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Emerging applications of intermetallics

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Abstract

Many intermetallic compounds display an attractive combination of physical and mechanical properties, including high melting point, low density and good oxidation or corrosion resistance. This has led to their utilization in many non-structural applications, but success in structural applications has, to date, been limited. This paper reviews the current status of intermetallic applications, with emphasis on new uses that are in place or pending. Most of the paper deals with aluminides and silicides, but there are several more complex intermetallics that are being employed in battery and magnetic applications. Research on improved processing and studies of the role of environment in mechanical behavior are shown to be key to developing practical alloys. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Intensive studies of the mechanical and physical properties of intermetallic compounds have led to many suggestions for potential structural and non-structural applications. These include high temperature gas turbine hardware, corrosion resistant materials, heat treatment fixtures, magnetic materials and hydrogen storage materials. It is the objective of this paper to describe in detail these and other applications, and to point out research that needs to be done to insure improved mechanical and/or physical properties.

2. Characteristics of intermetallics

For at least the past four decades research on intermetallic compounds has largely focussed upon mechanical properties, especially involving low temperature ductility and high temperature strength. Unfortunately, many intermetallics are brittle or semi-brittle at room temperature, rendering them difficult to fabricate or utilize in structural applications. In recent years it has been found that brittleness in several aluminides and silicides arises from an extrinsic environmental effect which can be overcome by alloying, microstructural control or coating. Examples of such compounds that are adversely affected by moist environments are FeAl, Fe_3Al, Ni_3Al and Ni_3Si. Intermetallics, which are of interest for elevated temperature applications, such as the titanium aluminides, $MoSi_2$ and several Laves phases, often display inadequate creep resistance. In some cases such resistance has been improved by alloying or compositing. Other key issues for many intermetallics are the ability to process them in a cost-effective manner and the provision of adequate corrosion or oxidation resistance. Finally, for most compounds an insufficient database exists for designers to have confidence in replacing existing materials with intermetallics.

Other compounds have been studied for their interesting physical properties, such as superconductivity, hydrogen storage capability or magnetic properties. Examples of intermetallics in each of these categories, together with their prospects for industrial application, will be discussed in subsequent sections of this paper. An overall summary of applications for intermetallics appears in Table 1.

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3. Intermetallics for structural, heat-resistant and corrosion-resistant applications

The most widely studied intermetallics in this class include aluminides of titanium, nickel, iron and niobium, silicides of nickel, molybdenum and niobium and Laves phases such as Cr_2Nb. The physical properties of these compounds are summarized in Table 2. Many of these compounds have excellent corrosion and oxidation properties because of the high content of elements that form protective oxides. Therefore, applications for these compounds sometimes extend far beyond their strength and ductility.

3.1. Ni_3Al

This compound has been the object of much research to understand the factors controlling low temperature ductility. It is now known that the brittleness of unalloyed Ni_3Al stems from an environmental effect, and boron serves to suppress the embrittlement. Numerous alloys based upon Ni_3Al have been developed with the aim of improving high temperature creep resistance. Although the mechanical properties are attractive, most current usage is mainly in corrosion-related structural applications. This is because oxidation and carburization resistance is high, as are resistance to wear and cavitation-erosion. A summary of current and potential applications appears in Table 3. These applications range from furnace rolls and radiant burner tubes for steel production to heat treating fixtures, forging dies and corrosion-resistant fixtures for chemical industries. A photograph of various sizes of heavy wall, centrifugally cast tubes of Ni_3Al alloy IC–221M (Ni–8wt.%Al–7.7 Cr-1.43Mo–1.7Zr–0.008B) appears in Fig. 1 [1]. Other applications for this alloy include radiant burner tubes, center posts for pit-carburizing furnaces and guide rolls for continuous casters. A stronger, more creep resistant Ni_3Al alloy, IC-438, (Ni–8.1wt.%Al–5.23Cr–7.02Mo–0.13Zr–0.005B) has been identified; this alloy allows potential users to extend the maximum use temperature of 1100°C for IC-221M to 1250–

Table 1
Applications of intermetallics

- Structural
  - automotive
  - aerospace
- Magnetic
- Energy storage
  - batteries
  - hydrogen storage
  - Heating elements
- Tools and dies
- Furnace hardware
- Corrosion-resistant
  - piping for chemical industries
  - cladding
  - coatings
- Electronic devices

Table 2
Properties of high temperature intermetallics

Compound	Structure	T_m °K	ρ g/cc	$E_{25°C}$ GPa	Comment
Cr_3Si	A15	2043	6.5	357	Solubility range
$MoSi_2$	C11	2303	6.24	425	Line compound
Cr_2Nb	C15	2043	7.7	218	C14 above 1858°K; line compound
Nb_3Al	A15	2233	7.29	–	Line compound
TiAl	$L1_0$	1723	3.9	173	Solubility range
Ti_3Al	DO_{19}	1873	4.2	147	Solubility range
Nb_5Si_3	D8	2793	7.16	–	Line compound
Nb_3Si	$L1_2$	2153	7.4	–	Limited range of stability

Table 3
Applications of Ni_3Al

Steel
- As furnace rolls
- Casting rolls
- Radiant burner tubes

Heat treating
- Fixtures for carburizing, furnaces, and air
- Link belts for heating treating furnaces
- Furnace muffles
- Radiant burner tubes

Chemical
- Reaction vessels for higher temperatures
- Tube hangers
- Pallet tips for phosphate ore calcination
- Pump impellers for slurries

Forging
- Forging dies
- Die repair as weld overlay

Chemical
- For ethylene crackers
- Air deflectors for burning of high sulfur fuel

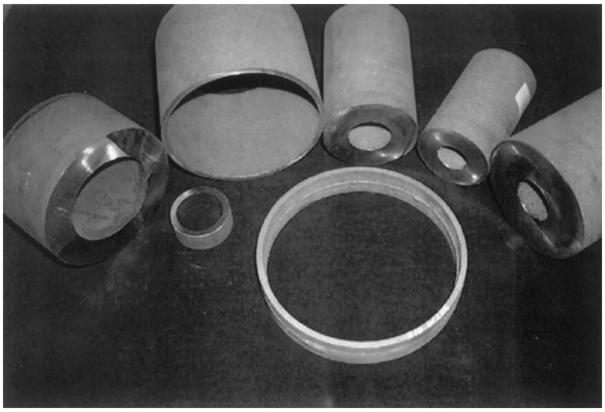

Fig. 1. Photograph of various sizes of heavy-wall centrifugally cast tubes of IC-221 M [1].

1300°C for IC-438. Creep rupture strengths of the two alloys, based upon the Larson–Miller parameter, are compared in Fig. 2 [1,2].

3.2. NiAl

Much effort has been invested in attempts to utilize NiAl alloys for gas turbine hardware. Unfortunately, while NiAl single crystals were developed with creep strengths comparable to those of Ni-base superalloy single crystals, other mechanical properties of NiAl were found to be inadequate. Ductility and fracture surfaces remain low. In addition, Walston and Darolia [3] showed in 1997 that impact resistance of high strength single crystals is inadequate for turbine blades, but might be sufficient for stationary parts such as vanes and combustor liners. A directionally solidified NiAl alloy was more resistant to impact. Physical vapor deposited thermal barrier coatings did not improve impact resistance. It appears unlikely that these shortcomings can be overcome in the near future.

3.3. FeAl and Fe_3Al

The iron aluminides, FeAl and Fe_3Al, are notable for their low cost, ease of fabrication and corrosion and oxidation resistance. In addition, FeAl is characterized by good resistance to catalytic coking, carburization, sulfidation and wear. As a result, FeAl has seen application as transfer rolls for hot rolled steel strip, ethylene crackers and air deflector for burning high sulfur coal. Structural applications for these compounds have been limited by low ambient ductility, due largely to embrittlement by moisture in air. However, several methods to combat environmental embrittlement have been developed. These include control of grain size and shape, use of alloying elements such as Cr for Fe_3Al and B for FeAl, and the application of oxide or copper coatings [4]. These developments, combined with improved creep and impact resistance provided by alloying, have improved the likelihood that monolithic iron aluminides may be utilized for structural applications. Alternatively, the excellent corrosion and oxidation resistance of iron aluminides suggests their possible usefulness as coatings. For example, steels have been successfully coated by $(Fe,Cr)_3Al$ by a two-step pack cementation process, as shown in Fig. 3 [5].

Another development that favors the near-term utilization of iron aluminides is the development of the Exo-Melt^{TM} process, see Fig. 4 [6]. This low cost, easily controllable process is useful also for nickel aluminides, as it exploits the exothermic heat of reaction between aluminum and other elements to reduce the need for external power during melting.

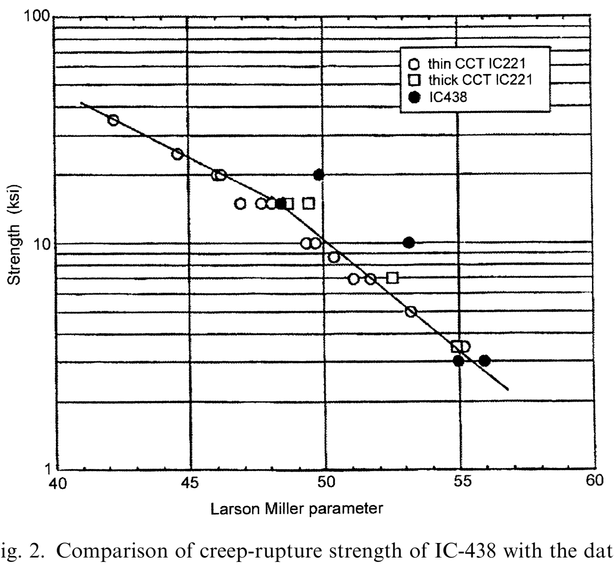

Fig. 2. Comparison of creep-rupture strength of IC-438 with the data for IC-221M [1].

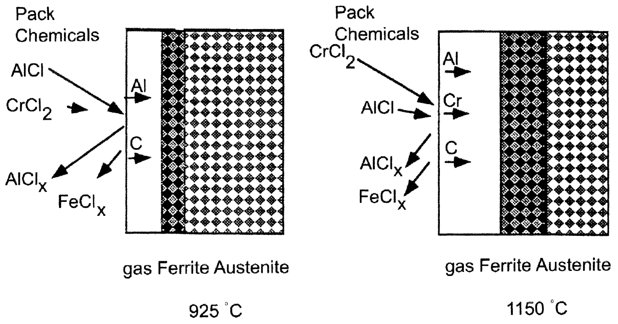

Fig. 3. Schematic of two-step pack cementation coating process. Longer arrows correspond to higher vapour pressures. The darkend area represents a zone of carbon enrichment in austenite. Microstructure of T11 steel coated in a pack with 2AI-18Cr, $2CrCI_2$ at 925°C for 4 h then at 1150°C for 3 h [5].

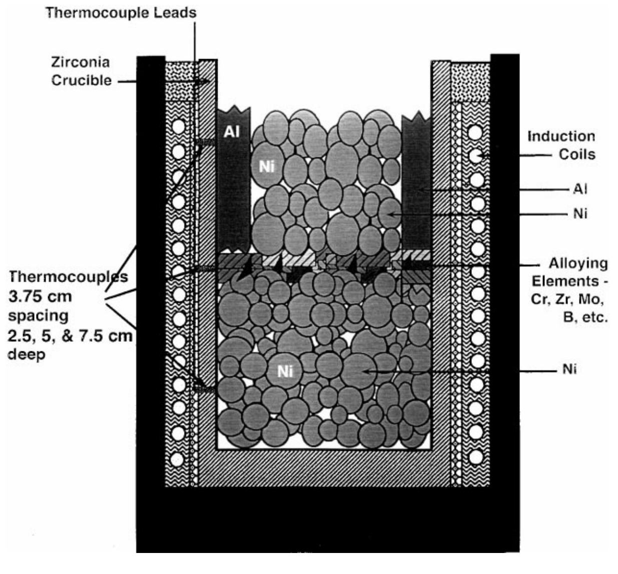

Fig. 4. Furnace-loading scheme of the EXO-Melt^{TM} process for melting of iron and nickel aluminides [6].

Yet another promising processing technique for iron aluminides is the use of superplastic forming. Li et al. [7] and Lin et al. [8] have demonstrated superplasticity for FeAl and Fe_3Al alloys, respectively. However, no applications utilizing this technique have been reported.

3.4. TiAl

One of the most promising intermetallics for turbine applications is TiAl. This compound has a higher melting point, better oxidation resistance and resistance to fires, as well as lower density than conventional titanium alloys, but has suffered from low room temperature ductility and fracture toughness. Nevertheless, numerous potential aircraft applications have been identified, see Table 4 [9]. However, the aircraft industry is extremely demanding in qualifying new alloys, and the difficulty in fabricating these compounds, coupled with the lack of an adequate data base of mechanical properties, have been serious impediments to implementation. An advantage of TiAl is that this compound has a higher melting point than competing alloys that combine the requisite ductility and creep resistance for turbine applications. One such alloy, developed by M.Nazmy and co-workers, is Ti–47at.%Al–2.1W–0.5Si. [10,11]. This alloy has improved oxidation and creep resistance, such that it is being proposed as a marine turbine alloy for a high speed ferry. In this application, the maximum turbine inlet temperature is 610°C. It has been successfully run in tests to 1856 h, when it underwent its first inspection (September, 1999). Additional uses of TiAl alloys may arise from the ability to superplastically deform this compound at relatively low temperatures [12] or to spray form deposits on a substrate, see Fig. 5 [13]. These processing techniques, as well as the ability to cast large shapes, avoid the problems arising from lack of formability by conventional working processes.

3.5. $MoSi_2$

This line compound is particularly noteworthy for its combination of very high melting point, low density and outstanding oxidation resistance. Unfortunately, the very low ductility and fracture toughness of the pure compound has limited usage to mostly non-structural applications. A list of current and proposed applications appears in Table 5. The most important use to date is as heating elements (Kanthal). Recent work by Akinc et al. [14] has shown that improvements in electrical resisivity of $MoSi_2$ can be achieved by alloying with B-containing phases, see Fig. 6. An important advantage of this compound is the ability to utilize a wide range of processing techniques to synthesize. One of the most promising of these techniques is powder processing to produce an alloy or a functionally gradient material (FGM) between $MoSi_2$ and ceramics such as Si_3N_4 [15]. The latter is particularly beneficial as a solute in $MoSi_2$ because increased strength is accompanied by resistance to catastrophic oxidation (pesting). A schematic drawing of a diesel energy combustion chamber, see Fig. 7 [16] illustrates the use of $MoSi_2$–Si_3N_4 glow plugs produced from a FGM process. Another recent application for FGM $MoSi_2$ is in a hybrid direct energy conversion system under development in Japan, as shown in Fig. 8 [17] This device aims to convert solar energy into electricity by combining thermionic and thermoelectric conversion stages in a single device. The objective is increased energy conversion efficiency. Other $MoSi_2$-ceramic alloys

Table 4
Aircraft engine applications for TiAl [9]

Low pressure turbine blades: CF6-80C2, GE 90
Carbon seal supports: F414
Transition duct beams: GE 90
Blade dampers, high pressure turbine
Compressor blades: Allison 14th stage
High speed civil transport components
Diffuser casting: advanced engines

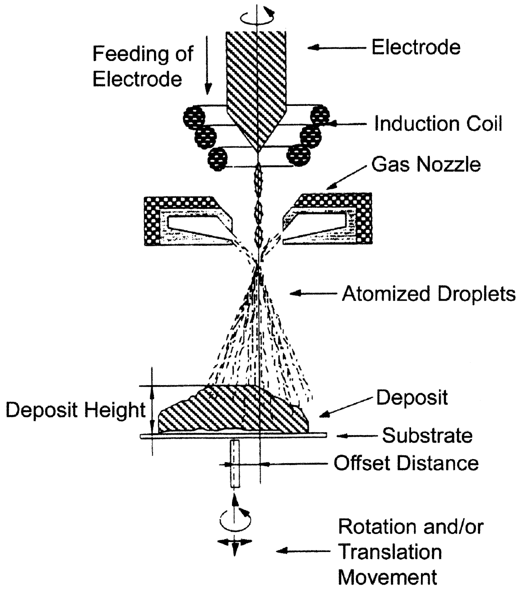

Fig. 5. Schematic drawing of EIGA setup for spray forming [13].

Table 5
Applications for $MoSi_2$

- Turbine hardware
  - vanes
  - combustor liners
- Flame holders
- Diesel engine glow plugs
- Igniters
- Electronic devices
- Heating elements
- Glass melting
- Energy conversion devices

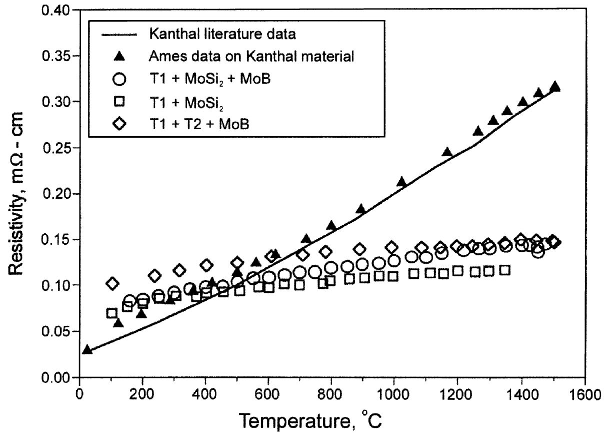

Fig. 6. Temperature dependence of electrical resistivity for boron-doped Mo_5Si_3 with commercial Kanthal® Super $MoSi_2$ heating element material for comparison (T1 : Mo_5Si_3 , T2 : Mo_5SiB_2) [14].

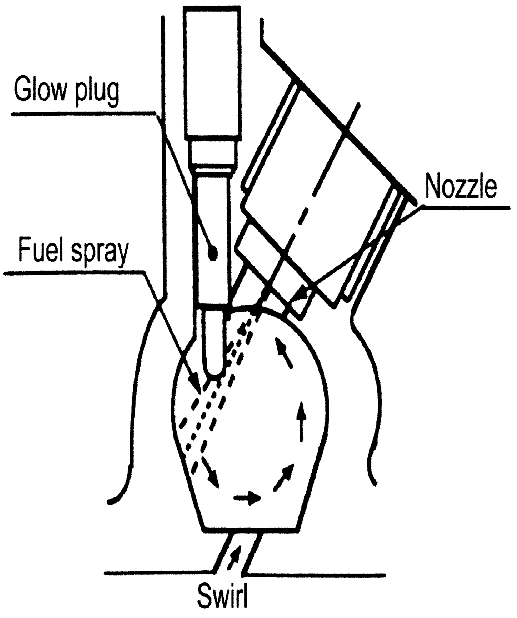

Fig. 7. Combustion chamber (Swirl chamber) for diesel engine [16].

have been patented for use as heating elements, igniters and heat sensors [18,19].

Because of high corrosion resistance, $MoSi_2$ tubes have been tested in closed-circuit monitoring systems for glass melters [20].

Recently, research on molybdenum silicides for high temperature applications has shifted from $MoSi_2$-base to Mo_5Si_3-base compositions. [21]. This is because the latter contain more Mo and demonstrate better creep resistance. Oxidation resistance of Mo_5Si_3 is not as good, but can be improved substantially by the addition of boron [22]. Considerable effort is now being devoted to study of the Mo–Si–B system [23].

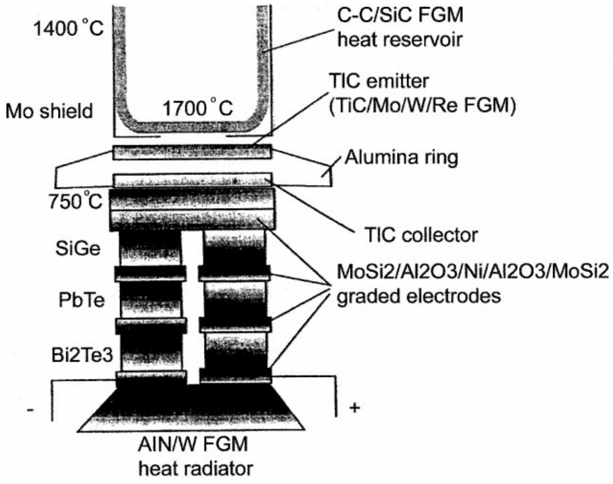

Fig. 8. The concept and the design of HYDECS (based on [17]).

3.6. Nb_3Si

Niobium silicides are among the most recent intermetallic alloys to be studied for possible high temperature structural applications. Bewlay and co-workers [24] have reported outstanding mechanical properties for such alloys, some of which are produced as directionally solidified eutectic composites. A comparison of temperature capability for less than 25% μm of metal loss in 100 hours for initial and more recent niobium silicide-based composites is shown in Fig. 9, together with the estimated goal [24]. Note that the present silicide composites are close to advanced nickel-base superalloy single crystals in their temperature capability.

3.7. Ni_3Si

This $L1_2$ intermetallic resembles Ni_3Al in that it is ductile when tested in inert environments, but is embrittled by contact with moisture. Both alloys are ductilized in air by the addition of small amounts of boron. Researchers at ORNL have demonstrated excellent mechanical properties of Ni_3Si alloys [25,26] at elevated temperatures. Such alloys have the potential for fabrication of complex components for use in chemical process systems. Two phase Ni_3Si–Ni alloys with excellent fabricability and weldability are currently being developed for structural use in acid and oxidizing environments [27].

4. Intermetallics for electronic, magnetic, battery applications

4.1. Electronics and sensors

The widespread use of silicides in the electronics industry has been reviewed by Kumar [28]. These compounds are used as superconductors, ohmic contacts for integrated circuits, for growth of epitaxial films and as infrared detectors and sensors. Other intermetallics are now being studied for electronic applications. For example, NiAl and Ni_3Al substrates are being used to form an insulating alumina layer by oxidation in air at temperatures between about 900 and 1200°C, prior to applying conductive elements to the alumina layer [29]. These circuit components have improved mechanical properties and higher thermal conductivity compared to alumina substrates sold in Japan and the United States.

The shape-memory alloys typified by TiNi have been examined extensively for possible use in small devices such as microvalves. These devices have the potential to be used in microelectromechanical systems (MEMS) [30].

4.2. Magnets

Several intermetallic compounds, including FeCo and rare earth compounds, have been used as permanent magnets. One of the most interesting compounds is $Nd_2Fe_{14}B$, which has the highest energy product of commercial permanent magnets [31]. Improvements in the fracture stress and toughness of these magnets would allow greater machinability, easier handling and use as a structural element. However, very little work has been done in recent years on the mechanical properties of hard magnets. Improved mechanical properties are needed to fabricate electric vehicle wheel motors. The use of improved permanent magnets in heat pump compressors and fan motors could provide substantial energy savings. Researchers at Oak Ridge National Laboratory have initiated an investigation of mechanical properties of $Nd_2Fe_{14}B$ [32].

4.3. Batteries

There is a large family of hydride-forming intermetallic compounds that lend themselves to use in Ni-metal

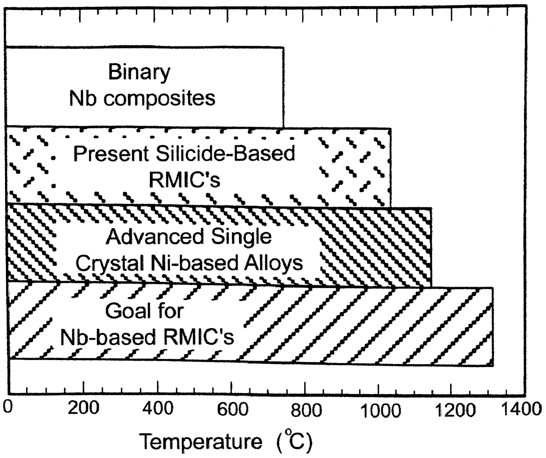

Fig. 9. A comparison of the temperature capability for less than 25μm of metal loss in 100 h for initial and more recent niobium silicide-based RMICs, together with the estimated goal. The temperature capability of an advanced single-crystal nickel based super-alloy is also presented in the figure for comparison [24].

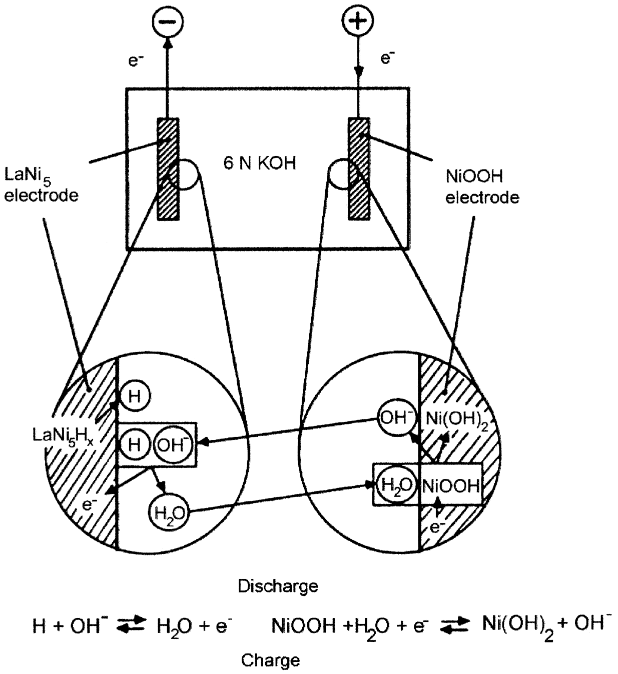

Fig. 10. A reversible battery with $LaNi_5$ metal hydride and NiOOH electrode and KOH electrolite [33].

Table 6
Families of hydride-forming intermetallic compounds for Ni-metal hydride batteries from [33]

Family	Prototype material	Crystal structure type		Hydride/deuteride
AB_5	$LaNi_5$	$CaCu_5$, $D2_d$ (hP6)		$LaNi_5H_{6.5}$
AB_2	$ZrMn_2$, $TiMn_2$	$MgZn_2$, C14 (hP12)	Laves phases	$ZrMn_2D_3$, $TiMn_2D_3$
	$ZrCr_2$, ZrV_2	$MgCu_2$, C15 (cF24)	Laves phases	$ZrCr_2H_{3.8}$, $ZrV_2H_{4.9}$
AB	TiFe	CsCl, B2 (cP2)		TiFeH, $TiFeH_{1.9}$
A_2B	Mg_2Ni	Mg_2Ni (hP18)		Mg_2NiH_4
	Ti_2Ni	Ti_2Ni (cF96)		Ti_2NiH
A_2B–AB	Ti_2Ni–TiNi	Multiphase alloy (cF96 and mP4)		Ti_2NiH, TiNiH

hydride batteries, see Table 6 [33]. A schematic of a reversible battery with $LaNi_5$ metal hydride and NiOOH electrodes in a KOH electrolyte is shown in Fig. 10 [34]. NiMH batteries comprise more than 30% of a $6 billion market for rechargeable batteries used in many portable electronic devices such as cell phones and laptop computers [34–36]. Advantages of NiMH batteries include higher storage capacity than Pb-acid and Ni-Cd batteries, less toxicity than lead and cadmium and lower cost than Li-ion batteries. However, NiMH batteries have lower energy density than Li-ion and high initial costs than Pb-acid and Ni-Cd batteries. New intermetallic alloys: $(Zr,Ti)(Ni,Cr,V,Mn)_2$ have been developed as hydrogen storage materials for possible use in electric cars. The capacity of batteries based upon the new compounds is 50% higher than for $LaNi_5$.

5. Summary

This paper has described a wide range of industrial applications of intermetallic compounds. Although many alloys with attractive high temperature strength and ductility have been developed, applications in aerospace have been sparse. This arises in part from the inherent conservatism of this industry when new materials are considered, especially in view of the lack of a large database for most intermetallics. Recent developments in processing (e. g. the use of powders to produce functionally gradient materials) suggests that intermetallics may be useful in structural applications where ceramics are now contemplated for use. Fortunately, numerous non-structural applications that exploit the electrical, thermal, magnetic and corrosion properties of intermetallics have been identified. Even in these applications, continuing research to improve strength, ductility and toughness will add to the usefulness of intermetallics. A summary of new alloys described in this paper, together with their major attributes, appears in Table 6. While alloy design principles are well understood, better computational techniques to aid in alloy development are needed. The major impact of processing techniques on mechanical properties demonstrates a need to optimize processing parameters to provide the best balance of strength and toughness or ductility. Further work on suppressing environmental embrittlement at low temperatures is desirable, as is the improvement of high temperature oxidation resistance for alloys slated for structural applications. The establishment of property databases and the ability to demonstrate scale-up of laboratory research to production are prerequisites for widespread application of intermetallic compounds. Finally, while not addressed in this paper, there is continuing necessity to hold down costs of finished products, notwithstanding the advantages of using intermetallics with abundant, low-cost elements such as aluminum and silicon.

Acknowledgements

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