JOURNAL OF MATERIALS SCIENCE 30 (1995) 4401–4406

Wear properties of oxide dispersion strengthened nickel alloys

S. IKENO, I. SIOTA*, M. NOBUKI, M. NAKAMURA
National Research Institute for Metals, 2-1, 1-chome, Sengen, Tsukuba-shi, Ibaragi 305, Japan

Wear resistance of Ni superalloys and oxide-dispersed Ni alloys was studied at room temperature. The wear resistance was connected with dislocation behaviour in the alloys. Dislocations in Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3 easily cross-slipped at dispersed alumina particles. Dislocation cell structures fully developed. Easiness of the cell structure formation corresponded to the lower wear resistance of Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3 than Ni. On the other hand, the dislocations in MA6000 hardly cross-slipped at the dispersed yttoria. Cell structure was not formed. Difficulty of cell formation corresponded to the higher wear resistance of MA6000 than Sumicolloy No. 6, a kind of stellite alloy.

1. Introduction

Oxide-dispersion-strengthened Ni alloys (ODSs) for high-temperature use have been developed and the mechanical properties of the ODSs have been extensively investigated [1, 2]. The ODSs have little ductility for turbine blades. However, their good creep properties are suitable for guide rolls of hot roller or under-earth pipes of oil wells. There, wear resistance at high temperatures is one of the most important properties of structural materials. Wear properties of the ODSs have not yet been studied.

The ODSs were produced by powder metallurgy methods. Good creep properties were obtained for small amounts of oxide particles (1%) and for small oxide particle size (2–30 nm) [3]. However, those conditions were not suitable for wear resistance. Composites of metals and ceramic particles exhibited higher wear resistance for large amounts of particles (above 5%) [4–7] and large sizes of particles (above 1 μm) [8, 9, 10], whether hard or soft particles. In wear studies of composites, counter faces of steel were scratched by dispersed hard particles and fine debris adhered on the composites [11]. The fine debris grew and wear particles were torn off from the metal matrix. In wear studies on metals, wear particles came from dislocation cell structures. Ease of dislocation cell formation induced the wear of metals. Therefore, metals of low stacking fault energies and h.c.p. metals have good wear properties [12]. In the ODSs under wear, interactions between dislocations and dispersed fine oxides influence dislocation structures. If the cell structure is easily formed by the interactions, wear resistance of the ODSs is low.

In this work, the wear resistance of Ni, annealed Ni, Ni–1%Al_2O_3, Ni–0.5%Y–1%Al_2O_3, IN600, MAR-M427, MA6000 and Sumicolloy No. 6 was examined by using an Ohgoshi-type wear testing machine in order to study effects of dispersion in ODSs. The tests were performed at room temperature. As it is known, wear properties in different kinds of materials are difficult to compare with each other. Therefore, the wear resistance was compared between Ni ODSs and Ni superalloys. As a standard for good wear resistance, Sumicolloy No. 6, a kind of stellite, was adopted. The main elements of stellite were Co, Cr and W. Sumicolloy No. 6 is used for counter faces to valve sheets in automobiles, by surface welding.

Dislocation structures of the alloys before and after wear were observed by a high voltage electron microscope.

2. Experimental details

The alloy contents are shown in Table 1. Ni was a vacuum melt and rolled rod of 20 mm. Some Ni specimens were annealed 6 h at 1173 K in vacuum. Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3 were produced by mechanical alloying and hot-extrusion, using carbonyl Ni powder of 1 μm, yttorium powder of 3 μm and Degusa's alumina particles of 20 nm. Reduction rate was 40 and extrusion temperature was 1323 K. The rods were of 10 mm diameter. IN600 is a wrought Ni alloy [13]. MAR-M427 is a cast Ni alloy [13]. MA6000 was an ODS Ni alloy containing yttoria particles of 20 nm [1].

Wear rates were measured with the Ohgoshi-type wear-testing machine, which was an improved Scoda Savan type. The principle of the testing machine is shown in Fig. 1. In the Ohgoshi testing machine, the load is applied proportional to the square root of the friction distance, so that the pressure is kept approximately constant during the test. Quenched S55C

* Present address: Kogakuin University, 2665-1 Nakano-cho, Hachiouji City, Tokyo 152, Japan.

TABLE I Contents of alloys

	C	Ni	Cr	Co	Mo	W	Ta	Nb	Hf	Al	Ti	V	B	Zr	Fe	Mn	Si	Others
Ni	0.02	bal.	0.02	–	–	–	–	–	–	–	–	–	–	–	0.0015	–	–	0.0015 Cu
Ni–1%Al_2O_3	0.01	bal.	–	–	–	–	–	–	–	–	–	–	–	–	0.002	–	–	1.0 Al_2O_3
Ni–0.5%Y–1%Al_2O_3	0.01	bal.	–	–	–	–	–	–	–	–	–	–	–	–	0.002	–	–	0.5 Y 1.0 Al_2O_3
IN600	0.08	bal.	15.5	–	–	–	–	–	–	–	–	–	–	–	8.0	0.5	0.2	
MAR-M247	0.16	bal.	8.2	10.0	0.6	10.0	3.0	–	1.5	5.5	1.0	–	0.00	0.09	–	–	–	
MA6000	0.05	bal.	15		2.0	4.0	2.0	–	–	4.2	2.5	–	0.01	0.15	–	–	–	1.0 Y_2O_3
Sumicolloy No. 6	1.27	2.45	26.8	62.08	0.09	3.96	–	–	–	–	–	–	–	–	2.39	–	0.96	

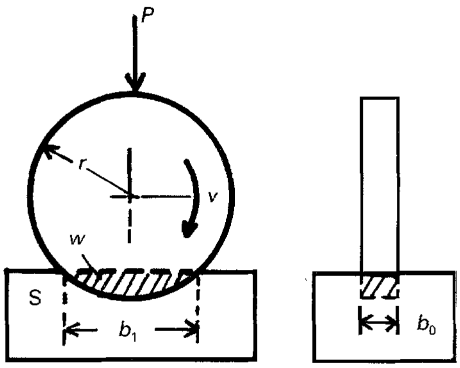

Figure 1 Principle of wear testing. A rotating plate (slider) is pressed onto a specimen surface. S: specimen, w: worn volume, v: sliding speed, r: radius of slider, P: load, b_0: breadth of sliding track, b_1: length of sliding track.

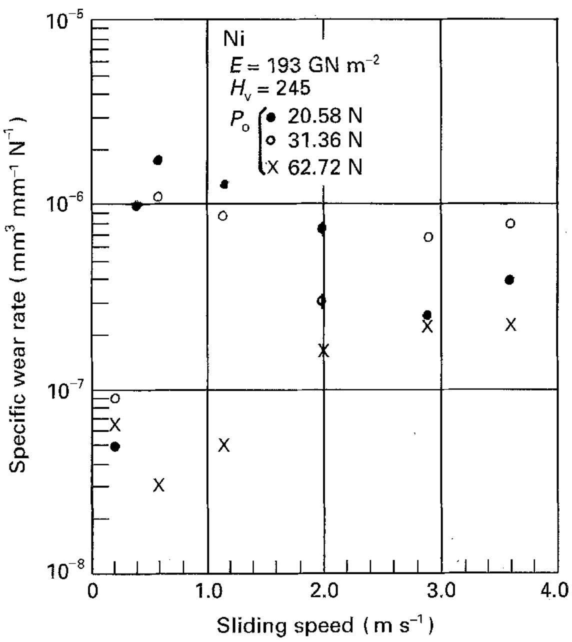

Figure 2 Wear rates of Ni. H_v: Vickers hardness, E: Young's modulus, P_0: final load.

(plain milled carbon steel) was used for a slider. Vickers hardness of quenched S55C was 655.

Specific wear rate was obtained from the following approximation:

$$W_s = b_1^3 b_0 / 8 r P_0 d (\mathrm{mm^3\,mm^{-1}\,N^{-1}})$$

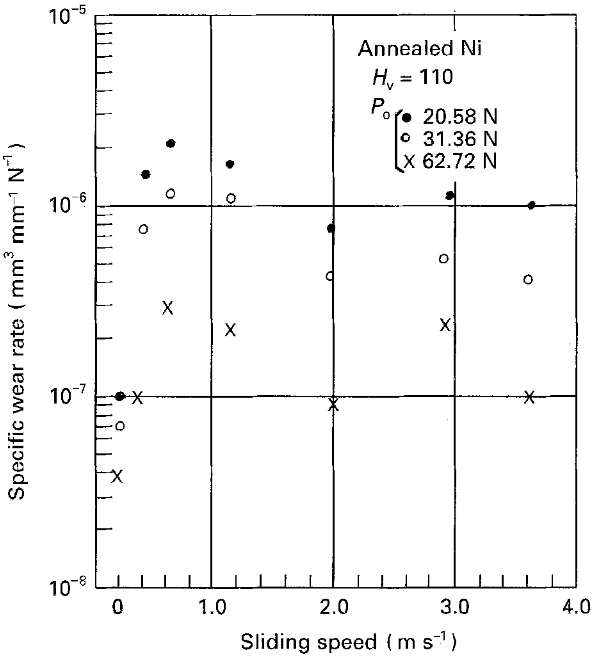

Figure 3 Wear rates of annealed Ni.

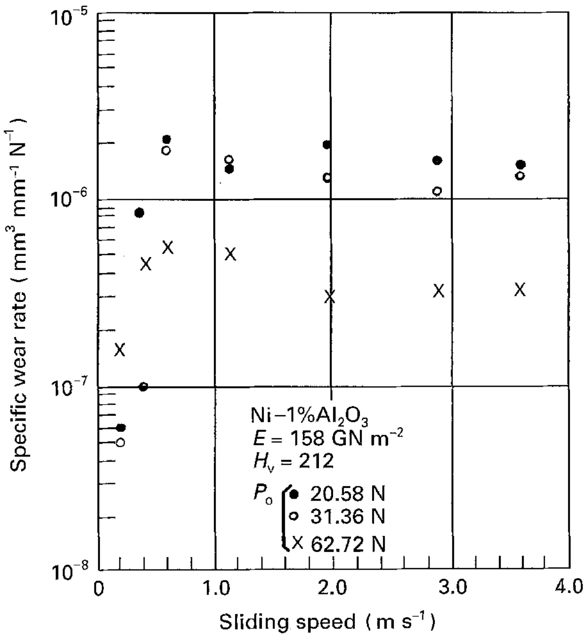

Figure 4 Wear rates of Ni–1% Al_2O_3, alumina-dispersed Ni.

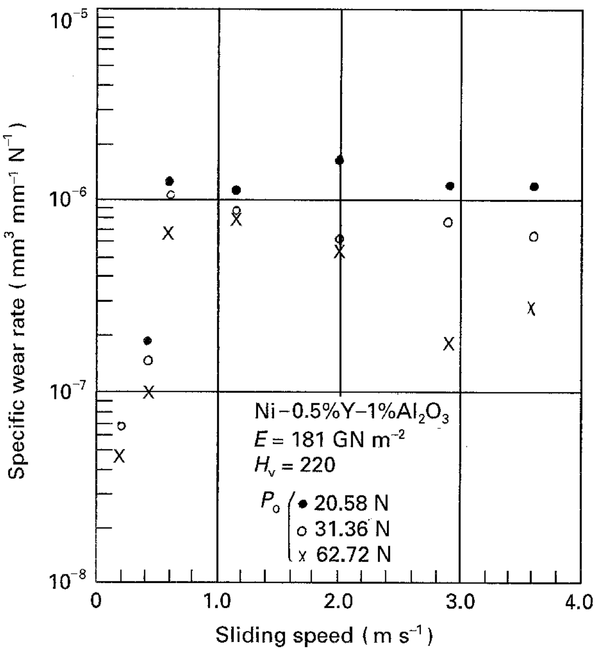

Figure 5 Wear rates on Ni–0.5% Y–1% Al_2O_3, alumina-dispersed Ni–0.5%Y.

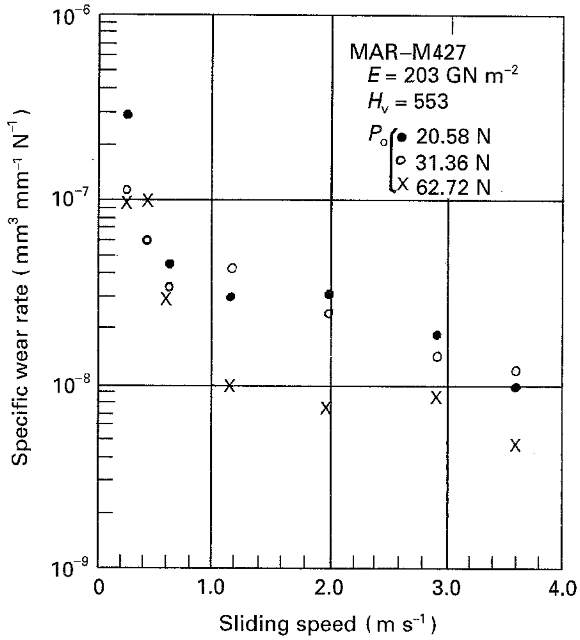

Figure 7 Wear rates of MAR-M427, cast Ni superalloy.

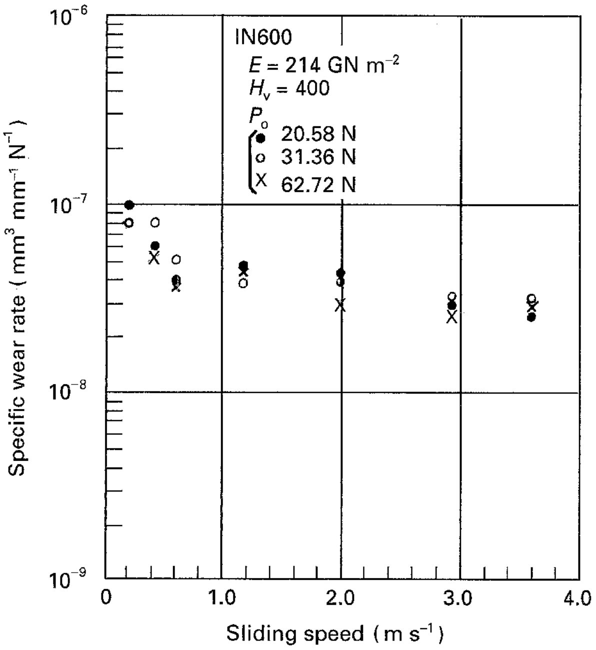

Figure 6 Wear rates of IN600, wrought Ni superalloy.

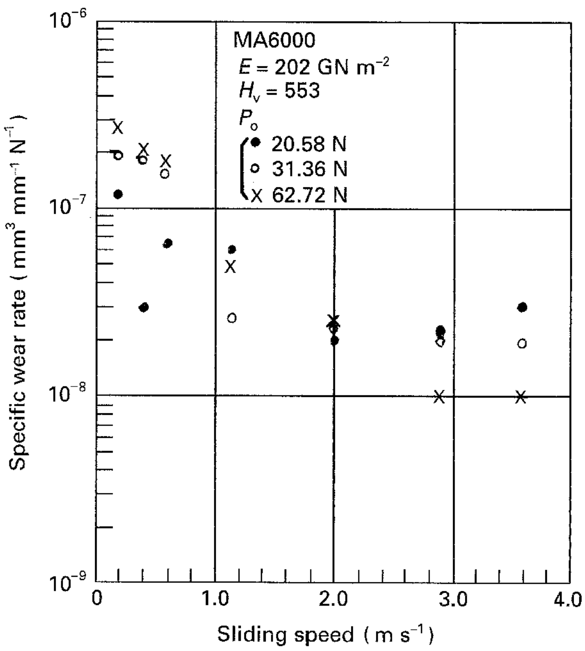

Figure 8 Wear rates of MA6000, yttoria-dispersed Ni superalloy.

where P_0 is a final load, 20.58 N, 31.36 N and 67.72 N in this work; the initial radius r was 30 mm; thickness b_0 was 2 mm, which corresponded to the sliding track breadth; b_l was the sliding track length. In this experiment, the friction distance d was fixed at 200 m. Sliding speeds do not appear in the formula. However, the speeds were changed from 0.2 to 3.6 m s^{-1}. The wear test was carried out in air at room temperature, and in 40–50% humidity.

Substructure of alloys were observed with a JEM 200 kV electron microscope. Thin films for the observation were prepared by electropolishing. A mixture of 80% ethanol and 20% perchloric acid was an electrolyte. The cathode voltage was 20 V.

3. Results

In Figs 2–9, specific wear rates of the alloys are shown. Vickers hardness H_v and elastic modulae E of the alloys are also shown in the figures.

In Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3, the wear rates were of the same order in Ni and became larger than in Ni with increased sliding speeds. This difference did not come from the difference in hardnesses alone, because annealed Ni was soft and showed lower wear rates than Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3, as shown in Fig. 3.

In IN600, MAR-M427 and MA6000, wear rates became one order lower than in Ni. Those three alloys exhibited wear rates of the same order and lower than

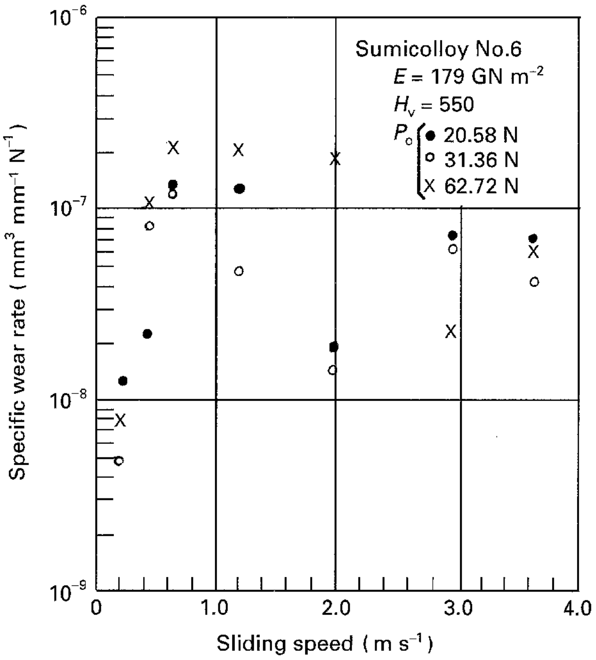

Figure 9 Wear rates of Sumicolloy No. 6, a kind of stellite.

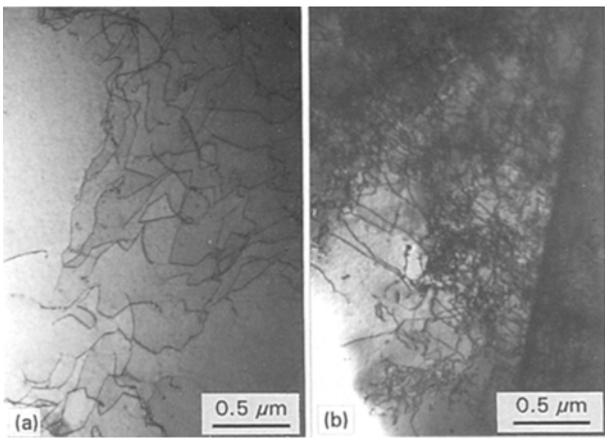

Figure 10 Dislocation structure of (a) the original Ni specimen and (b) a layer about 100 μm below the friction surface. Final load P_0: 20.58 N, sliding speed v: 3.6 m s^{-1}.

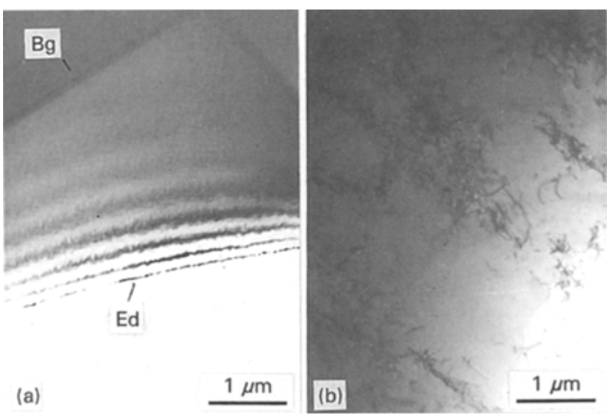

Figure 11 (a) Dislocation-free subgrain of annealed Ni and (b) dislocation structure of a layer about 100 μm below the friction surface. Bg = subgrain boundary, Ed = edge of specimen. P_0: 20.58 N, v: 3.6 m s^{-1}.

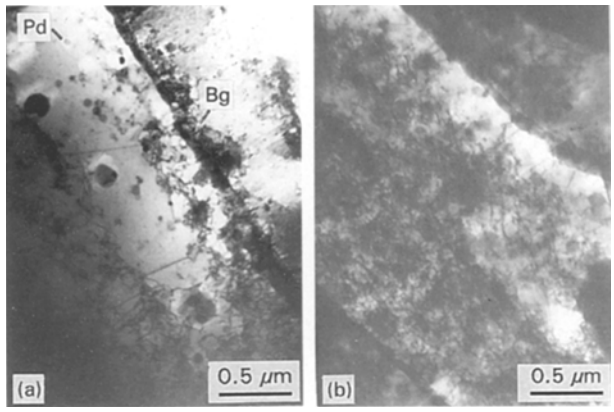

Figure 12 Dislocation structure of (a) the original Ni–1% Al_2O_3 specimen and (b) a layer about 100 μm below the friction surface. P_0: 20.58 N, v: 3.6 m s^{-1}. Pd = dispersed particle; Bg = grain boundary.

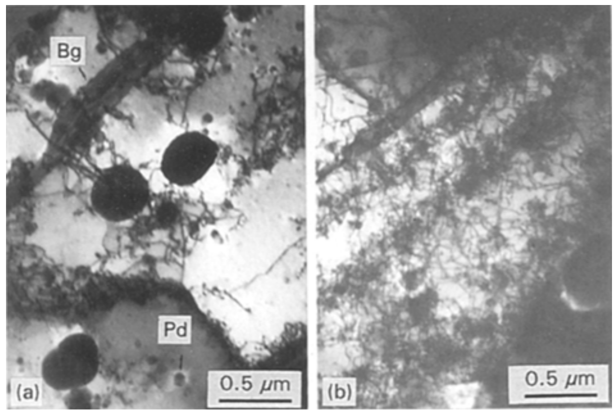

Figure 13 Dislocation structure of (a) the original Ni–0.5%Y–1% Al_2O_3 specimen and (b) a layer about 100 μm below the friction surface. P_0: 20.58 N, v: 3.6 m s^{-1}.

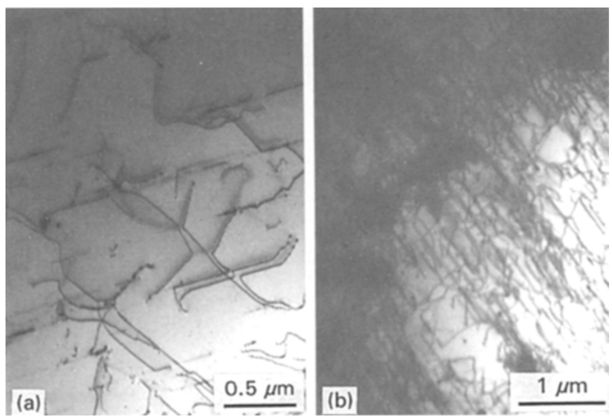

Figure 14 Dislocation structure of (a) the original IN600 specimen and (b) a layer about 100 μm below the friction surface. P_0: 20.58 N, v: 0.2 m s^{-1}.

Sumicolloy No. 6. The wear rates in IN600 were somewhat higher than in MAR-M427 and in MA6000.

In Figs 10–17, substructures of alloys are shown. In Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3, dense dislocation tangles were formed in layers below the friction surface. In IN600, dislocation cells of larger diameter were formed. In MAR-M427 and MA6000, a dislocation cell structure was not formed. In Sumicolloy

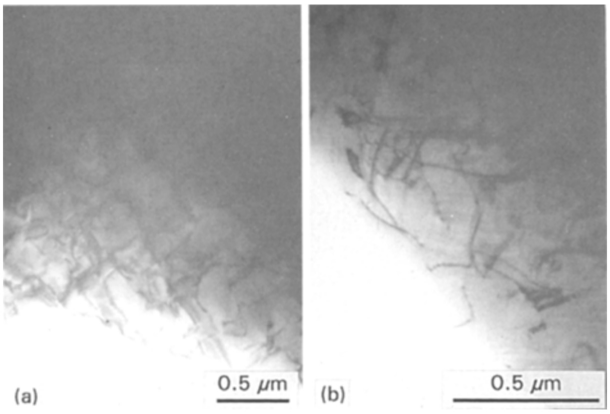

Figure 15 Dislocation structure of (a) the original MAR-M427 specimen and (b) a layer about 100 μm below the friction surface. P_0: 20.58 N, v: 0.2 m s^{-1}.

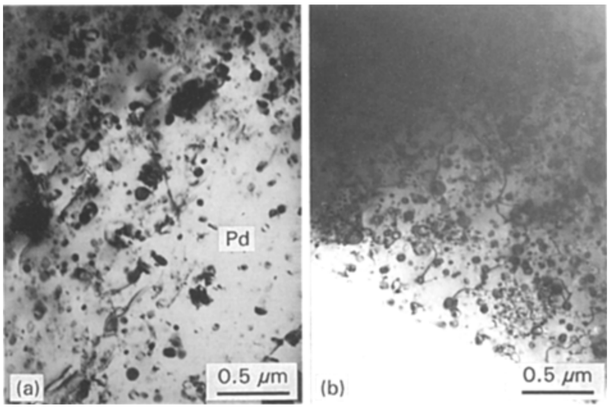

Figure 16 Dislocation structure of (a) the original MA6000 specimen and (b) a layer about 100 μm below the friction surface. P_0: 20.58 N, v: 0.2 m s^{-1}.

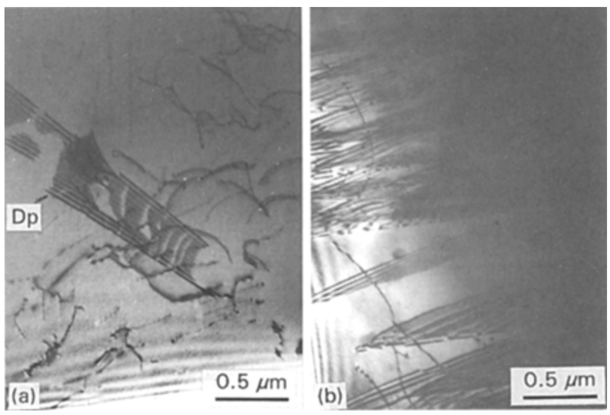

Figure 17 Dislocation structure of (a) the original Sumicolloy No. 6 specimen and (b) a layer about 100 μm below the friction surface. Dp: partial dislocation. P_0: 20.58 N, v: 3.6 m s^{-1}.

No. 6, partial dislocations operated and the dislocation cell structure was not formed.

4. Discussion

Addition of small amounts of fine alumina particles deteriorated the wear resistance of Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3. On the other hand, the addition of small amounts of fine yttoria particles in MA6000 yielded good wear resistance. This difference partly came from the difference between the wettabilities of dispersed particles with matrix metals.

Low wettability of alumina with Ni [14] is able to cause fragility in the deformation layer below the friction surface. Yttoria particles reacted with Al in MA6000 [15]. Wettability of the yttoria particles with matrix metals is somewhat higher than alumina particles. This partly brings toughness to the deformation layer below the friction surface. Ductility of alloys brings higher wear resistance in low-cycle fatigue type wear [16] or ratchetting failure type wear [17]. However, wettability of the yttoria particles was not so high as to confer ductility to ODSs. Extension of ODSs to failure was less than 2–3% [1,2].

A great difference in dislocation structures was observed among the ODSs. Dislocation tangles were well developed by cross-slip or climb by interactions between dislocations and fine particles [18–20], as in Ni–1%Al_2O_3 and Ni–0.5%Y–1%Al_2O_3. The tangles grew to the dislocation cell structures. Wear particles were easy to form [12]. On the other hand, by a computer-aided alloy design [21], alloy contents were controlled to maximize solution and precipitation hardening. Dislocations in MA6000 are hard to cross-slip or climb at dispersed yttoria particles. Dislocation cell structures were not formed and wear particles were hard to form [12].

For large particle size, dislocation cross-slip or climb are not easy [22]. Large amounts of particles diminish the flexibility of dislocations [23–25]. In both cases, dislocation cell structures were not formed, and neither were wear particles. Besides bearing of loads by ceramic particles, these effects brought good wear resistance to the composites, in the case of large size and large amounts of particles [4–9].

5. Conclusions

Addition of small amounts of fine particles to ODSs does not always bring lower wear resistance. If metal elements prevent a dislocation from cross-slipping or climbing at fine particles, ODSs exhibit better wear resistance than Sumicolloy No. 6, a kind of stellite alloy.

Acknowledgement

The authors are grateful to Dr Y. Kawasaki of NRIM for detailed information about computer-aided alloy design.

References

1. C. H. GESINGER, "Powder Metallurgy of Superalloys" (Butterworth, London, 1984) p. 211.
2. MICHIO YAMAZAKI, YOZO KAWASAKI and KATSUYUKI KUSUNOKI, "Structural Appreciations of Mechanical Alloying", edited by F.H. Froes and J.J. DeBarbadillo (ASM International, Materials Park, OH 44073, 1990) p. 33.
3. A. H. CLAUER and B. A. WILCOX, *Metal Sci. J.* **20** (1967) 86.
4. F. M. HOSKING, E. F. PORTILLO, R. WUDERLIN and R. MEHRABIAN, *J. Mater. Sci.* **17** (1882) 477.
5. T. P. MURALI, S. V. PRASAD, M. K. SURAPPA and S. V. ROHATGI, *Wear* **80** (1982) 149.

6. A. SATO and R. MEHRABIAN, *Metall. Trans.* **713b** (1976) 443.
7. M. SUWA, K. KOMURO and K. SUENO, *J. Japan. Inst. Met.* **40** (1976) 1074.
8. S.V. NAIR, J.K. TIEN and R.C. BATES, *Inst. Met. Rev.* **30** (1985) 275.
9. K. C. GORETTA, W. WU, J. L. ROUBORT and P. K. ROHATGI, "Tribology of Composites Materials", edited by P. K. Rohatgi, P. J. Blau and C. S. Yusut (ASM International, Materials Park, OH 44073, 1990) p. 147.
10. P. K. ROHATGI, Y. LIU and S. RAY, "Friction and Wear of Metal-Matrix Composites", edited by P. J. Blau (ASM International, Materials Parks, OH 44073, 1992) p. 801.
11. I. I. GARBAR and J. V. SKORININ, *Wear* **51** (1978) 327.
12. J. P. HIRTH and D. A. RIGNEY, *ibid.* **39** (1976) 133.
13. G. S. HOPPIN III and W. P. DANSEI, "Superalloys II", edited by Chester T. Sims *et al.* (John Wiley & Sons, New York, 1987) p. 549.
14. B. C. ALLEN and W. D. KINGERY, *Trans. AIME* **215** (1959) 30.
15. S. K. KANG and R. G. BENN, *Met. Trans.* **16A** (1985) 1285.
16. A. J. BLACK *et al., Proc. I. Mech. E. (Lond.)* **207C** (1993) 335.
17. A. KAPOOR, Fatigue, *Fract. Engng Mater. Struct.* **17** (1994) 201.
18. P. B. HIRSCH, *J. Inst. Metals* **86** (1957–58) 13.
19. F. J. HUMPHREYS and P. B. HIRSCH, *Proc. Roy. Soc. (Lond.)* **A318** (1970) 73.
20. S. R. MACEWIN, P. B. HIRSCH and V. VITEK, *Phil. Mag.* **28** (1973) 703.
21. H. HARADA, M. YAMAZAKI, Y. KOIZUMI, N. SAKUMA, N. FURUYAMA and H. KAMIYA, "High Temperature Alloys for Gas Turbines 1982", edited by R. Brunetaud *et al.* (D. Reidel Publ., Dordrecht Holland, 1982) p. 721.
22. S. KODA, K. MATSUURA and M. NEMOTO, *J. Aust. Inst. Metals* **8** (1963) 197.
23. N. F. MOTTO and F. R. N. NABARRO, *Proc. Phys. Soc.* **52** (1940) 86.
24. *Idem.*, "Report on strength of Solids" (Physical Society, London, 1948) p. 1.
25. N. F. MOTTO, "Imperfection in Nearly Perfect Crystals" (John Wiley & Sons, New York, 1952) p. 5173.

Received 16 June 1994
and accepted 21 February 1995