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Review

An Overview on Synthesis, Processing and Applications of Nickel Aluminides: From Fundamentals to Current Prospects

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Abstract: Nickel aluminides have desirable properties for use in high-temperature applications. Nickel aluminides have certain desirable qualities, but for almost a decade in the 1990s, those benefits were overshadowed by the challenges of processing and machining at room temperature. Manufacturing improvements, increased knowledge of aluminide microstructure and deformation processes, and developments in micro-alloying have all contributed to the development of nickel aluminides. Key developments in nickel aluminides, such as their microstructure, alloy addition and alloy development, are given and discussed at length. Methods of production from the past, such as ingot metallurgy and investment casting and melting are addressed, and developments in powder metallurgy-based production methods are introduced. Finally, the difficulties of producing nickel aluminides and possible solutions are examined. This paper gives an overview of the fundamentals, preparation, processing, applications and current trends in nickel aluminides.

Keywords: nickel aluminides; intermetallics; processing; applications

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1. Introduction

Intermetallic compounds are a class of metallic materials, which are now the subject of extensive research by scientists and engineers working in the field of materials science. Intermetallic compounds are used in higher temperature engineering applications, as they have properties intermediate of metals and ceramics. These materials are now necessary in a wide variety of applications and have the potential to provide additional advances in performance in a variety of domains such as magnetic materials, hydrogen storage materials, and high-temperature structural materials (>1200 °C), etc. [1–3]. Most intermetallic compounds have high melting temperatures and are brittle at normal temperature. Because of the low number of separate slip systems necessary for plastic deformation, intermetallics typically fracture in a cleavage or intergranular manner. However, some intermetallics, such as Nb-15Al-40Ti, exhibit ductile fracture modes. Alloying with additional elements can increase grain boundary cohesion, resulting in increased ductility in other intermetallics [4,5]. Figure 1 shows few compounds of current interest by comparing melting temperature and density. Examples of some intermetallics based on their properties are shown in Figure 2.

Sometimes, intermetallics are categorized based on crystal formation, and have highly complicated atomic arrangements with common structures adhering to the simple stoichiometric formulae AB, AB_2 and C [5,6]. The immense promise of intermetallics, particularly aluminides, arises from their numerous desirable features, including excellent oxidation resistance, corrosion resistance, comparatively low densities, stiffness at increased temperatures and the ability to preserve strength [7–9]. Despite its usefulness, poor ductility—especially at low and intermediate temperatures—is a major drawback of intermetallics. Different compounds have different reasons for lacking ductility, which is presented in Figure 3 [8–11].

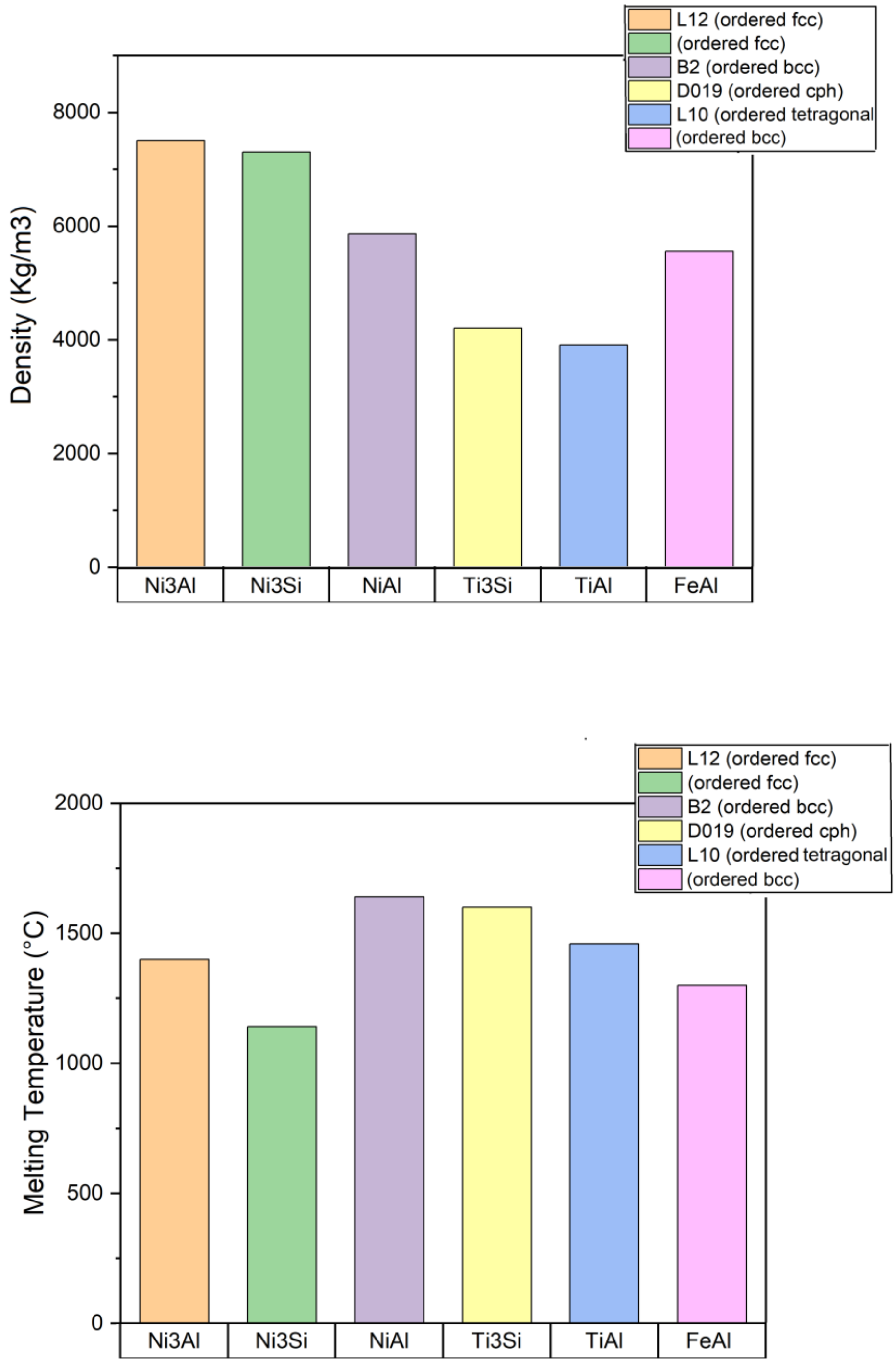


Figure 1. Few intermetallic compounds of current interest by comparing melting temperature and density.

Small amounts of alloying additives, however, have shown to improve ductility several intermetallics: Boron in Ni_3Al, Manganese in TiAl, and Niobium in TiAl [8]. Titanium aluminides and nickel aluminides systems have been the focus of the majority of research in the field of intermetallics [7]. Ni_3Al and NiAl are the two important aluminides that are found in the nickel–aluminum system. As a possible structural alloy, Ni_3Al has garnered a significant amount of attention recently. The majority of superalloys contain Ni_3Al, which functions as a strengthening phase [7,9].

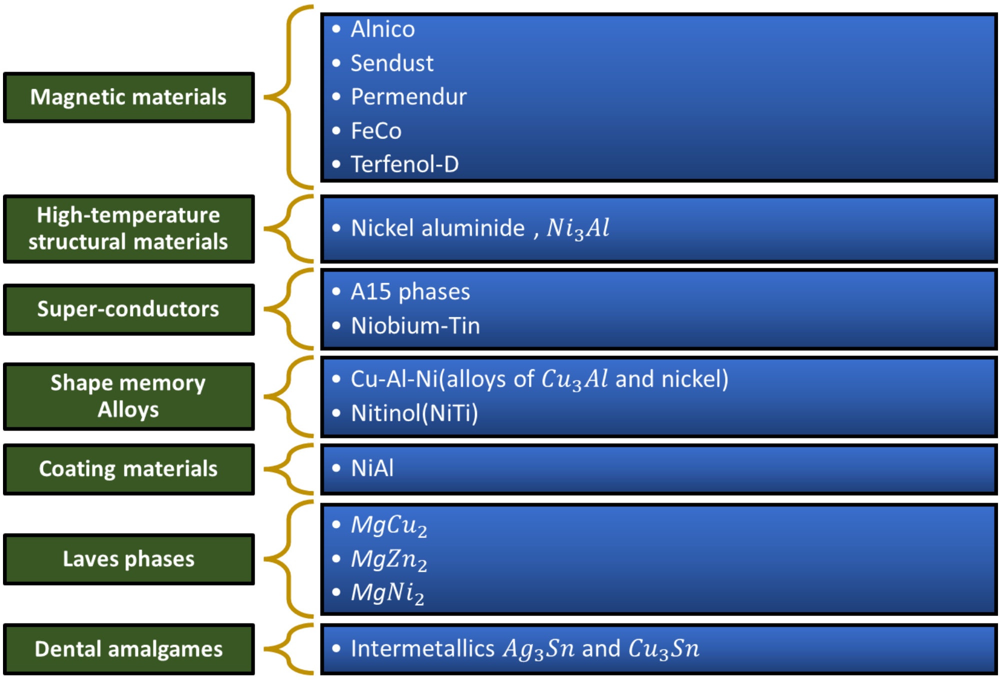


Figure 2. Classification of intermetallics based on properties.

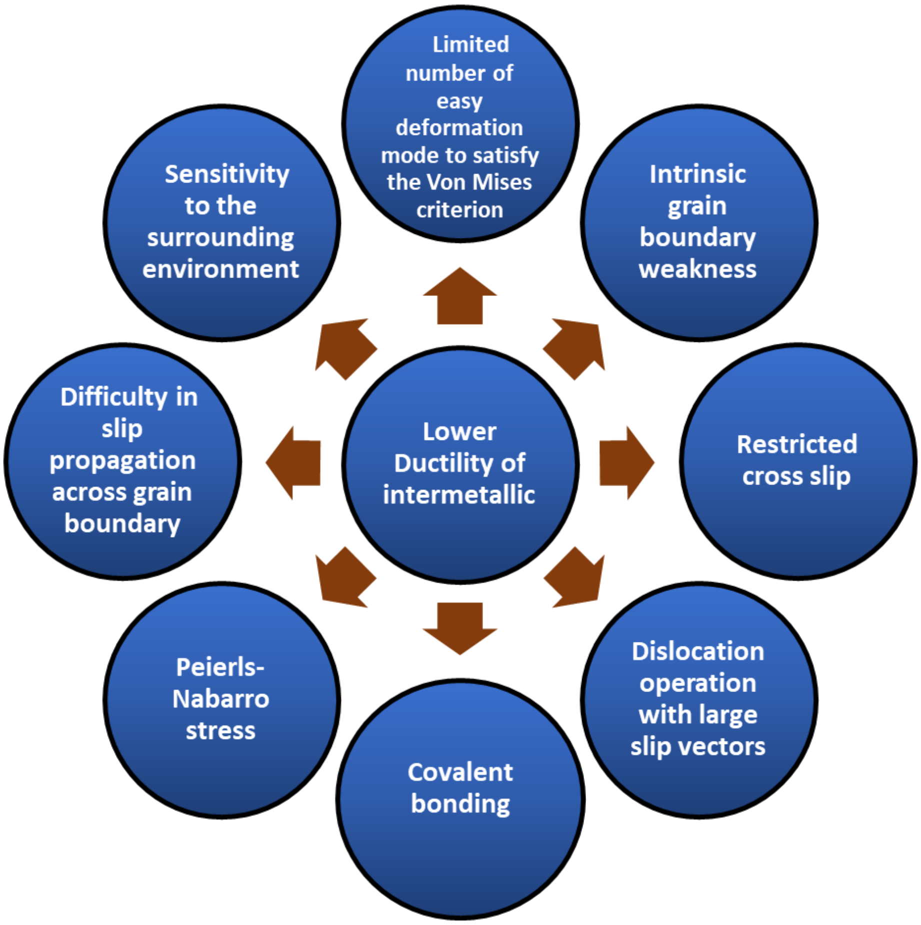


Figure 3. Factors that cause low ductility of intermetallics.

When exposed to oxygen-rich environments, the aluminide of a transition metal will produce a continuous, totally adhering alumina coating on its surface. Aluminides typically include aluminum concentrations between 10 and 30 wt%, which is much greater than the aluminum content of standard superalloy and alloy. Alumina layer that forms upon nickel surface and iron aluminides is what allows these materials to retain their superior oxidizing and carburizing resistivity at temperatures of 1000 °C or higher [10]. Therefore, aluminides do not always need chromium for producing layer of oxide upon material surface to counter higher temperature oxidizing and rust, in contrast to typical steels and superalloys based on Fe, Co and Ni [11]. The characteristics of alumnides are shown in Figure 4.

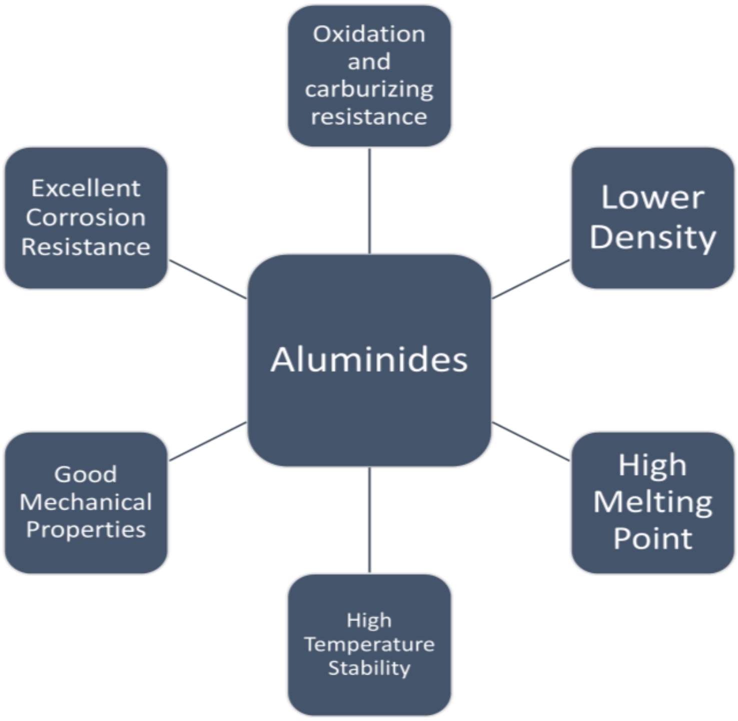


Figure 4. Characteristics features of Aluminides [12–15].

There are often many intermetallic equilibrium aluminide phases present in metal-aluminum binary systems. In thin-film bilayers, it is typically found that only a single phase is growing at any one moment [16,17]. This is in contrast to bulk diffusion couples, in which, after adequate indurating, all of the equilibrium stages normally occur. Located somewhere in the middle of these two patterns of behavior are lateral diffusion couples.

2. Importance of Nickel Aluminides

Nickel aluminides have a low density and great resistance to oxidation. They also keep their strength well at higher temperatures. Because of these characteristics, they are a good choice for high-temperature structural applications. One of Ni_3Al's most notable characteristics is the fact that its yield stress rises as its temperature rises to a maximum temperature of 600 °C, as shown in Figure 5 [8,18]. Table 1 indicates the weight percentage and melting point of aluminum based intermetallics. This behavior has been noticed in other $L1_2$ intermetallics as well. This effect is caused by the cross slip of screw dislocations, which are thermally triggered, moving from the planes labelled (1 1 1) to the planes labeled (1 0 0), which is where the antiphase boundary (apb) energy lies. Observations of apb energies using electron microscopy that are given in Table 2 illustrate that the apb energy on {1 0 0} declines with increasing amounts of aluminum content. This affects the composition dependency of the strength, which is shown in Figure 5. A significant work hardening rate is also caused by the cross-slipping of screw displacements by $\{1\overline{1}\overline{1}\}$ planes with cube planes.

Table 1. Intermetallics weight percentages of aluminum, the temperatures at which they form, and their melting points [19].

Intermetallics	Weight Percent (wt%) of Aluminum	Heat of Formation <298 (kcal/mol)	Melting Point (°C)
Ni_3Al	13.28	-66.6 ± 1.2	1395
NiAl	31.49	28.3 ± 1.2	1639
Ni_2Al_3	40.81	67.5 ± 4.0	1133
$degNiAl_3$	57.96	36.0 ± 2.0	854

Table 2. Anti-Phase Boundary Energies in Ni_3Al [8].

Alloy	γ111 (mJ/m^2)	γ111/γ100	γ100 (mJ/m^2)
Ni-23.5Al + 0.25B	170 ± 13	1.37	124 ± 8
Ni-26.5Al	175 ± 12	1.51	113 ± 10
Ni-25.5Al	175 ± 13	1.31	134 ± 8
Ni-24.5Al	179 ± 15	1.25	143 ± 7
Ni-23.5Al	183 ± 12	1.17	157 ± 8

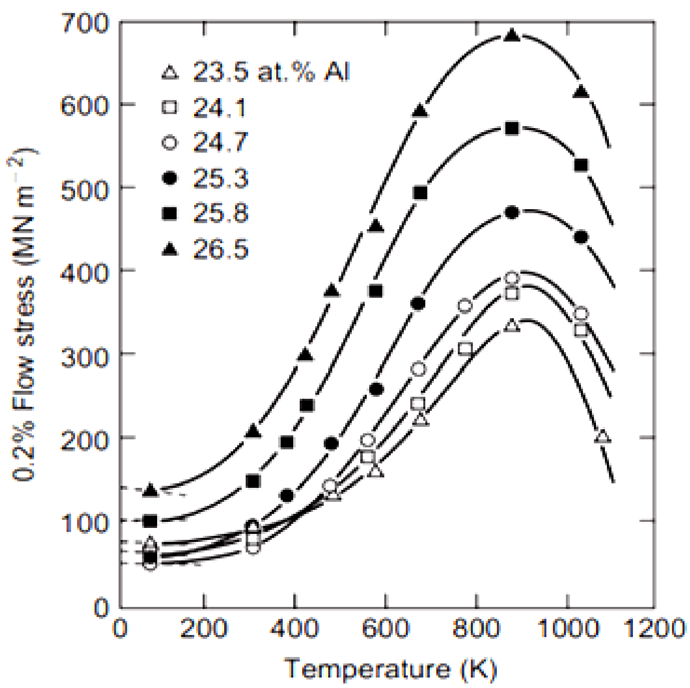


Figure 5. The influence of aluminum content on the temperature dependence of flow stress in Ni_3Al [8]. Reproduced with permission from Elsevier.

3. Challenges Involved in Nickel Aluminides

Nickel aluminide is a long range ordered intermetallic. Consequently, due to longer-ranged orders, there is a significant problem of lower ductility and inelastic intergranular fissure at room temperatures [19,20]. A limited number of simple slip systems, restricted cross-slip, large slip vectors and adversity of transferring slip through grain boundary are some of factors that may be the reason for the brittle failure of intermetallic alloys [8]. In spite of this, several metallurgical processes such as processing control, grain refining, micro and macro alloying, and quick solidification [6,8,20], have culminated noticeable improvements into ductility and toughness of material. For instance, it has been found that adding a minuscule amount of boron to Ni_3Al increases the grain boundary adhesion level, which in turn reduces the tendency for the polycrystalline material to crack along its brittle intergranular boundaries.

There are at least three different ways that may be improved upon for increasing ductility of NiAl as shown in Figure 6 [21–27]. The structural properties of NiAl and Ni_3Al are shown in Table 3.

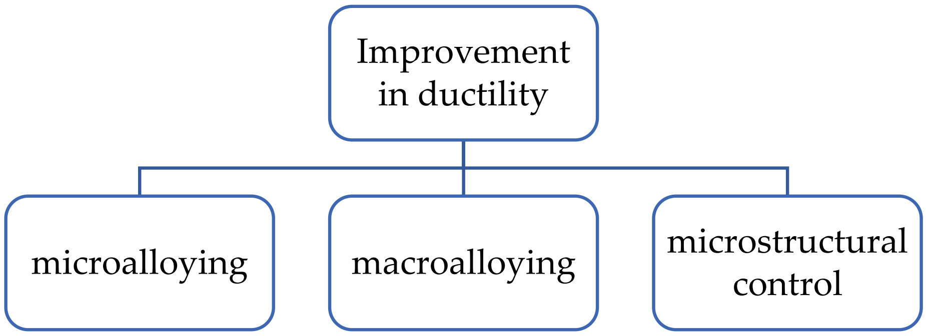
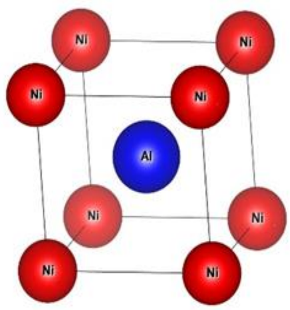
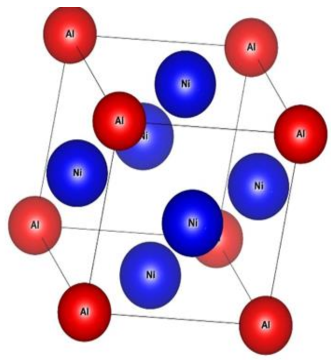


Figure 6. Different methods for improving ductility of NiAl.

Table 3. Structural properties of NiAl and Ni_3Al [28–38].

Particulars	NiAl	Ni_3Al
Lattice stelecructure	 Ordered body-centered cubic	 Ordered face-centered cubic
Phase formation	composition range of ~45–60 at% Ni below ~400 °C	23–28 at% Al
Strukturbericht-superstructure	B2, (ordered crystal structure of simple CsCl prototype)	L12, (systematized crystal structure of simple $AuCu_3$ prototype)
Space group	pm-3m (221)	cubic pm-3m (221)
Lattice parameter	2.887 A	0.356 nm (No ternary addition)—Bradley and Taylor 0.357 nm—by Mishima et al. and y Guard and Westbrook
sublattices (alpha and beta)	Ni in corners (0,0,0) Al atoms into center body positioning (1/2,1/2,1/2)	Al atoms into (0,0,0) lattice locations are coexisting with nickel atoms into (0,1/2,1/2, 1/2,0,1/2, and 1/2,1/2,0) lattice positions.
Ordering behavior	nonlinear second-order transition behavior [34]	Linear dependency of lattice constraints upon LRO constraints Order–order relaxation had been observed for one of the very first times in the Ni_3Al phase of an intermetallic compound [33,34]
Density	5.85 g/cm^3	7.50 g/cm^3
Youngs Modulus (GPa)	294	179

4. Phase Diagram of Nickel Aluminides

The phase diagram of NiAl is shown in Figure 7. Ni has a poor solubility in Al, making it very hard to obtain compounds with a higher availability of Al; nevertheless, Al becomes significantly soluble in Ni, being accountable for the formation of Ni-rich complexes upon its adding. When it comes to the primary phase regions, Al-Ni phase diagram is a very precise structure. It is possible to come across Ni_3Al with a percentage of Al between 73% and 76%. As per the binary phase diagram of Al-Ni, the compounds of Al_3Ni, Al_3Ni_2, AlNi, $AlNi_5$, and $AlNi_3$ are produced progressively with increasing Ni content. There are two eutectic processes and three peritectic zones in the Al-Ni phase diagram, with Al_3Ni, AlNi, and Ni_3Al as intermetallic compounds and $NiAl_3$ as an intermetallic compound with constant composition.

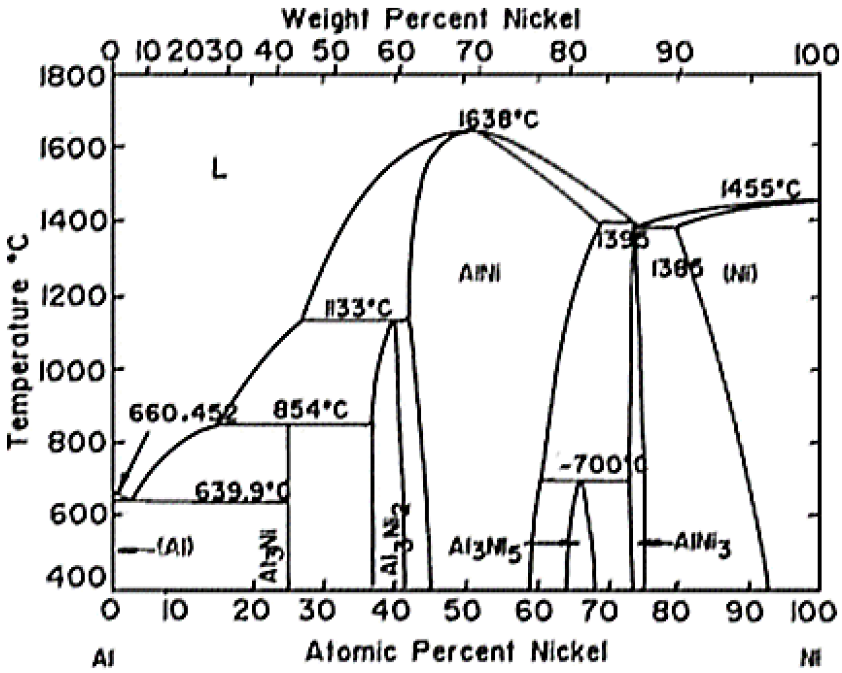


Figure 7. The Phase Relationships in the Al-Ni System: A Plot of the Al-Ni Binary Phase Diagram [7]. Reproduced with permission from Elsevier.

There has been a long period of development for the Al-Ni phase diagram, during which it has been tweaked and improved upon on numerous occasions by a number of experts. Evolution and development of the Ni-Al phase diagram is shown in Figure 8 [5,39].

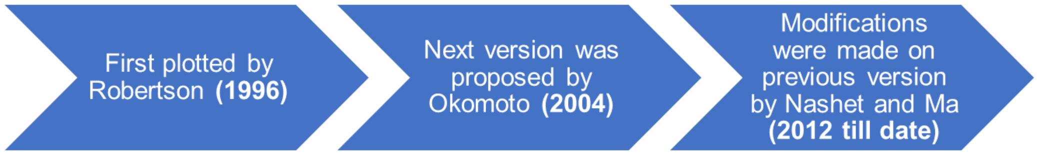


Figure 8. Evolution and development of Ni–Al phase diagram [5].

5. Properties of Nickel Aluminides

Comparisons of the mechanical and physicochemical characteristics of Ni_3Al intermetallic alloys comparing with traditional metallic materials have been subject of a significant amount of research in the scientific literature. The Ni_3Al alloys are, for the most part, exceptional when compared with commercialized alloys, particularly in the category of higher-temperature application, in conditions that are both oxidizing and carburizing.

5.1. Hardness

Unalloyed nickel aluminides show composition-dependent hardness, with stoichiometric NiAl having lower hardness than off-stoichiometric compositions [39,40]. The existence of triple defects was responsible for the shift in hardness at the stoichiometric ratio of 2.4 to 3.2 GPa. Triple defects, consisting of two vacancies with one sublattice and antisite upon other, are specific to intermetallic complexes. To no one's surprise, high hardness attributes observed for mildly Al- or Ni-rich stoichiometric complexes of $Ni_{52}Al$ and $Ni_{48}Al$ could be explained by the existence of thermally flustered vacancies upon the Al-rich side of stoichiometric NiAl and antisite kinds of deformities for the Ni-rich side of stoichiometric NiAl alloy [41,42].

Hardness deliberations of both stoichiometric and non-stoichiometric composites were also reported by Guard and Westbrook.

- Hardness was found to be lower for stoichiometric compositions than for Al-rich compounds with non-stoichiometric compositions, which had greater hardness values.
- Guard and Westbrook also looked at how hardness changed with temperature for materials of the same composition, finding that measures of hardness were lowest at low temperatures, and highest with a Ni:Al ratio of 3 [43,44].

5.2. Magnetic Properties

Ni_3Al is either highly paramagnetic or weakly itinerant ferromagnetic, with Tc (curie temperature) varying as a function of Al content [45,46]. Due to the presence of a larger number of nonmagnetic Al atoms, NiAl, like Ni_3Al, is a weekly ferromagnetic material whose magnetic moment diminishes by an upsurge in Al concentration. Whether alloying atoms are located into the Ni site or the Al site has no effect on whether adding Mn and Fe improves the total magnetic moment [47,48].

5.3. Electrical Properties

NiAl's electrical conductivity at normal temperature is composition dependent. 13×10^6 S/m at stoichiometric composition, but 6×10^6 S/m for Ni and Al-rich near stoichiometric configurations [49,50].

Despite having the same conduction, as-cast specimens were 50% less conductive than homogenized NiAl-Ag alloys. Due to higher Ag solubility into NiAl lattice, alloying with Ag reduces electric conduction at ambient temperatures or above 5 at%. Precipitation and coarsening increase conductivity in homogenized alloys [49–54].

5.4. Grain-Boundary Embrittlement

It is noteworthy that single crystals of Ni_3Al have a ductile structure, but pure polycrystalline Ni_3Al has a brittle structure at an ambient temperature due to intergranular fracture. In traditional materials, brittle intergranular fracture is typically followed by isolation of impurity elements like sulphur, phosphorus, and oxygen, which results in embrittlement at the grain boundaries. However, in sufficiently pure polycrystalline Ni_3Al, no evidence of such segregation has been detected. This leads one to believe that grain boundary is intrinsically friable. It is noticed that grain border fragility is linked to both a lack of grain-boundary cohesiveness and environmental fragility. Grain-boundary cohesion absence is connected to differences in the energy ordering, electronegativity, vacancies and size of atoms that exist amongst atomic components that make up the intermetallics. The formation of atomic hydrogen as a result of the interaction of Ni_3Al with moisture is what causes grain-boundary embrittlement [55–57].

5.5. Creep Behaviour

According to the findings of a few investigations, both single- and polycrystalline Ni_3Al exhibits the characteristic "inverse creep" behavior into average temperatures. In this case, creep curves have a transitory primary phase lasting until the 1% strain, and is distinguished with a drop-in strain rate having a rising strain. This stage is trailed with an "inverse" tertiary phase that exhibits increased creep that ultimately leads to failure. These creep curves do not display the steady phase creep stage anywhere in their progression. In the case of samples consisting of a singular crystal, creeping failure is not by the formation of voids but by necking.

In addition, creep studies conducted on single crystals of Ni_3Al with 1% Ta content revealed the existence of a steady-state creep stage for all orientations tested. It has been discovered, which is quite fascinating, that the steady-state creep rate of single crystal specimens orientated in a variety of directions scales, having resolved the shear stress of cube cross-slip planes. TEM experiments did show evidence of slip upon octahedral planes while in the primary phase of creep, and upon cube cross-slip planes while in the secondary creep phase. This finding is consistent with what was anticipated [58].

In Mo, Fe, and Co additions increase the proportion of metallic bonds into intermetallic framework of NiAl, hence shifting the electron concentration at the Fermi level. Peierls energy U_p and interrelated Peierls hindrance of plastic deforming R_p drop as covalent component of interatomic bonds decreases:

$$R_p = \frac{2pU_p}{ba}$$

here a: lattice constraint; b: Burgers vector.

Reduction of R_p enhances alloy plasticity and diminishes its strength. Such impact is supported with strong link amongst the microhardness and electronic structural properties of NiAl-based alloys as depicted in Figure 9 [4].

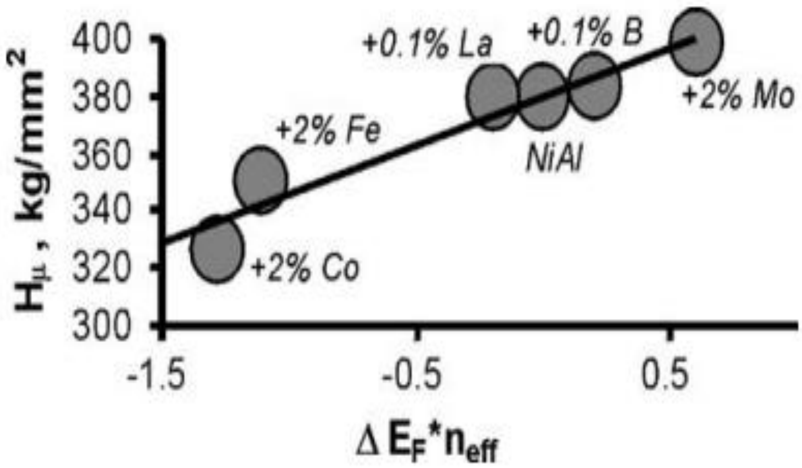


Figure 9. Correlation between micro-hardness and electronic structure characteristics of alloys on base of NiAl [4]. Reproduced with permission from Elsevier.

Examining the mechanical characteristics of nickel aluminide alloy in strain, compression, and impact toughness yielded the findings depicted in Figure 10. A cold fragility threshold for nickel aluminide compound is, as expected, in the range of a 0.43–0.45 of melting point—Tm. Every sample failed brittle as in tensile tests with temperatures under 500 °C, and high elongation values, following failures, were observed around 450–650 °C. The effect of alloying on NiAl's brittle/ductile transition temperature is most pronounced in tensile trials [4].

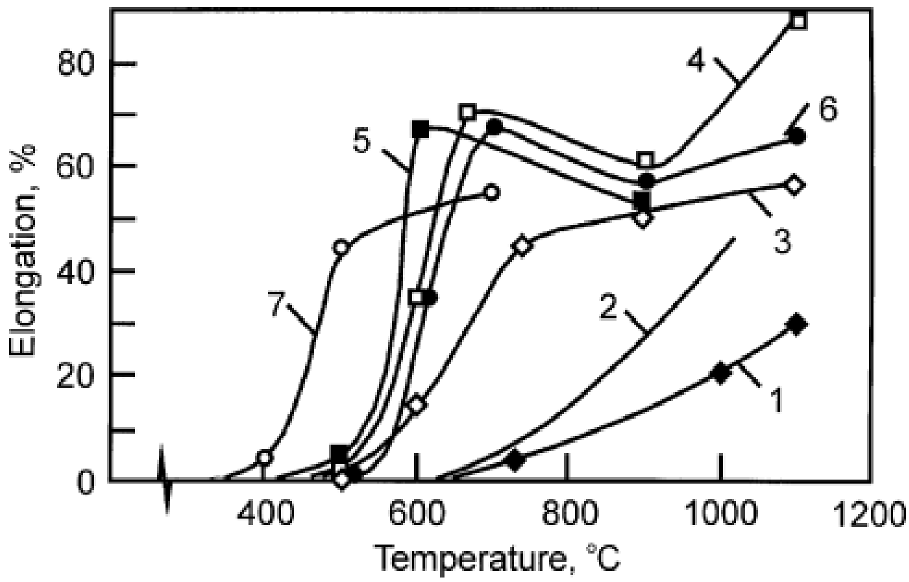


Figure 10. Elongation of NiAl alloys tested with 400–1200 °C. (1) casting of NiAl; (2) extruded NiAl; (3) NiAl(Mo); (4) NiAl(W); (5) NiAl(Fe); (6) NiAl(Cr); (7) NiAl (Co, B, La) [4]. Reproduced with permission from Elsevier.

6. Impact of Alloying upon Strength and Ductility

When Ni_3Al is alloyed with ternary, quaternary, and quinary elements, the oxidation resistance, scale adhesion, capacity to create an Al_2O_3 scale, and oxidation processes are dramatically altered. The effect of alloying elements is presented in detail in Table 4.

Table 4. Importance of Alloying elements on Nickel Aluminides [50–70].

Elements	Description	Reference
Boron	• Improved ductility. • Due to the substantial creation of geometric voids upon the substrate surface, adding B to Ni_3Al did not increase oxidizing resistivity or the oxide scale adhesion, but it did improve the aqueous corrosion resistance [70–72]. • Improve strength with addition of elements like Hf, Ti etc.	[51–58]
Chromium	• The general oxidation behavior of Ni3Al is marginally improved by Cr's presence, however this improvement is negated at temperatures above 1300 °C due to the creation of blisters caused by the transition of Cr_2O_3 into volatile CrO_3. • Nevertheless, oxidation rates may decrease at low temperatures when 8 at.% Cr is present. This is due to the fact that Cr enhances the capacity to produce a healing layer of Al_2O_3, which prevents further damage. • According to one traditional theory, Cr might play the role of the secondary getter of oxygen, therefore lowering flow of oxygen in alloy in event that the primary getter (Al) is destroyed because of corrosion.	[59–64]
Titanium	• When combined with B, Ti enhances the scale's adhesion, but this often leads to worse oxidation behavior due to large weight increases from the formation of Ti-containing oxides and the disruption of the Al_2O_3 scale. • although the addition of titanium alone to Ni_3Al at a weight percentage of 2.99% has a tendency to lower the cyclic oxidation resistance	[65]

Table 4. *Cont.*

Elements	Description	Reference
Lithium	• The higher temperature oxidizing resistivity of Ni_3Al alloys may be significantly improved by the addition of lithium. • According to the rule of Hauffe, replacing Ni with Li can bring about a reduction in the concentration of cation vacancy in p-type NiO. This, in turn, can bring about a slowdown in the rate of oxidation. In addition, adding Li altered the morphology of oxide scales, reduced the size of oxide grains, made the oxide more homogenous, densified oxide scales, and increased the mechanical characteristics of oxide scales.	[66]
Molybdenum	• The overall oxidation behavior is reduced due to the limited solubility of the molybdenum, and as a result, oxidation of the molybdenum-rich phases leads to the formation of volatile species. This is true even though the addition of 3 weight percent of molybdenum does reduce the overall oxide weight gain. • Improves strength at low and high temperatures [6].	[66]
Reactive elements	• Adherence of oxide scales can be enhanced with the existence of reactive elements including Hf, Y, and Zr. Incorporating Y as an oxide dispersion keeps the favorable advantages of adding a reactive element. Individually and in combination with B enhancements, Hf and Zr seem to give the greatest overall behavior. Ni_3Al's isothermal oxidation behavior was investigated by Kuenzly and Douglass from 900 to 1200 °C in air with and without Y addition (0.5 wt.%). They found scaling behavior in alloys following strict parabolic rule, because adding Y had no effect on the steady-state scale ratio of Ni_3Al.	[71–74]

Table 5 displays the effect of alloying on properties like ductility and strength for nickel aluminide. Compression testing at room temperature represents metal's soft stress condition. As a result, all of the samples into compression testing demonstrated adequately higher/lower temperature ductility [75–78].

Table 5. Effect of alloying on the strength and ductility characteristics of nickel aluminide (compression testing at room temperature) [4,11,19].

Alloy	$\sigma_{0.2}$ (MPa)	ε (%)	ψ (%)
NiAl	292	12.0	0
NiAl (B)	400	25.6	0
NiAl (La)	311	29.5	70.0
NiAl (Fe)	396	28.0	65.0
NiAl (Co)	384	30.8	69.0
NiAl (Cr)	421	24.8	60.8
NiAl (Mo)	340	26.0	17.0

When tested in air at room temperature, it was found that adding B to polycrystalline Ni_3Al with 25% Al increased its tensile ductility by a lot, so much so that the way it broke changed from intergranular to transgranular [79–82]. Ni_3Al microalloyed with 0.1 wt% B broke with a tensile strain of more than 50% in air [79]. Table 6 shows some of the results of tensile tests that were done on Ni_3Al, with and without B in different environments. [79,81–83].

Two ideas have been put forward to explain how adding B makes a material more ductile: (i) rise into cohesive strength at the grain boundary due to the addition of B [84–87] and (ii) slip transferring transversely with grain boundary [88–90].

Table 6. Tensile properties of Ni_3Al and Ni_3Al-B Alloys under different environments [8,10,79–81].

Alloy Composition	Strain Rate (s^{-1}) and Environment	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation to Failure (%)
Tests at room temperature				
Ni-24 Al	3.3×10^{-3}, air	280	333	2.6
Ni-24 Al	3.3×10^{-3}, oxygen	279	439	7.2
Ni-24 Al-500 ppm B	3.3×10^{-3}, air	290	1261	41.2
Ni-24 Al-500 ppm B	3.3×10^{-3}, oxygen	289	1316	39.4
Ni-24.8 Al-500 ppm B	3.3×10^{-3}, air	290	671	18.1
Ni-24.8 Al-500 ppm B	3.3×10^{-3}, oxygen	306	801	25.4
Ni-25.2 Al-500 ppm B	3.3×10^{-3}, air	221	300	8.4
Ni-25.2 Al-1000 ppm B	3.3×10^{-3}, air	344	552	10.2
Tests at −196 °C (77 K)				
Ni-23.4 Al		254–269	672–762	31.3–31.8

7. Processing of Nickel Aluminides

When deciding on a method of processing, it is important to consider the characteristics of the final product. A coating, for instance, would use a thin-film processing technology, while near-net-shaped bulk materials could benefit more from ingot metallurgy processing, which includes melting and casting, or appropriate powder metallurgy processing. For intermetallics, in order to prevent the oxidation of constituent elements and contamination of the products during processing, which could result in inadequate densification and the production of unwanted or deleterious phases as impurities, vacuum or inert gas conditions are typically recommended. Composites and alloys based on Ni aluminides can be treated with the ingot and powder metallurgical methods. Many commercially viable uses of these alloys have been developed because of their undeniable benefits over "conventional" materials [11,91]. Any material's microstructure and characteristics rely on how it is processed. As certain intermetallic alloys have complicated crystal structures, their characteristics are affected by stoichiometry, impurities, and defects. The intermetallic compounds have an ordered structure and distinctive chemistry. These alloys must have a certain atomic ratio of elements for a specified crystal structure and mechanical properties. In alloys with a variety of stoichiometry, microstructures and characteristics rely on atomic ratios.

7.1. Melting and Casting

Ni_3Al and NiAl have differing melting points, hence special consideration must be given to melting and casting each material. For instance, NiAl has a greater melting point than either Al or Ni individually. Because of the reaction of alloying elements with H and the absence of grain-boundary cohesion, fabrication of Nickel Aluminides by casting was not easily obtained. It was also attempted to employ fluxes for casting. However, this could lead to the creation of brittle compounds that weaken the grain boundary [92] due to reactivity amongst flux components and alloys. Maxwell and Grala [93] were effective in melting and casting in the 31.5–33 wt% Al range, but not the 31.5–34 wt% Al range. For Al contents above 35 wt%, castings failed and alloys shattered completely. Ordnance Research and Development Laboratory (ORNL) developed Exo-Melt casting for such alloys, which makes the advantage of heat reactivity in the efficacious cast of Ni_3Al alloy [93,94].

In 1996, ORNL came up with the "Exo-melt" process to lessen these effects [11]. In the process known as ExoMeltTM, the melt stock is divided into numerous sections and then loaded into the furnace in such a way that an extremely exothermal reactivity having higher adiabatic combusting temperature is preferred at the beginning. This results in the production of a molten product (Figure 11). For Ni_3Al, forming NiAl is an extremely exothermal process and the melting point of NiAl corresponds to the temperature at which it may be burned in an adiabatic reaction [12–15,94].

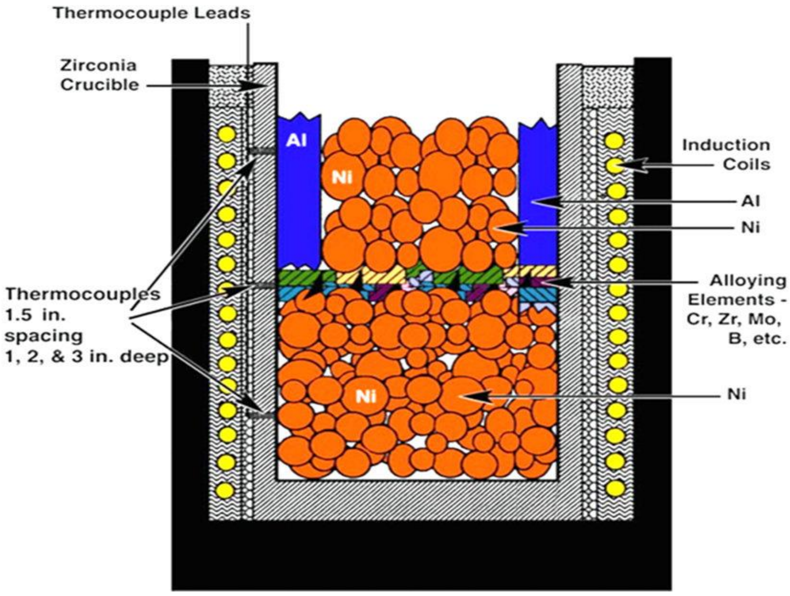


Figure 11. Exo-melt process [77]. Reused from MDPI under Creative Commons Attribution license.

Furthermore, the Exo-Melt procedure is even helpful into cutting production expenses. It saves about 50% both for energy and timing.

Casting processes like sand, investment, centrifugal casting, respectively, and directional solidifying can all be utilized in the production of aluminides. Other casting methods include directional solidification. Cast aluminides are then subjected to a subsequent processing step.

Utilizing a variety of metal formation procedures like hot extrusion, swaging, forging, flat and bar rolling, cold flat and bar rolling, and cold drawing in tube, rod and wire, all of which contribute to the microstructural refining and augmentation of mechanical characteristics of the metal. For instance, temperature ranging from 1050–1150 °C is used for the hot forging process when alloys of Ni3Al comprising less than 0.3 at.% Zr. It is possible to duce the reactive cast of NiAl-based intermetallic alloys with a mix of Ni and Al or NiCo and Al in liquid in air form, and then allowing the mixture to solidify to form a compound that is either NiAl or NiAl-Co, depending on which compound is desired. This approach was also used to cast the Fe-containing NiAl, and neither the failure of the casting due to cracking nor cracks presence had been recorded.

The hot fabricating of Ni_3Al intermetallics is negatively impacted with excess inclusion of Hf and Zr at levels greater than 103, which results in the development of surface fissures and early failure. Both ductileness and strength of nickel aluminides were demonstrated to be improved with adding alloy elements B, Cr, Co, C, and Ce, as well as by the strengthening element TiB2. The majority of nickel aluminide alloys used in the production of products comes from the commercial sector [91,95]. These alloys are used to make bars, wires, sheets, and strips.

A further noteworthy accomplishment was the invention of the casting process utilizing the software known as ProCast (Figure 12a). Because of its lower fluidic nature and shrinking of the material after it has been cast, casting alloys based on Ni3Al can be quite challenging. This fact should be brought to your attention. On the other hand, it was stated that a particular version of the ProCast software makes it possible to cast components that are free of flaws while having a complex shape (Figure 12b) [19,91,92].

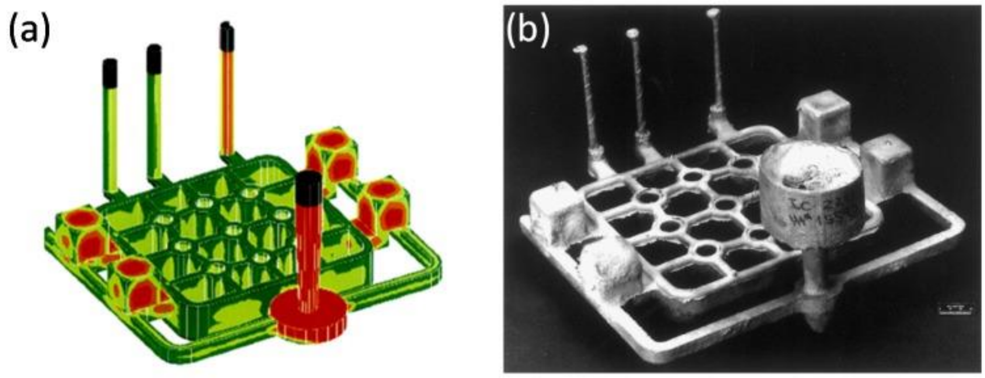


Figure 12. (**a**) Modeling in ProCast software and (**b**) actual casting [77]. Reused from MDPI under Creative Commons Attribution license.

7.2. Powder Metallurgy

Processing powder metallurgy can be done through spark plasma sintering, pressureless sinter, uni/multi-axial hot press, liquid phase-assist or reactive sintering by application or non-application of pressure, or uniaxial or multiaxial hot pressing. Atomization carried out in an environment devoid of oxygen results in the production of aluminide powders such as Ni_3Al.

After that, the powders are packed into cans and hot extruded at temperatures ranging from 1100 °C to 1200 °C using a reduction ratio of between 8 and 1. The products that are consequently created from these powder metallurgical procedures often has a tiny grain size as a result of dynamic recrystallization, and as a result, they are able to be molded using superplastic techniques in order to obtain near-net shapes.

7.3. Solid State Sintering

This is a common powder metallurgy process for producing Nickel Aluminide. Longer sintering makes compacts denser and grains increase. If hardness increases during sintering, the Kirkendall effect may make it tougher to obtain full density and good mechanical characteristics as it increases intermetallic phase volume percentage [5,21,24]. Powder metallurgy (P/M) was used to make B-alloyed Ni_3Al, and the effect of alloying was studied by adding Fe, Cr, Zr, and Mo while keeping the Al content at 23 at% [24]. The main problems with P/M-processed Ni_3Al alloys are their sensitivity to strain rates below 104 s^{-1} and their microstructures (FCC solid solutions) [5,21–23,95].

7.4. Mechanical Alloying

Mechanical alloying also was employed to effectively create nickel aluminides, but it is time-consuming and costly, and unalloyed aluminides are vulnerable to impurity contamination and oxide development. An Ni-containing Al-supersaturated solid solution containing unreacted Ni and Al is the first kind of intermetallic to emerge during mechanical alloying of Ni–Al mixtures. Milling parameters, such as milling duration and power, largely determine the final product's chemical makeup. To reach intermetallic NiAl, this phase must first be milled into Al_3Ni, where it may coexist with Ni_3Al and $AlNi_2$ [25–30].

7.5. Reaction Synthesis

In this method, the heat from an exothermal reaction amongst Ni and Al is used to make intermetallic. High temperatures, between 500 °C and 750 °C, are applied to contents of a container, while the container is kept under a vacuum [31,95]. During the reaction synthesis process, the reaction is often not complete. The unreacted parts may also make the final product stronger, since intermetallic powders are usually fragile and need more pressure to pack them together. Metallic powder size is an important factor in this process [96].

8. Applications of Nickel Aluminides

Many commercially viable uses of these alloys have been developed because of their undeniable benefits over "conventional" materials. Applications for Ni_3Al-based alloys are diverse. This is shown in Table 7. Commercialization of Ni_3Al alloys for specified applications is expected to happen very soon, since the degree of research into this material has been significantly higher than that of other aluminides.

Table 7. Overall Applications of nickel aluminides [80–97].

Application	Description	Example
Automotive: • dyes for hot press Fe-B-Nd magnetic powders • Turbocharger rotors Diesel trucks • Car bodies	1. able to withstand high temperatures without weakening, oxidation resistance, chemical compatibility low cost and improved fatigue life 2. Compared to common automotive materials, this one is more corrosion-resistant and can withstand high temperatures without deforming. It is also lighter and five times stronger than stainless steel. Since this is the case, Ni_3Al alloys may be utilized for a wide variety of purposes, including those requiring high strength or the absorption of energy, such as in the construction of car bodies.	IC-221M
Hydroturbine rotors	• Good cavitation • erosion resistance • Because of their great corrosion resistance, these materials may also be employed as working elements in a seawater environment.	Alloy IC-50
Glass processing	• Oxidizing resistivity, • higher temperature strength • higher weariness life	IC-221M
Chemical processing	• strength • corrosion resistance	IC-218LZr
Metal processing • As a Die material for isothermal forging. • The rollers for steel slab heating furnaces	• higher temperature oxidizing resistivity (1100 °C or below) • high strength	IC-221 IC-221 M
Binder for ceramics	• suitable for use in tungsten carbide systems in place of cobalt. Nickel aluminide-bonded tungsten carbide provides better higher- and lower-temperature strength and cutting capabilities	IC-50 IC218LZr
Roller bearings	• From room temperature to 650 °C, nickel aluminide's wear resistance improves by over a factor of 1000.	IC218LZr
Steel Industry • Transfer rolls in furnace for hydrogenation, carburization and used as a roll continuous casting process • Sometimes used as a replacement for currently used stainless steel	• considerable energy cost reductions by eliminating the need for water cooling • prolonging the operating life four to six times over presently utilized materials	IC-221M

Table 7. *Cont.*

Application	Description	Example
Compressor and Turbine Blades in Aircraft Engines	• high temperature structural materials • Ni_3Al base alloy, commercialized under the name IC6 to utilize into higher-performance jet engine turbine vanes and blades working at temperatures between 1050 °C and 1100 °C, was created. Second stage gas turbine vanes are being made from this material with a NiCrAlYSi coating.	IC6 IC10 VKNA's

8.1. Nickel Aluminide Coating

Coatings made of nickel-aluminide have received a lot of interest recently because of the fact that they offer a variety of potential applications in technology and science. NiAl has a long history of use as a protective coating for machinery and buildings. Its main purpose is to improve coating adherence, and its secondary purpose is to reduce thermo-mechanical stress at the substrate-coating interface. NiAl's lengthy history of usage may be attributed to the material's low density, high melting point, outstanding thermal conductivity, and great oxidizing resilience. [79,80,91].

NiAl coatings' high-temperature oxidation behavior in moving air is seen around 750 °C and 850 °C, according to previous studies [81,82]. The aerospace industry, along with other high-performance applications, has increased demand for nickel-aluminum alloys and its derivatives. This is because, for certain alloys, an increase in temperature also results in an increase in yield strength. The second major nickel aluminide, Ni_3Al, has also been receiving considerable notice of late. Ni_3Al is an essential component of NiAl that serves as a stiffening agent, and the two elements together are extensively used for higher temperature structural material for aircraft engines and aerospace applications. [79,80,93]. Table 8 shows the applications and properties of nickel aluminide coatings.

Table 8. Application and properties of nickel aluminide coating [80–85].

Applications	Properties
Furnace rollers for heating steel slabs	• High temperature strength • good oxidation • corrosion resistance
Hydro turbine rotors	• Excellent vibration • cavitation resistance in water
Jet engines turbine blades vanes	• Superior strength • Creep resistance
Cutting tools	• High and low temperature cutting tool strength

8.2. Ni_3Al Thin Foils

Ni_3Al intermetallics like thin foils and tapes are anticipated in contributing the production of highly advanced tools of MEMS and MECS. This is because Ni_3Al possess unique physical and chemical properties in addition to a relatively low weight. A comparison is shown in Figure 13.

Ni_3Al alloys do, however, have a few drawbacks, the majority of which are related to the fact that they have a lower vulnerability in plastic deforming and higher propensity in getting brittle crack. Because of these disadvantages, the manufacturing sector is unlikely to ever be able to mass-produce components, having a thickness of lesser than 400 μm [53,91]. However, two processing methods have matured to the point that they might be employed in a laboratory setting:

- directional solidifying and cold rolling
- directional crystallization: deliberated upon meticulous deforming of traditional cast of alloys.

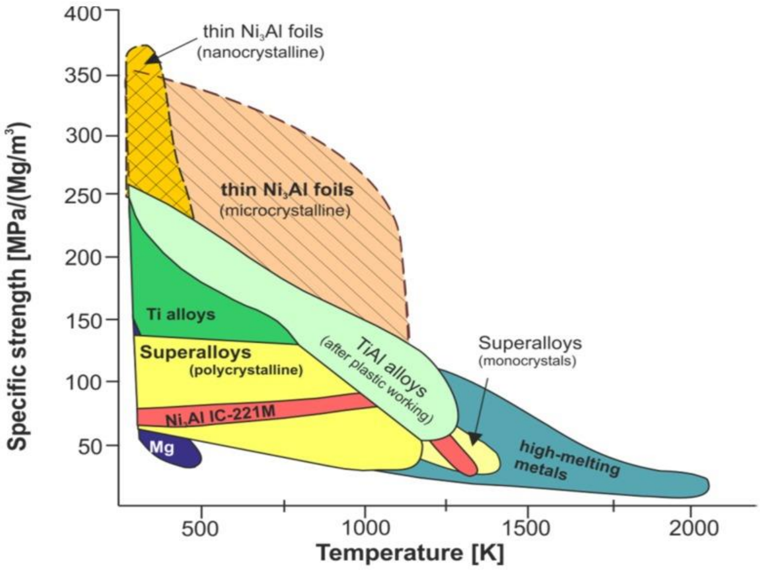


Figure 13. Temperature vs. specific strength for comparing Ni thin foils with other metal alloys [77]. Reused from MDPI under Creative Commons Attribution license.

Mechanical and electrical components (such as an actuator, a sensor, and a microprocessor) that can withstand their environments are integrated in MEMS and MECS systems, allowing for the fabrication of a device with both controlling and specialized capabilities [91–93].

It has been noticed that there is an increase in people's curiosity into Ni_3Al intermetallics with thin foils because these intermetallics have excellent explicit strength, higher environment resistivity, and higher catalyst activities. Additionally, the creation of composite materials has been reported by Ni_3Al-based alloys serving as the matrix and being toughened by elements such as TiC, ZrO_2, WC, SiC, and graphene [94–98].

Uses of foils and strips made of Ni_3Al-based alloys that are extremely promising include those known as MEMS or MECS devices. A comparison in mass gain and hydrogen production is shown in Figure 14 for Ni and Ni_3Al foils. It would appear that the creation of microsensors/systems of chemical separators, heat exchanger and micropumps would benefit enormously from the particular qualities that they possess [99–101].

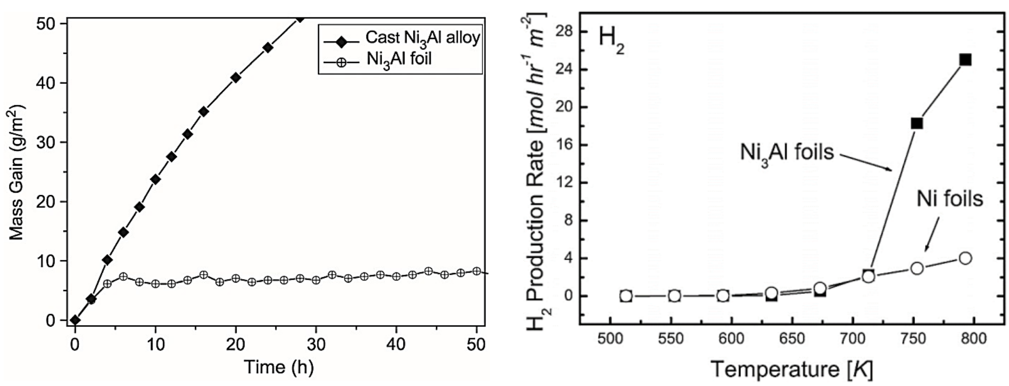


Figure 14. Comparison of production rates of H_2 in methanol decomposition of Ni_3Al foils and Ni foils [77]. Reused from MDPI under Creative Commons Attribution license.

9. Conclusions

This review paper seeks to improve understanding of the nickel aluminide structure, properties, and applications, as well as their scope, characteristics, advantages, and disadvantages. In addition, current alloy applications were summarized. The effect of alloying elements on phase transformation, mechanical properties, and corrosion was investigated. Furthermore, the most significant barriers to the widespread use of nickel aluminide were considered. To overcome the difficulties faced by alloys, different metal processing method were discussed. Properties and application of thin foil of nickel aluminides were discussed. Finally, characteristics of nickel coating were studied.

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