A review on high stiffness aluminum-based composites and bimetallics

Sajjad Amirkhanlou, and Shouxun Ji

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Sajjad Amirkhanlou, and Shouxun Ji
A review on high stiffness aluminum-based composites and bimetals

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ABSTRACT
The Young’s modulus of aluminum-based materials is one of the most important mechanical properties in controlling structural performance. The improvement of the Young’s modulus of castable aluminum-based materials is essential for improving their competitiveness in lightweight structural applications. Currently, there are limited options for cast aluminum alloys with outstanding Young’s modulus. Also, for further stiffness improvement and thereby weight-lightening, in-depth understanding of the relevant mechanisms for modulus improvement in aluminum alloys is necessary. This review focuses on the Young’s modulus of cast aluminum-based composites, as well as aluminum alloys reinforced with continuous metallic fibers (bimetallic materials). The effect of different chemical elements incast alloys, the constituents of in-situ and ex-situ formed aluminum matrix composites, and the wire-enhanced bimetallic materials on the Young’s modulus of alumina-based materials are reviewed. The Young’s modulus of cast aluminum alloys can be improved by: (a) introducing high modulus reinforcement phases — such as 

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1. Introduction

Weight reduction through applying aluminum structural components in aerospace and automobile industries is one of the most promising ways to decrease energy and fuel consumption. These structural components, in particular shaped castings, are usually designed on the criteria of either yield strength or stiffness. When the yield strength is used as the design criterion, aluminum alloys with much higher strength than pure aluminum are commercially available and these can be selected for industrial applications. However, when the stiffness is used as the design criterion, there are limited options for the aluminum alloys with significantly increased stiffness than that of aluminum. There is a lack of thorough understanding of the stiffness of aluminum alloys and aluminum-based materials that can be used to make castings. Moreover, some of the strengthening mechanisms, which result in a significant improvement in yield strength, have no obvious effect on the stiffness. This has limited the applications of aluminum alloys in the shaped castings and components that require high modulus to achieve further weight reduction in the aluminum structures.

As the intrinsic property of materials, the Young’s modulus of cast aluminum alloys can only be marginally influenced by manipulating traditional metallurgical variables that can change the microstructure of aluminum alloys significantly. Minor changes of microstructure by alloying elements as well as deformation and heat treatment processes cannot improve the stiffness of Al-based materials. Lucena et al. studied the variation in the Young’s modulus of AA1050 (>99.5% Al) with cold plastic deformation (tension test). Young’s modulus decreased from 69 GPa (initial material) to 63 GPa (2.5% strain), then increased to 65% (6% strain) and finally stabilized to 66 GPa (13% strain). Villuendas et al. showed that the Young’s modulus of AA2024 and AA7075 in solution treated, deformed, and aged alloys were slightly lower (<2% reduction) than those of the undeformed specimens. Despite of deformation and heat treatment, chemical composition and phase constituents are two main factors governing the stiffness properties of castings. Processes that can change the microstructure significantly can alter the Young’s modulus. The high concentration of alloying elements can have perceptible influence through the contribution in bind interaction. In fact, the high modulus phases can be introduced into the aluminum matrix through major addition of alloying elements and/or ceramic particles. The addition of ceramics into the aluminum matrix to form aluminum matrix composites (AMCs) has been the topic of numerous investigations, in which the high modulus phases can be generated by in-situ reactions with different metallic elements or nonmetallic ceramic compounds, or by direct injection of foreign phases. In a similar way, bimetallic materials such as wire-reinforced metallic structures can be recognized as a special category of composites in macroscale, which can be used for an effective increase of Young’s modulus. In general, the Young’s modulus of cast aluminum alloys is less sensitive to alloying as compared to the stiffer reinforcement in AMCs or bimetallic materials.

The understanding of the successes and challenges in the stiffness of materials can serve as a guidepost for where future work is needed in order to effectively propel the technology development. Therefore, this review focuses on the Young’s modulus of cast aluminum alloys, composites, and bimetallic materials and their fabrication processes, aiming to provide a snapshot of the current progress on cast aluminum alloys for improving their Young’s modulus. The paper is outlined as follows. Section two summarizes the effect of wire reinforcement on the Young’s modulus of aluminum-based bimetallic materials. The properties of commonly used reinforcements are discussed in association with the merits and limitations of processing. Section three focuses on the stiffness improvement by in-situ and ex-situ composites. A discussion on the processing, microstructure, and Young’s modulus of the in-situ and ex-situ reinforcement – including TiB₂, TiC, AlN, ZrB₂, and Al₂O₃ – in cast Al alloys is provided. Section five ends the paper with the summary and future outlook.

2. Stiffness improvement in bimetallic materials

Bimetallic materials can be considered as a special type of composites, in which continuous metallic wires/bars are used as skeletons or frames for overcasting with conventional casting methods. Overcasting is casting process when liquid molten metal is poured onto a solid-state metal/ceramic. The network structures, or skeletons or continuous fibers, have been extensively used in polymer/ceramic matrix composites, but the bimetallic materials are particularly used in this review for the metal–metal mixture made by casting, in which the metallic skeletons or frames made by high modulus reinforcement are covered partially or completely by aluminum alloys. The skeleton preforms not only provide a
controlled and stable reinforcement, but also offer new architectures and increase the Young’s modulus and provide more effective load transfer.28

Compared with the reinforcements such as particles,29 whiskers,30 short fibers, and continuous fibers31 used in AMCs, the metallic network structures or skeletons are likely desirable to perform more efficiently, especially in reinforcing the local area of a cast component with relatively low cost and more flexible in manufacturing through casting processes. AMCs usually present low fracture toughness due to the brittle nature of reinforcement, which restricts their applications. The network structure fabricated by metallic wires can be 1D, 2D, or 3D interconnected structures with appropriate surface treatment, which enhance the interface bonding during casting process and improve the modulus without sacrificing ductility and toughness. The network structure and the interface are two critical aspects for the manufacturing of sound bimetallic materials. According to the nature of metals, nickel and steel/iron are two popular options for making network structure in the existing literature. Limited studies for other potential metals have been performed.

2.1. Al/Nickel Bimetallic Materials

The interconnected network made by continuous wires of Inconel 601 (12 μm diameter) has been used to reinforce aluminum alloys through sintering the wires before infiltrating aluminum melt by squeeze casting.32,33 Figure 1(a) shows the stress–strain curves for pure Al and Al/Ni bimetallic materials.35 The remarkable improvement of ductility is attributed to the absence of defects in the microstructure of the Al/Ni bimetallic materials. Figure 1(b) shows the variation of the Young’s modulus of Al/Ni bimetallic materials as a function of the volume fraction of the reinforced wires, in which the upper and lower curves correspond to the ROM and IROM models computed using $E_{\text{Al}} = 70$ GPa and $E_{\text{In601}} = 206$ GPa. The Young’s modulus increases in the bimetallic materials with increasing the Ni volume fraction. Most of the results are close to the average between the two bounds defined by the ROM and IROM models. The Young’s modulus can reach a level of 95 GPa, while the elongation is still more than 7% in the Al/30 vol.% Ni wire-reinforced bimetallic materials.36 The deformation has no significant effect on the Young’s modulus of the Al/Ni bimetallic materials, as shown in Figure 2. The Young’s modulus under as-cast condition is very similar to that under as-deformed condition,34 which is due to the fact that heat treatment and metal forming do not change the volume fraction of high modulus phases in the aluminum alloys and thereby negligible change has been reported after these processes.14

The interface between Al matrix and wire reinforcement plays a critical role in stiffness
enhancement in the bimetallic materials. Salmon et al.\textsuperscript{38} investigated the influence of the oxidation of Ni wire on the mechanical properties of Al/Ni bimetallic materials and found that an optimum stress and ductility can be obtained with an appropriate oxidation of the Ni alloy during sintering. The mechanical properties can be justified as a result of compromise between the sufficient oxide roughness to the desired wire/matrix adhesion and the limited oxidation to prevent an excessive degradation of the wires. The tensile properties of Al/Ni bimetallic materials are sensitively affected by the nature of the layer of oxide barrier which protects the wires from the reaction with the matrix during casting.\textsuperscript{39} The ductility of Al/Ni bimetallic materials can be improved by tuning the annealing conditions during the sintering process and introducing a barrier layer into the Al/Ni interface. It has been found that the partial conversion of the barrier layer into a mixture of Al$_2$O$_3$ + Cr$_2$O$_3$ oxides forms the precipitation of a layer of NiAl$_3$ grains on top of the oxide layer, as shown in Figure 3.\textsuperscript{40} When the reduction process of Ni and Fe oxides by Al is completed, Al can diffuse across the oxide layer to form aluminate nodules by reacting with the constituents of the Ni wire. The formation of these nodules can increase the flow strength and the ductility in Al/Ni bimetallic materials.\textsuperscript{40,41}

The matrix materials also affect the Young's modulus of the bimetallic materials. Boland et al.\textsuperscript{41} investigated the stiffness of cast Al-13 wt.% Si alloy reinforced by Inconel 601 wires. As shown in Figure 4, the Young's modulus can be significantly increased with the increment of Ni contents in the Al-13 wt.% Si alloy. Comparing the results shown in Figures 1–4, the reinforcement is more effective in the alloys than that in the pure aluminum.

Two parameters are important in the processing of bimetallic materials. One is the initiation of a reaction between the wires and the matrix, which is normally controlled by the cooling rate during casting, and the second is the stability of the oxide passivation barrier at the surface of the wires. The stability of the oxide barrier can be increased either by a pre-oxidizing treatment for the reinforcement wires or by specified conditions.
alloying elements to decrease the melting temperature of the matrix. The Cr-rich passivation layer on the surface of IN601 can increase the refractoriness in oxidizing environments. This will reduce the reactivity of the wires toward Al during overcasting. On the other hand, when the matrix is Al-Si alloys, the Si platelets tend to nucleate preferentially at the wire/matrix interface. This phenomenon has been reported to occur commonly in the composites with SiC, Al₂O₃, or TiB₂ reinforcements with the particle pushing mechanism. Therefore, the presence of Si in Al induces a strong reduction of the reactivity between the wires and the matrix, which can result in the further improvement in the Young’s modulus of the bimetallic materials. As illustrated in Figure 5, no reaction compound in the matrix could be detected in the bimetallic materials processed using optimized pre-oxidized preforms. It is necessary to note that the interface requirement is different between the AMCs and the bimetallic materials. In AMCs, the interface is preferred to be clean without any reaction. However, a limited reaction layer is preferred in the bimetallic materials for the better mechanical properties.

2.2. Al/Stainless steel Bimetallic Materials

Fabrication of aluminum-based bimetallic materials reinforced by 3D entangled stainless steel wires has been successful using mono-filament annealed 304 stainless steel wires with 100 μm in diameter in a preform structure. The continuous wire was firstly coiled around a ø1.5 mm rod to form spring-like segments, which were subsequently stretched and entangled to form a pre-compacted sample for squeeze casting. The nominal compressive stress–strain curves are shown in Figure 6. The yield strength and the Young’s modulus of the bimetal material increase as the volume fraction of the steel wires increases. The yield strength can reach 318 MPa for the bimetallic material reinforced with the 35.4 vol.% of entangled stainless steel preform. The Young’s modulus of Al/26 vol.% stainless steel bimetallic material is 124 GPa, which shows a significant improvement in comparison with that of the A356 alloy.

The microstructures of A356 matrix alloy reinforced by 3D entangled wires are shown in Figure 7.
The wire segments show different morphologies in the matrix with homogeneous distribution. When the process is properly controlled, the introduction of wires has little influence on the microstructures of the matrix. In optimum conditions, the cohesion between the matrix and the wires is well obtained and no obvious traces of interface reaction can be observed because of the prevention of the reaction by the oxide barrier layer on the metallic wire, which offers the best improvement of the Young’s modulus.

The network structure of stainless steel can also be fabricated by sintering the wires before infiltrating the aluminum alloys through casting. The improvement of the Young’s modulus without significantly sacrificing the ductility is achievable in bimetallic materials reinforced by an interconnected network of continuous wires of stainless steel. Figure 8 shows the Young’s modulus and the density of Al/steel cast bimetallic materials versus the volume fraction of the interconnected network of continuous wires. It is obvious that the Young’s modulus increases with increasing steel volume fraction. When the interconnected structures are used to improve the Young’s modulus, the selection of the desirable volume fraction of the reinforcement and the structural design should be considered as important criteria.

2.3. Al/Iron Bimetallic Materials

Interconnected wires in the form of three-dimensional preforms are an approach to improve the Young’s modulus by continuous steel/iron reinforcement in Al alloys. Gupta et al. fabricated several types of 3D preforms using the galvanized AISI 1008 wire of 0.8 mm diameter coated by 10.8 vol.% zinc. The geometries of the two types of reinforcement preforms are shown in Figure 9.

The mechanical properties for the Al/Fe bimetallic materials with AA1050 (99.5 wt.% Al) as the matrix are shown in Table 1. The incorporation of 3–5 vol.% of iron wires as reinforcement increases the Young’s modulus, yield strength, and ultimate tensile strength, but degrades the ductility. The Young’s modulus is 88 GPa and the specific stiffness is 30.3 GPa/(g/cm³) for the Al/5 vol.% Fe bimetallic materials, which is much higher than that of the monolithic Al alloys. The measured Young’s modulus of the bimetallic Al/Fe materials exceeds the ROM prediction. This has been attributed to the combined effect of redistributing the fiber stress from the three-dimensional interconnected nature and the limited presence of the intermetallics at the interface. Gupta et al. fabricated aluminum-based bimetallic materials containing titanium particles and iron mesh (continuous) reinforcement. Ti particles and the galvanized iron wire mesh (0.4 vol.% zinc and 0.8 mm wire diameter) are utilized as the continuous/interconnected
with different wire arrangement.

Al/5vol.%Fe
Al/3vol.%Fe
Al/3vol.%Fe
Al/5vol.%Fe

and the mechanical properties of interface, by the layer, by immersing mild steel into Al-Si alloy melts, Dezellus et al. studied the formation of the interface casting aluminum melt onto the steel/iron surface. Immersing the steel/iron into aluminum melt or over steel/iron and aluminum melt can be obtained by compound casting. Arghavani et al. found that the Zn coating on the steel surface could enhance the wettability of bonding surface between steel and A5052 Al alloy. Liu et al. found that the intermetallic compounds Al5Fe2Zn and Al5FeZn are formed at the interface between hot-dip galvanized steel and pure Al after compound casting. Generally, the zinicate must be at an appropriate thickness for the reaction during overcasting. If the thickness is more than the diffusion distance, the Zn layer will still exist in the final microstructure after casting, which is detrimental to the mechanical properties. This has been partially confirmed by Schwankl et al. showing that the interface strength determined by zinc is the weakest part of the compound castings. If the coating is too thin, there are no sufficient compounds to provide bonding strength. Therefore, the bonding interface between the iron/steel and the aluminum alloy is the determining factor for manufacturing the bimetallic materials.

Table 1. Mechanical properties of aluminum reinforced with galvanized iron.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Ductility (%)</th>
<th>Density (g/cm³)</th>
<th>Specific stiffness (gPa/g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (matrix)</td>
<td>70±2</td>
<td>101±6</td>
<td>120±3</td>
<td>17±9</td>
<td>2.7</td>
<td>25.9</td>
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<tr>
<td>Al/3vol.%Fe</td>
<td>76±2</td>
<td>108±2</td>
<td>131±4</td>
<td>5±3</td>
<td>2.92</td>
<td>26.1</td>
</tr>
<tr>
<td>Al/3vol.%Fe*</td>
<td>81±2</td>
<td>152±4</td>
<td>186±15</td>
<td>5±4</td>
<td>2.81</td>
<td>28.8</td>
</tr>
<tr>
<td>Al/5vol.%Fe</td>
<td>81±2</td>
<td>150±6</td>
<td>173±16</td>
<td>3±2</td>
<td>2.80</td>
<td>28.9</td>
</tr>
<tr>
<td>Al/5vol.%Fe*</td>
<td>88±1</td>
<td>105±5</td>
<td>130±6</td>
<td>7±3</td>
<td>2.91</td>
<td>30.3</td>
</tr>
</tbody>
</table>

*With different wire arrangement.

reinforcement phase. The presence of reinforcement results in the 7.6% reduction in the coefficient of thermal expansion, the 10% increase in the Young’s modulus, the 20% increase in the 0.2% yield strength, and the 27% increase in the ultimate tensile strength.

As the critical characteristics in manufacturing the bimetallic materials, the interface between steel/iron and aluminum has been extensively studied through different approaches due to the avoidance of formation of detrimental phases. The interfaces between steel/iron and aluminum melt can be obtained by immersing the steel/iron into aluminum melt or overcasting aluminum melt onto the steel/iron surface. Dezellus et al. studied the formation of the interface layer, by immersing mild steel into Al-Si alloy melts, and the mechanical properties of interface, by the pushout test. The results showed that the Al5Fe2Si and Al5Fe2Si2 phases are formed at the interface and the crack initiation would occur in the intermetallic reaction layer. The formation of the intermetallic layer increases the mechanical properties of the bimetallic materials.

Viiala et al. and Manasijevic et al. prepared iron base insert reinforced Al-Si alloys by gravity casting and revealed that a continuous metallurgical bond at the iron insert/Al-Si alloy interface can be achieved via the formation of FeAl3 and Fe2Al3 intermetallic phases on the interface. Bouayad et al. found that several intermetallic compounds, including γ-Al2FeSi, η-Al2Fe2(Si), and β-Al2FeSi, can be formed at the interface. The types of reaction products depend on the times and temperatures. Kobayashi and Yakou reported that the common sequence to form the reaction layer is Fe/FeAl3/FeAl2/Al, but Zhang et al. showed that the sequence of the reaction layer is Fe/η-Al2Fe2(Si)/β-Al2FeSi/Al-Si. The experimental results have confirmed that the surface modification of aluminumizing can promote the formation of sound surface and metallurgical bonding between steel and Al, which can be achieved by compound casting. Arghavani et al. found that the Zn coating on the steel surface could enhance the wettability of bonding surface between steel and A5052 Al alloy. Liu et al. found that the intermetallic compounds Al5Fe2Znx and Al5FeZnx are formed at the interface between hot-dip galvanized steel and pure Al after compound casting. Generally, the zinicate must be at an appropriate thickness for the reaction during overcasting. If the thickness is more than the diffusion distance, the Zn layer will still exist in the final microstructure after casting, which is detrimental to the mechanical properties. This has been partially confirmed by Schwankl et al. showing that the interface strength determined by zinc is the weakest part of the compound castings. If the coating is too thin, there are no sufficient compounds to provide bonding strength. Therefore, the bonding interface between the iron/steel and the aluminum alloy is the determining factor for manufacturing the bimetallic materials.

2.4. Other Bimetallic Materials

The Young’s modulus of Al-based bimetallic materials reinforced by other metals can be roughly estimated by the ROM model and the results are shown in Figure 10. Comparing with the Young’s modulus of Fe and Ni at a level of ~200 GPa, the other continuous reinforcement – such as W and Mo – has a higher potential for the improvement of stiffness. However, the cost and processing procedure will remain an issue in its application.

3. Stiffness improvement in aluminum-based composites

Aluminum matrix composites reinforced with particles, short fibers whiskers, or continuous fibers have received considerable attention over the past decades due to the attractive properties resulting from the...
combination of their constituents.\textsuperscript{55–57} Al/TiB\textsubscript{2}, Al/TiC, Al/ZrB\textsubscript{2}, Al/SiC, Al/AlN, Al/Al\textsubscript{2}O\textsubscript{3}, and Al/Mg\textsubscript{2}Si have been reported to be able to improve the Young’s modulus of cast Al alloys.\textsuperscript{58–60} The improvement of Young’s modulus in AMCs can be successfully achieved through a variety of casting processes, including gravity casting, stirring casting, investment casting, die casting, vacuum-assisted casting, semisolid casting, and squeeze casting for manufacturing shaped components, or making billets by direct chill casting for further processing such as forging, extrusion or rolling.

The Young’s modulus of pure aluminum can be enhanced from 70 to 240 GPa by the reinforcement of 60 vol.\% continuous fiber.\textsuperscript{[19]} Similarly, the castings of Al-9Si/20 vol.\% SiC\textsubscript{p} composites significantly improve the Young’s modulus with the wear resistance equivalent or better than that of gray cast irons.\textsuperscript{61} Discontinuously reinforced AMCs have been demonstrated to offer essentially isotropic properties with substantial improvements in stiffness and strength. However, a 50\% increase in the Young’s modulus of Al alloys can be achieved by substituting a discontinuous reinforcement with continuous ones in AMCs.\textsuperscript{62} It is therefore capable of incorporating appropriate reinforcement in suitable volume fractions for casting aluminum components with improved Young’s modulus and other technological properties such as high thermal conductivity, high specific strength, tailorable coefficient of thermal expansion, improved strength, and low density, which is dependent upon the composition, grain size, microstructure, and fabrication process.

The stiffness property of some reinforcement phases is listed in Table 2. These phases show the much-increased Young’s modulus and melting point in comparison with pure aluminum. In AMCs, the reinforcement phase can be formed by \textit{in-situ} reaction or by \textit{ex-situ} additions. In the specific condition, the \textit{in-situ} particles can act as nucleating sites for grain refinement or as strengthening phases to hinder dislocation motion.\textsuperscript{65,66} Currently, several fabrication methods including liquid state processing, deposition process, and solid-state processing have been developed for the manufacture of AMCs. Figure 11 shows the detailed casting process routes for manufacturing AMCs, which include infiltration techniques,\textsuperscript{67,68} stirring techniques,\textsuperscript{69,70} and rapid solidification.\textsuperscript{71,72} Liquid state processing is usually involved with the casting process, which is energy-efficient and cost-effective for massive production. Products of complex shape can be formed directly through the melt mixture with reinforcement. It is very attractive to produce as-cast components of AMCs with a uniform reinforcement distribution of individual particles and structural integrity. However, during solidification, the particles ahead of the interface may get pushed, engulfed, or entrapped in the moving solidification front. The other difficulties in the casting process are the non-wettability of \textit{ex-situ} particles by liquid metal.

![Figure 10. Young’s modulus of aluminum-based bimetallic materials reinforced with different types of metallic wires estimated by rule of mixtures.](image)

### Table 2. Properties of typical reinforcements.\textsuperscript{63–64}

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Melting point (°C)</th>
<th>Young’s modulus (GPa)</th>
<th>UTS (MPa)</th>
<th>Density (g/cm\textsuperscript{3})</th>
<th>Thermal conductivity (W/m-K)</th>
<th>Coeff. of thermal expansion (10\textsuperscript{–6}/K)</th>
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</tbody>
</table>
and the particle–Al interface interaction. Although the addition of Ni, Mg, Li, Si, and Ca into Al melt can improve wettability either by changing the interfacial energy through some interfacial reaction or by modifying the oxide layer on the metal surface, the difficulty to obtain uniform dispersion of reinforcement particles is still an issue that hinders the adoption of AMCs in industry. In order to effectively improve the Young’s modulus of AMCs, the generation of high modulus phases, the reinforcement phases with covalent and ionic interatomic bonds in aluminum alloys are preferred approaches according to the nature of stiffness. Therefore, the in-situ method is better than the ex-situ method because the wettability between the in-situ formed phases and the aluminum matrix is significantly higher and is capable of forming clean and strong interfacial bonding in between. However, the in-situ method is suitable for particulate-reinforced AMCs because the in-situ techniques are not capable of making continuous fiber-reinforced AMCs. The Young’s modulus of composite materials can be estimated by theoretical modeling, which depends on the morphological arrangement of materials components. The most frequently used mathematical models include: (a) the rule of mixtures (ROM) and the inverse rule of mixtures (IROM), (b) the Halpin–Tsai model, (c) the Hashin–Shtrikman model, and (d) the Tuchinskii model. The ROM (upper bound) and IROM (lower bound) can be obtained according to the equal strain assumption and the equal stress assumption, respectively. The elastic properties of all of the composites are usually located between the ROM upper and IROM lower bounds. The Halpin–Tsai model has a more complicated mathematical structure than that of the ROM or IROM. In this model, the modulus of elasticity and the volume fraction of the components and the aspect ratio (ratio of the geometric dimensions) of the reinforcement are taken into account. It has been widely reported that Halpin–Tsai model is more accurate for particulate metal matrix composites. In the Hashin and Shtrikman (H-S) theorem, the upper bound rigorously corresponds to the composites containing the ‘soft’ inclusion matrix phase encapsulated by a ‘stiffer’ reinforcement phase, while the lower bound corresponds to the composites with a ‘softer’ inclusion reinforcement phase encapsulated by a ‘stiffer’ matrix phase. The H-S bounds are tighter than the ROM bounds and have been regarded as the best possible bounds on properties for isotropic two-phase composites. The Tuchinskii model considers a two-phase interpenetrating skeletal structure. The calculated value of modulus can be a good estimation of experimental guidance. However, this review will not focus the modeling approaches and principles. Some existing results from modeling are used to review the experimental data.

### 3.1. Al/TiB₂ Composites

TiB₂ is one of the most popular reinforcements for high modulus AMCs because of its Young’s modulus of 560 GPa and its easy synthesis using an in-situ process. The in-situ formed TiB₂ offers a better interface with the aluminum matrix than the ex-situ added particles. The in-situ Al/TiB₄ composites can be synthesized using K₂TiF₆ and KBF₄ salt reactions in molten Al through a self-propagating high-temperature synthesis (SHS) reaction via Al-Ti-B powder
compact/preform added to molten Al.\textsuperscript{91–93} through the reaction of TiO\textsubscript{2}-H\textsubscript{3}BO\textsubscript{3}-Na\textsubscript{2}AlF\textsubscript{6} with Al;\textsuperscript{94} or via chemical reactions among Al, TiO\textsubscript{2}, and B\textsubscript{2}O\textsubscript{3} particles.\textsuperscript{95} It is generally believed that the presence of a Al\textsubscript{3}Ti phase in Al/TiB\textsubscript{2} composites is beneficial for grain refinement but is detrimental to the mechanical properties.\textsuperscript{96} The Al\textsubscript{3}Ti can be eliminated during synthesis by the proper control of temperature, time, and ratios of the raw materials.\textsuperscript{91,97} The presence of Si in cast Al alloys can improve the dispersion of TiB\textsubscript{2} particles,\textsuperscript{98} although the TiB\textsubscript{2} particles are still partially segregated in the eutectic regions because of the pushing mechanism during solidification.\textsuperscript{99–101} The typical microstructure of Al/TiB\textsubscript{2} composites is shown in Figure 12. The Al-9Si-1Mg-0.7Cu/TiB\textsubscript{2} composite can be produced with clean, smooth, and well-bonded interfaces between the aluminum matrix and TiB\textsubscript{2} particles between 25 and 3,000 nm.\textsuperscript{103}

The TiB\textsubscript{2}-reinforced AMCs can remarkably improve the mechanical properties, in particular the stiffness. The typical Young's modulus and other mechanical properties of particulate-reinforced Al/ TiB\textsubscript{2} composites are summarized in Table 3. The increase of the Young's modulus of Al/TiB\textsubscript{2} composites can be up to 40% higher than that of pure aluminum.\textsuperscript{106,107} The strength at elevated temperatures and the wear and fatigue resistance can also have a significant increase.\textsuperscript{108} Kumar et al.\textsuperscript{102} reported an increase of 108% in hardness, 123% in yield strength, 43% in UTS, and 33% in Young's modulus of the Al-7Si cast alloy with 10 wt.% of TiB\textsubscript{2}, which provides a Young's modulus greater than 90 GPa. Han et al.\textsuperscript{109} studied the tensile properties of the Al-12Si alloy with 4 wt.% TiB\textsubscript{2} particles and found that the improvement of the Young's modulus can be observed in the temperature range of 25–350°C. Amirkhanlou et al.\textsuperscript{102} reported that Al-9Si-1Mg-0.7Cu/9 vol.% TiB\textsubscript{2} can provide a Young's modulus greater than 94 GPa and the yield strength up to 235 MPa by the formation of η-Al (Cu, Mg), Si, and TiB\textsubscript{2} phases in the microstructure. Lu et al.\textsuperscript{95} investigated the Al/TiB\textsubscript{2} composite and found that the Young's modulus reaches 107 GPa by adding 15% TiB\textsubscript{2} into the Al matrix. Obviously, the main reason for high stiffness properties is formation of high volume fraction TiB\textsubscript{2} with 565 GPa modulus.

### 3.2. Al/TiC composites

Titanium carbide (TiC) is a hard refractory ceramic material with FCC crystal structures. The Young’s modulus is approximately 400 GPa and the shear modulus is 188 GPa for the TiC,\textsuperscript{109,110} which is a good candidate as reinforcement for improving stiffness of aluminum alloys\textsuperscript{111,112}. Al/TiC in-situ composites can be synthesized by several techniques, including: (a) the reaction of K\textsubscript{2}TiF\textsubscript{6} salt and graphite, (b) the direct reaction of Ti and C powders, (c) the addition of Al-Ti-C powder into the Al melt, and (d) the reaction of CH\textsubscript{4} gas with the Al-Ti melt. The reactions can be at a level of 1000°C for 30 minutes for Al-4.5 Cu alloys.\textsuperscript{113,114} The in-situ formed TiC particles can be smaller than 1 μm in size or in a range of several micrometers.\textsuperscript{115,116} The formation of other phases, such as Al\textsubscript{3}C\textsubscript{3} and Al\textsubscript{4}Ti, is considered to be unfavorable in Al/TiC composites.\textsuperscript{116,117}

On top of the enhancement of mechanical properties, the addition of TiC particles into aluminum melt has a dramatic improvement on the Young’s modulus, as shown in Figure 13. Samer et al.\textsuperscript{118} obtained the Young’s modulus of 106 GPa, the yield strength of 450 MPa, and the elongation of 6% in the composites containing 22 vol.% TiC in pure Al. Mohapatra et al.\textsuperscript{119} confirmed that the Young’s modulus is increased from 70 GPa of pure aluminum to 88.78 GPa after adding 20 vol.% TiC. The mechanical properties of Al-4.5%Cu alloy reinforced with different amounts of TiC are summarized in Table 4, in which the addition of 10 wt.% TiC increases the
Young’s modulus to 99 GPa. In addition, the Young’s modulus of the Al/TiC composite is close to the upper limit calculated from the Hashin–Shtrikman model, suggesting that the in-situ synthesis of TiC particles leads to strong interfacial bonding and the attendant load transfer. Despite the high stiffness of Al/TiC in-situ composites, the porosity level and other oxide impurities in the melt are the main concerns because of the high synthesis temperature of 1000–1200 °C. High temperature processing also results in limitations for the industrial applications of in-situ Al/TiC composites.

3.3. Al/SiC Composites

SiC reinforcements are usually added into Al melt through ex-situ additions incorporating with stirring or mixing. Casting routes can be gravity casting and squeeze casting. Alternatively, the alloy is infiltrated into a porous preform formed by SiC reinforcements. The wettability between the SiC reinforcements and the aluminum alloy is a crucial concern in association with the optimum fluidity of the alloy. One of the main problems during the processing and casting of Al/SiC composites is that liquid aluminum attacks SiC reinforcements through chemical reaction, forming Al4C3 and Si. Particle clustering has greater effects on the flow behavior and mechanical properties of Al/SiC AMCs because the particle clustering microstructure experiences a higher percentage of particle fracture than that with particle random distribution. The stirring casting is an effective way to promote the distribution of ex-situ particles.

Table 3. Mechanical properties of Al/TiB2 cast composites synthesized by K2TiF6 and KBF4 salt reaction.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Temperature (°C)</th>
<th>Young's modulus (GPa)</th>
<th>0.2% Proof stress (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-7Si/5 vol.% TiB2</td>
<td>25</td>
<td>83.0</td>
<td>126</td>
<td>175</td>
<td>7.00</td>
</tr>
<tr>
<td>Al-7Si/10 vol.% TiB2</td>
<td>25</td>
<td>92.0</td>
<td>152</td>
<td>209</td>
<td>4.60</td>
</tr>
<tr>
<td>Al-12Si/4 wt.% TiB2</td>
<td>25</td>
<td>85.0</td>
<td>240</td>
<td>298</td>
<td>1.50</td>
</tr>
<tr>
<td>Al-12Si/4 wt.% TiB2</td>
<td>200</td>
<td>80.0</td>
<td>189</td>
<td>233</td>
<td>3.00</td>
</tr>
<tr>
<td>Al-12Si/4 wt.% TiB2</td>
<td>350</td>
<td>66.0</td>
<td>84</td>
<td>96</td>
<td>5.80</td>
</tr>
<tr>
<td>A356/2.1 vol.% TiB2</td>
<td>25</td>
<td>72.9</td>
<td>209</td>
<td>235</td>
<td>7.81</td>
</tr>
<tr>
<td>A356/4.7 vol.% TiB2</td>
<td>25</td>
<td>76.3</td>
<td>212</td>
<td>252</td>
<td>7.36</td>
</tr>
<tr>
<td>A356/8.4 vol.% TiB2</td>
<td>25</td>
<td>82.2</td>
<td>217</td>
<td>258</td>
<td>2.73</td>
</tr>
<tr>
<td>A356/2.1 vol.% TiB2</td>
<td>25</td>
<td>78.1</td>
<td>305</td>
<td>375</td>
<td>4.88</td>
</tr>
<tr>
<td>A356/4.7 vol.% TiB2</td>
<td>25</td>
<td>80.2</td>
<td>317</td>
<td>377</td>
<td>1.90</td>
</tr>
<tr>
<td>A356/8.4 vol.% TiB2</td>
<td>25</td>
<td>84.1</td>
<td>347</td>
<td>391</td>
<td>1.32</td>
</tr>
<tr>
<td>Al/5 vol.% TiB2</td>
<td>25</td>
<td>69.0</td>
<td>188</td>
<td>284</td>
<td>3.50</td>
</tr>
<tr>
<td>Al/10 vol.% TiB2</td>
<td>25</td>
<td>84.0</td>
<td>249</td>
<td>326</td>
<td>1.92</td>
</tr>
<tr>
<td>Al/5 vol.% TiB2</td>
<td>25</td>
<td>82.0</td>
<td>96</td>
<td>124</td>
<td>9.20</td>
</tr>
<tr>
<td>Al/10 vol.% TiB2</td>
<td>25</td>
<td>87.0</td>
<td>128</td>
<td>164</td>
<td>6.30</td>
</tr>
<tr>
<td>Al/15 vol.% TiB2</td>
<td>25</td>
<td>91.0</td>
<td>124</td>
<td>153</td>
<td>5.50</td>
</tr>
<tr>
<td>Al-Cu/10 vol.% TiB2</td>
<td>25</td>
<td>77.0</td>
<td>153</td>
<td>230</td>
<td>5.50</td>
</tr>
<tr>
<td>Al-Cu/10 vol.% TiB2</td>
<td>25</td>
<td>83.0</td>
<td>311</td>
<td>361</td>
<td>1.30</td>
</tr>
<tr>
<td>Al/15 vol.% TiB2</td>
<td>25</td>
<td>107.0</td>
<td>274</td>
<td>389</td>
<td>1.99</td>
</tr>
<tr>
<td>Al/15 vol.% TiB2</td>
<td>25</td>
<td>91.0</td>
<td>171</td>
<td>223</td>
<td>4.60</td>
</tr>
<tr>
<td>Al-Cu/15 vol.% TiB2</td>
<td>25</td>
<td>93.0</td>
<td>248</td>
<td>333</td>
<td>2.30</td>
</tr>
</tbody>
</table>

Table 5 summarizes the Young’s modulus and mechanical properties of ex-situ Al/SiC AMCs. The Young’s modulus of the AMCs with cast aluminum alloys can be enhanced to 114 GPa when the reinforcement is at a level of 20 vol.%. The castability is a significant concern when the SiC addition is beyond this level. For wrought aluminum alloys, the addition of SiC reinforcement can be at a level of 25 vol.% for casting and the subsequent plastic deformation processing. The Young’s modulus can be 140 GPa, which is double the Young’s modulus of pure aluminum.

3.4. Al/AlN Composites

Aluminum nitride (AlN) has a Young’s modulus of 310 GPa and therefore it can fairly increase the modulus of aluminum castings. However, because of
the low thermal expansion and good thermal conductivity, Al/AlN is attractive in some specific applications. *In-situ* Al/AlN composites are usually made by a direct reaction between N₂ and/or NH₃ gas with the molten aluminum alloys. The nitridation of Al is a thermodynamically exothermic process and is energetically favorable over an extensive temperature range. The formed AlN particles are smaller than 10 μm and show a hexagonal morphology. The AlN particles can be less than 2 μm in the Al/AlN composites synthesized by adding NH₃ into the melt in the temperature range from 1,100 to 1,270°C. In comparison with the purified N₂ bubbling gas, NH₃ can enhance the formation of the AlN phase in aluminum melt. Chedru studied *ex-situ* Al/AlN AMCs with squeeze casting and found that Al/AlN composites can significantly improve the mechanical properties, as shown in Table 6. Balog studied Al/AlN AMCs with cold isostatic pressing (CIP) and extrusion, and the results are shown in Figure 14. The Young's modulus of reinforced and non-reinforced materials.

### Table 4. Mechanical properties of Al matrix and Al–4.5Cu/TiC *in-situ* composites.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Vickers hardness (HV5)</th>
<th>Young's modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>UTS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al–4.5%Cu</td>
<td>55.19</td>
<td>72.8</td>
<td>81.5</td>
<td>118</td>
</tr>
<tr>
<td>Al–4.5Cu/5wt.% TiC</td>
<td>61.12</td>
<td>83.4</td>
<td>95.7</td>
<td>134</td>
</tr>
<tr>
<td>Al–4.5Cu/7wt.% TiC</td>
<td>69.43</td>
<td>91.8</td>
<td>103.4</td>
<td>156</td>
</tr>
<tr>
<td>Al–4.5Cu/10wt.% TiC</td>
<td>75.76</td>
<td>98.7</td>
<td>117.3</td>
<td>179</td>
</tr>
</tbody>
</table>

### Table 5. Young’s modulus and mechanical properties of *ex-situ* Al/SiC AMCs.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Reinforcement</th>
<th>Casting method</th>
<th>Young’s modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al–10Si–3Cu–1Mg–1.25Ni</td>
<td>10 vol.% SiC</td>
<td>Gravity</td>
<td>88</td>
<td>359</td>
<td>372</td>
<td>0.3</td>
</tr>
<tr>
<td>Al–10Si–3Cu–1Mg–1.25Ni</td>
<td>20 vol.% SiC</td>
<td>Casting</td>
<td>101</td>
<td>372</td>
<td>372</td>
<td>0.1</td>
</tr>
<tr>
<td>Al–9Si–0.5Mg</td>
<td>10 vol.% SiC</td>
<td>Gravity</td>
<td>86</td>
<td>303</td>
<td>338</td>
<td>1.2</td>
</tr>
<tr>
<td>Al–9Si–0.5Mg</td>
<td>20 vol.% SiC</td>
<td>Gravity</td>
<td>99</td>
<td>338</td>
<td>359</td>
<td>0.4</td>
</tr>
<tr>
<td>Al–10Si–1Fe–0.6 Mn</td>
<td>10 vol.% SiC</td>
<td>Pressure die cast</td>
<td>91</td>
<td>221</td>
<td>310</td>
<td>0.9</td>
</tr>
<tr>
<td>Al–10Si–1Fe–0.6 Mn</td>
<td>20 vol.% SiC</td>
<td>Pressure die cast</td>
<td>108</td>
<td>248</td>
<td>303</td>
<td>0.5</td>
</tr>
<tr>
<td>Al–10Si–3.25Cu–1Fe–0.6 Mn</td>
<td>10 vol.% SiC</td>
<td>Pressure die cast</td>
<td>94</td>
<td>241</td>
<td>345</td>
<td>1.2</td>
</tr>
<tr>
<td>Al–3.25Cu–1Fe–0.6 Mn</td>
<td>20 vol.% SiC</td>
<td>Pressure die cast</td>
<td>114</td>
<td>303</td>
<td>352</td>
<td>0.4</td>
</tr>
<tr>
<td>A356</td>
<td>10 vol.% SiC</td>
<td>Casting</td>
<td>81</td>
<td>283</td>
<td>303</td>
<td>0.6</td>
</tr>
<tr>
<td>A356</td>
<td>15 vol.% SiC</td>
<td>Casting</td>
<td>90</td>
<td>324</td>
<td>331</td>
<td>0.3</td>
</tr>
<tr>
<td>A356</td>
<td>20 vol.% SiC</td>
<td>Casting</td>
<td>97</td>
<td>331</td>
<td>352</td>
<td>0.4</td>
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<tr>
<td>Al–12Si–Ni–Cu</td>
<td>20 vol.% SiC</td>
<td>Squeeze casting</td>
<td>111</td>
<td>293</td>
<td>384</td>
<td></td>
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<tr>
<td>Al–7Si–Mg–Fe</td>
<td>15 vol.% SiC</td>
<td>Gravity</td>
<td>98</td>
<td>183</td>
<td>280</td>
<td>1.0</td>
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<tr>
<td>Al–3Mg</td>
<td>20 vol.% SiC</td>
<td>Gravity</td>
<td>105</td>
<td>377</td>
<td>408</td>
<td>1.4</td>
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<tr>
<td>Al–4Cu–Si–Mg</td>
<td>15 vol.% SiC</td>
<td>Gravity</td>
<td>107</td>
<td>342</td>
<td>350</td>
<td>1.6</td>
</tr>
<tr>
<td>Al–7Si–0.3Mg</td>
<td>10 vol.% SiC</td>
<td>Casting</td>
<td>82</td>
<td>287</td>
<td>308</td>
<td>0.6</td>
</tr>
<tr>
<td>Al–7Si–0.3Mg</td>
<td>15 vol.% SiC</td>
<td>Casting</td>
<td>91</td>
<td>329</td>
<td>336</td>
<td>0.3</td>
</tr>
<tr>
<td>Al–7Si–0.3Mg</td>
<td>20 vol.% SiC</td>
<td>Casting</td>
<td>98</td>
<td>336</td>
<td>357</td>
<td>0.4</td>
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<tr>
<td>A380</td>
<td>10 vol.% SiC</td>
<td>Casting</td>
<td>95</td>
<td>245</td>
<td>332</td>
<td>1.0</td>
</tr>
<tr>
<td>A380</td>
<td>20 vol.% SiC</td>
<td>Casting</td>
<td>114</td>
<td>308</td>
<td>356</td>
<td>0.4</td>
</tr>
<tr>
<td>AA6061</td>
<td>20 vol.% SiC</td>
<td>Casting-forming</td>
<td>119</td>
<td>448</td>
<td>551</td>
<td>1.4</td>
</tr>
<tr>
<td>AA6061</td>
<td>20 vol.% SiC</td>
<td>Casting-extrusion</td>
<td>108</td>
<td>414</td>
<td>545</td>
<td>2.0</td>
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<tr>
<td>AA6061</td>
<td>20 vol.% SiC</td>
<td>Casting-hot rolling</td>
<td>104</td>
<td>402</td>
<td>550</td>
<td>4.5</td>
</tr>
<tr>
<td>AA2014</td>
<td>15 vol.% SiC</td>
<td>Casting-forming</td>
<td>100</td>
<td>466</td>
<td>493</td>
<td>2.0</td>
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<tr>
<td>AA2014</td>
<td>20 vol.% SiC</td>
<td>Casting-forming</td>
<td>110</td>
<td>465</td>
<td>620</td>
<td>2.0</td>
</tr>
<tr>
<td>AA2014</td>
<td>25 vol.% SiC</td>
<td>Casting-forming</td>
<td>140</td>
<td>470</td>
<td>800</td>
<td>2.0</td>
</tr>
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<td>AA2014</td>
<td>15 vol.% SiC</td>
<td>Casting-hot rolling</td>
<td>96</td>
<td>530</td>
<td>650</td>
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<td>AA2014</td>
<td>15 vol.% SiC</td>
<td>Casting-hot rolling</td>
<td>110</td>
<td>330</td>
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<td>1.2</td>
</tr>
<tr>
<td>AA2618</td>
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<td>Casting-forming</td>
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<td>460</td>
<td>532</td>
<td>3.0</td>
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<td>17.8 vol.% SiC</td>
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<td>400</td>
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<tr>
<td>AA2618</td>
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<td>Casting-forming</td>
<td>105</td>
<td>405</td>
<td>560</td>
<td>7.0</td>
</tr>
<tr>
<td>AA2618</td>
<td>25 vol.% SiC</td>
<td>Casting-forming</td>
<td>116</td>
<td>490</td>
<td>630</td>
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<td>AA7075</td>
<td>15 vol.% SiC</td>
<td>Casting-forming</td>
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<td>556</td>
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<td>3.0</td>
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<td>2.0</td>
</tr>
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<td>AA7075</td>
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<td>Casting-forming</td>
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<td>665</td>
<td>735</td>
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<td>Casting-forming</td>
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<td>455</td>
<td>520</td>
<td>4.0</td>
</tr>
<tr>
<td>AA8090</td>
<td>13 vol.% SiC</td>
<td>Casting-forming</td>
<td>101</td>
<td>499</td>
<td>547</td>
<td>3.0</td>
</tr>
<tr>
<td>AA8090</td>
<td>17 vol.% SiC</td>
<td>Casting-forming</td>
<td>105</td>
<td>310</td>
<td>460</td>
<td>5.5</td>
</tr>
<tr>
<td>AA8090</td>
<td>17 vol.% SiC</td>
<td>Casting-forming</td>
<td>105</td>
<td>450</td>
<td>540</td>
<td>3.5</td>
</tr>
</tbody>
</table>

### Table 6. Young’s modulus and shear modulus of reinforced and non-reinforced materials.

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Young’s modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al–4Cu–1Mg</td>
<td>72.9</td>
<td>27.1</td>
</tr>
<tr>
<td>Al–4Cu–1Mg/45% AlN</td>
<td>146.3</td>
<td>56.5</td>
</tr>
<tr>
<td>Al–1Mg–0.5Si</td>
<td>72.5</td>
<td>27.1</td>
</tr>
<tr>
<td>Al–1Mg–0.5Si/42% AlN</td>
<td>141.3</td>
<td>54.6</td>
</tr>
<tr>
<td>Al–3Mg</td>
<td>71.3</td>
<td>26.6</td>
</tr>
<tr>
<td>Al–3Mg/48% AlN</td>
<td>149.5</td>
<td>58.2</td>
</tr>
</tbody>
</table>
due to high temperature manufacturing methods for in-situ Al/AlN composites.

3.5. Al/ZrB₂-Al₃Zr Composites

Al/ZrB₂-Al₃Zr composites use the hybrid reinforcement phases of ZrB₂ and Al₃Zr. The Young’s modulus is 350 GPa for ZrB₂ and 205 GPa for Al₃Zr. Al/ZrB₂-Al₃Zr in-situ composites are usually synthesized by the addition of K₂ZrF₆ and KBF₄ salts to Al melt. Zhang et al. synthesized in-situ ZrB₂ and Al₃Zr particles in A356 alloy with K₂ZrF₆ and KBF₄ salts. The ZrB₂ and Al₃Zr particles are from 0.3 to 0.5 μm, as shown in Figure 15. Zhao et al. reported that the morphologies of Al₃Zr are sensitive to the temperature of the Al melt. When the temperatures change from 850 to 1000°C, the morphologies of the Al₃Zr particles can be spherical shape, tetragon shape, rod shape, and fiber shape, but the ZrB₂ particles show no obvious diversity in morphology. The particulate-reinforced Al/ZrB₂-TiB₂ composites can also be formed by the addition of KBF₄, K₂ZrF₆, and K₂TiF₆ salts into Al melt, by which the formed TiB₂ and ZrB₂ particles are hexagonal with the average size less than 2 μm.

The Al/ZrB₂-Al₃Zr composites show valuable improvement in stiffness, strength, and wear properties with the increase in ZrB₂ contents. As shown in Figure 16, Selvam and Dinaharan verified the stiffness improvement of 7075/ZrB₂ composite, which is further attributed to ZrB₂ that has a covalent interatomic bond and high intrinsic modulus. However, Gautam et al. found that the improvement of the Young’s modulus in Al/ZrB₂-Al₃Zr hybrid composite is insignificant when the volume fraction of ZrB₂ particles increases. The main challenge for fabrication of high modulus in-situ composites by casting processes is volume fraction of reinforcement. In fact, it is difficult to form high volume fraction of particles through salt reaction or direct reaction between the gases with the molten aluminum alloys.

3.6. Other Particulate-reinforced AMCs

The other typical reinforcements listed in Table 2 are capable of being synthesized by in-situ reactions. However, the compounds with high modulus are more attractive. In addition to that described in the previous section, Al₂O₃, WC, B₄C, and VC are also good candidates for improving the Young’s modulus of aluminum composites. For example, the in-situ Al/Al₂O₃ composites can be synthesized by: (a) the direct melt oxidation of aluminum alloys at high temperature, (b) directly passing oxygen into the aluminum melt to form Al₂O₃, and (c) the displacement reactions between metal oxides and aluminum to produce Al₂O₃ particulate reinforcement. However, the experimental evidence for the improvement of Young’s modulus in those in-situ AMCs is not sufficient.

The manufacture and the properties of ex-situ AMCs have been comprehensively reviewed by Rohatgi et al. Al/SiC and Al/TiB₂ have also been discussed in the present paper. The other ex-situ AMCs processed by casting methods are shown in Table 7. It is possible to combine up to 20 vol.% of Al₂O₃ into different aluminum alloys for improving the Young’s modulus. The dominant factors in controlling the Young’s modulus of ex-situ AMCs are the type, shape, volume fraction, and distribution of reinforcement.
phases. The porosity and other microstructural characteristics are also critical for property improvement.\textsuperscript{155,156} The presence of matrix-particle decohesion, particle cracking, and void growth can decrease the load transfer capability of the interface and, consequently, decrease the Young's modulus of the AMCs. The subsequent mechanical processes are an effective approach to enhance the quality of the interface between matrix and reinforcement in ex-situ cast composites as well as the distribution of high modulus particles, as shown in Table 7. Secondary plastic deformation is not capable of altering the Young's modulus of AMCs;\textsuperscript{14} however, these processes can improve the toughness of the composites.

The main concern on the Young's modulus of ex-situ AMCs is their tendency to have relatively low ductility and fracture toughness, as shown in Table 7. The damage mechanism of ex-situ AMCs is mainly the reinforcement fracture and decohesion at the matrix/reinforcement interface. To achieve acceptable ductility and toughness, the composition, heat treatment process, size and shape distribution of the reinforcement should be precisely controlled. Also, secondary mechanical deformation will result in an improvement of ductility. In the presence of strong interfacial bonding, effective load transfer from the matrix to the reinforcement is enhanced, leading to good ductility and damage resistance.

### 3.7. AMCs with Continuous Reinforcement

Al alloys reinforced with continuous ceramic reinforcement, such as SiC and Al\textsubscript{2}O\textsubscript{3}, can be considered as alternative materials to achieve outstanding specific strength and modulus. The Al/SiC\textsubscript{p} and Al/Al\textsubscript{2}O\textsubscript{3} composites can be produced by the molten aluminum infiltration techniques, such as pressure-assisted, vacuum-driven, and pressureless or capillarity-driven processes. Aghajanian et al.\textsuperscript{57,157} reported the pressureless infiltration technique, by which the aluminum alloys infiltrated the reinforcement pre-forms spontaneously in a nitrogen atmosphere. This method is believed to be a cost-effective, nearly net shape technique with the combined processing of
materials and shaping of the components simultaneously. The basic problem encountered in the fabrication of these composites is the rejection of the ceramic phase by the liquid metal due to their lack of wettability.\(^{158}\) To improve the wetting of ceramics by liquid metals, a possible approach is to apply a metal coating on the ceramic particles, which essentially increases the overall surface energy of the solid, thereby promoting wetting by the liquid metal. Although the continuous ceramic reinforcement/fibers can provide 210 GPa Young’s modulus,\(^{159}\) they usually suffer from very low ductility – less than 0.2 – restricting their applications. Moreover, it is difficult to make shaped castings.

4. Summary and future outlook

The Young’s modulus of aluminum-based materials is one of the most important mechanical properties in controlling structural performance. The improvement of the Young’s modulus of castable aluminum-based materials is essential for increasing their competitiveness in lightweight structural applications. The capability of making complex shaped castings of these materials is critical in considering the massive production and the application in industry. The castability depends on the introduction methods, processing methods, volume fraction, size, and distribution of the high modulus phases. The influence of alloying elements on the Young’s modulus depends on the state. If the alloying elements are in a solid solution phase, the magnitude of the Young’s modulus is determined by the nature of the atomic interactions. If the alloying elements form second phases, the magnitude of the Young’s modulus is determined by the volume fraction and the intrinsic modulus of the second phase. Overall, the increase of Young’s modulus in conventional cast aluminum alloys is usually less than 15% through adding alloying elements for manufacturing complex shaped castings. Therefore addition of ceramic particles and reinforcement is necessary for significant improvement of the stiffness of Al alloys.

The improvement of the Young’s modulus through introducing high modulus reinforcement phases as AMCs is an effective approach because of their high Young’s modulus. The most capable reinforcement phases are TiB\(_2\) (\(E = 560\) GPa) and SiC (\(E = 480\) GPa) for making shaped castings. Reinforcement phases can be added by ex-situ or in-situ methods, in which the in-situ method with particulate reinforcement is preferred for making castings with relatively complex shape and cavity. The main factors governing the Young’s modulus of AMCs are the volume fraction, aspect ratio, and the interface. The bonding between the matrix and the reinforcement is the most important factor in determining mechanical properties. Strong interfacial bonding provides effective load transfer from the matrix to the reinforcement for improved Young’s modulus and other mechanical properties. The main concern on the performance of AMCs is their tendency to have relatively low ductility and fracture toughness when the materials provide high modulus. When using particulate-reinforced AMCs, the castability should be considered due to challenges in casting components with complex shape and cavity. The balance of castability/processibility and the improvement in Young’s modulus is the key for further development.

Bimetallic materials, made by metal wires with cast aluminum alloys, are effective for modulus improvement. In fact, bimetallic materials can be considered a special type of composite material. The preforms made by continuous metallic wires as skeletons or frames are a key step. The pretreatment of the surfaces is needed before casting. The overcasting can be any of the conventional casting methods. Knowledge in this area has not been well established for the variety of preform structures, pretreatments, and casting conditions; so continued study is necessary.

Stiff aluminum alloys are potentially one of the most promising materials for the significant reduction of structural weight with satisfied mechanical properties, including the Young’s modulus. There are some knowledge gaps and challenges for the further development of high modulus cast aluminum alloys, which include:

a. The Young’s modulus of aluminum alloys with multiple components is not fully understood. The development of complex Al-based alloys with the addition of desirable alloying elements is needed to ensure both high modulus and ductility properties.

b. Up to now, the main purpose for the addition of high modulus phase/reinforcement into the Al alloys has been to improve the wear resistance and high temperature performance. It is very important to carefully and specifically select the type as well as the volume fraction of reinforcement for modulus improvement.

c. Careful selection and combination of desirable alloying elements and in-situ formed reinforcement would possibly be the preferred option for developing the material with dominant stiffness properties, toughness, and good castability.
d. In bimetallic materials, reactivity between the reinforcement and the aluminum matrix must be carefully controlled to avoid the formation of brittle interface, which tends to lower the toughness of the interface. Bimetallic materials can be considered for local stiffness improvement of the aluminum components.

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