MATERIALS ASSESSMENT OF COMPONENTS OF THE EXTRAVEHICULAR MOBILITY UNIT

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Prepared By:	Enrique V. Barrera, Ph.D.
Academic Rank:	Assistant Professor
and:	John D. Olivas
	Graduate Student
University and Department:	Rice University
	Mechanical Engineering and Materials Science

NASA/JSC

Directorate:	Engineering
Division:	Crew and Thermal Systems
Branch:	
JSC Colleague:	Chin Lin, Ph.D.
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ABSTRACT

Current research interests for Extravehicular Mobility Unit (EMU) design and development are directed toward enhancements of the Shuttle EMU, implementation of the Mark III technology for Shuttle applications, and development of a next generation suit (the X suit) which has applications for prolong space flight, longer extravehicular activity (EVA), and Moon and Mars missions. In this research project two principal components of the EMU were studied from the vantage point of the materials and their design criteria. An investigation of the flexible materials which make up the lay-up of materials for abrasion and tear protection, thermal insulation, pressure restrain, and etc. was initiated. A central focus was on the thermal insulation. A vacuum apparatus for measuring flexing of the materials was built to access their durability in vacuum. Plans are to include a Residual Gas Analyzer on the vacuum chamber to measure volatiles during the durability testing. These tests will more accurately simulate space conditions and provide information which has not been available on the materials currently used on the EMU. Durability testing of the aluminized mylar with a nylon scrim showed that the material strength varied in the machine and transverse directions. Study of components of the EMU also included a study of the EMU Bearing Assemblies as to materials selection, engineered materials, use of coatings and flammability issues. A comprehensive analysis of the performance of the current design, which is a stainless steel assembly, was conducted and use of titanium alloys or engineered alloy systems and coatings was investigated. The friction and wear properties are of interest as are the general manufacturing costs. Recognizing that the bearing assembly is subject to an oxygen environment, all currently used materials as well as titanium and engineered alloys were evaluated as to their flammability. An aim of the project is to provide weight reduction since bearing weights constitute 1/3 of the total EMU weight. Our investigations have shown favorable properties using a titanium or nickel base alloy in conjunction with a coating system. Interest lies in developing titanium as a more nonflammable material. Methodology for doing this lies in adding coatings and surface alloying the titanium. This report is brief and does not give all necessary details. The reader should contact the authors as to the detailed study and for viewing of raw data.

INTRODUCTION

A broad-based project aimed at studying the flexible materials and the bearing assemblies on the Extravehicular Mobility Unit (EMU) was initiated. The emphasis of the study of the flexible materials became the thermal insulation layers of aluminized mylar with nylon scrim and its durability in flexure testing. The emphasis on the bearing assemblies was focused on flammability and improving the flammability of titanium and its alloys. Both components to this project were aimed at current Shuttle EMU material systems, applying Mark III technology, and criteria of the next generation suit, the X-suit. The outcome of this project is a plan in place for flexure testing of the flexible materials used on the Shuttle EMU where the materials evaluation occurs in vacuum to simulate space conditions. The plan is presented in this report as well as the assessment of the aluminized mylar. Recommendations for reducing frequent replacement of the aluminized mylar are also included. For the study on the bearing assemblies several recommendations are presented and methodology for further assessment is also given. In this summer program the faculty fellow and student participant focused on accomplishing the initial stages to a hopefully continued study. The objective of the program is to maintain a continued relationship where NASA interests are fulfilled. The report outlines solutions for that goal.

VACUUM DURABILITY TESTING OF EMU FLEXIBLE MATERIALS

Objectives

The durability and breakdown resistance of fabric materials currently used on the Shuttle Extravehicular Mobility Unit (EMU) will be determined using a Flex Machine developed during the 1995 NASA-ASEE Summer Faculty Fellowship Program. The Flex Machine is designed to simulate the flexing movements made by the astronauts during extravehicular activity (EVA) in vacuum conditions resembling that of low earth orbit (LEO). The tester is designed to work in vacuum and to minimize gas evolution from the fixture. Volatile gases will be measured during the testing. Gases that evolve during the tests are a product of the material degradation. As a result, the findings of this study will be used to improve materials that see frequent replacement or repair and to aid in selecting materials for prolonged EVA and time in space. Both current Shuttle EMU and X-suit materials will be evaluated. The benefits of conducting the tests in vacuum are that the volatile gases that would outgas in space can be measured and the modification/degradation of the materials being exposed to vacuum can be induced for observation by electron microscopy, microprobe analysis, and x-ray photoelectron spectroscopy. It is apparent that knowing the properties of the material degradation due to use in vacuum will further play a role for space suits left on the space station or that make trips to the Moon and Mars.

Aluminized mylar with a nylon scrim, the current thermal insulation material was tested in tension and in flexure modes in ambient conditions. The aluminized mylar failed before the nylon scrim and the machine direction was significantly stronger than the transverse direction. Expectations are that the method of processing the material system results in reduced strength in the transverse direction. Optical micrographs of the material showed lines in the material resembling Lüder's bands. These features are under continued study. The scrim shows two different conditions where nylon is twisted tight in one direction and is laid loose in the perpendicular direction. It is suspected that this feature does not alter the failure mode of the aluminized mylar but effects the percent elongation of the part in terms of final failure. The loose nylon elongates more before failure. The adhesive used on the thermal insulation causes the aluminized mylar to show draw up possibly due to shrinkage. This may impart small creases in the aluminized mylar which are associated with the low strength failure in the transverse direction.

Background

Current flexible materials on the Shuttle EMU include eight layers of various materials for flame, abrasion, and tear resistance, thermal insulation, micrometeorid protection, and pressure restraint [1]. The current materials and the selection process itself has gone through an evolution since the suits for the Mercury program were first designed, placing more and more emphasis on lighter weight, material stability, and extended durability[2]. Vacuum testing of space suit materials was conducted as far back as 1964 and continues as full mock up testing [3]. Current test apparatus at JSC allow for vacuum testing but do not provide for volatile gas measurement and extended materials analysis. Furthermore, durability tests are run in ambient conditions which serve as a *Safe Life* test (materials designed such that no failure will take place in the design lifetime). Many materials currently used and those being considered for the X-suit are composite materials, meaning that they take advantage of the properties of a number of component materials which make up one part or fabric [4]. These materials allow for some built in redundancy.

Research plan

Flex testing in vacuum will be conducted on current Shuttle flexible materials to evaluate durability for Shuttle and prolonged use. Temperature control will be put on the chamber during the project year. Extended materials analysis will be conducted on the vacuum tested materials. Material outgassing conditions will be mathematically modeled. Further design of current materials will be conducted in collaboration with Crew and Thermal Systems personnel and contractor companies. Emphasis is placed on improving the performance of the EMU while setting up a criteria for materials selection based on gas evolution during use in space (simulated on earth).

In the summer program, preliminary tests were conducted on the aluminized mylar in ambient conditions and the flex tester for vacuum testing was built. The following list of deliverables demonstrates the methodology by which this research will be continued and the long term goals of this study.

August 8, 1995:	Project starting date. Test and redesign frequently repaired or replaced materials.
October 15, 1995	Submission of a Regional University Grant Proposal: "Development of thermal and radiation insulation".
January 15, 1996	Report I: Interim report.
February 15, 1996	Submission of an unsolicited proposal: "Development of composite material for weight savings and functionality".
May 14, 1996	Project ending date.
June 14, 1996	Final Report: Including expenditures

Recommendations

The aluminized mylar with a nylon scrim is the current choice for thermal insulation on Shuttle EMU. To reduce the number of repairs currently seen for the Shuttle suit care must be taken in aligning the material with the machine direction in the direction of the major loads. Cross plying sounds like a possible solution yet will result in failure of half the layers as opposed to failure of all the layers. Recommendations of this study are to align the machine direction with the direct of maximum loading. This will lead to a longer life of the insulation and no failure in the transverse direction.

MATERIAL SELECTION FOR EMU BEARING ASSEMBLIES

In analyzing the application of a material system to the EMU bearing assembly, the selections were evaluated based on the qualifying parameters listed in Table 1. Prior to evaluating potential material systems, baseline data of the current material selection was compiled to provide a starting point for evaluation. This criteria established the minimum needed to justify making a material change. The material properties are seen in Table 2.

TABLE 1.- REQUIREMENTS FOR EMU BEARING MATERIAL SELECTION

Property	Consequence
Low weight	Minimize mass
High stiffness	Minimal deflection
	Minimal torsional distortion
Non flammable in 100% O_2	Minimum 4.3 psia
	Maximum 6.6 psia
Manufacturing ease	Easily machined
	Easily cast
	Available in stock blanks
Good wear characteristics	Bearing race application
	Bearing ball application
Impact resistant	High fracture toughness
Commercial application	Non-aerospace applications
Cost	To be determined based on selections

TABLE 2.- BASELINE DATA FOR EXISTING BEARING MATERIALS [3]

Material	Bearing Component	Treatment	Tensile Strength (MPa/ksi)	Combustion 4.3-6.6 psi O_2	Thermal Expansion ($\times 10^{-6}$/°C)	Hardness (HRC)	Density (lbs./in^3)
440C	Balls	Temper @ 300 °C	1970/285	No	10.1	60	0.275
17-4PH	Race rings	H900	1310/190	No	10.4	40-48	0.28

Given the bearing requirements, the most stringent is compatibility of the material with an oxygen enriched environment [5]. There are two engineering components to the issue of combustion; ignition source and material combustion. Non-flammable materials are those in which combustion is not supported in an oxygen enriched environment, as defined by NASA White Sands Test Facility (WSTF) [6]. Risk of ignition can be minimized by reducing the potential for spark or flame ignition. Ideally both aspects should be satisfied, however, significantly reducing one may increase the ability to use the material. In order to evaluate a greater number of materials, the investigation was divided into three material classes; metals, ceramics and composites. A number of materials of each class were evaluated based on the above criterion. Recommendations based on material class follow each section as well as an overall recommendation.

Metals evaluation

Investigation of potential metal selections for bearing applications was performed using published ASM data [7] and available vendor information. Realistic metal systems which were initially identified as having a density lower than that of stainless steel (17-4 PH) were titanium, aluminum, graphite, beryllium and their associated alloys. Previous designs eliminated aluminum as a potential choice due to low stiffness and graphite due to low toughness. Although beryllium has an excellent strength to weight ratio, poor fracture toughness and toxicity also eliminated this material as a potential selection [8].

Titanium and titanium alloys were determined to be the best potential selection among metal systems. A comparison of several commercially available titanium alloys are listed in Table 3. These represent those alloys which possess comparable properties to the baseline data in Table 1.

TABLE 3.- RELEVANT MECHANICAL PROPERTIES FOR TITANIUM ALLOYS

Material	Bearing Component	Treatment	Tensile Strength (MPa/ksi)	Combustion 4.3-6.6 psi O_2	Hardness (HRC)	Density (lbs./in^3)
Ti6Al4V	Race	Annealed	895/130	Yes	36	0.16
	Race	Solution	1035/150	Yes	39	0.16
Ti6Al6V2 Sn	Race	Solution	1030/150	Unknown	39	0.165
Ti7Al4Mo	Race	Solution	1170/170	Unknown	32-38	0.162
Ti6Al2Sn4 Zr6Mo	Race	Solution	1170/170	Unknown	36-42	0.168
Ti6Al2Sn2 Zr2Mo2Cr	Race	Solution	1160/168	Unknown	42	0.165
Ti10V2Fe 3Al	Race	Solution	1275/185	Unknown	50	0.168

Draw backs to this material selection class are in the area of combustion. WSTF demonstrated clearly that titanium, Ti-6Al-4V, and several other titanium alloys provided the poorest combustion performance for all metals tested [9]. Recognizing that the primary alloying agent is highly combustible, it is expected that other systems would perform comparably, although different phases appear to play a role in the combustion of some systems.

It is acknowledged that the bearings would not likely be exposed to direct flame contact as simulated in WSTF material combustion test. Testing a proposed bearing in the configurational and component test may provide sufficient support to warrant the use of titanium in this application, however, with regard to the initial criteria, titanium cannot be recommended in the as commercially available conditions without the risk of being consumed in a combustion condition. In conclusion, of the metals currently available and which have been tested by WSTF, none can be recommended without a compromise in either mechanical or combustion properties.

Ceramics evaluation

Several important properties are characteristic of this class material. In general, they are more stable at higher temperature, have high strengths and low weights, are suitably hard, and somewhat machinable. However, drawbacks include the potential for low fracture toughness (brittle), varying degrees of porosity, poor surface finish, and difficulties in some fabrication processes. The ceramics which are presented posses the most favorable of these initial concerns and comply with the requirements as defined in Table 1 unless otherwise stated.

Ceramic bearings and bearing elements (balls, races, etc.) have been fabricated since the early 1980's and a significant amount of work has been reported in the literature. Although problems were encountered early in the development of the material system, many of the obstacles have been overcome. Table 4 represents the properties of the most common and well studied structural ceramic material for bearing and load carrying applications.

TABLE 4.- RELEVANT MECHANICAL PROPERTIES FOR CERAMICS

Material	Bearing Component	Trade Name	Flexural Strength (MPa/ ksi)	Fracture Toughness ksi √in	Combustion 4.3-6.6 psi O_2	Thermal Expansion (x10^{-6}/°C)	Hardness (HRC)	Density (lbs./in^3)
Si_3N_4	Race/Ball	NBD-200	980/142	6.4	No	2.9	>70	0.115
Sialon	Race/Ball	NT-451	920/133	6.4	Unknown	3.6	>70	0.117
Si_3N_4	Race/Ball	NT-154	910/132	6.4	No	3.9	>70	0.117
B_4C	Race/Ball	NORBIDE	300/44	2.8	Unknown	5.8	>70	0.091
Y-ZrO_2	Race/Ball	YZ-110	1400/203	8.3	Unknown	10	>70	0.219
Y-ZrO_2	Race/Ball	YZ-130	1000/145	4.6	Unknown	10	>70	0.218
Y-ZTA	Race/Ball	AZ-67	900/131	6.4	Unknown	8.5	>70	0.159
Y-ZTA	Race/Ball	AZ-93	1180/171	5.5	Unknown	9	>70	0.174
Ce-ZTA	Race/Ball	CAZ-94	650/94	7.4	Unknown	9	>70	0.188

Of the ceramics listed, the only material for which WSTF combustion test data exists is Si_3N_4 (NBD-200) [8]. This performed very well and appears to satisfy all the characteristics defined in Table 1. Mass fabrication and production of bearing parts and bearing assemblies have proven to be successful in many commercial application [13-19]. For example, ceramic bearings were used successfully in the LOX turbo pump on STS-70. Strides which the ceramic industry have made in the last 10 years have been significant in resolving the problems with using these materials in bearing applications. Based on published information and communication with material vendors, the sizes required by the EMU can be fabricated. In order to keep cost down on fabrication of raw material, it may be necessary to consider some slight alterations in the current design.

Composite evaluation

Most of the composite systems which rely on internal reinforcement for increased strength characteristics will intuitively posses the same problems as do the metals. That is, the exposure of a combustible material to an environment conducive for combustion will lead to material and component failure. Regressing from these conventional ideas, a composite can also be designed by applying a protective coating developed to protect the base material from the combustion environment. Thus the susceptibility of the bulk material to failure can effectively be eliminated. Furthermore, the coating (or film depending on thickness) could be tailored to specifically satisfy other demands placed on the surface. Since the 1950's, the bearing industry has been using a variety of diffusion and deposited coatings on load bearing surfaces to increase hardness, reduce wear, or increase corrosion resistance [20-22].

Recalling from the materials outlined in Section 2, titanium alloys would be an excellent choice provided that one could prevent the material from coming into contact with an ignition source or combusting. Therefore, proper coating selection and design may additionally satisfy the wear, friction, strength, and material compliance requirements so that titanium alloys could safely be used in the oxygen enriched environments. The coated titanium alloy assembly will result in a weight savings over the stainless steel systems currently used.

Since titanium alloys are inherently self passivating and very corrosion resistant, published coating technology has been limited to increasing surface hardness [23]. Similarly, since titanium alloys do not posses the type of hardnesses traditionally found in bearing materials, it represents only a small portion of total data available from bearing applications in contrast to more popular metals such as 440C or M-50 steels. However, several deposition techniques exist (eg., Chemical Vapor Deposition, Physical Vapor Deposition, Sublimation Deposition, etc.) and the design of such a coating is possible with further research. Table 5 demonstrates differences in surface hardness of substrates and coatings the properties of some typical coating used in bearing applications. Additionally, significant data exists on wear properties of various coating combinations. Presented in Table 6 are friction and wear characteristics of a few coating combinations [22].

Many non-combustible metals and alloys are applied to steel alloys for enhanced wear and protection characteristics, such as chrome and nickel electroplating. It is also acknowledged that both are less combustible than titanium. While no previous work of these system on titanium was discovered, applications are possible. Similarly, elements such as cobalt and copper metals and alloys are not combustible in oxygen enriched environments and may prove to be a potential coating selection.

TABLE 5.- HARDNESS OF COATINGS AND RELEVANT METALS USED IN BEARING APPLICATIONS

Material substrate/coating	Hardness (HV)
440C stainless steel (HRC 60)	697
17-4 PH stainless steel (HRC 47)	471
Ti-6Al-4V (HRC 36)	354
Hard chrome plating	1000-1200
Nitrided steel	1300-1700
WC+Co	1400-1800
TiN	2000
Ruby, sapphire, corundum	2500-300
SiC	4000
B_4C	5000
Diamond	>10000

TABLE 6.- PIN ON DISK FRICTION AND WEAR CHARACTERISTICS OF VARIOUS COATING COMBINATIONS [22]

Contacting Surfaces Pin-Disc	Friction Coefficient	Wear Rate	
	Humidity 0.5%-5%	Pin	Disc
TiC-TiN	0.18	4.5	20
TiC-SiC	0.26	0.33	<3
TiC-TiC	0.32	0.25	16
TiN-TiC	0.31	0	25
SiC-TiC	0.35	0	36
SiC-SiC	0.47	6	22
Al_2O_3-TiC	0.37	0.7	20
	Humidity 50%		
100Cr6-SiC	0.23	1.2	3.8
100Cr6-TiC	0.25	0.07	7.6
100Cr6-TiN	0.49	95	0
100Cr6-X205 CrWMoV121	0.53	104	0
100Cr6-Fe_xB	0.76	58	0
100Cr6-Cr_7C_3	0.79	1.1	76
Al_2O_3-100Cr6	0.45	10	1500
Al_2O_3-TiC	0.19	0.1	10
Al_2O_3-boronized cement carbide	0.62	3.3	1.8
TiC-TiC	0.14	4.4	
TiN-TiN	0.19	4.3	
Cr_7C_3-Cr_7C_3	0.29	29.3	
Fe_xB-Fe_xB	0.40	0.3	
Ruby-TiC	0.12	4	
100Cr6-TiC	0.11	3	

Recommendations

Although a material which satisfies all the requirements listed is not readily available, a number of opportunities exist in solving the problem. The quickest solution may lie in fabricating the bearings from Si_3N_4. While bearings approaching the size of the waist bearing assembly are not fabricated in bulk, current machining technology may be able to accommodate the design. Major manufacturers such as Timeken and SKF may have capabilities in fabricating these components. Additionally there are two manufacturers (in Japan and Germany) who specialize in ceramic bearings and are accustomed to special orders. They may also be able to aid in redesigning to accommodate more standard sizes and special considerations in using ceramics.

Another opportunity exists in trying to alter the microstructure of an existing titanium alloy or design a new one. Chemical composition being held constant, gamma titanium has demonstrated better combustion characteristics than alpha, alpha-beta, or beta microstructures as measured by WSTF. This dependency on microstructure gives rise to the need to understand the mechanisms behind combustion of solid metals. Since theoretical models do not adequately predict this behavior [23-29], it is recommended to conduct research into developing a more suitable mathematical model of combustion. This work can then be implemented on developing a more suitable material with optimal stable phases which suppress the combustion process and maintain desired strength levels. While it is not likely that this option will completely resolve the combustion problems, it may sufficiently alter the characteristic such that certain materials may be used.

Developing a composite system using a bulk titanium alloy and combustion protective coating presents another attractive solution. As mentioned, these alloys are rarely coated, therefore, research would be required to investigate which systems would be compatible. There has been sufficient work done in this field to demonstrate that such a coating would be possible. Additionally, some degree of control on specific characteristics such as hardness, wear, and friction, can be exercised in the new design.

DISCUSSION

Many of the materials used as flexible materials on the EMU are polymeric and in turn exhibit some outgasing in a vacuum condition. Short term outgasing is expected to be either minimum in intensity or to happen quickly at the onset of vacuum. Knowledge of the long term exposure to vacuum of the current materials is unknown. Continued degradation of less than thirty years or for durations considered long term exposure limit these materials for use on the X-suit. This is the reason for vacuum flex testing and volatile gas measurement. Any of the solutions recommended for the bearing assemblies would have broad appeal to commercial industry. While specific to the EMU, reporting the results of this application will be immediately evaluated by industries where light weight, high strength, and combustion potential exists. These may include, but are not limited to, gas turbine, chemical processing, and utility distribution applications. For any the recommendations selected, a sound theoretical model would go a long way toward understanding fundamental kinetics and thermodynamics which drive the combustion process. The development of noncombustible titanium would impact the space program as a whole since there are a number of applications where good strength to weight titanium in the nonflammable condition would be of interest.

CONCLUSIONS

A study was conducted on aluminized mylar, the thermal insulation on the Shuttle EMU and bearing assemblies used on the various EMU designs. Recommendations for improved performance were presented for both problems and long range studies were outlined to further contribute to enhanced EMU design.

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