A review of wear resistance materials used in power-screw mechanism for aerospace applications

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1. Abstract

In today’s industrial requirement, good wear resistant materials with the same or better mechanical properties are the need of the hour. In the present paper, an actuator that is used to lift the load is under study. It uses a linear actuation mechanism involving a screw-like motion to lift the loads. It employs a stainless steel of high quality. Since there are various types of wearing involved in the system, choice of the materials becomes the prime factor for determining the maintenance cost and the cycle life of the actuator. There are many research advances made in this field which provides us with the best type of material for its particular type of job. The present paper discusses the materials that could be substituted in place of the existing material choice i.e., in place of AMS5659 and aluminium-bronze. The two materials stated above are known for its superior wear handling and excellent mechanical properties.

Keywords: AMS 5659, Aluminium bronze, wear resistance materials

2. Introduction

The necessity to find the highly wear resistant materials is of high importance to any industry as it affects the performance and quality of the products it produces. Wear of a material is defined as surface phenomenon and deals with the removal of material from one or both of the solid surfaces in sliding, rolling or impact motion relative to one another [1, 2]. The present paper deals with a power-screw mechanism that deals with two materials in contact with each other. A power-screw mechanism is used when the rotary motion of the screw is to be converted to a required linear motion overall [3]. It employs two parts, namely, the screw and the nut. The screw material under study is the AMS 5659 stainless steel and the nut material under study is the Aluminium bronze. Tables 1 and 2 shows the properties of the metals used. The major challenges faced during the usage of these materials is that due to the rise in temperature between the materials during the operations, the softer material being Aluminium bronze, melts over the surface of the screw material, AMS 5659. This adhesive wear causes problems in the mechanism over the long run. Due to the accumulation of the softer particles on the harder material, the service life of the mechanism reduces. Also, the maximum extension of the mechanism cannot be achieved due to the increase of friction between the two components. Hence, this reduces the overall usage of the mechanism. The main aim of this paper is to suggest a different range of materials that could be used for the mechanism that could replace either or both of the materials in the mechanism. The range of materials could be from metals, non-metals, metallic coatings, hybrid composites and polymers.
Table 1: Mechanical properties of AMS 5659 under different heating conditions [4]

| Materials         | Condition | Ultimate tensile strength | % Reduction in Area | Rockwell Hardness |
|-------------------|-----------|---------------------------|---------------------|-------------------|
| Alloy 15-5 PH Bar AMS 5659 | Cond A    | -                         | -                   | 363 HB max        |
| Alloy 15-5 PH Bar AMS 5659 | H900      | 190                       | 35                  | 388-444           |
| Alloy 15-5 PH Bar AMS 5659 | H925      | 170                       | 38                  | 375-429           |
| Alloy 15-5 PH Bar AMS 5659 | H1025     | 155                       | 45                  | 331-401           |
| Alloy 15-5 PH Bar AMS 5659 | H1075     | 145                       | 45                  | 311-375           |
| Alloy 15-5 PH Bar AMS 5659 | H1100     | 140                       | 45                  | 302-363           |
| Alloy 15-5 PH Bar AMS 5659 | H1150     | 135                       | 50                  | 277-352           |

Table 2: Mechanical properties of Aluminium-bronze [5]

| Properties                              | Values |
|-----------------------------------------|--------|
| Hardness, Rockwell C                    | 27     |
| Tensile Strength (MPa)                  | 690    |
| Yield Strength (MPa)                    | 380    |
| Compressive yield strength (MPa)        | 880    |
| (At permanent set of 1%)                |        |
| Poisson’s Ratio                         | 0.34   |
| Shear Modulus (GPa)                     | 42.3   |

3. Materials used in the domain

As mentioned earlier, the materials selection could vary from metals to non-metals to polymers. The selection of materials is based on the cost of handling the material, the availability of the material, transportation costs and the mechanical properties of them. The wear resistance of a material is directly
proportional to the hardness of the material. Keeping these factors in mind, the following is the list of materials that could be chosen in order to replace the above-mentioned parent materials.

### 3.1 Coatings

#### 3.1.1 Diamond-like carbon coating:
Diamond-like carbon (DLC) is defined as an amorphous carbon (a-C) having structural, mechanical, electrical, optical, chemical, and acoustic properties similar to those of diamond [6]. The name “diamond-like carbon” is currently used widely when at least one property is similar to diamond. Diamond-like carbon coating (DLC) are very popular as a result of their superior properties such as high hardness and low coefficient of friction. The major challenges faced in the diamond-like carbon coating is that it develops high internal compressive stress and has a low adhesion. The internal stresses increases with increasing sp³ content in the (sp³/sp²) ratio.

#### 3.1.2 Plasma Nitriding:
Plasma nitriding produce high surface hardness, good wear resistance, increased fatigue strength and toughness. The major advantages of using the plasma nitriding process are that at a lower working temperature (about 300°C), nitriding can be performed. Also, the treatment time taken for the plasma nitriding process is much faster when compared with the other nitriding processes [7]. Even though it has advantages, it has a certain drawbacks as well. The initial cost of setup for the plasma nitriding is high and also the nitriding of complex parts is difficult.

#### 3.1.3 PVD Coating:
PVD (or Physical Vapour Deposition) refers to a variety of thin film deposition techniques in which a solid material is vaporised in a vacuum environment and deposited on substrates as pure metals or alloy composition coating [8,9]. There are three methods of PVD coating which could be employed for a material. They are:
1. Evaporation PVD
2. Sputtering PVD
3. Cathodic Arc PVD

PVD Coatings have more advantages when compared to other types of deposition techniques as they do not use any chemicals in their process and they do not require extensive clean up [10]. The major disadvantage of using PVD coating is it has higher cost of operation. Also, the process requires a skilled operator and complex machinery. The rate of operation of PVD is also quite slow. However, PVD coating remains one of the most effective way of coating.

#### 3.1.4 Salt bath Nitriding:
In salt bath nitriding the nitrogen donating medium is a nitrogen containing salt such as cyanide salt. The salts used also donate carbon to the workpiece surface making salt bath a nitro carburizing process. The temperature used is typical of all nitro carburizing processes: 550 to 570 °C [11]. The advantages of salt nitriding is that it achieves higher diffusion in the same period of time compared to any other method. Also, the processing time for this process is very quick usually in the order of 4 hours to achieve. The drawbacks of this process are that because it uses highly toxic salts as a source of nitrogen to diffuse through the ferrous matrix, any substance containing Nitrogen (N) and Carbon (C) releases cyanide gas when subjected to heat conditions.

#### 3.1.5 Silicon Carbide Coating:
Silicon carbide (SiC) is one of the most important advanced ceramics in contemporary usage [12]. With an exceptional hardness of 25 GPa, and a low density of 3.21 g cm⁻³, SiC ceramics see their most important commercial use as lightweight armour ceramics, with wear resistant linings another leading application [13,14]. The advantage of using this material is that it has a high temperature resistance and can be used as a refractory material. Also, due to its high hardness value, it could be used in multiple applications [15]. The thermal conductivity of this material is limited and the power loss in this material is considerably high.

### 3.2 Metals
3.2.1 HARDOX400 Stainless steel: HARDOX 400 stainless steel is an abrasion resistant stainless steel with a nominal hardness of 400 HBW. It is an all-around stainless steel. The very important property of HARDOX 400, which guarantees the long life of products, is a fact, that HARDOX 400 plates are full hardened. HARDOX 400 steel can be welded without initial warming up until the plates' thickness 40 mm. The impact strength and plasticity of HARDOX 400 are on the high level. The HARDOX 400 can be used in some cases as a construction plate carrying the load. The high hardness of HARDOX steel is acquired thanks to heat treatment in continuous process [17].

3.2.2 EN41B with active screen plasma nitriding: The process parameters of 500°C temperature for 4 hours with the gas flow in the ratio of H₂:N₂= 1:1 were used for the treatment. The improvement in the surface was assessed by the micro hardness as well as SEM (Scanning electron microscope) and XRD (X-Ray Diffusion). The micro hardness value reveals that there is 4 times more hardness than the parent EN41B material [18].

3.2.3 Boron Carbo-nitride: Ternary compounds containing boron, carbon and nitrogen are potential candidates as super-hard materials. These compounds are essentially carbon alloys. The major advantages of using this metal is that it is known to have excellent erosion characteristics and high resistance to wear under high energy loads. However, one of the drawbacks of boron carbo-nitride is that it starts oxidising at temperatures of over 500°C [19].

3.3 Hybrid Composites: Hybrid composites prepared from ceramics and polymers are a class of materials that combines the benefits of both phases to produce materials with enhanced properties not achieved by either phase alone. The advantages of using the hybrid composites are balanced strength and stiffness, balanced bending and membrane mechanical properties, balanced thermal distortion stability, reduced weight and/or cost and improved fatigue resistance [20, 21]. However, the challenges faced in this are high cost, high density, and high weight [22, 23]. In addition to this it have large impact on environment while preparing these fibres and their related composites.

3.4 Polymers: Polymers are replacing classical metal parts in terms of sliding parts because of their rapid development with better tribological, mechanical and corrosion properties. The successful applications of unfilled polymers in engineering purposes led to use of polymers as composites, where modifications to properties could be achieved by adding one or several reinforcing fillers [24]. The fillers provide high hardness, strength or elasticity, while the matrix, which is a polymeric material, adds a self-lubricating effect. This unique combination combines the best and suppresses the worst properties of the individuals. In the recent research of materials, self-healing polymers have been discovered [25]. These materials reorganize polymeric bonds and structures under external stresses, which makes them highly wear resistant. In bearing and wear applications, polymers provide extensive advantages over metals by allowing for lower power motors for moving parts due to lower frictional properties of polymer wear components compared to metals [26]. Also, the lower wear rates allow for the less maintenance related downtime. Even with the said advantages, the polymers have a certain set of disadvantages. It has low thermal resistance, high coefficient of thermal expansion. Under extensive usage, temperature is bound to increase which will change the geometric dimensions of the material, hence, rendering it as a liability. Also, polymers have a low strength and low stiffness (modulus of elasticity).
4. Comparison of properties

**Coatings**

**Table 3**: Comparison of properties of various coatings

|                          | Hardness     | Tensile Strength | Yield Strength |
|--------------------------|--------------|------------------|----------------|
| Diamond-like carbon Coating (DLC) | 71-80 HRC | 420 MPa | 220 MPa |
| Plasma Nitriding         | 58-63 HRC | 370-741 MPa | 337-679 MPa |
| PVD Coating              | 67 HRC     | 570 MPa | 243 MPa |
| Salt bath nitriding      | 50-70 HRC | 535 MPa | 240 MPa |
| Silicon Carbide coating  | 2480-2960 HK | 240 ksi | 21 GPa |

From the above table, it can be seen that the hardness value of Silicon carbide coating is the highest owing to the fact that the material behaves as a ceramic and hence, the hardness value [6-15].

**Metals**

**Table 4**: Comparison of properties of various metals

|                          | Hardness     | Tensile Strength | Yield Strength |
|--------------------------|--------------|------------------|----------------|
| HARDOX400 SS             | 370-470 HB   | 1250 MPa         | 900 MPa        |
| EN41B with active screen plasma nitriding | 201-277 HB | 700-925 MPa | 480-525 MPa |
| Boron Carbonitride       | 1261 HV     | 240-315 MPa | 150 MPa        |

The above table depicts the comparison of metallic elements that have a good wear resistance when compared with the parent materials. Hardox 400 stainless steel has very high values and is the best suitable metal for the application. The active screen plasma nitriding refers to the fact that the covering screen also participates in the nitriding process. The range of values for the EN41B material is due to the fact that there are two types of compounds formed during the nitriding: R and S type. The range of values is the combined values of both R and S types. The R and S types refers to the heating conditions of martensitic steel [16-19].
Non-metals

Table 5: Comparison of properties of various Non-metals

| Material         | Maximum service temperature (°F) (oxidising conditions) | Room temperature hardness (Knoop) | Melting point (°F) |
|------------------|----------------------------------------------------------|-----------------------------------|-------------------|
| Diamond          | 1500                                                     | 7000                              | 1800 (carbonizes) |
| TiB₂             | 1800                                                     | 2700                              | 5250              |
| ZrO₂             | 4200                                                     | -                                 | 4850              |
| WC               | 1200                                                     | 1880                              | 4770              |
| BeO              | 4300                                                     | 1220                              | 4660              |
| TiC              | 1800                                                     | 2460                              | 5660 (sublimates) |
| BC               | 1800                                                     | 2800                              | 4430              |
| SiC              | 1750                                                     | 2500                              | 4160              |
| Al₂O₃ (dense)    | 3500                                                     | 2000                              | 3720              |
| Cr₃C₂            | -                                                        | -                                 | 3600              |
| Cr-Mo-Al₂O₃ cermet | 2300                                                   | 50 RC                              | 3360 (approx.)    |

Diamond is the hardest known material among the non-metals and even in the metals. Owing to the fact that diamond is quite expensive, it cannot be used everywhere. A diamond tip could be given to tools which are involved in the manufacturing of very high important components that require high precision. Of the other non-metals, the ceramic natured compounds like TiC, SiC, and BC and so on have the hardness values exceeding 2000 in Knoops hardness. As mentioned earlier, higher the hardness value, higher is the wear resistance of that material. Hence, among the other non-metallic materials, BC and TiB₂ have the highest wear resistance [28].

5. Future Materials

Tribology, the science of friction, wear and lubrication, has often been regarded as standing on the sidelines of material sciences. It is important to appreciate that “wear resistance” is emphatically not a materials property. In considering a simple mechanical problem such as deflection of beams, it is clear that the behaviour does not depend only on the beam material but also the geometry of the beam.
Similarly, the rates of wear in a tribological system in which two solid bodies slide against each other depend not only on the properties of the materials involved, but also on geometry of contact, velocity of sliding, the ambient temperature and environmental conditions. There has been a rapid recent progress in the development of new materials. Among the “conventional” bulk metals, polymers and ceramics, most improvements in wear resistance have in the past been incremental and will probably remain so in the future. Nevertheless, with a better understanding of the factors that influence wear rate, significant further improvements will undoubtedly be possible, and maybe achieved with lesser problems that there has been in the past.

No review of future developments would be complete without the mentions of “smart materials” [29]. These are the materials that possess some ability to sense their environment and to respond in a controlled way to that stimulus. It can be argued that so far no truly smart materials have been developed and demonstrated. A smart material for a tribological application might respond to the stimulus of surface tractions or deformations by changing some aspects of its surface in order to improve its ability to resist wear or to reduce frictional traction. For example, the good resistance of Hadfield manganese steel to certain types of impact abrasion, for instance, is due to the stress-induced transformation of the austenitic structure to martensitic structure when the surface is deformed; the hardness increases locally from 200 to 600 HV [30]. Whether concepts such as these can provide methods for improving the tribological performance of the material and whether it might be possible locally to modify the surface stresses remains a stimulating question for future [31].

6. Conclusion

A lead screw, also known as a power screw or translation screw, is a screw shaft that rotates causing a nut to move linearly along the shaft. It’s difficult to pinpoint when lead screws were first invented because you could say that the original grape and olive presses were a form of lead screw. Lead screws have also been used for many years in various types of vices, jacks, and machine slides. The power screw mechanism is used in places where a rotary motion is to be converted to a linear motion. Various materials have been used in the power screw mechanism in order to evade the wearing of the materials and hence, limit the usage of the mechanism. A continuous research is being done with respect to finding the best suitable material for all the right applications. In the recent days, a platinum gold alloy has been developed that is claimed to have the hardness close to the value of the diamond. It is supposed to have a durability 100 times more than that of steel. The alloy consists of 90% platinum and 10% gold.

For the present case however, there cannot be a particular material that could replace the parent material as each class of material has its own properties. Hence, choosing a material from the class is more advisable than just choosing a single particular material.

Observing the properties of the above stated materials, the silicon carbide coating produces the highest wear resistance amongst all the other coatings. However, the salt bath nitriding produces a considerably high hardness value and is comparatively cheaper that the other processes. Hence, among the coatings, salt bath nitriding would be a good choice for the material coating.

Among the metals, replacement of the material is only possible. From the table 4, it is clearly visible that the HARDOX400 Stainless steel is the best choice of metal. It has the highest hardness value in the metals and also shows a good tensile strength. Also, the material cost is cheaper than that of other two metals. Platinum gold alloy is the hardest metal available but the major drawback is that the cost per gram of the material is very high. Hence, this metal is used only for high accuracy and precision jobs and cannot be used for all industrial purposes.

Polymeric compounds are being preferred owing to their high hardness value equal to their metallic counterparts but with more advantages. The hybrid composites are also considered to be a part of the polymeric compounds. The hybrid composites and polymers are considered to be the future of wear resistant materials. Of the Non-metallic compounds that has the highest hardness values from the table 5, SiC is found out to be the best choice of material. It has a very high hardness value and also the cost of the material is the lowest among all others.
It is to be noted that the comparison made above is with respect to the parent materials, AMS 5659 and Aluminium bronze. All the values are compared with respect to the two metals.

Reference

[1] “Uniform wear theory”, https://mechdiploma.com/explain-i-uniform-pressure-theory-iuniform-wear-theory-clutches-and-bearing
[2] J.B K Das, P.L Srinivasa Murthy, “Design of machine elements 2”, Sapna publications, PP 491.
[3] Zhijian ling, Whenxiang Zhao, Peter Onand Rasmussen, Jinghua Ji, “Design and manufacture of linear actuator based on magnetic screw transmission”, IEEE transactions on Industrial electronics, Vol. 68, No. 2, 2021, PP 1095-1107.
[4] “15.5 PH Stainless steel- AMS5659 data handbook”, https://www.ssacorp.com/documents/Data%20Sheet%2015-5PH-AMS5659.pdf
[5] Jianlin Xu and Zhiping Wang, “Research into a new high-strength aluminium bronze alloy”, International journal of Materials and product technology, Vol.21, No.5, 2004, PP 444-453.
[6] Abdul Wasy Zia, Zhifeng Zhou and Lawrence Kwok-Yan Li, “Structural, mechanical and Tribological characteristics of diamond-like carbon coatings”, Diamond and related materials, Elsevier Publications, Volume 10, Issue 3-7, 2001, PP 171-189.
[7] Wolfgang Tillmann, Nelson Filipe Lopes Dias, Dominic Stangier, “Influence of plasma Nitriding pretreatments on the tribo-mechanical properties of DLC coatings sputtered on AISI H11”, Surface and Coatings Technology, 2018, https://doi.org/10.1016/j.surfcoat.2018.11.002, S0257-8972(18)31212-X.
[8] Kedhong Zhang; Jainxin Deng; Xuhong Guo; Lining Sun; Shuting Lei, “Study on adhesion and tribological behavior of PVD TiAlN Coatings with a multi-scale textured substrate surface”, International journal of refractory and hard materials, 2018, PP 292-305.
[9] E.J. Bienk, H. Reitz, N.J. Mikkelsen, “Wear and friction properties of hard PVD coatings”, Surface coatings and technology, 1995, PP 475-480.
[10] T. Leyendecker, O. Lemmer and S. Esser, “The development of the PVD coating TiAIN as a commercial coating for cutting tools”, Surface and Coatings technology, 1991, PP 175-178.
[11] “Salt bath nitriding process and its safer alternative”, https://www.paulo.com/salt-bathnitriding-process-safer-alternative/
[12] “SI-TUFF”, https://haydale.com/wp-content/uploads/2019/10/HTI-SI-TUFFPerformance-SiC-Applications-Guide-Nov-2016.pdf
[13] S. Suresha, B.K. Shridhara, “Effect of silicon carbide particulates on wear resistance of graphitic aluminium matrix composites”, Materials and design, 2010, PP 4470-4477.
[14] Nand Kee Kanu, Amogh Mangalam, Eva Gupta, Umesh Kumar Vates, Gyanendra Kumar Singh, Devendra Kumar Sinha, “Investigation on secondary deformation of ultrafine SiC particles reinforced LM25 metal matrix composites”, Materials Today: Proceedings, Vol. 47, Part 11, 2021, ISSN 2214-7853, PP 3054-3058, DOI: https://doi.org/10.1016/j.matpr.2020.10.640.
[15] “4 wear resistant coatings for lightweight metals”, https://blog.keronite.com/4-wearresistant-coatings-for-lightweight-metal
[16] “SSAB Boron”, https://www.ssab.com/products/brands/ssab-boron-steel
[17] Henryk Buglacki, Monika Smajdor, “Mechanical properties of abrasion-resistant HARDOX400 Steel and their welded joints”, Advances in material science, 2003, Vol. 4, No. 2(4).
[18] Nand kumar, B. Ganguli, Bidesh Roy, Bachu Deb, “Investigation of surface properties of EN8, EN24, EN41B low alloy steel treated by active screen plasma nitrinding”, Indian institute of metals, 2021, No. 74(4), PP 799-810.
[19] Osamu Takai, “Super hard materials”, Chapter 34, 2003, http://dx.doi.org/10.1016/B978-008044163-4/50034-6
[20] Abhishek Chauhan, Umesh Kumar Vates, Nand Jee Kanu, Eva Gupta, Gyanendra Kumar Singh, Bhupendra Prakash Sharma, Srinivasa Rao Gorrepati, “Fabrication and characterization of novel nitinol particulate reinforced aluminium alloy metal matrix composites (NiTip/AA6061 MMCs)”, Materials Today: Proceedings, Vol. 38, Part 5, 2021, PP 3027-3034, ISSN 2214-7853, DOI: https://doi.org/10.1016/j.matpr.2020.09.326.
[21] Dora Shiva Prasad, Chintada Shoba, “Hybrid composites- a better choice for high wear resistant materials”, Journals of materials research and technology, 2014, No. 3(2), PP 172-178.
[22] Shankar Kadam and Sachin Chava and Nand Jee Kanu, “An insight into advance self-healing composites”, Materials Research Express, 2021, Vol. 8, Number 5, DOI: 10.1088/2053-1591/abfba5
[23] Nand Jee Kanu, Eva Gupta, Umesh Kumar Vates, Gyanendra Kumar Singh, “Self-healing composites: A state-of-the-art review”, Composites Part A: Applied Science and Manufacturing, Vol. 121, 2019, PP 474-486, ISSN 1359-835X, DOI: https://doi.org/10.1016/j.compositesa.2019.04.012.

[24] “Wear of polymer composites”, Elsevier Publications, DOI: 10.1533/9781782421788.133

[25] Klaus Friedrich, “Wear of reinforced polymers by different abrasive counterparts”, Polymer and composites group, Elsevier publications, Volume 1, 1986, PP 233-287.

[26] Vahid Adibnia, Marziye Mirbhageri, Jimmy Faivre, Jordan Robert, Jeungjun Lee, Krzystof Matyjaszewski, Dong Woog Lee, Xavier Banquy, “Bio-inspired polymers for wear resistance and lubrication”, Progress in polymer science, Elsevier publication, 2020, https://doi.org/10.1016/j.progpolymsci.2020.101298

[27] Nand Jee Kanu, Saurabh Bapat, Harshad Deodhar, Eva Gupta, Gyanendra Kumar Singh, Umesh Kumar Vates, Girish C. Verma & Vivek Pandey, “An Insight into Processing and Properties of Smart Carbon Nanotubes Reinforced Nanocomposites”, 2021, Smart science, DOI: 10.1080/23080477.2021.1972911

[28] W.A. Glaeser, “Wear characteristics in non-metallic materials”, Wear journal, Elsevier publications, Volume 6, Issue 2, 1963, PP 93-105.

[29] Nand Jee Kanu, Umesh Kumar Vates, Gyanendra Kumar Singh & Sachin Chavan, “Fracture problems, vibration, buckling, and bending analyses of functionally graded materials: A state-of-the-art review including smart FGMS, Particulate Science and Technology”, 2019, Smart Science, 37:5, PP 583-608, DOI: 10.1080/02726351.2017.1410265

[30] I.M. Hutchings, “Wear resistant materials: Into the next century”, Material science and engineering, 1994, PP 185-195.

[31] Ayushi, Umesh Kumar Vates, Sanjay Mishra, Nand Jee Kanu, “Biomimetic 4D printed materials: A state-of-the-art review on concepts, opportunities, and challenges”, Materials Today: Proceedings, Vol. 47, Part 11, PP 3313-3319, ISSN 2214-7483, DOI: https://doi.org/10.1016/j.matpr.2021.07.148.