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Evaluation of Ti-48Al-2Cr-2Nb Under Fretting Conditions

Kazuhisa Miyoshi, Bradley A. Lerch, Susan L. Draper, and Sai V. Raj
Glenn Research Center, Cleveland, Ohio

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Glenn Research Center, Cleveland, Ohio

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Kazuhisa Miyoshi, Bradley A. Lerch, Susan L. Draper, and Sai V. Raj
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract: The fretting behavior of Ti-48Al-2Cr-2Nb[a] (γ-TiAl) in contact with the nickel-base superalloy 718[b] was examined in air at temperatures from 296 to 823 K (23 to 550 °C). The interfacial adhesive bonds between Ti-48Al-2Cr-2Nb and superalloy 718 were generally stronger than the cohesive bonds within Ti-48Al-2Cr-2Nb. The failed Ti-48Al-2Cr-2Nb debris subsequently transferred to the superalloy 718. In reference experiments conducted with Ti-6Al-4V against superalloy 718 under identical fretting conditions, the degree of transfer was greater for Ti-6Al-4V than for Ti-48Al-2Cr-2Nb. Wear of Ti-48Al-2Cr-2Nb generally decreased with increasing fretting frequency. The increasing rate of oxidation at elevated temperatures led to a drop in wear at 473 K. However, fretting wear increased as the temperature was increased from 473 to 823 K. At 723 and 823 K, oxide film disruption generated cracks, loose wear debris, and pits on the Ti-48Al-2Cr-2Nb wear surface. Both increasing slip amplitude and increasing load tended to produce more metallic wear debris, causing severe abrasive wear in the contacting metals.

[a]Composition, at.%: titanium, 47.9; aluminum, 48.0; niobium, 1.96; chromium, 1.94; carbon, 0.013; nitrogen, 0.014; and oxygen, 0.167.

[b]Composition, wt.%: nickel, 50–55; chromium, 17–21; iron, 12–23; niobium plus tantalum, 4.75–5.5; molybdenum, 2.8–3.3; cobalt, 1; titanium, 0.65–1.15; aluminum, 0.2–0.8; silicon, 0.35; manganese, 0.35; copper, 0.3; carbon, 0.08; sulfur, 0.015; phosphorus, 0.015; and boron, 0.006.

Introduction

Adhesion, a manifestation of mechanical strength over an appreciable area, has many causes, including chemical bonding, deformation, and the fracture processes involved in interface failure. A clean metal in contact with another clean metal will fail either in tension or in shear because some of the interfacial bonds are generally stronger than the cohesive bonds within the cohesively weaker metal [*1*]. The failed metal subsequently transfers material to the other contacting metal. Adhesion undoubtedly depends on the surface cleanliness; the area of real contact; the chemical, physical, and mechanical properties of the interface; and the modes of junction rupture. The environment influences the adhesion, deformation, and fracture behaviors of contacting materials in relative motion.

Clean surfaces can be created by repeated sliding in vacuum, making direct contact of the fresh, clean surfaces unavoidable in practical cases [*2*]. This situation also applies in some degree to sliding contact in air, where fresh surfaces are continuously produced on interacting surfaces in relative motion. Microscopically small, surface-parallel relative motion, which can be vibratory (in fretting or false brinnelling) or creeping (in fretting), produces fresh, clean interacting surfaces and causes junction (contact area) growth in the contact zone [*3–5*].

Fretting wear produced between contacting elements is adhesive wear taking place in a nominally static contact under normal load and repeated microscopic vibratory motion [*6–10*]. The most damaging effect of fretting is the possibly significant reduction in the fatigue capability of the fretted component, even though the wear produced by fretting appears to be quite mild [*10*]. For example, Hansson, et al. reported that the reduction in fatigue strength by fretting of Ti-47Al-2Nb-2Mn containing 0.8 vol.% TiB_2 was approximately 20 percent.

Fretting fatigue is a complex problem of significant interest to aircraft engine manufacturers [*11–14*]. Fretting failure can occur in a variety of engine components. Numerous approaches, depending on the component and the operating conditions, have been taken to address the fretting problem. The components of interest in this investigation were the low-pressure turbine blades and disks. The blades in this case were titanium aluminide and the disk was a nickel-base superalloy. A concern for these airfoils is the fretting in fitted interfaces at the dovetail where the blade and disk are connected. Careful design can reduce fretting in most cases, but not completely eliminate it, because the airfoils frequently have a skewed (angled) blade-disk dovetail attachment, which leads to a complex stress state. Further, the local stress state becomes more complex when the influence of the metal-metal contact and the edge of contact is evaluated.

Because titanium and titanium-base alloys in the clean state will exhibit strong adhesive bonds [*2, 15*] when in contact with themselves and other materials, this adhesion causes heavy surface damage and high friction in practical cases. Therefore, it is possible that fretting will be a serious concern in this application.

The objective of this investigation was to evaluate the extent of fretting damage on Ti-48Al-2Cr-2Nb (γ-TiAl) in contact with the nickel-base superalloy 718 at temperatures from 296 to 823 K. Selected reference experiments were also conducted with Ti-6Al-4V. There is a large experience base with Ti-6Al-4V, which has been used extensively as a compressor blade material. The parameters of microscopic, surface-parallel motion, such as fretting frequency, slip amplitude, and load, were systematically examined in this study. Scanning interference microscopy (noncontact optical profilometry) was used to evaluate surface characteristics, such as topography, roughness, material transfer, and wear volume loss. Scanning electron microscopy with energy-dispersive spectroscopy was used to determine the morphology and elemental composition of fretted surfaces, transferred material, and wear debris.

Materials

The Ti-48Al-2Cr-2Nb specimens were determined to be of the following composition (in atomic percent): titanium, 47.9; aluminum, 48.0; niobium, 1.96; chromium, 1.94; carbon, 0.013; nitrogen, 0.014; and oxygen, 0.167. The tensile properties are shown in Table 1.

Table 1—*Tensile Properties of Ti-48Al-2Cr-2Nb*

Temperature, K	Modulus, GPa	Ultimate tensile strength, MPa
293	170	410
923	140	460

The nickel-base superalloy 718 specimens were of the following nominal composition (in weight percent): nickel, 50–55; chromium, 17–21; iron, 12–23; niobium plus tantalum, 4.75–5.5; molybdenum, 2.8–3.3; cobalt, 1; titanium, 0.65–1.15; aluminum, 0.2–0.8; silicon, 0.35; manganese, 0.35; copper, 0.3; carbon, 0.08; sulfur, 0.015; phosphorus, 0.015; and boron, 0.006 [*16*]. Superalloy 718 was solutioned and aged according to Aerospace Material Specification AMS 5596G, SAE, Warrendale, PA, 1987, yielding Rockwell C-scale hardness H_{RC} of 36. The tensile properties [*16*] are shown in Table 2. The ultimate tensile strength of superalloy 718 is greater than that of Ti-48Al-2Cr-2Nb by a factor of ~3.5 at room temperature and ~2 at high temperature (~1000 K).

Table 2—*Tensile Properties of Nickel-Base Superalloy 718*

Temperature, K	Modulus, GPa	Ultimate tensile strength, MPa
293	200	1434
811	171	1276
1033	154	758

The reference Ti-6Al-4V specimens were of the following nominal composition (in weight percent): titanium, balance; aluminum, 5.5–6.75; vanadium, 3.5–4.5; iron, ≤0.30; carbon, ≤0.08; nitrogen, ≤0.05; oxygen, ≤0.20; and hydrogen, ≤0.015 [*17*].

Experiments

Figure 1 presents the fretting wear apparatus used in this investigation. Fretting wear experiments were conducted with 9.4-mm-diameter, hemispherical nickel-base superalloy 718 pins in contact with Ti-48Al-2Cr-2Nb flats or with 6-mm-diameter, hemispherical Ti-48Al-2Cr-2Nb pins in contact with nickel-base superalloy 718 flats in air

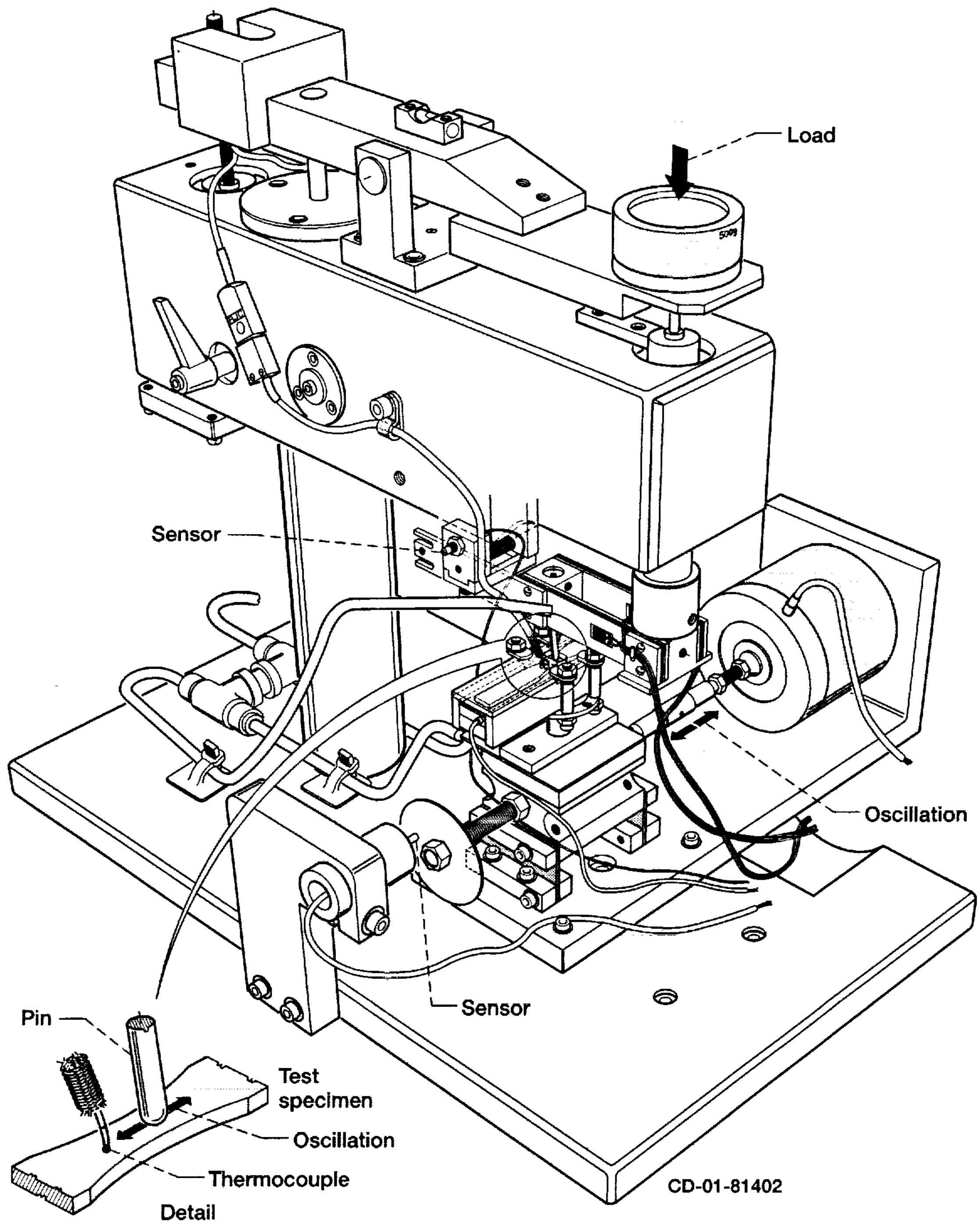

Figure 1—*Fretting apparatus.*

at temperatures from 296 to 823 K. All the flat and pin specimens used were polished with 3-μm-diameter diamond powder. Both pin and flat surfaces were relatively smooth, having centerline-average roughness R_a in the range 18 to 83 nm (Table 3). The Vickers hardness, measured at a load of 1 N, for the polished flat and pin specimens is also shown in Table 3.

Table 3—*Surface Roughness and Vickers Hardness of Specimens*

Specimen	Centerline-average roughness, R_a, nm		Vickers hardness[a], H_V, GPa	
	Mean	Standard deviation	Mean	Standard deviation
9.4-mm-diameter, hemispherical, nickel-base superalloy 718 pin	40	8.9	5.52	0.44
6-mm-diameter, hemispherical Ti-48Al-2Cr-2Nb pin	42	7.1	4.12	0.42
9.4-mm-diameter, hemispherical Ti-6Al-4V pin	83	2.0	3.85	0.092
Ti-48Al-2Cr-2Nb flat	35	3.3	3.78	0.57
Nickel-base superalloy 718 flat	18	7.2	4.78	0.21

[a]Load, 1 N.

All fretting wear experiments were conducted at loads from 1 to 40 N, frequencies of 50, 80, 120, and 160 Hz, and slip amplitudes between 50 and 200 μm for 1 million to 20 million cycles. Both pin and flat surfaces were rinsed with 200-proof ethyl alcohol before installation in the fretting apparatus.

Two or three fretting experiments were conducted with each material couple at each fretting condition. The data were averaged to obtain the wear volume losses of Ti-48Al-2Cr-2Nb and Ti-6Al-4V. The wear volume loss was determined by using an optical profiler (noncontact, vertical scanning, white-light interferometer). It characterizes and quantifies surface roughness, height distribution, and critical dimensions (such as area and volume of damage, wear scars, and topographical features). It has three-dimensional profiling capability with excellent precision and accuracy (e.g., profile heights ranging from ≤1 nm up to 5000 μm with 0.1-nm height resolution). The shape of a surface can be displayed by a computer-generated map developed from digital data derived from a three-dimensional interferogram of the surface. A computer directly processes the quantitative volume and depth of a fretted wear scar. Reference fretting wear experiments were conducted with 9.4-mm-diameter hemispherical Ti-6Al-4V pins in contact with nickel-base superalloy 718 flats.

Results and Discussion

Observations

Surface and subsurface damage always occurred on the interacting surfaces of the Ti-48Al-2Cr-2Nb fretted in air. The surface damage consisted of material transfer, pits, oxides and debris, scratches, fretting craters and/or wear scars, plastic deformation, and cracks.

Adhesion and Material Transfer—Figure 2 presents a backscattered electron image and an energy-dispersive x-ray spectrum (EDS) taken from the fretted surface of the nickel-base superalloy 718 pin after contact with the Ti-48Al-2Cr-2Nb flat. Clearly, Ti-48Al-2Cr-2Nb transferred to superalloy 718. The Ti-48Al-2Cr-2Nb failed either in tension or in shear because some of the interfacial adhesive bonds (solid state or cold welding) were stronger than the cohesive bonds within the cohesively weaker Ti-48Al-2Cr-2Nb.

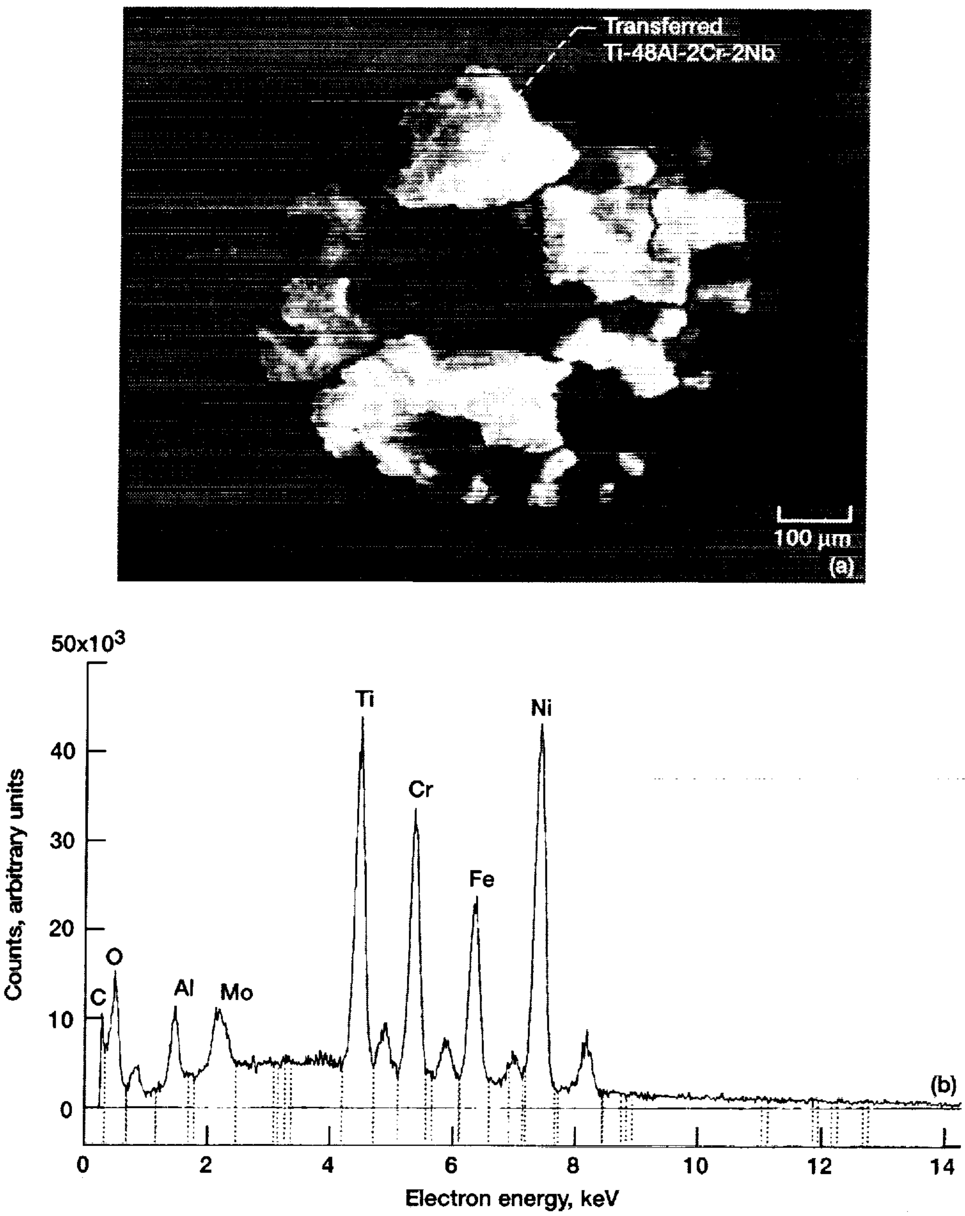

Figure 2—*Wear scar on superalloy 718 pin fretted against Ti-48Al-2Cr-2Nb flat. (a) SEM backscattered electron image. (b) X-ray energy spectrum with EDS. Fretting conditions: load, 1.5 N; frequency, 80 Hz; slip amplitude, 50 μm; total number of cycles, 1 million; environment, air; and temperature, 823 K.*

The ultimate tensile strength of superalloy 718 is greater than that of Ti-48Al-2Cr-2Nb by a factor of ~3.5 at room temperature and ~2 at high temperature (~1000 K). The failed Ti-48Al-2Cr-2Nb subsequently transferred to the superalloy 718 surface in amounts ranging from 10 to 60 percent of the superalloy 718 contact area at all fretting conditions in this study. The thickness of the transferred Ti-48Al-2Cr-2Nb ranged up to ~20 μm.

As with the materials pair of Ti-48Al-2Cr-2Nb and superalloy 718, material transfer was observed on the superalloy 718 flat surface after fretting against the Ti-6Al-4V pin at 696 and 823 K in air. However, the degree of material transfer was remarkably different and greater, ranging from 30 to 100 percent of the superalloy 718 contact area for identical fretting conditions. The thickness ranged up to 50 μm.

Fretting Wear—Figure 3 shows typical wear scars produced on the Ti-48Al-2Cr-2Nb pin and the superalloy 718 flat with fretting. Because of the specimen geometry a large amount of wear debris was deposited just outside the circular contact area. Pieces of the metals (both Ti-48Al-2Cr-2Nb and superalloy 718) and their oxides were torn out during fretting. It appears that the cohesive bonds in some of the contact area of both metals fractured. Scanning electron microscopy (SEM) and EDS studies of wear debris produced under fretting verified the presence of metallic particles of both Ti-48Al-2Cr-2Nb and superalloy 718. In the central region of wear scars produced on Ti-48Al-2Cr-2Nb there was generally a large, shallow pit, where Ti-48Al-2Cr-2Nb had torn out or sheared off and subsequently transferred to superalloy 718. The central regions of wear scars produced on Ti-48Al-2Cr-2Nb and on superalloy 718 were morphologically similar (Fig. 3), generally having wear debris, scratches, plastically deformed asperities, and cracks.

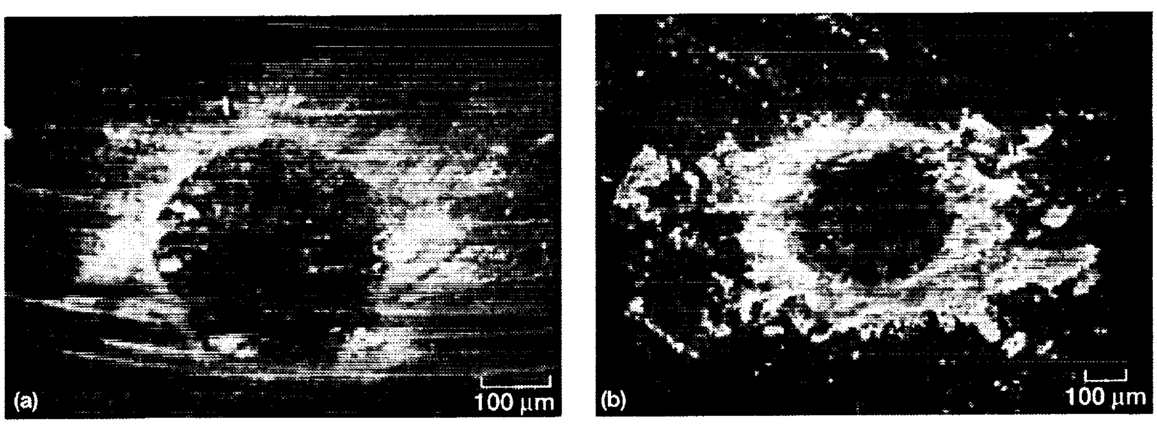

Figure 3—*Wear scars (a) on Ti-48Al-2Cr-2Nb pin and (b) on superalloy 718 flat. Fretting conditions: load, 1 N; frequency, 80 Hz; slip amplitude, 50 μm; total number of cycles, 1 million; environment, air; and temperature, 823 K.*

Figure 4 shows examples of surface damage: metallic wear debris of Ti-48Al-2Cr-2Nb and superalloy 718, oxides and their debris, scratches (grooves), small craters, plastically deformed asperities, and cracks. The scratches (Fig. 4(a)) can be caused by hard protuberances (asperities) on the superalloy 718 surface (two-body conditions) or by wear particles between the surfaces (three-body conditions). Abrasion is a severe form of wear. The hard asperities and trapped wear particles plow or cut the Ti-48Al-2Cr-2Nb surface. The trapped wear particles have a scratching effect on both surfaces; and because they carry part of the load, they cause concentrated pressure peaks on both surfaces. The pressure

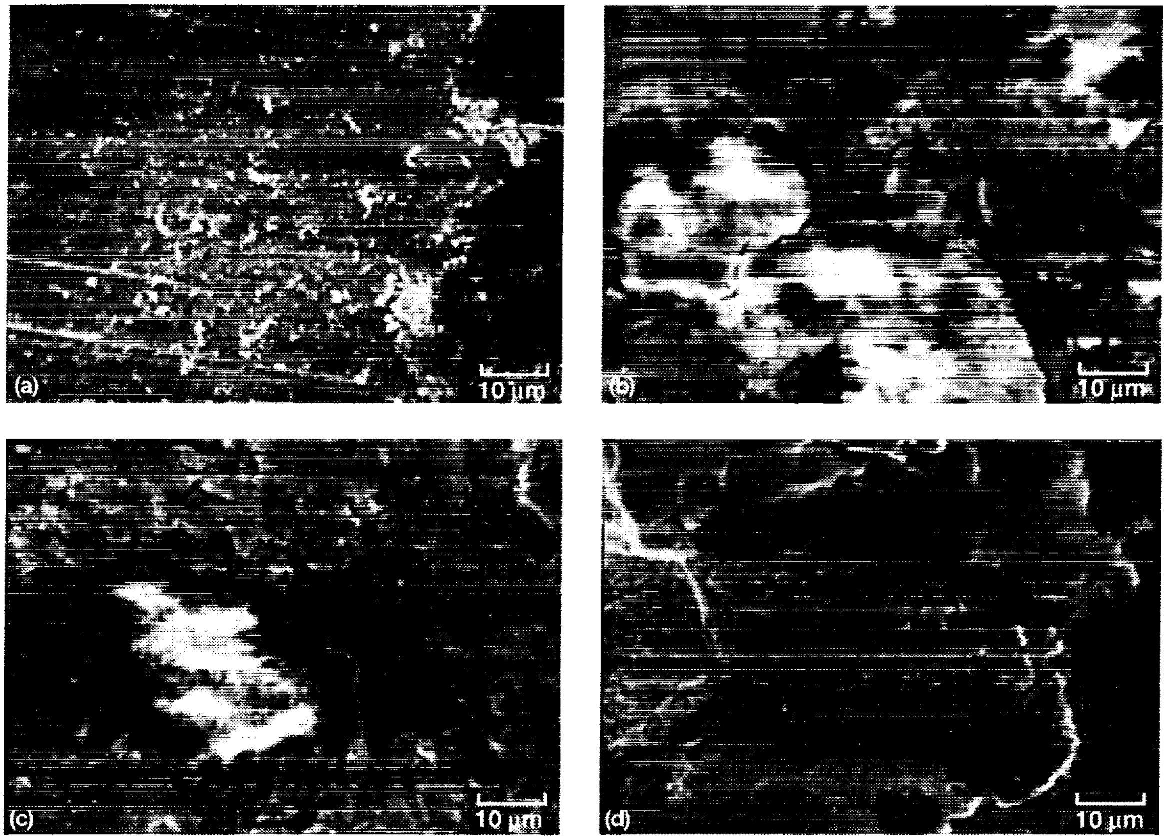

Figure 4—*Surface and subsurface damage in Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin. (a) Scratches. (b) Cracks in oxide layers. (c) Cracks in metal. (d) Fracture pits and plastic deformation. Fretting conditions: load, 1 N; frequency, 80 Hz; slip amplitude and total number of cycles: (a) 50 µm and 1 million, (b) 60 µm and 10 million, (c) 50 µm and 1 million, (d) 70 µm and 20 million; environment, air; and temperature, 823 K.*

peaks may well be the origin of crack nucleation in the oxide layers and the bulk alloys. Two types of crack were observed on the wear surface of Ti-48Al-2Cr-2Nb: cracks in the oxide layers, and cracks in the bulk Ti-48Al-2Cr-2Nb.

Oxide layers readily form on the Ti-48Al-2Cr-2Nb surface at 823 K and are often a favorable solution to wear problems. However, if the bulk Ti-48Al-2Cr-2Nb is not hard enough to carry the load, it will deform plastically or elastically under fretting contact. With Ti-48Al-2Cr-2Nb, cracks occurred in the oxide layers both within and around the contact areas (Fig. 4(b)).

Fractures in the protective oxide layers produced cracks in the bulk Ti-48Al-2Cr-2Nb (Fig. 4(c)) and also produced wear debris; chemically active, fresh surfaces; plastic deformation; and craters or fracture pits (Fig. 4(d)). The wear debris caused third-body abrasive wear (Fig. 4(a)). Local, direct contacts between the fresh surfaces of Ti-48Al-2Cr-2Nb and superalloy 718 resulted in increased adhesion and local stresses, which may cause plastic deformation, flake-like wear debris, and craters (e.g., the fracture pits in the Ti-48Al-2Cr-2Nb shown in Fig. 4(d)).

Cross sections of a wear scar on Ti-48Al-2Cr-2Nb revealed subsurface cracking and craters. For example, Fig. 5 shows propagation of subsurface cracking, nucleation of small cracks, formation of a large crater, and generation of debris. Cracks are transgranular and have no preference to the microstructure.

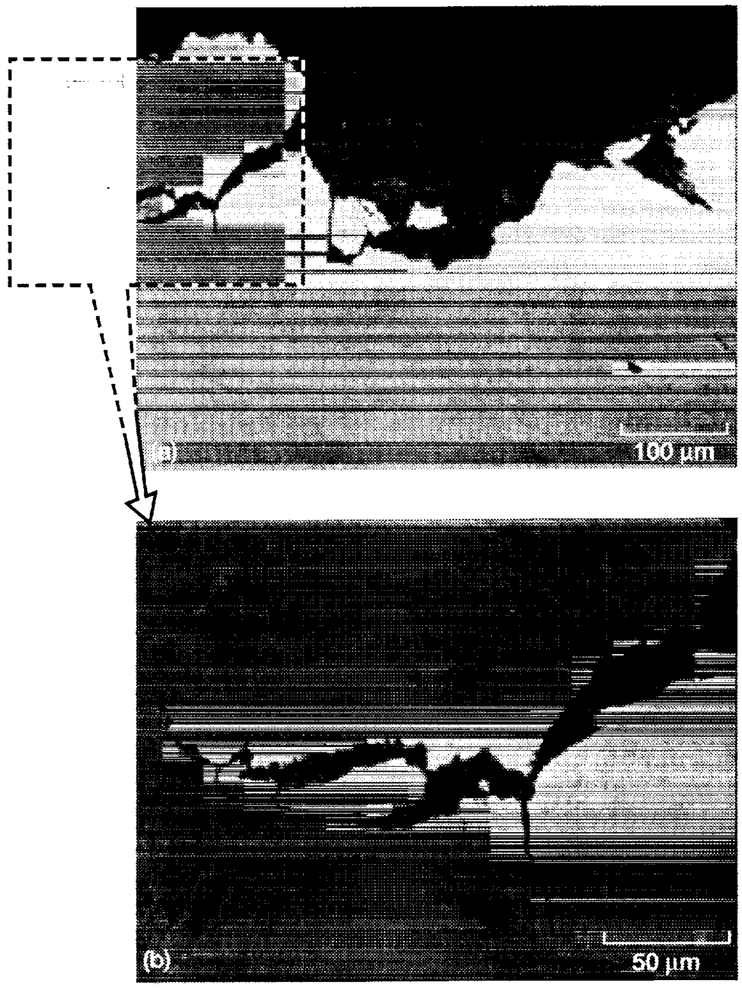

Figure 5—*Cross-section view of wear scar on Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin. (a) Overview. (b) Crack growth. Fretting conditions: load, 30 N; frequency, 80 Hz; slip amplitude, 70 µm; total number of cycles, 20 million; environment, air; and temperature, 823 K.*

Parameters Influencing Wear Loss of Ti-48Al-2Cr-2Nb

Figure 6 shows the wear volume loss measured by the optical interferometer as a function of fretting frequency for Ti-48Al-2Cr-2Nb in contact with superalloy 718. Although there were some exceptions, the wear volume loss generally decreased with increasing fretting frequency. A reasonable amount of material transfer from the Ti-48Al-2Cr-2Nb specimen to the superalloy 718 specimen was observed at all frequencies. At the lowest frequency of 50 Hz remarkable plastic deformation (grooving) and surface roughening in the Ti-48Al-2Cr-2Nb wear scar were observed. At high frequencies wear scars were noticeably smooth with bulk cracks in the Ti-48Al-2Cr-2Nb surface.

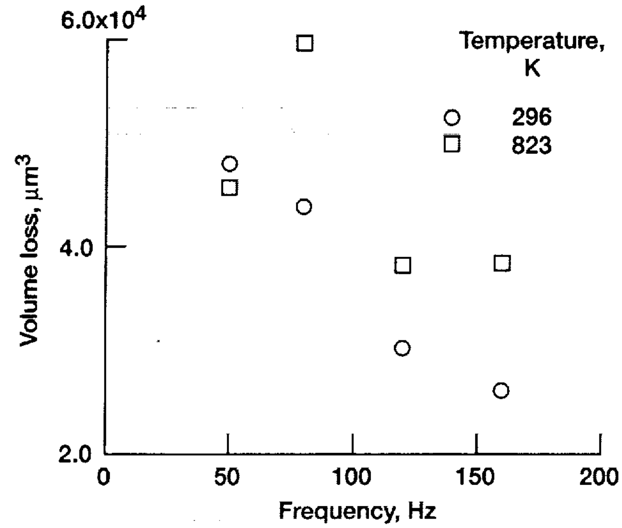

Figure 6—*Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin in air as function of fretting frequency. Fretting conditions: load, 30 N; slip amplitude, 50 μm; total number of cycles, 1 million; environment, air; and temperatures, 296 and 823 K.*

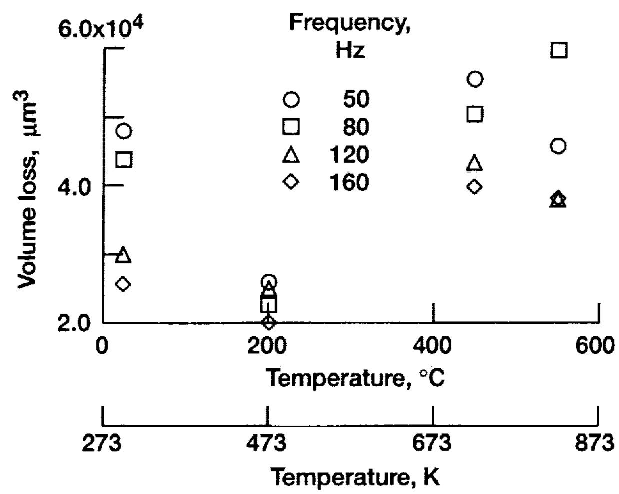

Figure 7—*Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin in air as function of fretting temperature. Fretting conditions: load, 30 N; slip amplitude, 50 μm; total number of cycles, 1 million; environment, air; and fretting frequencies, 50, 80, 120, and 160 Hz.*

Temperature influences the adhesion, deformation, and fracture behaviors of contacting materials in relative motion. It is known that temperature interacts with the fretting process in two ways: first, the rate of oxidation or corrosion increases with temperature; and second, the mechanical properties, such as hardness, of the materials are also temperature dependent [9]. Figure 7 presents the wear volume loss measured by optical interferometry as a function of temperature for Ti-48Al-2Cr-2Nb in contact with superalloy 718. Also, SEM images and EDS spectra were taken from the fretted Ti-48Al-2Cr-2Nb surfaces. The wear volume loss dropped to a low value at 473 K. The worn surface at 473 K was predominantly oxide and relatively smooth. A protective oxide film prevented direct metal-to-metal contact and ensured, in effect, that a mild oxidative wear regime prevailed. However, fretting wear increased as the temperature was increased from 473 to 823 K. The highest temperatures of 723 and 823 K resulted in oxide film disruption with crack generation, loose wear debris, and pitting of the Ti-48Al-2Cr-2Nb wear surface.

Figure 8 shows the wear volume loss measured by optical interferometry as a function of slip amplitude for Ti-48Al-2Cr-2Nb in contact with superalloy 718. The fretting wear volume loss increased as the slip amplitude increased. Increases in amplitude tended to produce more metallic wear debris, causing severe abrasive wear in the contacting metals. Figure 9 presents a three-dimensional, optical interferometry image of the Ti-48Al-2Cr-2Nb wear scar at a slip amplitude of 200 µm and a temperature of 296 K. In the wear scar are large, deep grooves where the wear debris particles have scratched the Ti-48Al-2Cr-2Nb surface in the slip direction.

Figure 10 shows the measured wear volume loss as a function of load for Ti-48Al-2Cr-2Nb in contact with superalloy 718 at a temperature of 823 K, a fretting frequency of 80 Hz, and a slip amplitude of 50 µm for 1 million cycles. The fretting wear volume loss generally increased as the load increased, generating more metallic wear debris in the contact area, the primary cause of abrasive wear in both Ti-48Al-2Cr-2Nb and superalloy 718.

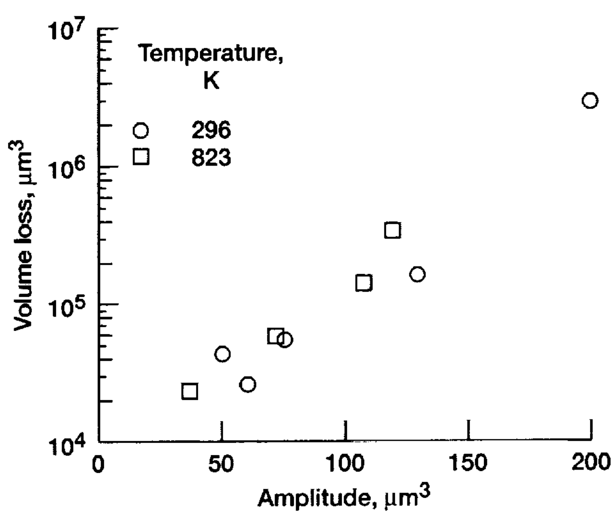

Figure 8—*Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin in air as function of slip amplitude. Fretting conditions: load, 30 N; frequency, 50 Hz; total number of cycles, 1 million; environment, air; and temperatures, 296 and 823 K.*

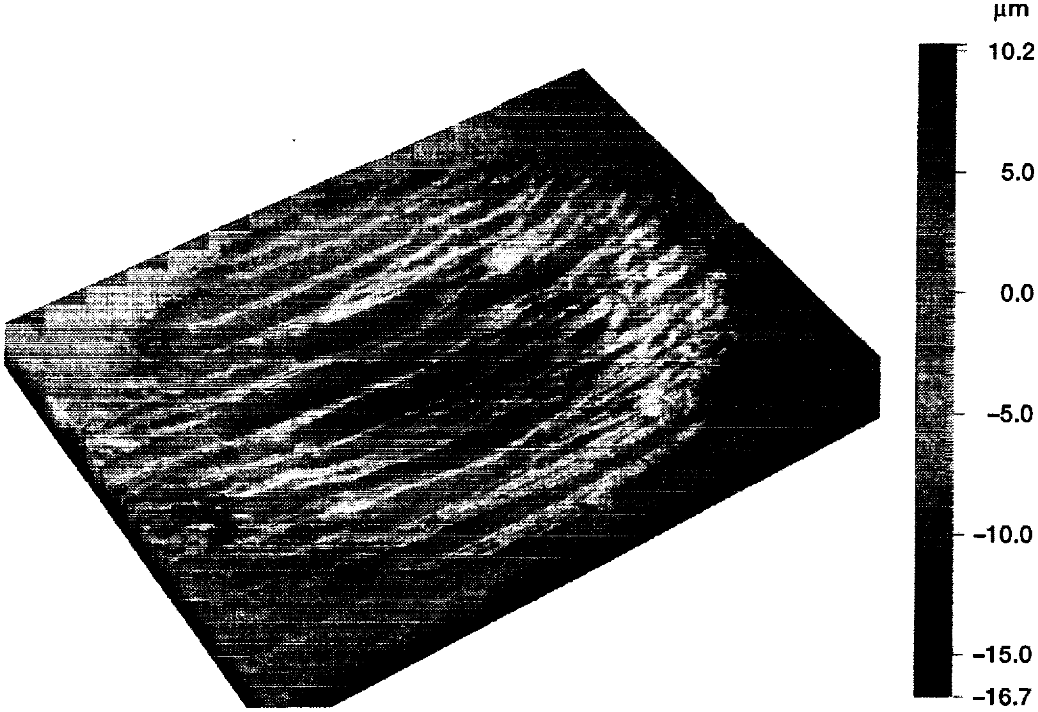

Figure 9—*Wear scar on Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin, showing scratches. Fretting conditions: load, 30 N; frequency, 50 Hz; slip amplitude, 200 µm; total number of cycles, 1 million; environment, air; and temperature, 296 K.*

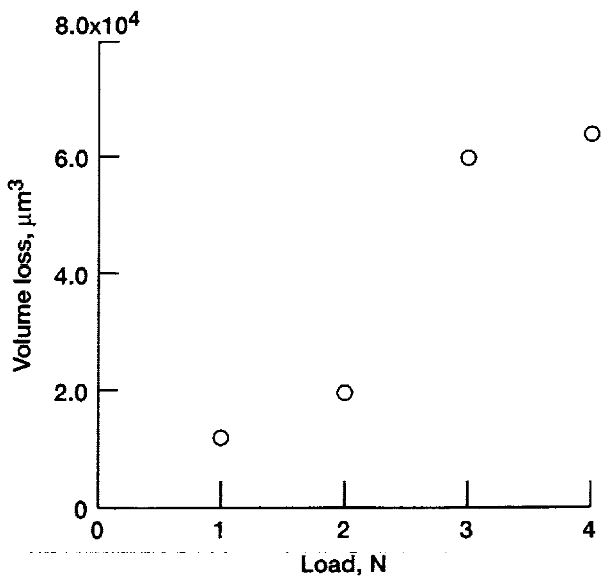

Figure 10—*Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with superalloy 718 pin as function of load. Fretting conditions: frequency, 80 Hz; slip amplitude, 50 µm; total number of cycles, 1 million; environment, air; and temperature, 823 K.*

Concluding Remarks

The fretting behavior of γ-TiAl (Ti-48Al-2Cr-2Nb) in contact with nickel-base superalloy 718 in air at temperatures of 296 to 823 K was examined with the following results:

1. The Ti-48Al-2Cr-2Nb transferred to the superalloy 718 at all fretting conditions, such that from 10 to 50 percent of the superalloy 718 contacting surface area became coated with the Ti-48Al-2Cr-2Nb. The maximum thickness of the transferred Ti-48Al-2Cr-2Nb was approximately 20 μm. In reference experiments Ti-6Al-4V transferred to superalloy 718 under identical fretting conditions. Compared with Ti-48Al-2Cr-2Nb transfer, the degree of Ti-6Al-4V transfer was greater, such that from 30 to 100 percent of the superalloy 718 contacting surface area became coated with the Ti-6Al-4V. The thickness of the transferred Ti-6Al-4V ranged up to 50 μm.
2. The wear scars produced on Ti-48Al-2Cr-2Nb contained metallic and oxide wear debris, scratches, plastically deformed asperities, cracks, and fracture pits.
3. Although oxide layers readily formed on the Ti-48Al-2Cr-2Nb surface at 823 K, cracking readily occurred in the oxide layers both within and around the contact areas.
4. The wear volume loss of Ti-48Al-2Cr-2Nb generally decreased with increasing fretting frequency, increased with increasing temperature, and increased with increasing slip amplitude.
5. Mild oxidative wear and low wear volume were observed at 473 K.

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Kazuhisa Miyoshi, Bradley A. Lerch, Susan L. Draper, and Sai V. Raj

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13. ABSTRACT ***(Maximum 200 words)***

The fretting behavior of Ti-48Al-2Cr-2Nb (γ-TiAl) in contact with the nickel-base superalloy 718 was examined in air at temperatures from 296 to 823 K (23 to 550 °C). The interfacial adhesive bonds between Ti-48Al-2Cr-2Nb and superalloy 718 were generally stronger than the cohesive bonds within Ti-48Al-2Cr-2Nb. The failed Ti-48Al-2Cr-2Nb debris subsequently transferred to the superalloy 718. In reference experiments conducted with Ti-6Al-4V against superalloy 718 under identical fretting conditions, the degree of transfer was greater for Ti-6Al-4V than for Ti-48Al-2Cr-2Nb. Wear of Ti-48Al-2Cr-2Nb generally decreased with increasing fretting frequency. The increasing rate of oxidation at elevated temperatures led to a drop in wear at 473 K. However, fretting wear increased as the temperature was increased from 473 to 823 K. At 723 and 823 K, oxide film disruption generated cracks, loose wear debris, and pits on the Ti-48Al-2Cr-2Nb wear surface. Both increasing slip amplitude and increasing load tended to produce more metallic wear debris, causing severe abrasive wear in the contacting metals.

14. SUBJECT TERMS

Materials; Ti-48Al-2Cr-2Nb; Fretting wear; Fatigue; Oxidation; High temperature; Ni-base superalloy 718

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