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Static and Dynamic Friction Behavior of Candidate High Temperature Airframe Seal Materials

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Abstract

The following report describes a series of research tests to evaluate candidate high temperature materials for static to moderately dynamic hypersonic airframe seals. Pin-on-disk reciprocating sliding tests were conducted from 25 to 843°C in air and hydrogen containing inert atmospheres. Friction, both dynamic and static, was monitored and serves as the primary test measurement. In general, soft coatings lead to excessive static friction and temperature affected friction in air environments only.

Introduction

Advanced flight vehicles operating at supersonic and hypersonic speeds present many structural and dynamic engineering challenges to designers. One of these challenges is airframe and engine panel seals (Ref. 1). These seals are designed to prevent leakage of ambient air or combustion gases from damaging internal components. A hypersonic cruise vehicle utilizing ducted scamjet/ramjet propulsion, for example, experiences not only significant frictional air skin heating but also engine combustion heating in the presences of air, hydrogen and water vapor (Ref. 2). These conditions require the use of advanced seals which must accommodate a wide variation of temperatures and environments.

One advanced type, metallic "E-Seals" are designed to operate as panel to panel seals in both airframe and ducted engine applications. These types of seals, depicted in Figure 1, provide the required deflection characteristics to accommodate anticipated temperature extremes.

The static and dynamic friction between the seal and its adjacent mating panel are critical design parameters. Typical friction valves under anticipated conditions of load, temperature and environment are needed to address strength, stress and deflection requirements of the seals. Unfortunately, this type of tribological design data is not generally available for the advanced candidate materials and coating combination being considered. To address this problem, the following report describes a tribological test program to evaluate the static and dynamic friction characteristics of candidate seals materials. Specimens in the form of pins and disks with and without various lubricant/compliant coatings are tested at simulative loads and temperatures using a pin-on-disk tribometer at NASA Lewis Research Center. The output data includes static and dynamic friction coefficients and general surface morphological characteristics after testing.

Materials

The high temperature panel seals under design consideration consist of an elastic wave seal made from Incoloy 909, Haynes 188, René 41 or Waspaloy. The panels they seal against are made from Incoloy 909, Haynes 188, Narloy Z, or MoRe depending on their location and specific application. Table I gives the room temperature thermal, physical and strength properties and nominal composition of these materials. Haynes 188, Waspaloy and René 41 are superalloys chosen for their high temperature strength and oxidation resistance. MoRe, although requiring oxidation protective coatings, offers excellent high temperature strength and low thermal expansion. Incoloy 909, an iron based superalloy, also exhibits relatively low thermal expansion simplifying design details. Finally, Narloy Z, a copper alloy is chosen for actively cooled heat exchange applications for its high thermal conductivity.

Narloy Z, Incoloy 909 (I909) and MoRe lack sufficient oxidative resistance at high temperatures. For certain tests, Narloy Z and I909 are coated with Cu-Cr for oxidation protection. All of the MoRe specimens are coated with Pt to prevent high temperature oxidation. Additionally some I909 specimens coated with Cu-Cr are also top coated with lubricant films of silver. These coating-specimen combinations are given in Table II. The lubricants Ag I and Ag II are electropated silver films approximately 10-15μm thick designated by specification as Ag-2411-D-MOD and Ag-QQ-S-365 respectively. The Ag I is a standard electroplate while Ag II is a standard electroplate deposited over a thin bond layer electroplated under a high rate condition. In addition to functioning as a lubricant, the silver films act as a compliant, conformal layer improving sealing.

Test Apparatus and Procedure

The pin and disk specimens are tested in reciprocating sliding in a pin-on-disk tribometer. The tribometer, described in detail in Ref. 3 consists mainly of an oscillating spindle, driven by a crank rocker mechanism on which the disk is mounted. A torque tube which holds the pin specimen. The pin is loaded against the oscillating disk face using dead weights. The specimens are positioned inside a resistance heated furnace capable of attaining 1200°C. For controlled atmosphere tests (Ar-H_2) an inner chamber made of Inconel X-750 is placed around the specimens inside the furnace and purged with the separate test gas. A schematic of the rig is shown in Figure 2.

To simulate the anticipated application conditions, a step-wise heating, loading, sliding test procedure is used as depicted in Figure 3. The test loads and temperatures are representative of the seals. Table III shows the two test loads, Pa and Pb, used and the resulting nominal hertzian contact stresses for the material combinations tests. Tables IVa and Va give the specific conditions (temperature, loads, environment) for the tests.

Both static and dynamic friction coefficients are measured during the test cycle. Dynamic friction is measured using a computer data acquisition system which averages 25 samplings over a one second interval. This acquisition system is described in Ref. 4. The static friction measurement is made by manually rotating the disk while observing a high speed oscilloscope type chart recorder (oscillograph).

Prior to testing, the samples are cleaned with pure ethyl alcohol and rinsed with deionized water. Uncoated samples are further cleaned by scrubbing with levigated alumina and water followed by a deionized water rinse and air drying. The test atmosphere is either room air at 40-60% relative humidity or Argon gas doped with 4% hydrogen (Ar-H_2). The room air tests simulate seals operating near the inlet of an engine or on the airframe. The Ar-H_2 gas simulates seal operating near the combustion zone or in proximaty of hydrogen cooled panels. After tribotesting, the pin and disk specimens are analyzed using optical microscopy to observe the wear surface morphology. Stylus surface profilometry and scanning electron microscopy on selected specimens are used to further characterize the wear surfaces.

<u>Friction</u>

Tables IVb and Vb give the static and dynamic friction coefficients for the material combinations tested. The measured friction ranged from about 0.2 to over 3.0 depending on the specimen pair, temperature and sliding condition (static or dynamic). Although the data covered in the table vary greatly, some general trends were observed:

Soft Coated Pin Surfaces

For pin surfaces that were coated with silver or gold sliding against unlubricated disks (Tests 3-12, and 17-24), several noticiable trends appear. Friction coefficients, both static and dynamic, generally increase as the test temperature increased and as the test load increased. The static friction typically exceeded dynamic friction by at least a factor of 2. For silver coated specimens, friction in air is slightly higher than friction measured during sliding in an $Ar\text{-}H_2$ environment. Gold coated specimens exhibit no such sensitivity to the test atmosphere.

Pt Coated MoRe Disk Surfaces

For MoRe disk surfaces coated with platinum (Tests 1, 2, 31, 32, 35 and 36), static friction is greater than dynamic friction. Friction in air (Tests 2, 32 and 36) is significantly lower than friction measured in an $Ar\text{-}H_2$ environment and decreases as the test temperature increases. For $Ar\text{-}H_2$ tests no such temperature sensitivity is noted.

Nickel Based Superalloy Disks/Pins - Uncoated

Uncoated nickel based superalloy disks (René 41, Waspaloy) sliding against uncoated nickel based superalloy pins (Tests 30, 33 and 34) exhibit behavior typical of these materials in that as the temperature increases friction generally decreases and the friction in air (Test 34) is lower than in $Ar\text{-}H_2$ atmosphere (Test 33) (Ref. 5). However, for these combinations, static friction is approximately equal to dynamic friction.

Discussion

The friction results suggest that interfaces where one component is hard and another is soft (for examples Tests 4, 9, 10) yield high static friction. This may be due to adhesion and severe plowing of the soft material by the harder counterface. Evidence for this behavior can be seen in Figure 4 which shows the pin specimen from Test 4. Here, plastically deformed silver is smeared beyond the contact area. Since sliding friction is roughly proportional to contact area, friction is increased when the smearing occurs (Ref. 6). For sliding pairs were both surfaces are hard, the contact areas are small and friction tends to be lower, especially static friction. Figure 5, from Test 30, shows a pin wear scar of a René 41 pin after sliding against a Waspaloy disk surface. Since plowing and cold welding is minimized, static friction is approximately equal to dynamic friction.

For tests at the highest temperature (843°C), dynamic friction in air is generally lower than in Ar-H_2. For example, Tests 1 and 2 represent H188 sliding against Pt coated MoRe where a two to four fold reduction in friction in air is exhibited at 843°C. This reduction may be due to the formation of a lubricious oxide layer which forms on the H188 at temperatures above about 500°C[5]. When tested in Ar-H_2, however, no such oxide layer can form and thus friction is not reduced.

Concluding Remarks

When selecting and incorporating materials for seals, consideration must be made of both static and dynamic friction. When soft coatings are used, excessive static friction can arise. The use of soft coatings such as gold and silver should be limited to critical applications where excellent compliance and conformability are required. The data tabulated in this report represent an additional database available for seal design and can be used for material candidate screening. More extensive testing and evaluations should be done for final material selection.

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Table I. Material Properties C 25°C

Material	Nominal Composition	Density, P	Tensile Strength, MPa	CTE/°C $x10^{-6}$	Elastic Modulus, mPa	Thermal Conductivity W/m°K
H188	37Co, 22Ni, 22Cr, 14.5W, 3Fe, 0.1C,	9.13	960	17	207	20
Incoloy 909	38Ni, 42Fe, 13Co, 4.7N6, 1.5Ti, .4Si	8.3	1310	7.7	159	14.8
René 41	55Ni, 19Cr, 11Co, 10Mo, 3.1Ti, 1.5Al	8.25	1420	15.6	210	23.1
Narloy Z	96.5Cu, 3Ag, 0.5Zr	9.13	315	16.5	126	355
MoRe	50Mo-50Re	13.7	1600	6.0	347	5.25
Waspaloy	57.5Ni, 19.5Cr, 13.5Co, 4.2Mo, 1Fe, 1.2Al, 3Tn	8.2	1280	16	213GPa	24.1

Table II. Test Materials

Pin Materials	Oxidation Coating	Lubricant Overlay
Incoloy 909	Cu-Cr	Au
Incoloy 909	Cu-Cr	Ag I
Incoloy 909	Cu-Cr	Ag II
Incoloy 909	None	Ag I
Incoloy 909	None	Ag II
Incoloy 909	None	None
Haynes 188	None	None
Waspaloy	None	None
René 41	None	None
Disk Materials	**Oxidation Coating**	**Lubricant Overlay**
MoRe	Pt	None
Incoloy 909	Cu-Cr	None
Narloy Z	Cu-Cr	None
Haynes 188		

Table III. Nominal Hertizian Contact Calculations
(Values calculated using room temperature elastic properties, Pin radius of curvature: 0.0508M)

Pin Material	Elastic Moduli, GPa	Disk Material	Elastic Modulus, GPa	Load I N	Contact Stress, MPa	Contact Diameter, μm	Load II, N	Contact Stress, MPa	Contact Diameter, μm
I909	210	I909	210	3.06	145	166	4.33	163	185
I909	210	H188	207	2.90	142	163	4.10	159	183
I909	210	NARLOY Z	126	2.65	114	174	3.30	122	187
H188	207	MoRe	347	2.60	158	146	3.16	169	156
René 41	210	H188	207	2.60	137	157	3.16	146	168
René 41	210	MoRe	347	2.60	159	146	3.16	170	156
Waspaloy	213	H188	207	2.60	137	157	3.16	147	167
Waspaloy	213	MoRe	347	2.60	160	145	3.16	171	155

Table IVa. Tribotest Conditions for Tests 1-2 and 23-36.

Test No.	Pin			Disc		Environment	Pin Load (Grams)		Temperatures (°C)		
	Material	Coating	Lubricant	Material	Coating		Pa	Pb	T_1	T_2	T_3
1	H188	None	None	MoRe	Pt	Ar-4H	265	322	232	483	843
2	H188	None	None	MoRe	Pt	Air	265	322	232	483	843
23	I909	None	Au	H188	None	Ar-4H	296	418	232	483	--
24	I909	None	Au	H188	None	Ar-4H	296	418	232	483	--
25	I909	Cu-Cr	Ag-2411D-Mod	I909	Pt	Ar-4H	312	441	232	483	--
26	I909	Cu-Cr	Ag-2411D-Mod	I909	Pt	Air	312	441	232	483	--
27	I909	None	Ag-2411D-Mod	H188	Pt	Air	296	418	232	483	--
28	I909	None	Ag-2411D-Mod	H188	None	Ar-4H	296	418	232	483	--
29	Waspaloy	Cu-Cr	Ag-2411D-Mod	I909	Pt	Ar-4H	312	441	232	483	843
30	Waspoloy	None	None	H188	None	Air	265	441	232	483	843
31	Waspaloy	None	None	MoRe	Pt	Ar-4H	312	418	232	483	843
32	Waspaloy	None	None	MoRe	Pt	Air	265	322	232	483	843
33	Rene 41	None	None	H188	None	Ar-4H	265	322	232	483	843
34	Rene 41	None	None	H188	None	Air	265	322	232	483	843
35	Rene 41	None	None	MoRe	Pt	Ar-4H	265	322	232	483	843
36	Rene 41	None	None	MoRe	Pt	Air	265	322	232	483	843

Table IVb. Tribotest Conditions for Tests 3-22.

Test No.	Pin			Disc		Environment	Pin Load (Grams)		Temperatures (°C)		
	Material	Coating	Lubricant	Material	Coating		Pa	Pb	T_1	T_2	T_3
3	I909	None	Ag-QQ-S-365	I909	None	Ar-4H	312	441	232	483	-
4	I909	None	Ag-QQ-S-365	I909	None	Air	312	441	232	483	-
5	I909	None	Ag-QQ-S-365	Narloy Z	Cu-Cr	Ar-4H	270	336	232	427	-
6	I909	None	Ag-QQ-S-365	Narloy Z	Cu-Cr	Air	270	336	232	427	-
7	I909	None	Ag-QQ-S-365	H188	None	Ar-4H	296	418	232	483	-
8	I909	None	Ag-QQ-S-365	H188	None	Air	296	418	232	483	-
9	I909	Cu-Cr	Ag-2411-D-MOD	I909	Cu-Cr	Ar-4H	312	441	232	483	-
10	I909	Cu-Cr	Ag-2411-D-MOD	I909	Cu-Cr	Air	312	441	232	483	-
11	I909	Cu-Cr	Ag-2411-D-MOD	H188	None	Ar-4H	296	418	232	483	-
12	I909	Cu-Cr	Ag-2411-D-MOD	H188	None	Air	296	418	232	483	-
13	I909	None	None	I909	None	Ar-4H	312	441	232	483	-
14	I909	None	None	I909	None	Air	312	441	232	483	-
15	H188	None	None	H188	None	Ar-4H	265	322	232	483	843
16	H188	None	None	H188	None	Air	265	322	232	483	843
17	I909	None	Au	I909	None	Ar-4H	312	441	232	483	-
18	I909	None	Au	I909	None	Air	312	441	232	483	-
19	I909	None	Ag-2411-D-MOD	I909	None	Ar-4H	312	441	232	483	-
20	I909	None	Ag-2411-D-MOD	I909	None	Air	312	441	232	483	-
21	I909	Cu-Cr	Au	I909	Cu-Cr	Ar-4H	312	441	232	483	-
22	I909	Cu-Cr	Au	I909	Cu-Cr	Air	312	441	232	483	-

Table Va. Tribodata for tests 1-2 and 23-36.

Test No.	Dynamic Friction (μ_D)						Static Friction (μ_S)					
	Pa			Pb			Pa			Pb		
	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
1	$.88 \pm .10$	$1.01 \pm .06$	$1.09 \pm .27$	$.86 \pm .05$	$1.01 \pm .07$	$1.13 \pm .18$	1.7	1.31	1.13	1.54	1.58	2.13
2	$.62 \pm .12$	$.48 \pm .06$	$.28 \pm .03$	$.54 \pm .03$	$.52 \pm .09$	$.29 \pm .02$	.92	1.14	1.15	1.37	.96	.87
23	$.49 \pm .06$	$.61 \pm .03$	-	$.43 \pm .03$	$.65 \pm .03$	-	.47	.57	-	.38	.7	-
24	$.30 \pm .01$	$.35 \pm .04$	-	$.31 \pm .01$	$.34 \pm .01$	-	.57	1.2	-	.62	.98	-
25	$.82 \pm .08$	$.84 \pm .05$	-	$1.04 \pm .05$	$1.13 \pm .05$	-	1.29	1.73	-	1.34	1.66	-
26	$.87 \pm .05$	$.79 \pm .04$	-	$.90 \pm .04$	$.78 \pm .04$	-	.67	.92	-	.75	.72	-
27	$.51 \pm .05$	$.61 \pm .05$	-	$.45 \pm .02$	$.57 \pm .02$	-	.6	.66	-	.46	.53	-
28	$.46 \pm .01$	$.41 \pm .02$	-	$.51 \pm .01$	$.37 \pm .01$	-	1.42	2.43	-	1.48	2.03	-
29	$.74 \pm .06$	$.65 \pm .04$	$.71 \pm .05$	$.75 \pm .06$	$.70 \pm .06$	$.79 \pm .06$	.7	.61	.53	.65	.55	.45
30	$.53 \pm .04$	$.42 \pm .03$	$.23 \pm .01$	$.52 \pm .03$	$.31 \pm .04$	$.23 \pm .01$	.58	.54	.32	.53	.36	.28
31	$1.29 \pm .08$	$1.33 \pm .07$	$1.05 \pm .07$	$1.19 \pm .05$	$1.47 \pm .07$	$1.07 \pm .06$	2.3	2.53	1.74	2.51	2.48	1.07
32	$.59 \pm .04$	$.54 \pm .03$	$.24 \pm .02$	$.54 \pm .03$	$.52 \pm .03$	$.23 \pm .01$	1.51	1.0	.40	1.12	1.12	.44
33	$.81 \pm .09$	$.68 \pm .05$	$.76 \pm .06$	$.78 \pm .05$	$.63 \pm .08$	$.81 \pm .06$	.72	.82	.81	.74	.66	.68
34	$.56 \pm .04$	$.42 \pm .05$	$.21 \pm .01$	$.52 \pm .03$	$.33 \pm .01$	$.21 \pm .01$	.57	.44	.34	.52	.34	.26
35	$1.38 \pm .15$	$1.01 \pm .15$	$.61 \pm .04$	$1.05 \pm .23$	$.96 \pm .06$	$.74 \pm .03$	2.74	2.29	.72	2.31	1.67	1.1
36	$.79 \pm .14$	$.58 \pm .06$	$.26 \pm .03$	$.64 \pm .11$	$.63 \pm .04$	$.23 \pm .02$	.63	.60	.19	.57	.64	.16

Table Vb. Tribodata for tests 3-22.

Test No.	Dynamic Friction (μ_D)						Static Friction (μ_S)					
	Pa			Pb			Pa			Pb		
	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
3	.20±.01	.39±.03	--	.23±.01	.44±.02	--	0.49	1.13	--	.44	1.53	--
4	.48±.02	.53±.02	--	.41±.02	.67±.06	--	0.59	2.89	--	1.67	3.99	--
5	.25±.06	.43±.03		.17±.01	.62±.07		0.59	1.91		0.39	1.99	
6	.32±.07	.48±.01	--	.57±.07	.49±.02	--	0.36	2.02	--	0.65	2.00	--
7	.15±.01	.33±.04		.18±.02	.38±.04		0.40	0.37		0.51	0.56	
8	.44±.10	.52±.02	--	.51±.04	.51±.02	--	0.22	1.20	--	1.11	1.85	--
9	.75±.07	1.20±.10	--	.81±.05	1.41±.12	--	1.20	2.14	--	3.34	3.00	--
10	1.20±.08	1.67±.09	--	1.13±.03	1.5±.06	--	2.17	2.48	--	2.30	3.90	--
11	0.12±.01	.53±.04		0.27±.05	0.51±.04		0.29	1.39		0.28	1.43	
12	.30±.09	.38±.02	--	.48±.03	.48±.02	--	0.30	1.19	--	0.74	2.53	--
13	0.11±.05	.36±.03	--	.68±.15	.34±.01	--	0.12	0.83	--	0.23	0.69	--
14	.65±.07	.34±.01	--	.59±.03	.33±.01	--	0.79	0.57	--	1.09	0.59	--
15	.60±.02	.42±.02	.21±.01	.63±.03	.46±.01	.21±.01	1.20	1.14	.6	1.18	0.93	0.50
16	.53±.03	.50±.02	.24±.01	.53±.02	.50±.03	.21±.01	0.47	1.17	0.9	1.08	0.98	0.43
17	.19±.03	.45±.05	--	.25±.01	.62±.03	--	0.28	1.01	--	0.37	1.69	--
18	.22±.02	.41±.02	--	.26±.02	.39±.02	--	0.39	.85	--	0.51	0.82	--
19	.30±.04	.49±.04	--	.39±.03	.68±.04	--	0.53	1.95	--	0.59	1.96	--
20	.44±.11	.78±.07	--	.58±.02	.87±.07	--	0.35	3.45	--	0.90	4.00	--
21	.60±.04	.67±.04	--	.61±.03	.72±.04	--	1.17	1.49	--	1.18	1.53	--
22	.60±.04	.29±.05	--	.64±.03	.24±.07	--	1.05	1.75	--	1.36	2.32	--

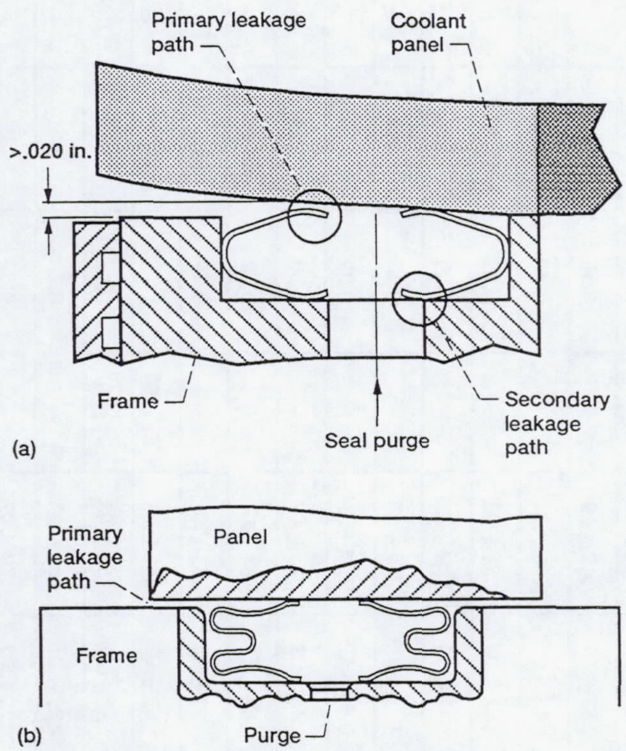

Figure 1.—Schematic of typical panel seal applications.
(a) Typical "U" seal application. (b) "E" seal application.

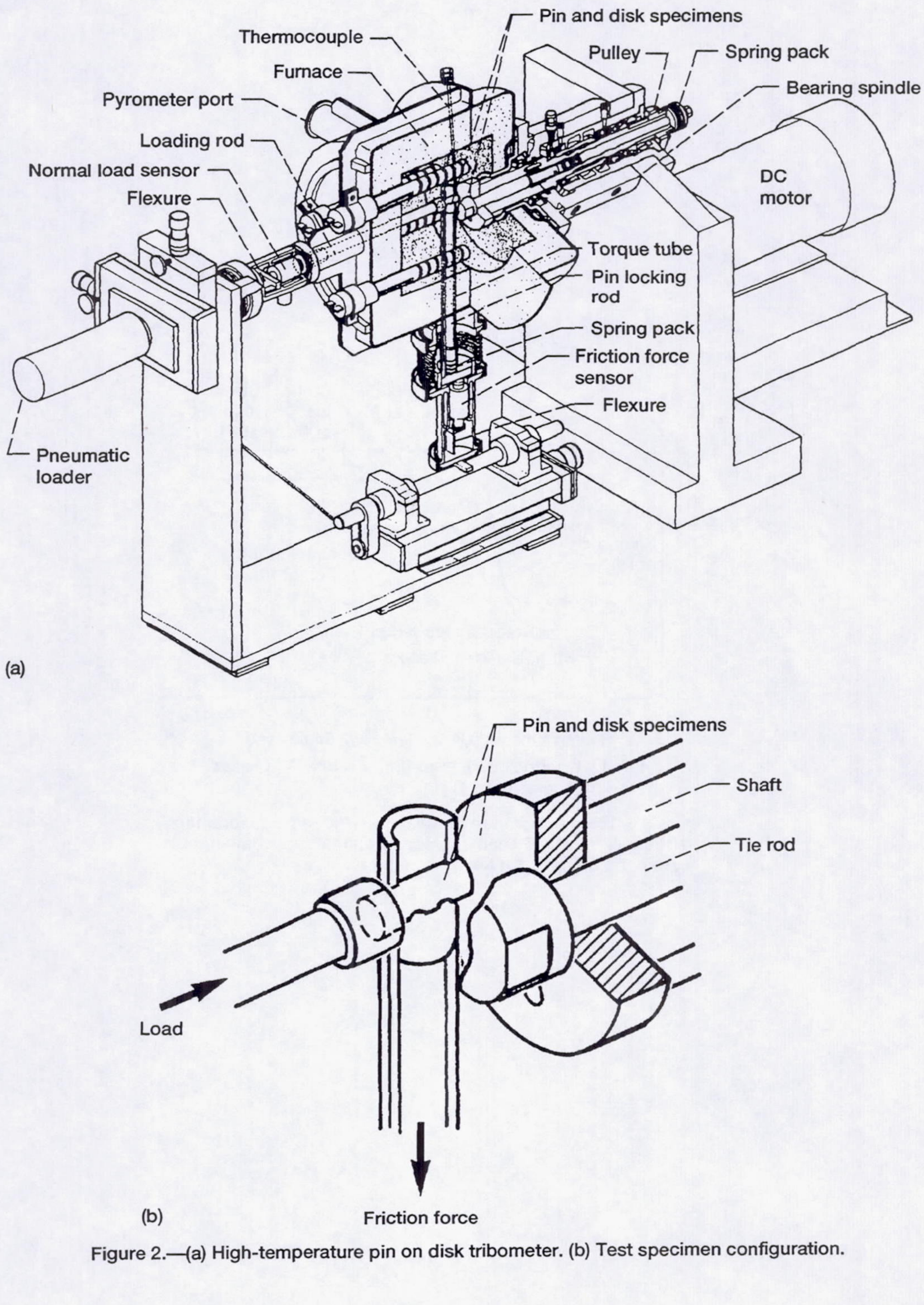

Figure 2.—(a) High-temperature pin on disk tribometer. (b) Test specimen configuration.

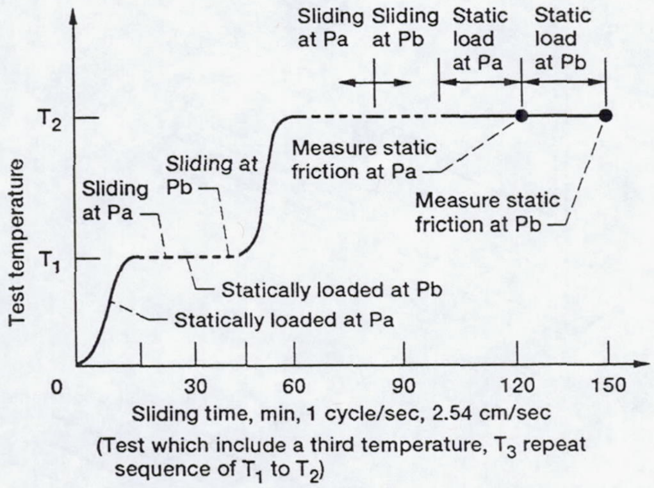

Figure 3.—Test temperature ramping and friction measurement sequence. Pa, Pb, T_1 and T_2 depend on material combination tested and are given in tables IVa and Va.

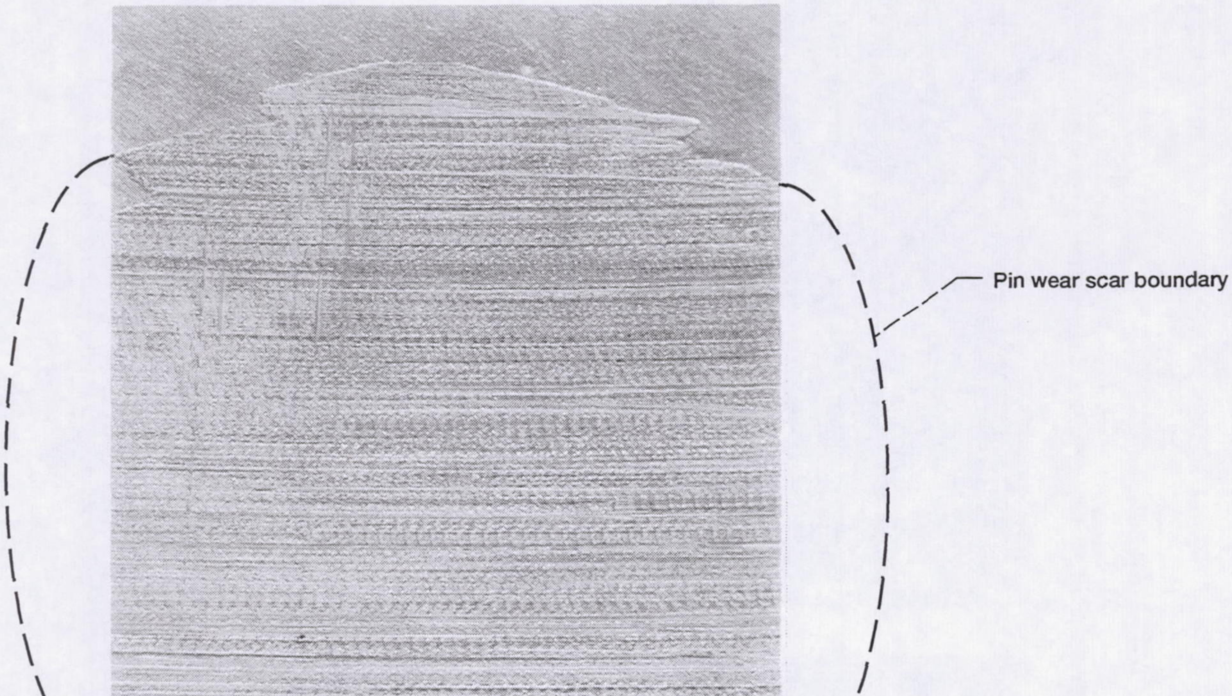

Figure 4.—Pin wear scar of Ag coated Incoloy 909 showing plowing of Ag film.

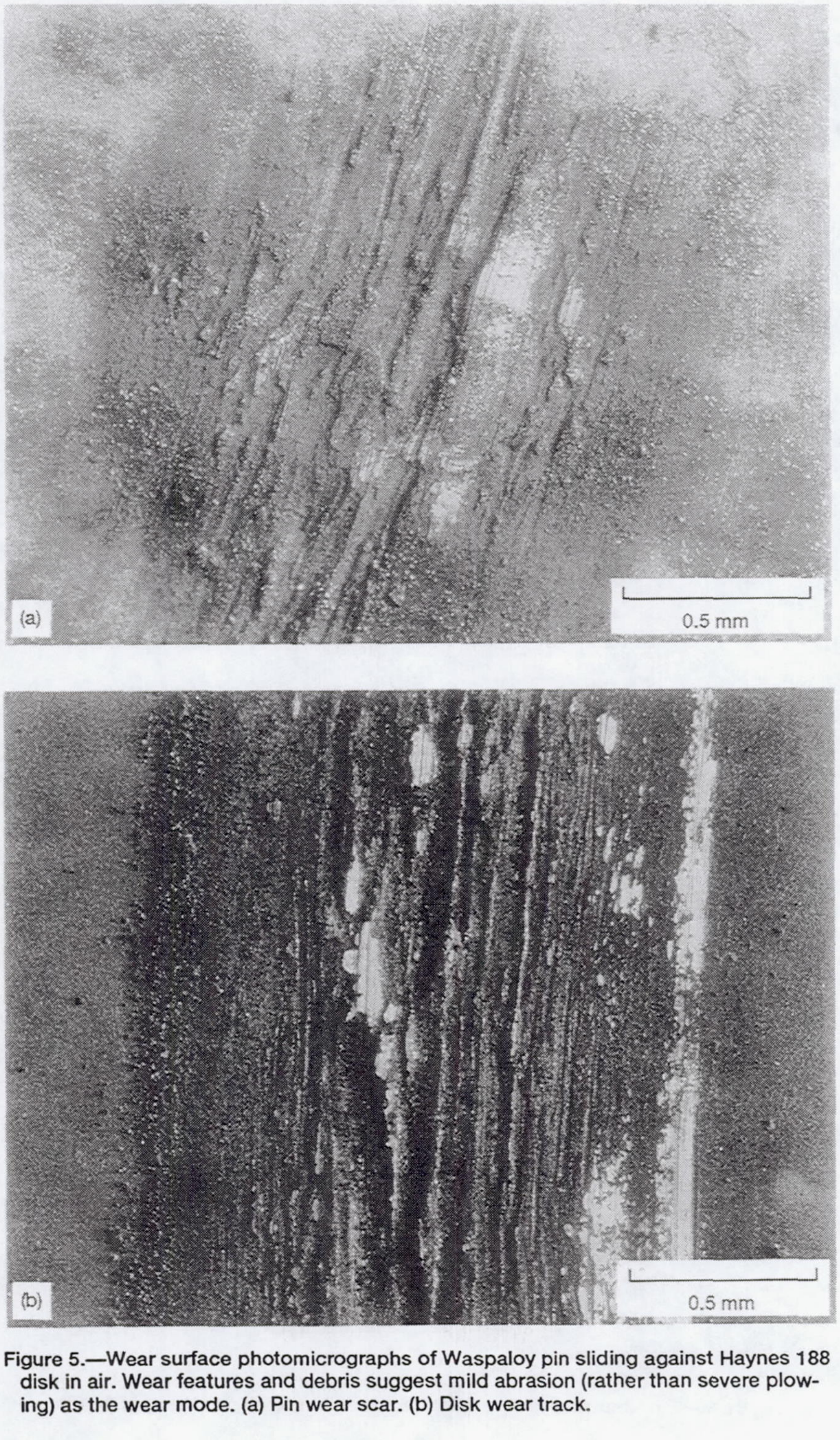

Figure 5.—Wear surface photomicrographs of Waspaloy pin sliding against Haynes 188 disk in air. Wear features and debris suggest mild abrasion (rather than severe plowing) as the wear mode. (a) Pin wear scar. (b) Disk wear track.

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13. ABSTRACT ***(Maximum 200 words)***
The following report describes a series of research tests to evaluate candidate high temperature materials for static to moderately dynamic hypersonic airframe seals. Pin-on-disk reciprocating sliding tests were conducted from 25 to 843°C in air and hydrogen containing inert atmospheres. Friction, both dynamic and static, was monitored and serves as the primary test measurement. In general, soft coatings lead to excessive static friction and temperature affected friction in air environments only.

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