Author names and affiliations

Ken Gall Martin L. Dunn Yiping Liu Paul Labossiere

Department of Mechanical Engineering, University of Colorado, Boulder, CO, 80309

Huseyin Sehitoglu Department of Mechanical and Industrial Engineering, University of Illinois,

Urbana, IL, 61801

Yuriy I. Chumlyakov Physics of Plasticity and Strength of Materials Laboratory, Siberian Physical and Technical Institute, Micro and Macro Deformation < of Single Crystal NiTi

We present experimental results on the instrumented Vickers micro-indentation and compression of solutionized N-rich NIT single crystals. The fests are conducted at room temperature where the solutionized Ti-50.9 at percent Ni material is 18 degrees above A_f and the solutionized Ti-51.5 at percent Ni material is more than 100 degrees above A_f and the solutionized Ti-51.5 at percent Ni material is more than 100 degrees above A_f as the first product of the size of the size

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Abstract

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CRITICAL REVIEW

Critical Review: Adhesion in surface micromechanical structures

Rova Maboudiana)

Berkeley Sensor and Actuator Center, and Department of Chemical Engineering, University of California, Berkeley, California 94720

Roger T. Howe

Berkeley Sensor and Actuator Center, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720

(Received 15 November 1996; accepted 15 November 1996)

We present a review on the state of knowledge of surface phenomena behind adhesion in surface micromechanical structures. After introducing the problem of release-related and in-use adhesion, a theoretical framework for understanding the various surface forces that cause strong adhesion of micromechanical structures is presented. Various approaches are described for reducing the work of adhesion. These include surface roughening and chemical modification of polycrystalline silicon surfaces. The constraints that fabrication processes such as release, drying, assembly, and packaging place on surface treatments are described in general. Finally, we briefly outline some of the important scientific and technological issues in adhesion and friction phenomena in micromechanical structures that remain to be clarified. © 1997 American Vacuum Society. [S0734-211X/97/02301-9]

Title

Abstract

Title Author names and affiliations

Corresponding author contact information

a)Electronic mail: maboudia@uclink4.berkeley.edu

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Roya Maboudian^a

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I. INTRODUCTION

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cently, a modular process that embeds the polysilicon microstructure in the wafer prior to CMOS fabrication was developed.⁸

Surface microstructures typically range from 0.1 to several arm in thickness with lateral dimensions of 10-500 arm. and lateral and vertical gaps to other structures or to the substrate of around 1 µm. A representative polysilicon-based integrated MEMS device" is shown in Fig. 1. The large surface area and small offset from adjacent surfaces makes these microstructures especially vulnerable to adhesion upon contact. As an example, the "pull-off" force of a displaced surface microstructure in contact with an adjacent surface ranges from a few µN for an airbag accelerometer sense element to nN for highly compliant microstructures with submicron flexure widths. 16 These forces are considerably weaker than interfacial forces, and hence, permanent adhesion results upon contact. Since in many microdevices, one is not only dealing with a vertical pull-off force but also with a peeling (friction) phenomenon, this problem is more generally called stiction, a term borrowed from the magnetic recording media industry.11 The adhesion of the microstructure to adiacent surfaces can occur either during the final stens of the micromachining process (release-related adhesion) or after packaging of the device, due to overrange input signals or electromechanical instability (in-use adhesion).12 The distinction between the two classes will be useful, since their causes and strategies for eliminating or minimizing adhesion

It must be noted that high-aspect ratio microstructures of single crystal silicon ^{13,14} and other materials ¹³ are also susceptible to adhesion. These structures are typically sus-

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Ken Gall Martin L. Dunn Yiping Liu Paul Labossiere

Department of Machanical Engineering, University of Colorado, Enuidar, CO, 80909

Huseyin Sehitoglu Department of Machanical and Industrial Engineering University of Elina E, Octobra II., 61801

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(TEM) [25]. Understanding the microscopic mechanisms of cyclic degradation in NIB materials is particularly important for emerging share memory allows technologies.

Ougoing workshops [26] and conferences [27] have suggested that a lacerative fatter for shape memory materials such as Nill inc in the areas of micro-declare-enchanted systems (MEMS) and covil influstractures. Long-life reliability same in these applications demand tools to understand and societately predict the evolution of the Nill material response rader cyclic looking. To improve our state-of-the-set approaches [26—25] sained at modeling the cyclic behavior of Nill shape memory alloys, we must increase our methication understandings at the microscorie care Publication timeline

Contributed by the Materials Division for publication in the JOURNAL OF ENGINEERING MATERIALS AND TECHNOLOGY. Manuscript received by the Materials Division October 31, 2000; revised manuscript received April 18, 2001. Associate Editor: E. Werner.

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5 Conclusions

- 1 Micro-indentation hardnesses as a function of surface normal orientation do not correlate with the macroscopic compressive transformation or "yield" strength. The indentation response of Ti-50.9 at percent Ni deformed 18 deg above A_f results in elastic and plastic deformation, and a stress-induced martensitic transformation. The material hardness with orientation correlates best with the resistance to dislocation motion. The hardest orientations are those near the [100] pole, consistent with the difficulty of slip in (100) directions for BCC materials as the surface normal orientation approaches the [100] pole. Indentation of Ti-51.5 at percent Ni is elasto-plastic, with a negligible orientation dependence.
- 2 The macroscopic compressive response of solutionized Ti-50.9 at percent Ni deformed 18 deg above A_f is dependent on the crystallographic orientation of the testing axis. As the normal axis moves towards near the [111] pole, plastic flow dominates. Orientations closer to [210] (near the theoretical maximum Schmid factor for Type II-1 twins) deform mainly by a stress-induced martensitic transformation.
- 3 The orientation of the (100){001} and (100){011} families of slip systems, with respect to the applied stress-state, strongly influences the development of plasticity in NiTi shape memory alloys. Specimens with crystal orientations that do not favor slip on these systems show better overall recoverability relative to other orientations that are more favorably oriented for the transformation and plastic flow.
- 4 The strain-hardening of highly symmetric orientations such as [111] or [100] is more pronounced if plastic flow rather than a stress-induced transformation govern the deformation response. This observation indicates that either stress-induced martensite plates interact with low energy, or multiple plates do not form. Slip systems show relatively strong interactions.

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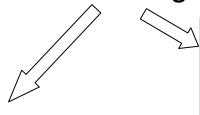
References

- Wayman, C. M., 1980, J. Metals, 52, June, pp. 129-137.
- Knowles, K. M., and Smith, D. A., 1981, Acta Metall., 29, pp. 101-110.
 Matsumoto, O., Miyasaki, S., Otsuka, K., and Tamura, H., 1987, Acta Metall.
- 55, pp. 2137–2144.
 [4] Otsuka, K., and Wayman, C. M., 1988, Shape Memory Materials, Cambridge
- [4] Otsuka, K., and Wayman, C. M., 1988, Shape Memory Materials, Cambridge University Press, UK.
- [5] Melton, K. N., and Mercier, O., 1979, Acta Metall., 27, pp. 137–144.
- [6] Miyazaki, S., Imai, T., Igo, Y., and Otsuka, K., 1986, Metall. Mater. Trans. A, 17, p. 115.
- [7] Lim, T. J., and h6cDowell, D. L., 1995, J. Intell. Mater. Syst. Struct., 6, p. 817.
 [8] Strusdel, B., Ohsshi, S., Ohtsuka, H., Ishihara, T., and Miyaraki, S., 1995,
- Mater Sci. Eng., A, 202, p. 148.

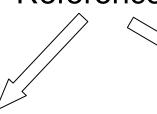
 [9] Stradel, B., Ohsshi, S., Ohtraka, H., Miyazaki, S., and Ishihara, T., 1995,
- Mater. Sci. Eng., A, 205, p. 187.

Conclusions

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References



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- ¹H. C. Nathanson, W. E. Newell, R. A. Wickstrom, and J. R. Davis, Jr., IEEE Trans. Electron Devices ED-14, 117 (1967).
- ²R. T. Howe, J. Vac. Sci. Technol. B 6, 1809 (1988).
- ³R. T. Howe, B. E. Boser, and A. P. Pisano, Sens. Actuators A 56, 167 (1996)
- ⁴L. J. Hornbeck, Proceedings of the IEEE International Electron Devices Meeting, Washington, D.C., 1993, pp. 381-384; Proc. SPIE 2639, 2 (1995).
- ⁵J. B. Sampsell, J. Vac. Sci. Technol. B 12, 3242 (1994).
- ⁶R. S. Payne, S. Sherman, S. Lewis, and R. T. Howe, Proceedings of the IEEE International Solid-State Circuits Conference, San Francisco, CA, 1995, pp. 164-165.

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Journal Papers and Reviews

Ken Gall Martin L. Dunn Yiping Liu Paul Labossiere

Department of Mechanical Engineering University of Colorado, Equidar, CO, 80908

Huseyin Sehitoglu Department of Mechanical and Industrial Engineering University of University University 4,14801

Yuriy 1. Chumlyak ov Physics of Plasticily and Strength of Malenials Laborating, Siberian Physical and Technical Inel fire, 624/50 Termst, Russia

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(TEM) [25]. Understanding the microscopic mechanisms of cyclic degradation in NIT materials is particularly important for energing shape memory alloys technologies. Ougoing workshops [26] and conferences [27] have suggested

that a lucrative future for shape memory materials such as NiTi lies in the areas of micro-dectro-mechanical systems (MEMS) and civil infrastructures. Long-life reliability issues in these seedications demand tools to understand and accurately predict the evolution of the NiTi material response under cyclic loading. To improve our state-of-the-art approaches [20-23] simed at modeling the cyclic behavior of NeTi shape memory alloys, we must increase our mechanistic understandings at the microscopic scale. Moreover, the loading conditions [28-30] and material microstructure [31] in MEMS actuators (usually thin films) are quite different than bulk Ne'll components. Consequently, without accounting for the local deformation mechanisms it becomes difficult to extend our macroscopic cyclic models [20-23] to smaller scale meterial systems without possible deficiencies. In addition, micro-scale studies on NiTi materials are critical to provide a tool for characterization of emerging smart MEMS technologies.

One of the primary reasons that the micro-mechanisms of cychic evolution and degradation effects have studed research efforts is because fundamental research on the NiTi alloy system has not explicitly focused on the mechanisms and implications of plastic flow. Ignoring the effects of plastic flow is a visible assumption under monotonic loading since its influence is negligible over one leading cycle. However, under cyclic leading, the local plantic flow characteristics of the B2 matrix have a strong influence on the evolving NiTi material response [24]. During the transformation, the material microstructure is a mixture of macteriate, the B2 parent phase, and untransformable precipitates (present in Ni or Ti rich materials). Repeated growth of the martenaite through a heterogeneous microstructure causes local slip to accumulate to significent levels in the weaker B2 phase. To our knowledge, there is only one study that examines microscopic also characteratics in NiTi materials [32], where TEM is used to identify the (100)(001) and (100)(011) families as dominant slip systems in EQ NeTh. Notably, experimental [33] and atomistic [34] studies in similar B2 NiAl intermetallics have provided consistent findings with the

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