

University of Wollongong Thesis Collections

University of Wollongong Thesis Collection

University of Wollongong

Year 2005

Sintering, microstructure and properties
of WC-FeAl-B and WC-Ni₃Al-B
composite materials

Mehdi Ahmadian-Najafabadi
University of Wollongong

Ahmadian-Najafabadi, Mehdi, Sintering, microstructure and properties of WC-FeAl-B and WC-Ni₃Al-B composite materials, PhD thesis, School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, 2005. <http://ro.uow.edu.au/theses/546>

This paper is posted at Research Online.
<http://ro.uow.edu.au/theses/546>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Chapter 7 References

1. Upadhyaya, G.S., Sintered metallic and ceramic materials: preparation, properties and applications. 2000, Chichester: UK: John Wiley & Sons Ltd.
2. Baker, I., et al., The room temperature strengthening effect of boron as a function of aluminum concentration in FeAl. *Intermetallics*, 1998. 6(3): p. 177-183.
3. Farooq T., D.T.J., Preparation of some new tungsten carbide hardmetals. *Powder Metallurgy International*, 1990. 22(4): p. 12-16.
4. Brookes, K.J.A., *Hardmetals and other hard materials*. 3rd ed. 1998, East Barnet, Hertfordshire: International Carbide Data.
5. Shetty, D.K., et al., Indentation fracture of WC-Co cermets. *Journal of Materials Science*, 1985. 20: p. 1873-1882.
6. W. Precht, R.K.V., J.D.Venables, Abrasion resistance of cermets containing Co/Ni binders, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 815-828.
7. Prech W., W.R.K., Venables J. D., Abrasion resistance of cermets containing Co/Ni binders, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 815-828.
8. Henry J. Scussel, G.V., Friction and wear of cemented carbides, in *ASM Handbook, Materials Characterisation*. 1990, ASM. p. 795-800.
9. Tiegs, T.N., K.B. Alexander, K.P. Plucknett, P.A. Menchhofer, P.F. Becher, S.B. Waters, S. B., Ceramic composites with a ductile Ni3Al binder phase. *Materials Science and Engineering A*, 1996. 209(1-2): p. 243-247.
10. Plucknett, K.P., et al., Ductile intermetallic toughened carbide matrix composites. *Ceramic Engineering & Science Proceedings*, 1996. 17(3): p. 314-321.
11. Schneibel, J.H., et al., Liquid-phase sintered iron aluminide-ceramic composites. *Intermetallics*, 1997. 5(1): p. 61-67.
12. Plucknet, K.P., P.F. Becher, and K.B. Alexander, In situ SEM Observation of the Fracture Behaviour of Titanium Carbide/Nickel Aluminide Composites. *Journal of Microscopy*, 1997. 185: p. 206-216.
13. Spriggs, G.E., A History of Fine Grained Hardmetal. *International Journal of Refractory Metals and Hard Materials*, 1995. 13(5): p. 241-255.
14. Shao, G.-Q., et al., Sintering of nanocrystalline WC-Co composite powder. *Reviews on Advanced Materials Science*, 2003. 5(4 December): p. 281-286.
15. Mayo, M.J., processing of Nonocrystalline Ceramics from Ultrafine Particles. *International Materials Review*, 1996. 41(3): p. 85-115.

16. Tulhoff, H., On the Grain Growth of WC in Cemented Carbides. *Modern Development in Powder Metallurgy*, 1981. 14: p. 269-279.
17. Lu, K., Nanocrystalline metals crystallized from amorphous solids: nanocrystallization, structure, and properties. *Materials Science and Engineering: R: Reports*, 1996. 16(4): p. 161-221.
18. Wilson Acchar, C.Z. and P. Greil, Microstructure and Mechanical Properties of WC-Co Reinforced With NbC. *Materials Research*, 2004. 7(3): p. 445-450.
19. Schubert, W.D., A. Bock, and B. Lux, General Aspects and Limits of Conventional Ultrafine WC Powder Manufacture and Hard Metal Production. *International Journal of Refractory Metals and Hard Materials*, 1995. 13(5): p. 281-296.
20. Holleck, H., Constitutional aspects in the development of new hard materials, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 849-861.
21. McLaren T., L.J.B., Fracture toughness as an aid to alloy development, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 689-707.
22. Wisvanadham R. K., L.P.G., Peck J.A., Preparation and properties of WC-(Ni,Al), in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 873-889.
23. Scussel, H.J. and G. Valentine, Friction and Wear of Cemented Carbides, in *Metals Handbook*. 1990, ASM International: Materials Park, OH. p. 795-810.
24. Upadhyaya, G.S. and S.K. Bhaumik, Sintering of submicron WC-10wt%Co hard metals containing nickel and iron. *Materials Science and Engineering A*, 1988. 105-106: p. 249-256.
25. Almond, E.A. and B. Roebuck, Identification of optimum binder phase compositions for improved WC hardmetals. *Materials Science & Engineering A*, 1988. 105/106: p. 237-248.
26. Tiegs, T.N. and P.A.P. Menchhofer, K P. Alexander, K B. Becher, P F. Waters, S B. Hardmetals based on Ni₃Al as the binder phase. in *R/M in Aerospace Defense and Demanding Applications Proceedings of the International Conference on Powder Metallurgy in Aerospace, Defense and Demanding Applications*. 1995. Princeton, NJ, USA: Metal Powder Industries Federation.
27. Cahn, R.W., A.G. Evans, and M. McLean, *High-temperature structural materials*. 1996, London: Chapman & Hall for the Royal Society.
28. Kumar, K.S. and G. Bao, *Intermetallic Matrix Composites: An Overview*. *Composites science and technology*, 1994. 52: p. 127-150.
29. Panov, V.S., F. Kots, and A.A. Filimonova, Interaction Between Phases In The WC-Ni₃Al System. *Soviet Powder Metallurgy And Metal Ceramics*, 1990. 29(7(331)): p. 564-567.
30. Stoloff, N.S., C.T. Liu, and S.C. Deevi, Emerging applications of intermetallics. *Intermetallics*, 2000. 8(9-11): p. 1313-1320.

31. Jin, J.-H. and D.J. Stephenson, The sliding wear behaviour of reactively hot pressed nickel aluminides. *Wear*, 1998. 217(2): p. 200-207.
32. Subramanian, R. and J.H. Schneibel, Intermetallic bonded WC-based cermets by pressureless melt infiltration. *Intermetallics*, 1997. 5(5): p. 401-408.
33. Deevi, S.C. and V.K. Sikka, Nickel and iron aluminides: an overview on properties, processing, and applications. *Intermetallics*, 1996. 4(5): p. 357-375.
34. Subramanian, R. and J.H. Schneibel, FeAl-TiC and FeAl-WC composites—melt infiltration processing, microstructure and mechanical properties. *Materials Science and Engineering A*, 1998. 244(1): p. 103-112.
35. Arenas, F.J., et al., Densification, mechanical properties and wear behavior of WC-VC-Co-Al hardmetals. *International Journal of Refractory Metals and Hard Materials*, 2001. 19(4-6): p. 381-387.
36. Mosbah, A., D. Wexler, and A. Calka, Tungsten carbide iron aluminide hardmetals: nanocrystalline vs microcrystalline. *Materials Science Forum*, 2001. 360-362: p. 649-54.
37. Liu C. T., E.P.G., P. J. Maziasz, and J.H. Schneibel, Recent advances in B2 iron aluminide alloys: deformation, fracture and alloy design. *Materials Science and Engineering A*, 1998. 258(1-2): p. 84-98.
38. Tiegs, T.N., et al., Hardmetals based on Ni₃Al as the binder phase. *P/M in Aerospace Defense and Demanding Applications Proceedings of the International Conference on Powder Metallurgy in Aerospace, Defense and Demanding Applications 1995*. Metal Powder Industries Federation, Princeton, NJ, USA., 1995: p. 211-218.
39. Johnson, M., et al., The resistance of nickel and iron aluminides to cavitation erosion and abrasive wear. *Wear*, 1990. 140(2): p. 279-289.
40. Sikka, V.K., Processing and applications of iron aluminides, in *Properties, processing and applications of iron aluminides*, M.A.C. Schneibel J. H., Editor. 1994, TMS. p. 3-18.
41. Munroe, P.R., High temperature ordered intermetallic compounds. *Materials Forum*, 1997. 21: p. 79-99.
42. Liu, C.T. and E.P. George, Environmental Embrittlement in Boron-Free and Boron-Doped FeAl (40 at. % Al) Alloys. *Scripta Metallurgica et Materialia*, 1990. 24: p. 1285-1290.
43. Westbrook, J.H. and R.L. Fleischer, Structural applications of intermetallic compounds. *Intermetallic Compounds*. 2000, Chichester, England: John Wiley.
44. German, R.M., *Sintering Theory and Practice*. 1996: John Wiley & Sons, Inc.
45. Tiegs, T.N., et al., Ceramic composites with a ductile Ni₃Al binder phase. *Materials Science and Engineering A*, 1996. 209(1-2): p. 243-247.
46. Tumanov, A.V., et al., Wetting of TiC-WC system carbides with molten Ni₃Al. *Soviet Powder Metallurgy and Metal Ceramics*, 1986. 25(5): p. 428-430.
47. Joachim, S., J. H. and Becher, P. F., Iron and Nickel Aluminide Composites. *Journal of the Chinese Institute of Engineers*, 1999. 22(1): p. 1-12.

48. Joachin, H., J.H. Schneibel, and R. Subramanian. Bonding of WC with an iron aluminide (FeAl) intermetallic. in advances in powder metallurgy of particulate materials. 1996. TN, USA.
49. Prakash, U., et al., Structure and Properties of Ordered Intermetallics Based on the Fe-Al System. ISIJ International, 1991. 31(10): p. 1113-1126.
50. Mosbah, A.Y.A.-A., Sintering, microstructure and properties of WC-FeAl composite materials, in Dept. of Materials Engineering. 2001, University of Wollongong: Wollongong.
51. Inoue, M., et al., Fracture properties of Fe-40 at.% Al matrix composites reinforced with ceramic particles and fibers. Materials Science and Engineering A, 1998. 258(1-2): p. 298-305.
52. Inoue, M., K. Sugauma, and K. Nichara, Mechanical properties of aluminide matrix composites fabricated by reactive hot-pressing in several environments. Intermetallics, 2000. 8(9-11): p. 1035-1042.
53. Ward-Close, C.M., R. Minor, and P.J. Doorbar, Intermetallic-matrix composites, a review. Intermetallics, 1996. 4(3): p. 217-229.
54. Reshetnyak, H. and J. Kubarsepp, Structure sensitivity of wear resistance of hardmetals. International Journal of Refractory Metals and Hard Materials, 1997. 15(1-3): p. 89-95.
55. Han, Y.F., S.H. Li, and M.C. Chaturvedi, Effect of boron additions on microstructure and mechanical properties of a DS gamma prime -Ni3Al base alloy. Proc First Int Symp Struct Internet. Publ by Minerals, Metals & Materials Soc (TMS), Warrendale, PA, USA, 1993: p. 453-462.
56. Bitmayer, P., Hardmetals and Cermets. Ann. Rev. Mat. Sci. Vol. 19. 1989: Annual Reviews Inc. 145-164.
57. Upadhyaya, G.S., Carbide and Binder Phases in Cemented Carbides. Review on Powder Metallurgy and Physical Ceramics, 1990. 4(1): p. 59-78.
58. German, R.M., Liquid phase sintering. 1985, New York: Plenum Press.
59. William H. Cubberly ; Ramon Bakerjian, Tool and manufacturing engineers handbook. Desk ed. 1989, Dearborn, Mich.: Society of Manufacturing Engineers.
60. Yang, J.-M., W.H. Kao, and C.T. Liu, Development of Nickel aluminide matrix composites. Materials Science and Engineering A, 1989. 107: p. 81-91.
61. Leroux, L., Microstructure and Transverse Ruture Strength of Cemented Carbides. International Journal of Refractory and Hard Materials, 1984. 3: p. 99-100.
62. Nelson, R.J. and D.R. Milner, Densification Processes in the Tungsten Carbide-Cobalt System. Powder Metallurgy, 1971. 15: p. 346-363.
63. Gang-qin Shao, X.-l.D., Ji-ren Xie, Xiao-hua Yu, Wei-feng Zhang and R.-z. Yuan, Sintering of nanocrystalline WC-Co composites powder. Review on Advanced Materials Science, 2003(5): p. 281-286.

64. Kaysser, W.A., Liquid Phase Sintering. Powder metallurgy : an overview, ed. J.W. I. Jenkins. 1991, London: Institute of Metals.
65. Subramanian R. and J.H. Schneibel, Processing iron-aluminide composites containing carbides of borides. JOM, 1997. 49(8): p. 50-56.
66. Haller, M.N., Cemented Carbides. 10 ed. Metals Handbook. Vol. 9. 1990: ASM. 273.
67. Hawk, J.A., et al., Laboratory abrasive wear tests: investigation of test methods and alloy correlation. Wear, 1999. 225-229(Part 2): p. 1031-1042.
68. Chermant, J.L., A. Deschanvres, and F. Osterstock, Factors Influencing the Rupture Stress of Hardmetals. Powder Metallurgy, 1977. 20: p. 63-69.
69. Chawla, K.K., Composite materials : science and engineering. 1987, New York: Springer-Verlag.
70. Snowball, R.F. and D.R. Milner, Densification Processes in the Tungsten Carbide-Cobalt System. Powder Metallurgy, 1968. 11: p. 23-40.
71. Kaysser, W.A., Liquid Phase Sintering. Processing and properties for powder metallurgy composites : proceedings of a symposium, ed. K.V. P. Kunar, A. Ritter. 1988, Colorado: AIME.
72. Jia, K., T.E. Fischer, and B. Gallois, Microstructure, hardness and toughness of nanostructured and conventional WC-Co composites. Nanostructured Materials, 1998. 10(5): p. 875-891.
73. Tiegs T N., K.P.P., P. A. Menchhofer, and P.F. Becher. Ni3Al-bonded WC and TiC hardmetals. in Powder metallurgy and particulate. 1996.
74. Hanyaloglua C., B.A. and J.D. Boltonb, Production and indentation analysis of WC/Fe-Mn as an alternative to cobalt-bonded hardmetals. Materials Characterization, 2001. 47: p. 315-322.
75. Reddy, B.V. and S.C. Deevi, Thermophysical properties of FeAl (Fe-40 at.%Al). Intermetallics, 2000. 8(12): p. 1369-1376.
76. Sauthoff G., State of intermetallics development. Oxidation of intermetallics, ed. H.J. Grabke. 1998, New York Weinheim: Wiley ; VCH.
77. Almond E. A., R.B., Extending the use of indentation, in Science of hard materials, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 597-614.
78. Cohron, J.W., et al., Room-temperature mechanical behavior of FeAl: effects of stoichiometry, environment, and boron addition. Acta Materialia, 1998. 46(17): p. 6245-6256.
79. Stauthoff G., State of intermetallics development, in Oxidation of intermetallics, M.S. Grabke H. J., Editor. 1998, Wiley ; VCH: New York Weinheim.
80. Lang, F., et al., Effect of pre-oxidation on the corrosion behavior of Fe-40Al sheet in a N2-11.2O2-7.5CO2-500 ppm SO2 atmosphere at 1273 K. Intermetallics, 2003. 11(2): p. 129-134.

81. Draper, S.L., Gaydosh, D. J., Nathal, M. V., and Misra, A. K., Compatibility of Fe-40Al with Various Fibers. *Journal of Materials Research*, 1990. 5(9): p. 1976-1984.
82. Gaydosh, D.J., et al., Room temperature flow and fracture of Fe-40at.%Al alloys. *Materials Science and Engineering A*, 1992. 150(1): p. 7-20.
83. Munroe, P.R. and H.K. C., The effect of ternary additions on vacancy hardening in near stoichiometric FeAl. *Intermetallics*, 1996. 4(5): p. 403-415.
84. Schneibel, J.H., Selected Properties of Iron Aluminides, in *Processing, properties and applications of iron aluminides*, J.H. Schneibel and M.A. Crimp, Editors. 1994, TMS: San Francisco, California. p. 329-342.
85. Kim, Y.-S. and Y.-H. Kim, Sliding wear behavior of Fe₃Al-based alloys. *Materials Science and Engineering A*, 1998. 258(1-2): p. 319-324.
86. Morsi, K., H.B. McShane, and M. McLean, Processing defects in hot extrusion reaction synthesis. *Materials Science and Engineering A*, 2000. 290(1-2): p. 39-45.
87. Joseph, D.R. and J.L. John, Fracture toughness of monolithic nickel aluminide intermetallics. *Materials Science and Engineering A*, 1992. 149: p. 143-151.
88. Feng Di, Y.E.W., H. A. N. Guangwei, and L.U.O. Heli, Application research on the Ni₃Al intermetallic compound in CISRI. *Acta Metallurgica Sinica (English Letters)*, 1995. 8(4-6): p. 503-508.
89. Chuang T. H., The mutual effects of boron, zirconium and aluminium on grain boundary segregation in Ni₃Al intermetallic compounds. *Materials Science & Engineering A*, 1991. 141: p. 169-178.
90. George, E.P., C.T. Liu, and D.P. Pope, Intrinsic Ductility and Environmental of Binary Ni₃Al. *Scripta Metallurgica et Materialia*, 1993. 28: p. 857-862.
91. Nathal, M.V. and C.T. Liu, Intrinsic ductility of FeAl single crystals. *Intermetallics*, 1995. 3(1): p. 77-81.
92. Pierron X and I Baker. An overview of environmental effects in iron aluminides. in *Design fundamentals of high temperature intermetallics and metal-ceramics systems*. 1996. California, USA: TMS.
93. George, E.P., C.T. Liu, and D.P. Pope, Mechanical behavior of Ni₃Al: effects of environment, strain rate, temperature and boron doping. *Acta Materialia*, 1996. 44(5): p. 1757-1763.
94. Chen, G.L. and C.T. Liu, Moisture Induced Environmental Embrittlement of Intermetallics. *International Materials Review*, 2001. 46(6): p. 253-270.
95. Liu, C.T., C. L. Fu, and George E. P., Environmental embrittlement in FeAl aluminides. *ISIJ International*, 1991. 31(10): p. 1192-1200.
96. Yang L., a. and R.B. McLellan, The solubility of hydrogen in Ni₃Al. *Acta Materialia*, 1994. 42: p. 3993-3996.
97. Cohron, J.W., et al., Hydrogen-Boron Interaction and its Effect on the Ductility and Fracture of Ni₃Al. *Acta Materialia*, 1997. 45(7): p. 2801-2811.

98. Liu, C.T., Intergranular Fracture and Boron Effects on Ni₃Al and other Intermetallics-Introductory Paper. *Scripta Metallurgica et Materialia*, 1991. 25: p. 1231-1236.
99. Takasugi, T., Structure of grain boundaries, in Basic mechanical properties and lattice defects of intermetallic compounds, J.H. Westbrook and R.L. Fleischer, Editors. 2000, John Wiley: Chichester, England. p. 157-181.
100. Skoglund H., et al., Processing of fine-grained mechanically alloyed FeAl. *Intermetallics*, 2004. 12(7-9): p. 977-983.
101. Westbrook, J.H., Mechanical properties of intermetallic compounds : a symposium held during the 115th meeting of the Electrochemical Society at Philadelphia, Pennsylvania, May 3-7, 1959. 1960, London: John Wiley.
102. Webb, G., P. Juliet, and A. Lefort, Optimization of the boron content in FeAl (40 at.% Al) alloys. *Scripta Metallurgica et Materialia*, 1993. 28(7): p. 769-772.
103. Fu, C.L. and J. Zou, Site preference of ternary alloying additions in FeAl and NiAl by first-principles calculations. *Acta Materialia*, 1996. 44(4): p. 1471-1478.
104. Morris, D.G. and M.A. Morris-Munoz, The influence of microstructure on the ductility of iron aluminides. *Intermetallics*, 1999. 7(10): p. 1121-1129.
105. Inoue, M., K. Suganuma, and K. Niihara. Mechanical Behavior of Reactivity Hot-Pressed Aluminide Matrix Composites. in High Temperature Ordered Intermetallic Alloys VII. 1997. Pittsburgh, Pennsylvania: Materials Research Society.
106. Hanada S., A.C., H. Z. Guo , and S. Watanabe. Ductility of Ni₃Al doped with substitutional elements. in Critical issues in the development of high temperature structural materials. 1993. Warrendale, PA, USA: TMS.
107. Liu, C.T. and V.K. Sikka, Nickel aluminides for structural use. *Journal of Metals*, 1986. 38(5): p. 19-21.
108. Ochiai, S., Y. Oya, and T. Suzuki, Alloying behaviour of Ni₃Al, Ni₃Ga, Ni₃Si and Ni₃Ge. *Acta Metallurgica*, 1984. 32(2): p. 289-298.
109. Crimp M. A. and K.Vedula, Effect of boron on the tensile properties of B2 FeAl. *Materials Science & Engineering*, 1986. 78: p. 193-200.
110. Baker, I., et al., Effects of boron and grain size on the strain-rate sensitivity of Fe-45Al. *Scripta Metallurgica et Materialia*, 1994. 30(7): p. 863-868.
111. Cadel E., A.F. and D. Blavette, Atomic scale investigation of impurity segregation to crystal defects. *Ann. Rev. Mater. Res.*, 2003. 33: p. 215-231.
112. Pang, L. and K.S. Kumar, On the impact toughness of Fe-40Al-based B2 aluminides. *Intermetallics*, 2000. 8(2): p. 157-163.
113. Klein, O. and I. Baker, The Effect of Boron on the Temperature Dependence of the Flow and Fracture of Fe-45Al. *Scripta Metallurgica et Materialia*, 1994. 30(11): p. 1413-1417.
114. Calonne, O., A. Fraczkiewicz, and F. Louchet, Yield strength anomaly in b2-ordered FeAl alloys: role of boron. *Scripta Materialia*, 2000. 43(1): p. 69-75.

115. Cadel E., L.D., Gay A. S., Fraczkiewicz, A. and Blavette, D., Atomic scale investigation of boron nanosegregation in Fe Al intermetallics. *Scripta Materialia*, 1999. 41(4): p. 421-426.
116. Fraczkiewicz, A., A.-S. Gay, and M. Biscondi, On the boron effect in FeAl (B2) intermetallic alloys. *Materials Science and Engineering A*, 1998. 258(1-2): p. 108-114.
117. Cadel E., A.F. and D. Bavette, Suzuki effect on {001} stackig faults in boron-doped FeAl intermetallics. *Scripta Materialia*, 2004. 51: p. 437-441.
118. Kim, Y.S. and Y.H. Kim, Sliding wear behaviour of Fe3Al based alloys. *Materials Science & Engineering A*, 1998. 258(1-2): p. 319-324.
119. Cadel, E., A. Fraczkiewicz, and D. Blavette, Suzuki effect on {0 0 1} stacking faults in boron-doped FeAl intermetallics. *Scripta Materialia*, 2004. 51(5): p. 437-441.
120. Baker I., L.X., Xiao, H., , R. Carleton, and E.P. George, The room temperature strengthening effect of boron as a function of aluminum concentration in FeAl. *Intermetallics*, 1998. 6(3): p. 177-183.
121. Baker, I.S., E. M. J. R. Michael, and R.A. Padgett, Grain boundary chemistry in Ni3Al and Ni3Si. *jornal de physique (paris), Collogue*, 1990. C-1(0449-1947): p. 77-82.
122. Aoki, A., O. Izumi, Improvement in room temperature ductility of the L12 type intermetallic compound Ni3Al by Boron addition. *Nippon Kinzoku Gakkai-shi (J. Jpn. Inst. Met.)*, 1979. 43: p. 1190-1196.
123. Liu, C.T., C.L. White, and J.A. Horton, Effect of boron on grain-boundaries in Ni3Al. *Acta Metallurgica*, 1985. 33(2): p. 213-229.
124. Baker, I., et al., Grain boundary chemistry in Ni3Al and Ni3Si. *jornal de physique (paris), Collogue*, 1990. C-1(0449-1947): p. 77-82.
125. Stoloff, N.S., Physical and mechanical metallurgy of Ni3Al and its alloys. *International Materials Review*, 1989. 34(4): p. 153-183.
126. Liu, C.T., C.L. White, and J.A. Horton, Effect of boron on grain-boundaries in Ni3Al. *Acta Metallurgica*, 1985. 33(2): p. 213-229.
127. Blavette D., E.C. and B. Deconihout, The role of the atom probe in the study of nickel-based superalloy. *Materials Characterization*, 2000. 44: p. 133-157.
128. Klein, O. and I. Baker, Effect of Heat Treatment on the Tensile Behavior of Iron-Rich FeAl and FeAl+B. *Scripta Metallurgica et Materialia*, 1994. 30: p. 627-632.
129. Wan, X.J., et al., Hydrogen diffusivity in boron-doped polycrystalline Ni3Al. *Scripta Metallurgica et Materialia*, 1994. 31(6): p. 677-681.
130. Liu C. T., S., J., Mundy, J. N., Horton, L. L., and Angelini, P., Ordered intermetallic alloys: an assessment. *Intermetallics*, 1997. 5(8): p. 579-596.
131. White, C.L., et al., Surface and grain boundary segregation in relation to intergranular fracture: Boron and sulfur in Ni3Al. *Scripta Metallurgica*, 1984. 18(12): p. 1417-1420.

132. Takasugi, T., et al., Intergranular fracture and grain boundary chemistry of Ni₃Al and Ni₃Si. *Scripta Metallurgica*, 1985. 19(4): p. 551-556.
133. Horton, J.A. and M.K. Miller. An atom probe study of boron segregation to line and planer defects in Ni₃Al. in symposium processing. 1987. Pittsburg, PA, USA: Materials research society.
134. Horton, J.A. and M.K. Miller, Atom probe analysis of grain boundaries in rapidly-solidified Ni₃Al. *Acta Metallurgica*, 1987. 35(1): p. 133-141.
135. Horton, J.A. and C.T. Liu, Anisotropic antiphase boundaries in rapidly solidified Ni₃Al. *Acta Metallurgica*, 1985. 33(12): p. 2191-2198.
136. Lemarchant D, E.C., Chamberland S, and B. D., Investigation of grain boundary structure-segregation relationship in an N18 nickel-based superalloy. *Philosophical Magazine A*, 2002. 82(9): p. 1651-1669.
137. messner R. P. and C. L. briant, The role of chemical bonding in grain boundary embrittlement. *Acta Metallurgica*, 1982. 30(2): p. 457-468.
138. Lee, K.H., J.T. Lukowski, and C.L. White, Kinetics of water vapor reactions with intergranular fracture surfaces of Ni₃Al with and without boron. *Scripta Materialia*, 1996. 35(10): p. 1153-1159.
139. Lee C. S., G.W.H., R. E. Smallman, D. Feng, and K. L. Lai, The influence of boron-doping on the effectiveness of grain boundary hardening in Ni₃Al. *Acta Materialia*, 1999. 47(6): p. 1823-1830.
140. F.J. Arenas, A.M., M. Cabezas, C. Di Rauso, C. Grigorescu, Densification, mechanical properties and wear behavior of WC-VC-Co-Al hardmetals. *International Journal of Refractory and Hard Materials*, 2001. 19: p. 381-387.
141. Krasnowski, M., A. Witek, and T. Kulik, The FeAl-30%TiC nanocomposite produced by mechanical alloying and hot-pressing consolidation. *Intermetallics*, 2002. 10(4): p. 371-376.
142. Gao, M.X., et al., Strength improvement and fracture mechanism in Fe₄₀Al/TiC composites with high content of TiC. *Intermetallics*, 2005. 13(5): p. 460-466.
143. Povirk G. L., J.A.H., C. G. McKamey, T. N. Tiegs, and S.R. Nut, Interfaces in nickel aluminide/alumina fiber composites. *Journal of Materials Science*, 1988. 23: p. 3945-3950.
144. Kobayashi, K., Matsumoto, A., Ozaki, K., Nishio, T., Mechanical properties of WC-20mass%Fe₃Al alloy synthesized by mechanical alloying for short time milling. *Journal of the Japan Society of Powder and Powder Metallurgy*, 2001. 49(4): p. 284-289.
145. Guuillermet, A.F., Thermodyndmic Properties of the Co-W-C System. *Metallurgical Transactiobus, A*, 1989. 20A: p. 935-956.
146. Misra, A.K., Identification of Thermodynamically Stable Ceramic Reinforcement Materials for Iron Aluminides. *Metallurgical Transactiobns, A*, 1990. 21A: p. 441.
147. Panov V. S., Y.F.K. and A.A. Filimonova, Interaction between phases in the WC-Ni₃Al system. *Soviet Powder Metallurgy and Metal Ceramics*, 1990. 29(7(331)): p. 564-567.

148. Szutkowska, M., Fracture toughness measurement of WC-Co hardmetals by indentation method. *Journal of advanced materials*, 1999. 31(3): p. 3-7.
149. Richard Warren, H.M., Indentation testing of a broad range of cemented carbides, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 563-582.
150. Zhu, S.-M.G., Xing-Sheng. Shibata, Koji. Iwasaki, Kunihiko, Microstructure and mechanical and tribological properties of high carbon Fe₃Al and FeAl intermetallic alloys. *Materials Transactions*, January 2002. 43(1): p. 36-41.
151. Maupin, H.E., R.D. Wilson, and J.A. Hawk, An abrasive wear study of ordered Fe₃Al. *Wear*, 1992. 159(2): p. 241-247.
152. Kim, Y.-S., Sliding wear behaviour of Fe₃Al based alloys. *Materials Science & Engineering A*, 1998. 258(1-2): p. 319-324.
153. Sharma, G.S., M. Prabhu, N. Goswami, G L., Sliding wear resistance of iron aluminides. *Bulletin of Materials Science*, Apr 2003. 26(3): p. 311-314.
154. Maupin, H.E., R.D. Wilson, and J.A. Hawk, Wear deformation of ordered Fe-Al intermetallic alloys. *Wear*, 1993. 162-164(1): p. 432-440.
155. da Costa, C.E., et al., Wear behaviour of aluminum reinforced with nickel aluminide MMCs. *Journal of Materials Processing Technology*, 1999. 92-93: p. 66-70.
156. Upadhyaya, A., D. Sarathy, and G. Wagner, Advances in sintering of hard metals. *Materials & Design*, 2001. 22(6): p. 499-506.
157. Axen, N. and S. Jacobson, A model for the abrasive wear resistance of multiphase materials. *Wear*, 1994. 174(1-2): p. 187-199.
158. Fischer, T.E. and K. Jia, Abrasion resistance of nanostructured and conventional cemented carbides. *Wear*, 1996. 200(1-2): p. 206-214.
159. Gant, A.J. and M.G. Gee, Wear of tungsten carbide-cobalt hardmetals and hot isostatically pressed high speed steels under dry abrasive conditions. *Wear*, 2001. 251(1-12): p. 908-915.
160. Quercia, G., et al., Friction and wear behavior of several hard materials. *International Journal of Refractory Metals and Hard Materials*, 2001. 19(4-6): p. 359-369.
161. Alman, D.E. and J.A. Hawk, The abrasive wear of sintered titanium matrix-ceramic particle reinforced composites. *Wear*, 1999. 225-229(Part 1): p. 629-639.
162. Anand, K.C., H., Microstructure and scaling effects in the damage of WC-Co alloys by single impacts of hard particles. *Journal of Materials Science*, Aug 1988. 23(8): p. 2931-2942.
163. Larsen-Basse, J., Resistance of cemented carbides to sliding abrasion, in *Science of hard materials*, D.J.R. R.K. Viswanadham, and J. Gurland, Editor. 1983, Plenum Press: New York. p. 797-813.
164. P. K. Rohatri, Y.L., S. Ray, Friction and wear of metal-matrix composites, in *ASM Materials Characterisation*. 1990, ASM International. p. 802-811.

165. Tylczak, J.H., J.A. Hawk, and R.D. Wilson, A comparison of laboratory abrasion and field wear results. *Wear*, 1999. 225-229(Part 2): p. 1059-1069.
166. Gille, G., et al., Advanced and new grades of WC and binder powder - their properties and application. *International Journal of Refractory Metals and Hard Materials*, 2000. 18(2-3): p. 87-102.
167. Kim, B.K., G.H. Ha, and D.W. Lee, Sintering and Microstructure of Nanophase WC/Co Hardmetals. *Journal of Materials Processing Technology*, 1997. 63(1-3): p. 317-321.
168. Gleiter, H., Nanostructured materials: state of the art and perspectives. *Nanostructured Materials*, 1995. 6(1-4): p. 3-14.
169. Roming A.D., Analytical transmission electron microscopy. *Metals Handbook*. Vol. 9. 1990: ASM International.
170. Peters, C.T., The relationship between Palmqvist indentation toughness and bulk fracture toughness for some WC-Co cemented carbides. *Journal of Materials Science*, 1979. 14: p. 1619-1623.
171. Chandra, N. and C.R. Ananth, Analysis of interfacial behavior in MMCs and IMCs by the use of thin-slice push-out tests. *Composites Science and Technology*, 1995. 54(1): p. 87-100.
172. Anstis G. R., C.P., Lawn B. R., and Marshall D. B., A Critical Evaluation of Indentation Techniques for Measuring Fracture Toughness: I, Direct Crack Measurements. *Journal of American Ceramic Society*, 1981. 64(9): p. 533-538.
173. Ravichandran, K.S., A simple model of deformation behavior of two phase composites. *Acta Metallurgica et Materialia*, 1994. 42(4): p. 1113-1123.
174. Rettenmayr, M., H.E. Exner, and W. Mader, Electron microscopy of binder phase deformation in WC-Co alloys. *Materials Science & Technology*, 1988. 4(11): p. 984-990.
175. Cairney, J.M. and P.R. Munroe, Preparation of transmission electron microscope specimens from FeAl and WC powders using focused-ion beam milling. *Materials Characterization*, 2001. 46(4): p. 297-304.
176. Cairney Julli M., R.D.S. and P.R. Monroe, Transmission electron microscope specimen preparation of metal matrix composites using the focused ion beam miller. *Microscopy and Microanalysis*, 2000. 6: p. 452-462.
177. Kato, K.M., Takami., Influence of boron addition on the tensile properties of sintered FeAl compacts by powder injection molding. *Journal of the Japan Society of Powder & Powder Metallurgy*, 2002. 49(9): p. 787-792.
178. Yeh, C.L.S., W Y., Combustion synthesis of Ni₃Al by SHS with boron additions. *Journal of Alloys & Compounds*, 2005. 390(1-2): p. 74-81.
179. Lindahl P., T.M., H. Jonsson, and H. O. Andrent, Microstructure and mechanical properties of a (Ti, W, Ta, Mo)(C, N)-(Co, Ni) type cermet. *Journal of hard materials*, 1993. 4: p. 187-204.

180. Wang Y, D.A., Lay S, Pauty E, and A. CH, Morphology and growth of WC grains in WC-Co cermets: Effect of C/W ratio and Cr addition. *Materiaux*, 2002(AF-01-082).
181. Skoglund, H., M.K. Wedel, and B. Karlsson, Processing of fine-grained mechanically alloyed FeAl. *Intermetallics*, 2004. 12(7-9): p. 977-983.
182. Håkan Engqvist and U. Wiklund¹, Mapping of mechanical properties of WC-Co using nanoindentation. *Tribology letters*, 2000. 8: p. 147-152.
183. Quercia G., I.G.b., H. Contreras b, C. Di Rauso b, D. Gutierrez-Campos, Friction and wear behavior of several hard materials. *International Journal of Refractory Metals & Hard Materials*, 2001. 19: p. 359-369.
184. Engqvist H., G.A.B.b., S. Ederyd c, M. Phaneuf d, J. Fondelius e, N. Axen, Wear phenomena on WC-based face seal rings. *International Journal of Refractory Metals & Hard Materials*, 2000. 18: p. 39-46.
185. Alman, D.E., et al., Wear of iron-aluminide intermetallic-based alloys and composites by hard particles. *Wear*, 2001. 251(1-12): p. 875-884.