim 1 wherein said stator is robust at temperatures exceeds 1200 degrees Fahrenheit.

14. The system of claim 1 wherein said rotor comprises a hard coating having a hardness of at least HRC 70.

15. A sealing system for use in an oxidizing environment, said system comprising:

a sliding portion a sealing portion;

one of said sealing portion comprising a solid lubricant or a surface treatment with said sliding portion being hardened, and said sliding portion comprising said solid lubricant or said surface treatment with said sealing portion being hardened; and

said sealing portion located proximate said sliding portion to provide a seal, said sealing portion and said sliding portion being robust at temperatures above 700 degrees Fahrenheit such that at least one of said sealing portion and said sliding portion have a wear rate and surface roughness sufficient to maintain an operating gap between said sealing portion and said sliding portion.

16. The sealing system wherein said operating gap is about 0.0002 inches.

17. The system of claim 15 wherein said sliding portion consists of CrC-NiCr Coated Inconel 718.

18. The system of claim 15 wherein said sealing portion comprises Boronized Inconel 718.

19. The system of claim 15 wherein said sealing portion comprises hot pressed Hexagonal boron nitride.

20. The system of claim 15 wherein said sealing portion comprises NASA PS304 Coated Inconel 718.

21. The system of claim 15 wherein said sliding portion and said sealing portion comprise a high temperature hydrodynamic lift seal.

22. The system of claim 15 wherein said sliding portion and said sealing portion comprise a sump seal for an aircraft engine.

23. The system of claim 15 wherein a roughness of said sealing portion is less than 12 micro inches Ra when subjected to a load of about 3.5 psi for about an hour at a temperature of up to about 1200 degrees Fahrenheit.

24. The system of claim 15 wherein said sealing portion comprises a surface roughness of less than about 2.0 micro inches Ra.

25. The system of claim 15 wherein said sealing portion is robust at temperatures up to about 1200 degrees Fahrenheit.

26. The system of claim 15 wherein said sealing portion is robust at temperatures up to about 1000 degrees Fahrenheit.

27. The system of claim 15 wherein said sealing portion is robust at temperatures exceeds 1200 degrees Fahrenheit.

28. The system of claim 15 wherein said sliding portion comprises a hard coating having a hardness of at least HRC 70.

29. The system of claim 15 wherein said sliding portion and sealing portion remain in contact with one another throughout operation.

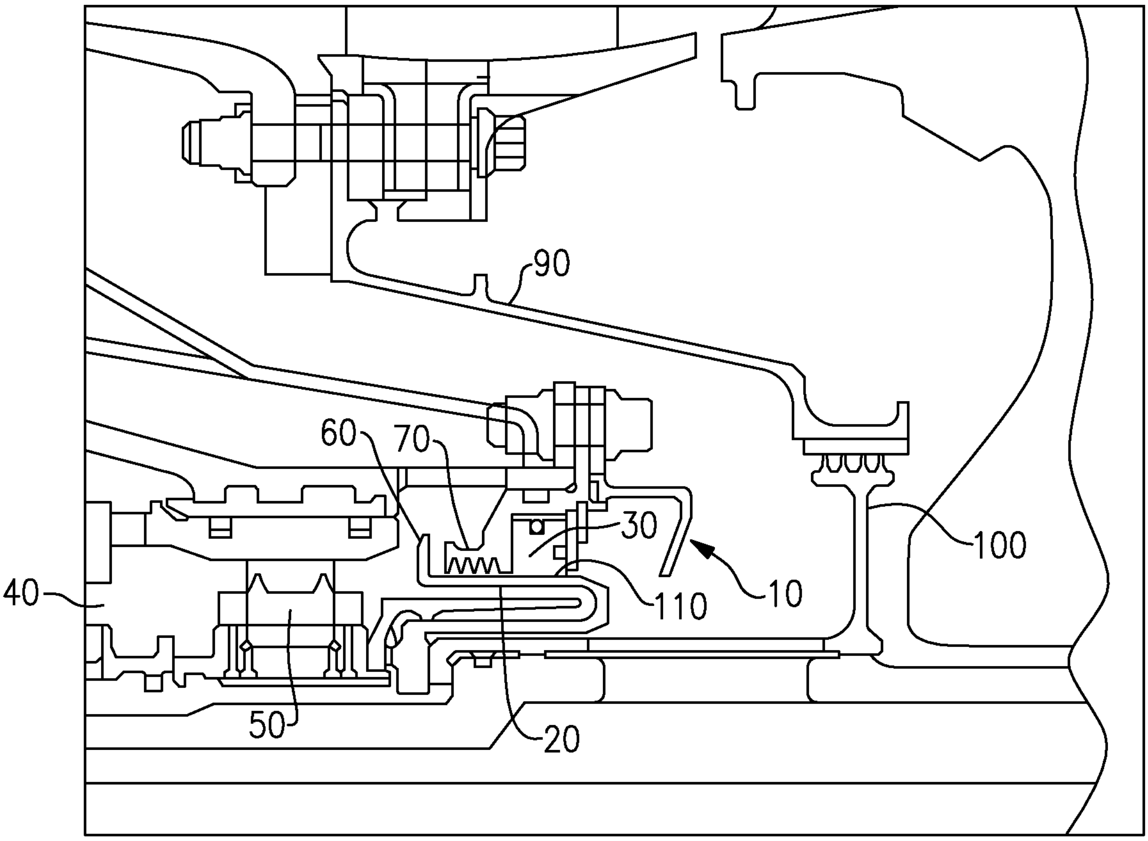


FIG.1

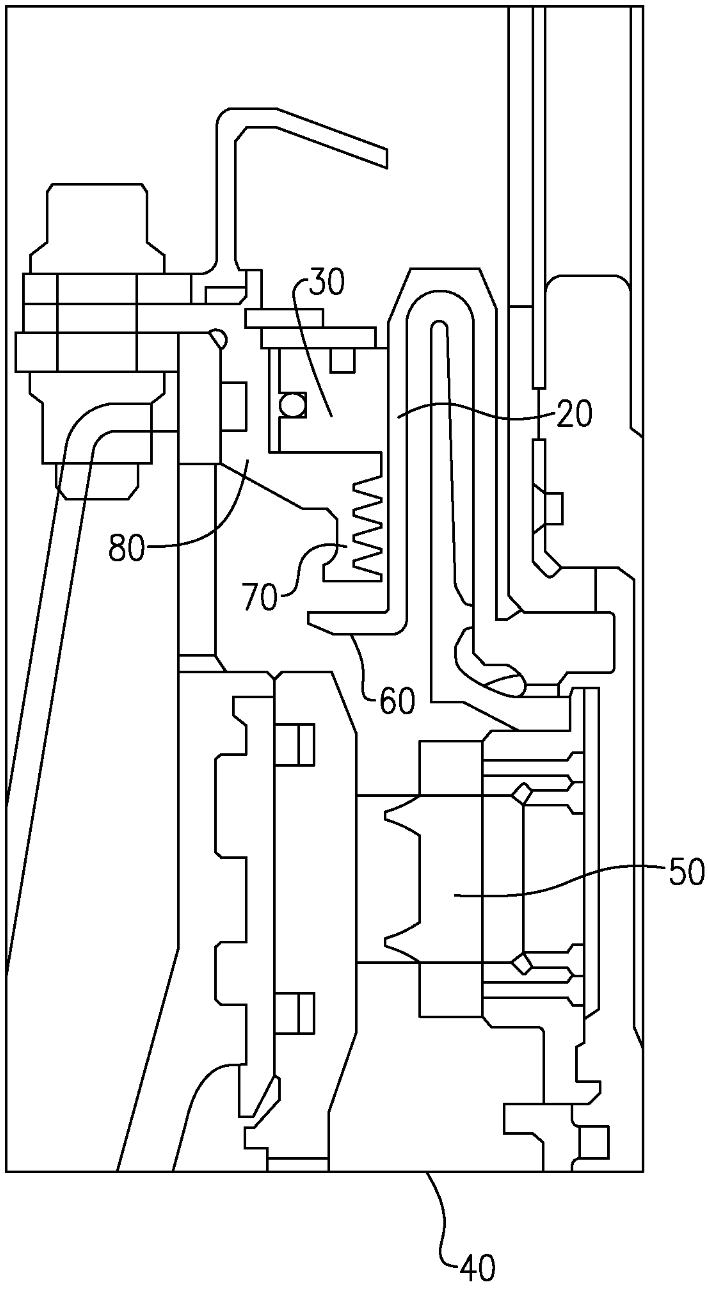


FIG.2

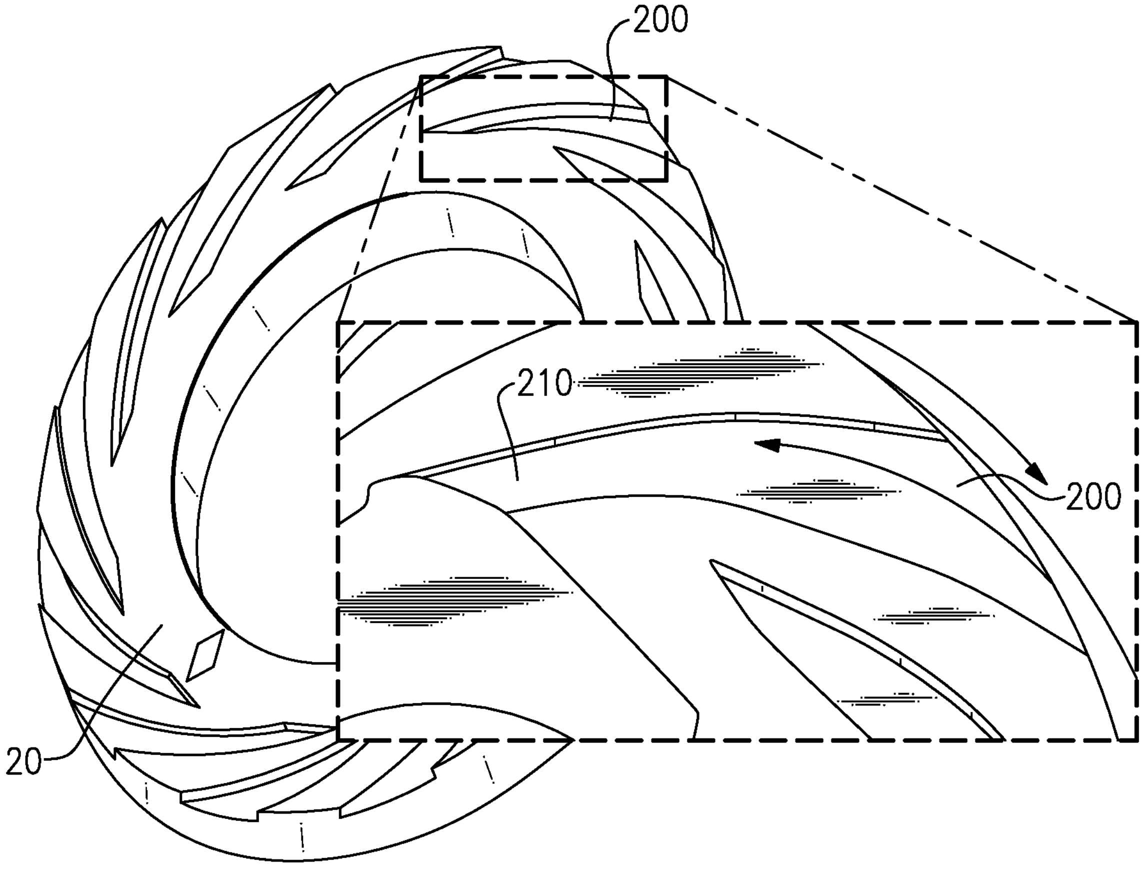


FIG.3

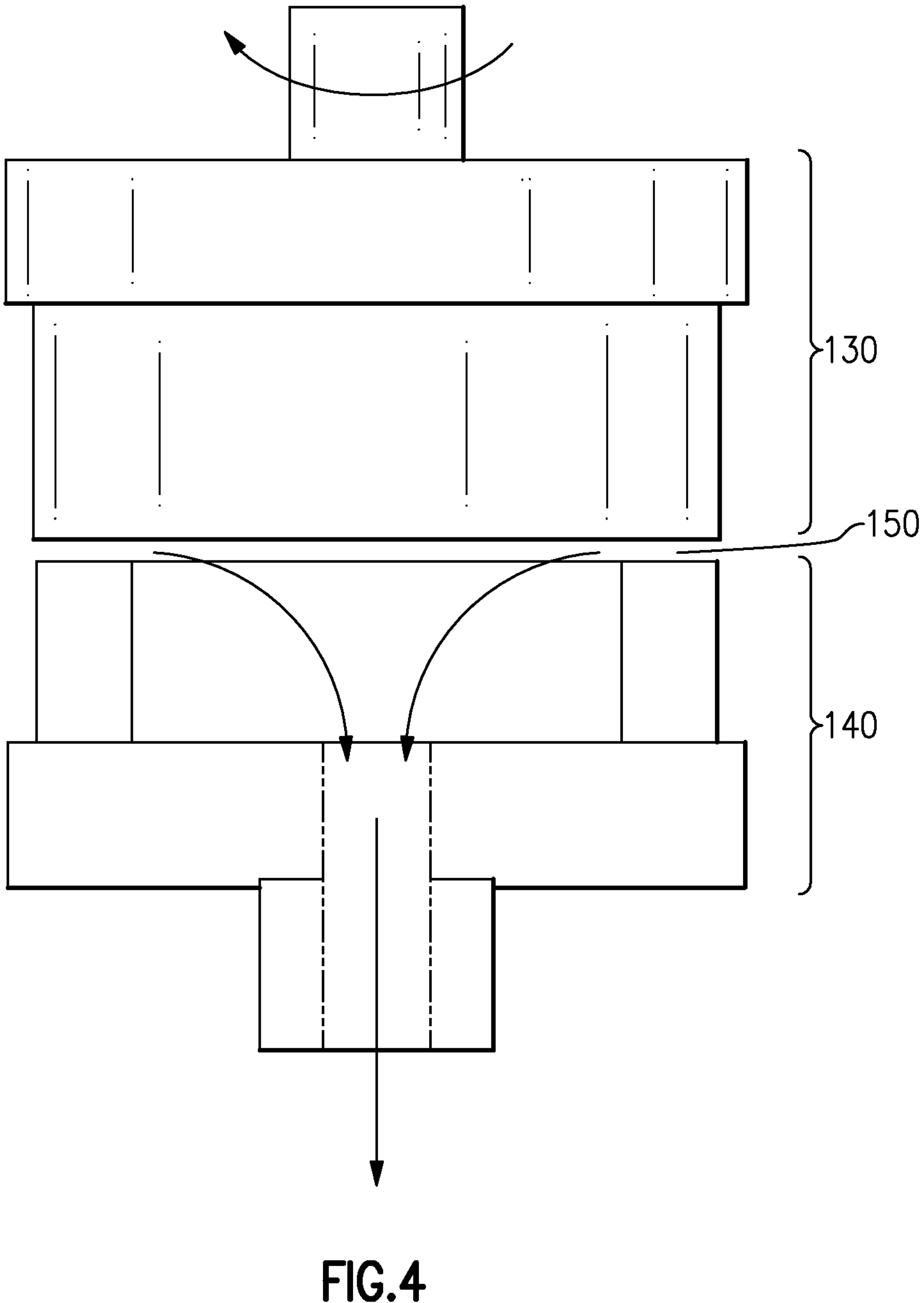


FIG.4

SUMMARY OF MATERIALS TESTED IN PHASE 1 OF TASK 3 AND TASK 4

TASK 3

TEST #	STATOR	ROTOR
1	METCAR M-45 ELECTROGRAPHITE	WC-CO COATED INCONEL 718
2	SAINT GOBAIN HEXOLOY SP SiC	CrC-NiCr COATED INCONEL 718
3	CERADYNE EKASIC T Si_3N_4	CrC-NiCr COATED INCONEL 718
4	SAINT GOBAIN ZSBN HEXAGONAL BORON NITRIDE	CrC-NiCr COATED INCONEL 718
5	SAINT GOBAIN HP HEXAGONAL BORON NITRIDE	CrC-NiCr COATED INCONEL 718

TASK 4

TEST #	STATOR	ROTOR
6	TRIBALOY T-800 COATED INCONEL 718	CrC-NiCr COATED INCONEL 718
7	BORONIZED INCONEL 718	CrC-NiCr COATED INCONEL 718
8	ALCRONA COATED INCONEL 718	CrC-NiCr COATED INCONEL 718
9	NASA PS304 COATED INCONEL 718	CrC-NiCr COATED INCONEL 718
10	TiAl ALLOY COATED INCONEL 718	CrC-NiCr COATED INCONEL 718

FIG.5

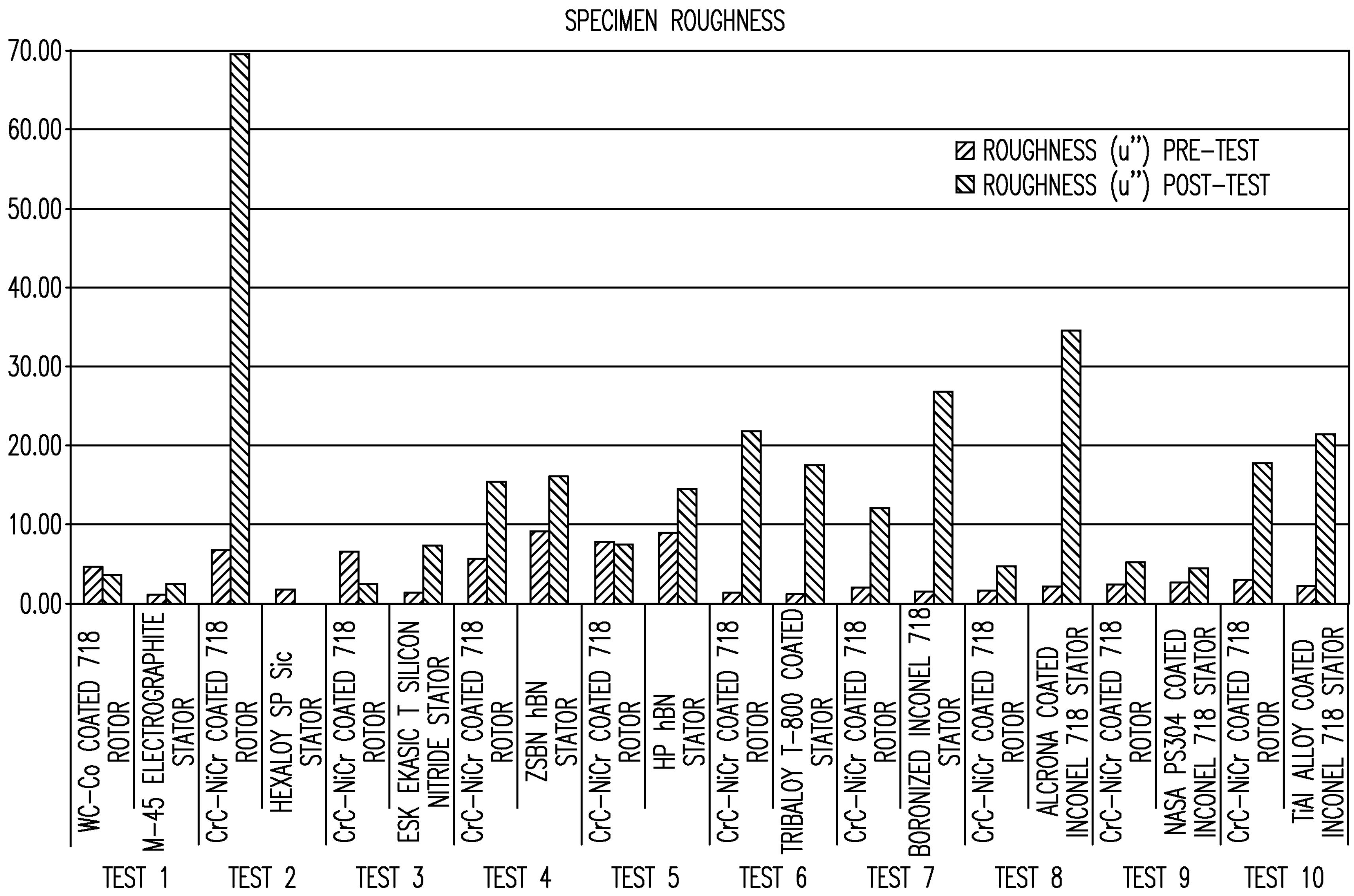

SPECIMEN ROUGHNESS
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
▨ ROUGHNESS (u") PRE-TEST
▧ ROUGHNESS (u") POST-TEST
WC-Co COATED 718 ROTOR
M-45 ELECTROGRAPHITE STATOR
TEST 1
CrC-NiCr COATED 718 ROTOR
HEXALOY SP Sic STATOR
TEST 2
CrC-NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
TEST 3
CrC-NiCr COATED 718 ROTOR
ZSBN hBN STATOR
TEST 4
CrC-NiCr COATED 718 ROTOR
HP hBN STATOR
TEST 5
CrC-NiCr COATED 718 ROTOR
TRIBALOY T-800 COATED STATOR
TEST 6
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 7
CrC-NiCr COATED 718 ROTOR
ALCRONA COATED INCONEL 718 STATOR
TEST 8
CrC-NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
TEST 9
CrC-NiCr COATED 718 ROTOR
TiAl ALLOY COATED INCONEL 718 STATOR
TEST 10

FIG.6

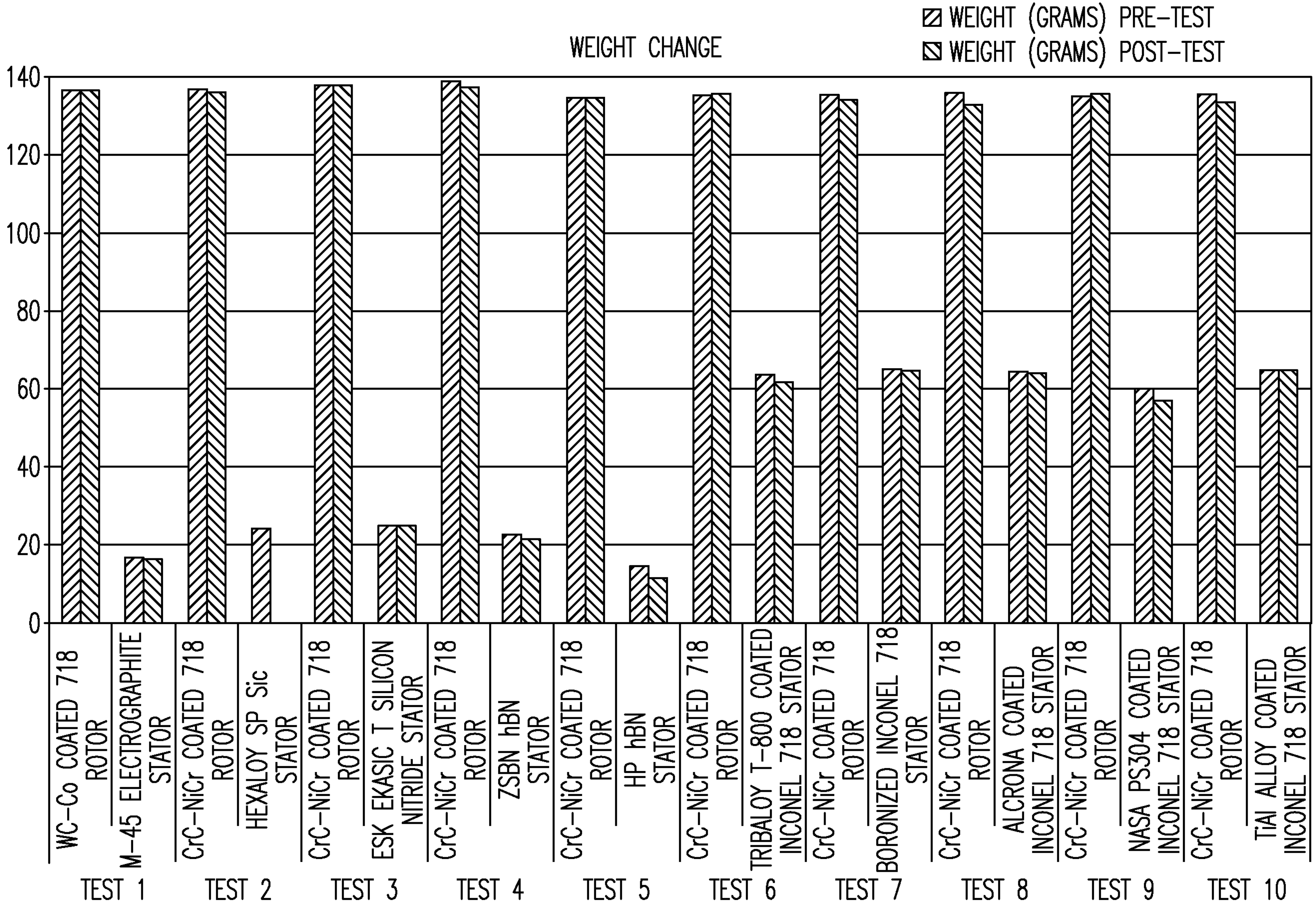
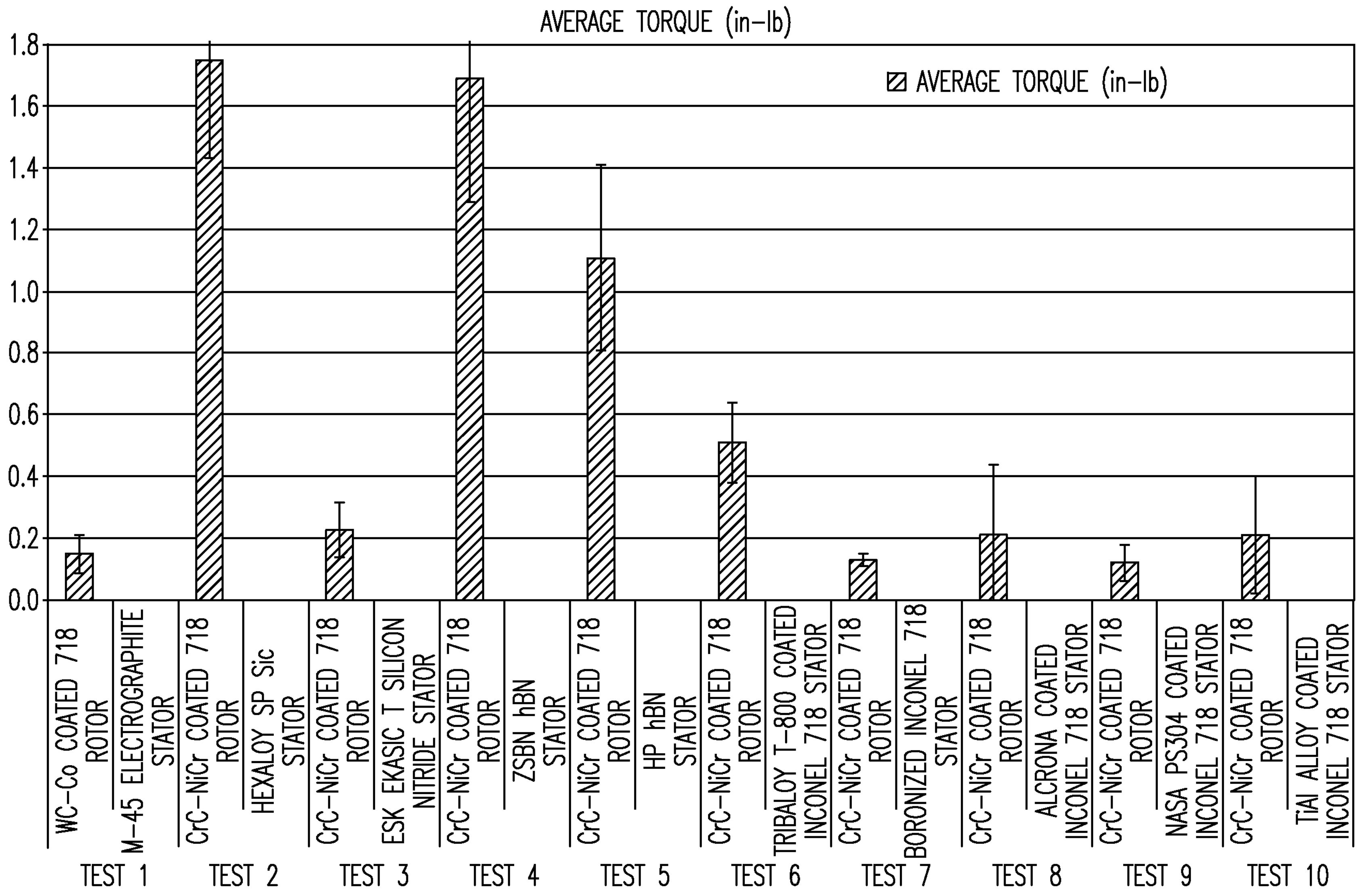

WEIGHT CHANGE
▨ WEIGHT (GRAMS) PRE-TEST
▧ WEIGHT (GRAMS) POST-TEST
140
120
100
80
60
40
20
0
WC-Co COATED 718 ROTOR
M-45 ELECTROGRAPHITE STATOR
CrC-NiCr COATED 718 ROTOR
HEXALOY SP Sic STATOR
CrC-NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
CrC-NiCr COATED 718 ROTOR
ZSBN hBN STATOR
CrC-NiCr COATED 718 ROTOR
HP hBN STATOR
CrC-NiCr COATED 718 ROTOR
TRIBALOY T-800 COATED INCONEL 718 STATOR
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
CrC-NiCr COATED 718 ROTOR
ALCRONA COATED INCONEL 718 STATOR
CrC-NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
CrC-NiCr COATED 718 ROTOR
TiAl ALLOY COATED INCONEL 718 STATOR
TEST 1
TEST 2
TEST 3
TEST 4
TEST 5
TEST 6
TEST 7
TEST 8
TEST 9
TEST 10

FIG.7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▨ AVERAGE TORQUE (in-lb)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
WC-Co COATED 718 ROTOR
M-45 ELECTROGRAPHITE STATOR
TEST 1
CrC-NiCr COATED 718 ROTOR
HEXALOY SP Sic STATOR
TEST 2
CrC-NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
TEST 3
CrC-NiCr COATED 718 ROTOR
ZSBN hBN STATOR
TEST 4
CrC-NiCr COATED 718 ROTOR
HP hBN STATOR
TEST 5
CrC-NiCr COATED 718 ROTOR
TRIBALOY T-800 COATED INCONEL 718 STATOR
TEST 6
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 7
CrC-NiCr COATED 718 ROTOR
ALCRONA COATED INCONEL 718 STATOR
TEST 8
CrC-NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
TEST 9
CrC-NiCr COATED 718 ROTOR
TiAl ALLOY COATED INCONEL 718 STATOR
TEST 10

FIG.8

		ROUGHNESS (u")		WEIGHT (GRAMS)		AVERAGE TORQUE (in-lb)	STDEV	MAX. STATOR TEMP.
		PRE-TEST	POST-TEST	PRE-TEST	POST-TEST			
TEST 1	WC-Co COATED 718 ROTOR	4.65	3.62	136.92	136.99	0.15	0.06	1097degF
	M-45 ELECTROGRAPHITE STATOR	1.18	2.55	16.89	16.62			
TEST 2	CrC-NiCr COATED 718 ROTOR	6.78	69.48	136.85	136.19	1.75	0.32	1317degF
	HEXALOY SP Sic STATOR	1.82	NA	24.53	NA			
TEST 3	CrC-NiCr COATED 718 ROTOR	6.49	2.47	138.19	138.13	0.23	0.09	1105degF
	ESK EKASIC T SILICON NITRIDE STATOR	1.41	7.36	25.27	25.27			
TEST 3	CrC-NiCr COATED 718 ROTOR	5.78	15.45	139.30	137.45	1.69	0.40	1561degF
	ZSBN hBN STATOR	9.12	15.93	22.86	21.63			
TEST 5	CrC-NiCr COATED 718 ROTOR	7.74	7.45	135.07	135.08	1.11	0.30	1404degF
	HP hBN STATOR	8.86	14.40	14.77	11.53			
TEST 6	CrC-NiCr COATED 718 ROTOR	1.43	21.76	135.47	135.91	0.51	0.13	1192degF
	TRIBALOY T-800 COATED INCONEL 718 STATOR	1.10	17.55	63.88	61.99			
TEST 7	CrC-NiCr COATED 718 ROTOR	2.13	12.12	135.49	134.34	0.13	0.02	1346degF
	BORONIZED INCONEL 718 STATOR	1.54	26.87	65.18	64.96			
TEST 8	CrC-NiCr COATED 718 ROTOR	1.67	4.73	136.24	133.31	0.21	0.23	1233degF
	ALCRONA COATED INCONEL 718 STATOR	2.24	34.50	64.63	64.40			
TEST 9	CrC-NiCr COATED 718 ROTOR	2.56	5.11	135.27	135.73	0.12	0.06	1195degF
	NASA PS304 COATED INCONEL 718 STATOR	2.59	4.42	60.05	57.16			
TEST 10	CrC-NiCr COATED 718 ROTOR	3.05	17.82	135.82	133.98	0.21	0.19	1228degF
	TiAL ALLOY COATED INCONEL 718 STATOR	2.17	21.34	65.09	64.89			

FIG.9

SUMMARY OF MATERIALS TESTED IN PHASE 2 OF TASK 3 AND TASK 4

TASK 3

TEST #	STATOR	ROTOR
11	BORONIZED INCONEL 718	CrC-NiCr COATED INCONEL 718
12	CERADYNE EKASIC T Si_3N_4	CrC-NiCr COATED INCONEL 718
13	TRIBALOY T-800 COATED INCONEL 718	CrC-NiCr COATED INCONEL 718
11A	BORONIZED INCONEL 718	CrC-NiCr COATED INCONEL 718

FIG.10

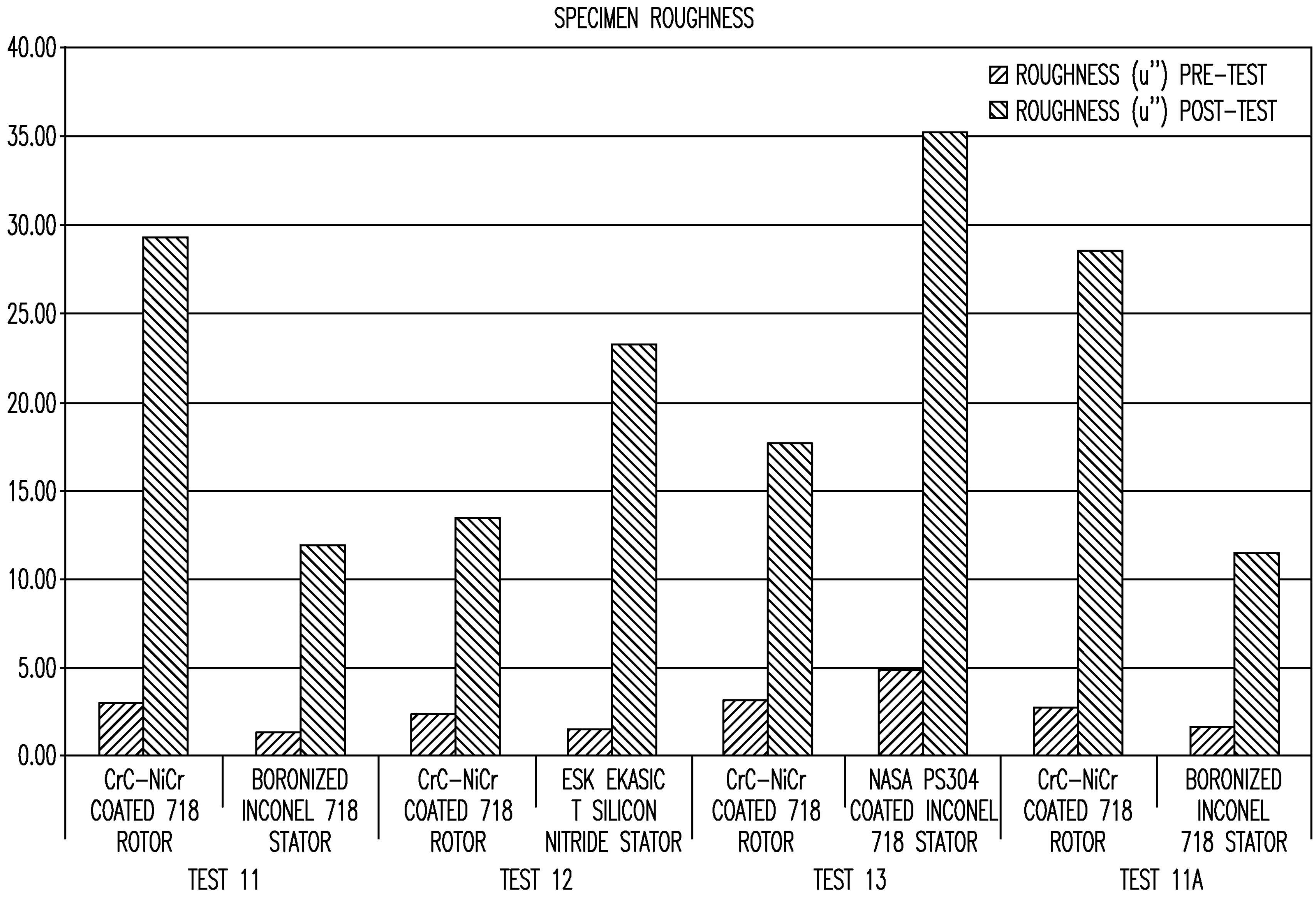
SPECIMEN ROUGHNESS
▨ ROUGHNESS (u") PRE-TEST
▧ ROUGHNESS (u") POST-TEST
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11
CrC-NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
TEST 12
CrC-NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
TEST 13
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11A

FIG.11

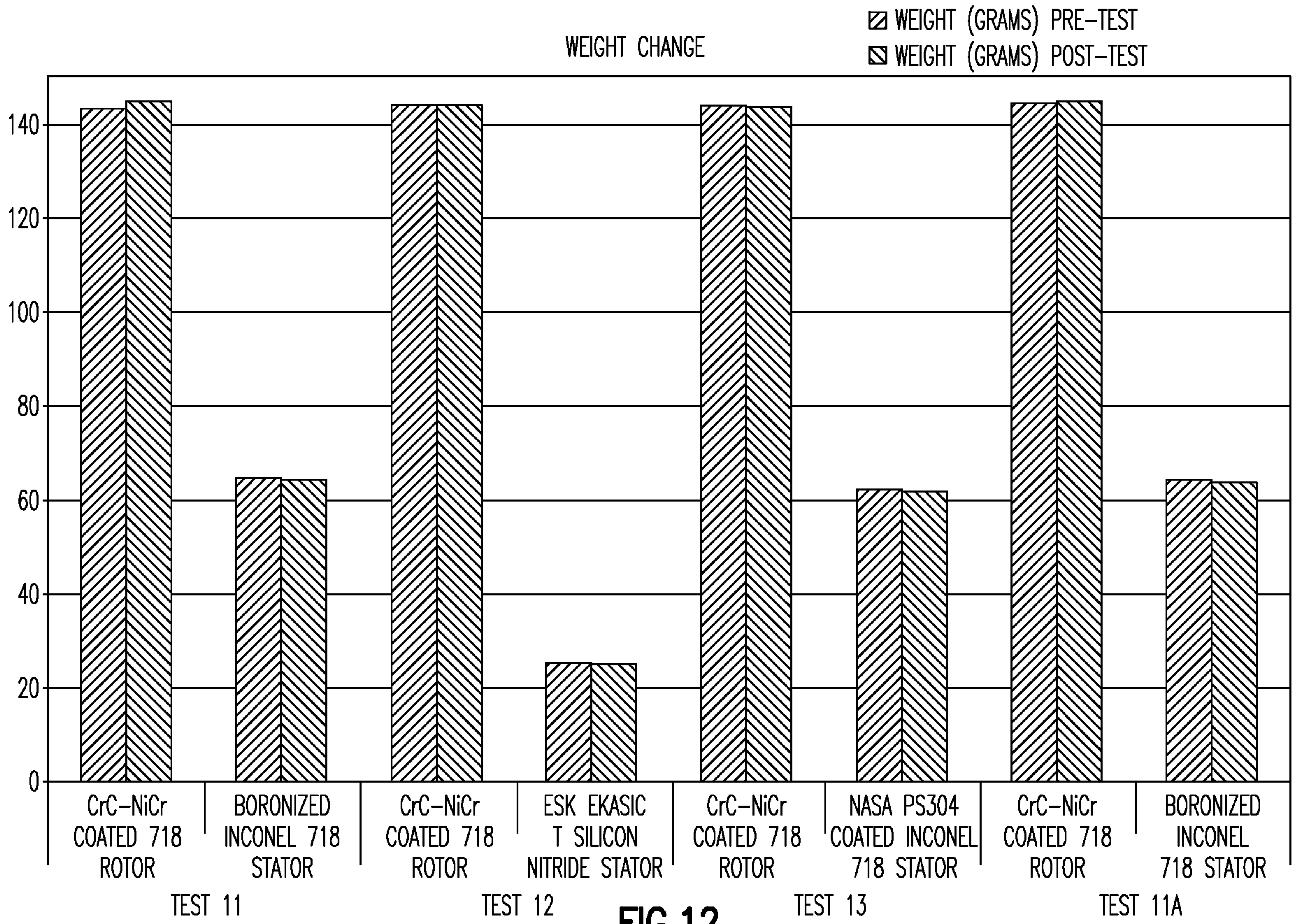
WEIGHT CHANGE
▨ WEIGHT (GRAMS) PRE-TEST
▧ WEIGHT (GRAMS) POST-TEST
140
120
100
80
60
40
20
0
CrC–NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11
CrC–NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
TEST 12
CrC–NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
TEST 13
CrC–NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11A

FIG.12

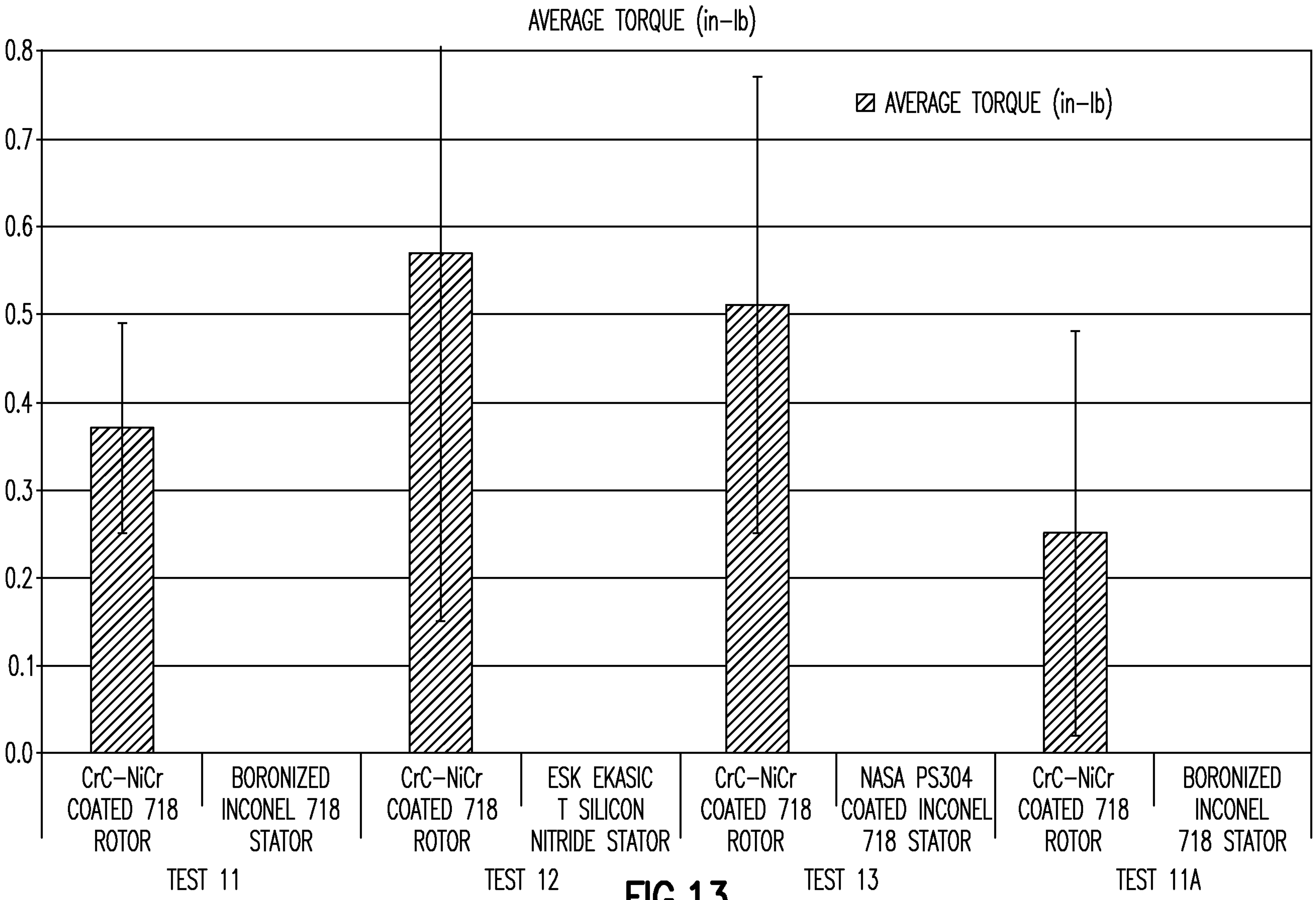
AVERAGE TORQUE (in-lb)
▨ AVERAGE TORQUE (in-lb)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11
CrC-NiCr COATED 718 ROTOR
ESK EKASIC T SILICON NITRIDE STATOR
TEST 12
CrC-NiCr COATED 718 ROTOR
NASA PS304 COATED INCONEL 718 STATOR
TEST 13
CrC-NiCr COATED 718 ROTOR
BORONIZED INCONEL 718 STATOR
TEST 11A

FIG.13

		ROUGHNESS (u")		WEIGHT (GRAMS)		AVERAGE TORQUE (in-lb)	STDEV
		PRE-TEST	POST-TEST	PRE-TEST	POST-TEST		
TEST 10	CrC-NiCr COATED 718 ROTOR	2.97	29.24	143.46	145.03	0.37	0.12
	BORONIZED INCONEL 718 STATOR	1.36	11.92	64.6787	64.54		
TEST 12	CrC-NiCr COATED 718 ROTOR	2.45	13.42	144.01	144.01	0.57	0.12
	ESK EKASIC T SILICON NITRIDE STATOR	1.51	23.25	25.12	25.11		
TEST 13	CrC-NiCr COATED 718 ROTOR	3.14	17.60	144.18	143.86	0.51	0.26
	NASA PS304 COATED INCONEL 718 STATOR	4.87	35.2	62.27	61.92		
TEST 11A	CrC-NiCr COATED 718 ROTOR	2.76	28.50	144.84	145.03	0.25	0.23
	BORONIZED INCONEL 718 STATOR	1.66	11.4	64.40	63.86		

FIG.14

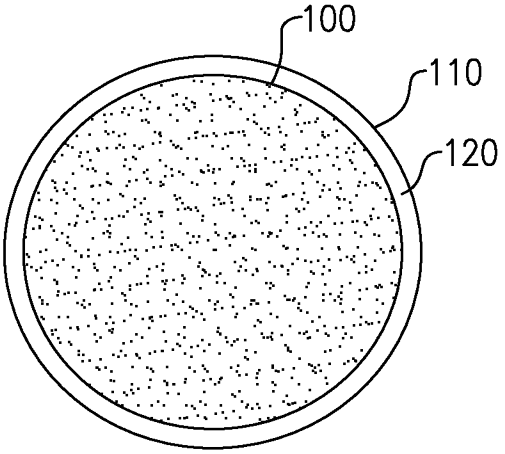

FIG.15

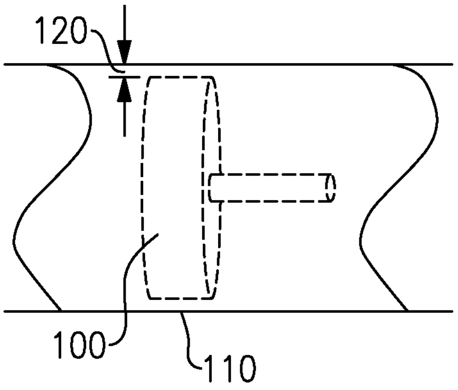

FIG.16

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/051783

A. CLASSIFICATION OF SUBJECT MATTER
INV. F01D11/02 F16J15/453
ADD.

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)
F01D F16J

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 7 703 774 B2 (AWTAR SHORYA [US] ET AL) 27 April 2010 (2010-04-27) column 4, lines 8-18 -----	1-3, 15-17 5,19
Y	WO 2011/111433 A1 (MITSUBISHI HEAVY IND LTD [JP]; UEHARA HIDEKAZU [JP]; SHINOHARA TANEHIR) 15 September 2011 (2011-09-15) abstract & US 2012/261884 A1 (UEHARA HIDEKAZU [JP] ET AL) 18 October 2012 (2012-10-18) paragraphs [0096], [0102] - [0104]; figures 3,6 -----	5,19
X Y	US 2003/098132 A1 (MANSDORFER GARY A [US]) 29 May 2003 (2003-05-29) paragraphs [0023], [0024]; figure 3 ----- -/--	1,15 2-14, 16-29

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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
16 November 2012

Date of mailing of the international search report
22/11/2012

Name and mailing address of the ISA/
European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer
Steinhauser, Udo

3

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2012/051783

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 505 837 B1 (HESHMAT HOOSHANG [US]) 14 January 2003 (2003-01-14) column 3, lines 27-38; figure 1 column 6, lines 35-49	1,15
Y	US 2010/213674 A1 (GARRISON GLENN M [US] ET AL) 26 August 2010 (2010-08-26) paragraphs [0048], [0055] - [0057]; figure 1	2-14, 16-29
X	GB 1 201 949 A (UNITED AIRCRAFT CORP [US]) 12 August 1970 (1970-08-12) page 4, lines 76-104; figure 4	1,15
X	GB 455 474 A (GUSTAV HUHN) 21 October 1936 (1936-10-21) page 2, line 126 - page 3, line 23; figure 3	1,15
A	US 5 755 445 A (ARORA GULSHAN K [US]) 26 May 1998 (1998-05-26) column 6, lines 24-46; figures 2,5	1-29
A	EP 2 056 004 A1 (GEN ELECTRIC [US]) 6 May 2009 (2009-05-06) paragraph [0017]; figure 2	1-29

3

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2012/051783

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