RECENT DEVELOPMENT OF METALLIC MATERIALS

C. T. Liu[1] and T. G. Nieh[2]
[1]Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6115
[2]Materials Science and Technology Division, Lawrence Livermore National Laboratory, Livermore, CA 94550

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-96OR22464. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

ABSTRACT

Metallic materials play a vital role in the development of advanced engineering systems for industrial applications. In this paper, the recent development of two metallic alloy families will be briefly reviewed: (1) ordered intermetallics, and (2) bulk metallic glasses. Ordered intermetallic alloys based on aluminides and silicides possess many promising properties for structural use at elevated temperatures in hostile environments. This is because these alloys have excellent oxidation and corrosion resistance, high temperature strength, and relatively low material density. Bulk metallic glasses containing multiple alloying elements constitute a new and exciting class of metallic materials with attractive mechanical, chemical, and magnetic properties for structural and functional use. Recent development indicates that bulk metallic glasses with high glass forming ability can be readily produced by conventional melting and casting techniques.

INTRODUCTION

As stated by Dr. Tadahiro Sekimote, former President of NEC Corporation in Japan, "Those who dominate materials dominate technology." It is true that, from jet engines to clean cars and from battery materials to computer chips, materials have always played a vital role in developing advanced engineering systems. In this paper, the recent development of two metallic materials will be reviewed: (1) ordered intermetallics, and (2) bulk metallic glasses (BMGs). Both metallic materials possess unique properties for structural and functional use.

Ordered intermetallic alloys based on aluminides and silicides possess attractive high-temperature properties, including excellent oxidation and corrosion resistance, high yields strength, and relatively low material density for structural applications.[1] The yield strength of conventional alloys decreases with increasing test temperature; as a result, they become too weak to be used as structural members at sufficiently high temperatures. Many intermetallics, on the other hand, show a striking mechanical behavior, i.e., their yield strength increases, rather than decreases, with temperature; they actually become stronger at higher temperatures. However, the major obstacle that limited their use as engineering material was low ductility and poor fracture resistance at ambient temperatures. For the past decade or so, substantial progress has been made on both the understanding of brittle fracture and the design of ductile intermetallic alloys based on nickel, iron and titanium aluminides for structural use.

Metallic glasses were first synthesized by Paul Duwez and his co-workers in the 1960s; however, a critical cooling rate of 10^6 K/s was necessary for retaining the super-cooled liquid state to room temperatures. Because of this requirement, only foils of ~60 μm thickness could be produced. Limited progress has been made in improving the glass forming ability until multi-component alloys[2] were developed in 1989. For the past decade, substantial progress has been achieved in reducing the

critical cooling rates (to ~10 K/s); as a result, bulk metallic glasses with cross thickness >3 cm can now be readily produced by conventional melting and casting techniques.[3,4] These BMGs have unique physical and mechanical properties for structural and functional use.

BRIEF REVIEW OF RECENT PROGRESS

Intermetallic alloys were considered to be intrinsically brittle for a long time until in 1989 when Liu et al. first demonstrated that nickel and iron aluminides are quite ductile and their low tensile ductility and brittle fracture was mainly caused by environmental embrittlement

aluminide alloys are much stronger that conventional alloys such as stainless steel and Hastelloy-X.

Dual-phase titanium aluminides based on TiAl with lamellar structures have attracted a great deal of interest for structural use because of their extremely low material density and good mechanical and metallurgical properties at elevated temperatures.[7] However, initial application of TiAl alloys had been limited by their poor fracture resistance at ambient temperatures. For the past 5 years, considerable effort has been devoted to TiAl alloys and significant progress has been achieved in material processing, microstructural control, and alloy design. The tensile elongation is

instance, FeAl aluminide showed a low tensile ductility of 2% in air but as high as 18% in dry oxygen at room temperature (Fig. 1). Mechanistically, the embrittlement involves the interaction of Al atoms with moisture in air and the generation of atomic hydrogen, and the penetration of hydrogen at crack tips results in hydrogen-induced brittle failure. This embrittlement has been observed in nickel aluminide and other intermetallic alloys.

The understanding of the cause of brittle fracture has led to metallurgical methods to improve the ductility of intermetallic alloys. For instance, microalloying with B dramatically improves the room temperature ductility of Ni_3Al aluminide.[6] Auger analyses indicates that B has a strong tendency to segregate to Ni_3Al grain boundaries and to slow down the inward penetration of hydrogen, resulting in alleviating the moisture-induced hydrogen embrittlement. Alloy design efforts have resulted in the development of ductile and strong nickel and iron aluminide alloys for structural use at elevated temperatures. As shown in Fig. 2, the yield strength of Ni_3Al increases with test temperature and it can be further improved by alloying with Mo, Cr, and Zr additions. The comparison in Fig. 2 indicates that nickel

increase in ductility with decreasing colony size. The yield strength, on the other hand, is sensitive to interlamellar spacing. Hall-Petch relationships hold well for both yield strength and tensile elongation at room and elevated temperatures.[7] The tensile elongation of ~5% and yield strength of ~1000 MPa are achieved by controlling both colony size and interlamellar spacing. These TiAl alloys are comparable to strong Ni-base superalloys in strength, but their density is only half that of superalloys.

Although metallic glasses were first synthesized by rapid solidification in early 1960s, the initial use of these materials was hindered by high manufacture cost and limited sample size (~60 μm in thickness) because extremely high cooling rates were required (~10^6 K/s). Breakthrough in design of metallic glasses was first obtained in 1989 when bulk quantities of material were successfully synthesized with multi-element systems.[2] The critical cooling rate of these BMGs containing multiple alloying elements approaches that of oxide glasses. The high glass forming ability of BMGs can be related to the factors:[4] (1) multiple elements, ≥3, (2) large atomic size difference for constituent elements, usually

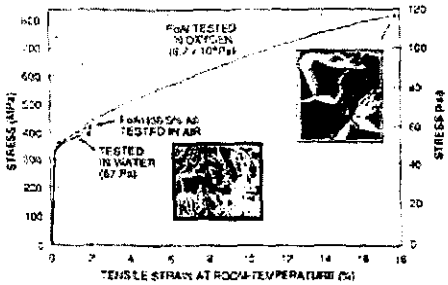

Fig. 1. Effect of B additions on tensile elongation and fracture behavior of Ni_3Al tested at room temperature (ref. 6).

≥12%, and (3) negative heats of mixing with no single intermetallic phase stable. Recent advances indicate that BMGs with thickness >3 cm can be readily produced by conventional melting and casting techniques.[3,4,8,9]

At present, BMGs based on Zr, Ti, Ni, Fe, Al, and rare-earth elements have all been successfully synthesized.[4,9] These BMGs exhibit many exciting mechanical and metallurgical properties, including high strength (300 ksi or 2 GPa), excellent wear and corrosion resistance, high fracture toughness (50 MPa $m^{1/2}$), excellent castability and net-shape forming capability, as well as low cost for alloy preparation and fabrication.[8,9] Figure 3 shows a $La_{55}Al_{25}Ni_{20}$ specimen superplastically deformed (15000%!) in the super-cooled liquid state. Also, Fe-base BMGs developed recently have excellent soft magnetic properties for many functional applications[4]. As shown in Fig. 4, these BMGs exhibit a very low energy loss due to hysteresis in magnetic fields.

CONCLUSION REMARKS

Two exciting new metallic alloy systems have recently been developed. The intermetallic alloys based on nickel, iron, and titanium aluminides have unique properties for structural applications. For instance, Ni_3Al alloys

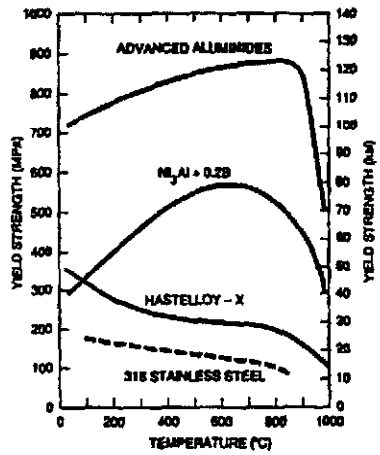

Fig. 2. Comparison of the yield strength of Ni_3Al alloys with that of commercial alloys 316 stainless steel and Hastelloy X (ref.6).

developed recently possess a combination of promising properties, including excellent corrosion resistance in both oxidizing and carburizing environments, good strength at high temperatures, good fatigue and wear properties, low cost for material preparation (taking advantage of exothermic reaction and air casting), and excellent resistance to cavitation erosion.[6] Industrial interest in these aluminides is high, and they are currently being evaluated for a variety of applications, including high-temperature dies and molds, hot gas filters for energy conversion systems, automobile parts (i.e., exhaust valves, supercharger rotors), jet engine components, rollers for steel slab fabrication, etc.

BMGs with multiple alloying elements constitute a new and exciting class of metallic materials with attractive mechanical, chemical, and magnetic properties for structural and functional use.[8,9] Potential applications include forming parts to net shape (such as gears), cutting tools, highly elastic springs, hydrogen storage, corrosion-resistant containers, golf club heads, fishing poles, transformer cores, etc. The Fe-base BMGs developed recently have excellent soft magnetic properties and are expected to have many functional applications.[4]

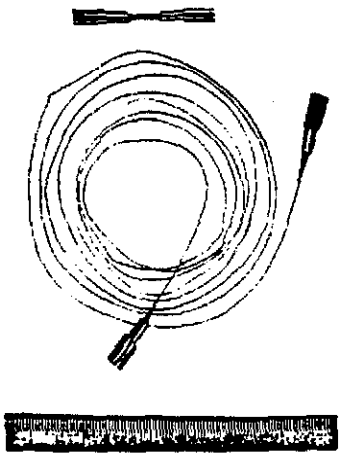

Fig. 3. $La_{55}Al_{25}Ni_{20}$ deformed up o 15,000% by tensile testing in the super-cooled liquid state (ref. 9).

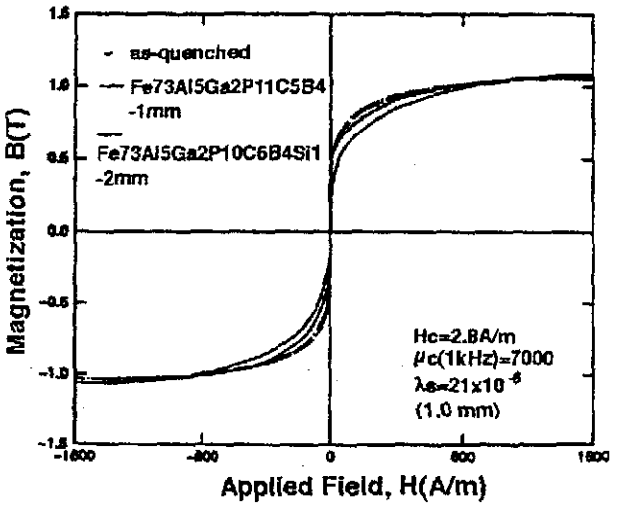

Fig. 4. Hysteresis B-H loop of cast Fe-base BMGs (ref. 4).

REFERENCES

1. C. T. Liu, J. O. Stiegler, and F. H. Froes, "Ordered Intermetallics," pp. 913-942 in ASM Metals Handbook Vol. 2, "Properties and Selection: Non-Ferrous Alloys and Special-Purpose Materials," 10th Edition, ASM Publication, 1990.
2. A. Inoue, T. Zhang, and T. Masumoto, Mater. Trans. JIM 30, 965-72, 1989.
3. A. Peker and W. L. Johnson, J. Appl. Phys. Letter 63, 2324-44, 1993.
4. A. Inoue, A. Takeuchi, and T. Zhang, Metall. Trans. A 29A, 1779-93, 1998
5. C. T. Liu, E. H. Lee, and C. G. McKamey, Scri. Metall. 23, 875-80, 1989.
6. C. T. Liu and E. P. George, pp. 21-32 in ASM Procs. "Nickel and Iron Aluminides: Processing, Properties, and Applications", ASM Publication, 1997.
7. C. T. Liu and P. J. Maziasz, Intermetallics 6, 653-61 (1998).
8. C. T. Liu et al., *Metall. Mat. Trans.* A 29A, pp. 1811-1820 (1998).

ACKNOWLEDGEMENT

Research was sponsored by the Division of Materials Sciences, Office of Science, U.S. Department of Energy, under contract De-AC05-96OR22464. Thanks are due to Judy McKinney for manuscript preparation and Joe Wright for photo scanning.

1995.