J Mater Sci (2010) 45:3457–3464
DOI 10.1007/s10853-010-4373-z

Mechanical properties of an Al/Mg/Al trilaminated composite fabricated by hot rolling

**X. P. Zhang · T. H. Yang · J. Q. Liu ·
X. F. Luo · J. T. Wang**

Received: 12 October 2009 / Accepted: 1 March 2010 / Published online: 23 March 2010

Abstract An Al/Mg/Al composite with a trilaminate structure was fabricated by hot rolling and its mechanical properties at quasi-static rates of strain were investigated. The bonding strength of the trilaminated composite is about 40 MPa, mainly attributing to the mechanical bond at the interfaces. The first layer failure strength of the laminated composite increases from 305 to 372 MPa when the relative thickness of aluminium alloy layer increases from 0.235 to 0.265. The tensile and bending properties of the laminates were calculated based on the Classical Laminate Theory (CLT). The calculations of first layer failure strength based on CLT agree with the experimental data in the error of 2.9–18%. Thus, the first layer failure strength of the Al/Mg/Al trilaminated composite fabricated by hot rolling can be calculated by CLT with the maximum stress criteria. The calculations also show that the tensile modulus, the tensile rigidity, the specific tensile rigidity and the first layer failure strength of the laminated composite increase almost linearly with the relative thickness of the aluminium alloy component. The bending rigidity of the laminated composite increases with the relative thickness of aluminium alloy, and approximates to a fixed value after the relative thickness over 0.3. The specific bending rigidity increases with the relative thickness of aluminium alloy and reaches a maximum value when the relative thickness is 0.25.

X. P. Zhang (✉) · T. H. Yang · J. Q. Liu ·
X. F. Luo · J. T. Wang
Department of Materials Science and Engineering, Nanjing University of Science and Technology, 210094 Nanjing, People's Republic of China
e-mail: zxp_0517@163.com

Introduction

Magnesium alloys have been used in various applications to reduce parts' weight, such as in automotive, instrument panels, radiator support, and aerospace equipments. However, in comparison with aluminium and its alloy, the uses of magnesium and its alloys are still limited because of their intrinsic disadvantages, such as poor corrosion resistance, low wear resistance, and low formability. If aluminium alloys and magnesium alloys were fabricated as an Al/Mg/Al trilaminated composite using aluminium alloys as protective layers, improvement of the corrosion resistance of the magnesium alloys would be expected. Liu et al. [1] reported that corrosion resistance of pure magnesium could be improved by using aluminized coating.

Much magnesium-based laminated composites have been developed using various techniques. Usually, the laminated composites are fabricated by the solid-state joining techniques, such as diffusion bonding, extrusion, friction-stir welding, friction, and roll welding. Li et al. [2] studied the phase constitutions near the interface of Mg/Al bimetal prepared by a vacuum diffusion bonding method at 480 °C. Zhang and Zhao [3] investigated the interface structure and shear strength of AZ31B/Al6061 joints prepared by diffusion boning without and with a Zn alloy as interlayer. Rolling is more efficient and economic comparing other techniques. Matsumoto et al. [4] fabricated an Al/Mg–Li alloy clad layer by a cold rolling method. Ueda et al. [5] started their investigations on synthesis and hydrogen storage properties of Mg-based laminated composites prepared by repetitive-rolling. Takeichi et al. [6] reported the hydrogen storage properties of Mg/Cu and Mg/Pd laminated composites prepared by repetitive-rolling. However, there are few reports on Al/Mg/Al laminated composites fabricated by hot rolling.

Flexibility in design is one of the most valuable features for laminated composite. It allows the designers to ''tailor'' both shape and material architecture (for example, thickness of single layer, distribution of layers) to achieve the best performance. The reports mentioned above focused on the manufacturing technology of magnesium-based laminated composites and the experimental measurement of their mechanical properties. From a design perspective, it would be desirable if mechanical properties of the laminated composites could be calculated using a suitable failure criterion. It could lead to significant decrease in weight through an increased confidence in the mechanical response of these multilayered materials.

In this study, a 7075 aluminium alloy/Mg–12Gd–3Y–0.5Zr magnesium alloy/7075 aluminium alloy trilaminated composite was fabricated by a hot rolling method. The tensile strength and bonding strength of the laminated composite were investigated at quasi-static rates of strain. The tensile and bending properties of the laminated composite were calculated based on Classical Laminate Theory (CLT). The tensile strength of the laminated composite was measured to evaluate the calculation, and the discrepancy was discussed.

Experimental and calculation procedures

Experimental procedure

The experimental materials were as-rolled Mg–12Gd–3Y–0.5Zr magnesium alloy and 7075 aluminium alloy. The mechanical properties were measured using the SANS-CMT5105 tensile testing machine, and the data were used to calculate the mechanical properties of the laminated composites.

Mg–12Gd–3Y–0.5Zr magnesium alloy and 7075 aluminium alloy were cut into rectangular pieces with a dimension of 100 mm × 75 mm × 10 mm and 100 mm × 75 mm × 5 mm, respectively. The two components were cleaned and mechanically ground orderly using 240 and 600 grit SiC papers to remove the oxidation films and bring forth a rugged surface. Subsequently, drying treatment was performed for both components after rinsing in ethanol.

The laminated composites were prepared by roll bonding at 723 K with a 50% rolling reduction in one single pass.

The shape and dimension of the specimens for tensile testing and for the measurement of bonding strength of the composites were illustrated in Fig. 1. The tensile test and bonding strength test were performed using the SANS-CMT5105 tensile testing machine with an initial strain rate of $1 \times 10^{-3}\ s^{-1}$ and the measurement temperature was 293 K. The average bonding strength is taken as,

$$\text{Average bonding strength} = \text{Average load}/(\text{Bond width} \times \text{Bond length}) \quad (1)$$

The bonding interface was separated by the force along the F direction as shown in Fig. 2. Microstructure of the bond interfaces was observed by scanning electron microscopy (SEM) using a Philips Quanta200 instrument with an Energy Dispersive X-ray Detector (EDX).

Calculation method of tension properties of Al/Mg/Al laminated composite

Schematic of Al/Mg/Al trilaminated composite is shown in Fig. 3. The thickness of 7075 aluminium alloy layer and that of Mg–12Gd–3Y–0.5Zr magnesium alloy layer are designated as t_1 and t_2, respectively. The relative thickness of the 7075 aluminium alloy layer is defined as $\frac{t_1}{2t_1+t_2}$.

In this study, CLT was used to calculate the elastic modulus and the first ply failure (FPF) strength of the laminated composite.

The symmetric balanced laminated composite studied in this research was subjected to the uniaxial tensile loading conditions as outlined in "Experimental procedure" section. The tensile modulus E_x parallel or vertical to the

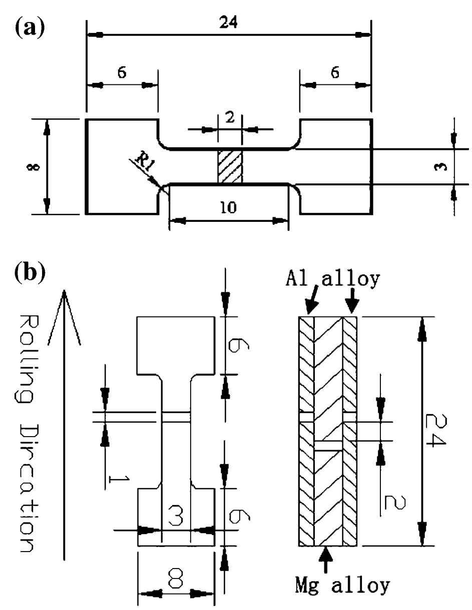

Fig. 1 A schematic view of the specimens for tensile strength test (**a**) and bonding strength test (**b**)

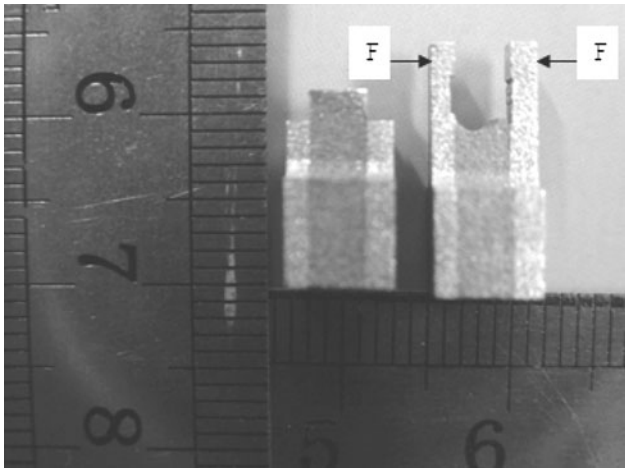

Fig. 2 Macrograph of the experimental laminated composite

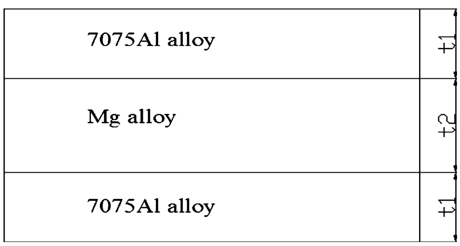

Fig. 3 Cross-sectional schematic of the Al/Mg/Al laminated composite

rolling direction was calculated using CLT, where it can be shown that [7, 8]:

$$E_x = \frac{1}{h}\left[A_{11} - \frac{A_{12}^2}{A_{66}}\right] \tag{2}$$

where the A_{11}, A_{12}, and A_{16} are the tensile stiffness, and given by [7, 8]:

$$\begin{cases} A_{11} = 2(Q_{11})_1 t_1 + (Q_{11})_2 t_2 = A_{22} \\ A_{12} = 2(Q_{12})_1 t_1 + (Q_{12})_2 t_2 \\ A_{16} = A_{26} = 0, A_{66} = 2(Q_{66})_1 t_1 + (Q_{66})_2 t_2 \end{cases} \tag{3}$$

where $Q_{11} = \frac{E}{1-v^2}$, $Q_{12} = \frac{vE}{1-v^2}$, $Q_{66} = G = \frac{E}{2(1+v)}$, E is the Young's modulus, G is the shear modulus, and v is the Poisson's ratios.

Because the laminated composite has a symmetrical structure, the constitutive equations were written as [7, 8]:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{11} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{4}$$

The coupling stiffness matrix B_{ij} and the flexural stiffness matrix D_{ij} were [7, 8]:

$$B_{ij} = 0 \tag{5}$$

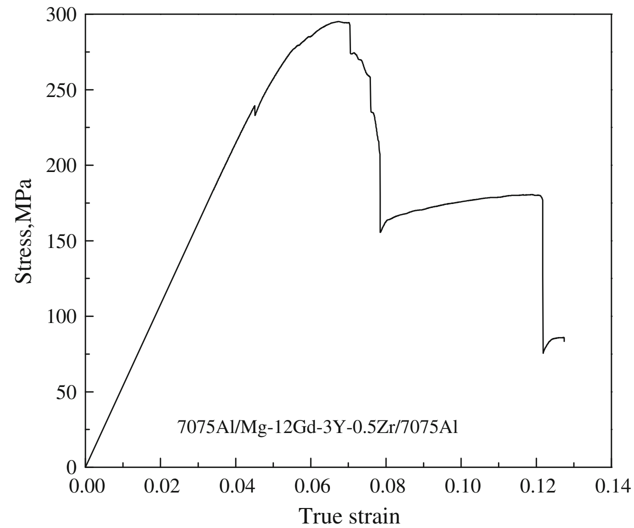

Fig. 4 A typical strain–stress curve of the Al/Mg/Al laminated composite

$$\begin{cases} D_{11} = \frac{2}{3}(Q_{11})_1\left[\left(\frac{t_2}{2}+t_1\right)^3 - \left(\frac{t_2}{2}\right)^3\right] + \frac{1}{12}(Q_{11})_2 t_2^3 = D_{22} \\ D_{12} = \frac{2}{3}(Q_{12})_1\left[\left(\frac{t_2}{2}+t_1\right)^3 - \left(\frac{t_2}{2}\right)^3\right] + \frac{1}{12}(Q_{12})_2 t_2^3 = D_{21} \\ D_{16} = D_{26} = 0 \\ D_{66} = \frac{2}{3}(Q_{66})_1\left[\left(\frac{t_2}{2}+t_1\right)^3 - \left(\frac{t_2}{2}\right)^3\right] + \frac{1}{12}(Q_{66})_2 t_2^3 \end{cases} \tag{6}$$

For calculating the mechanical properties of a laminated composite, three failure criteria have been commonly used: independent conditions (maximum strain and stress criteria), quadratic criteria (Tsai-Wu, Hoffman, and Tsai-Hill), and partly interactive criteria (simple Puck, modified Puck, and Hashin) [7, 8]. In this study, the maximum stress failure criterion was applied to calculate the strength of the laminated composites. In other words, the laminated composite failed when any of the stress components reached its corresponding strength value.

A typical measured curve of strain–stress relationship during tension is shown in Fig. 4. The first layer failure strength was studied in the work because the applied load decreases sharply after the first layer failure.

Results and discussion

Microstructure and mechanical properties of the experimental materials

Figure 5 is a photograph of the Al/Mg/Al laminated composite fabricated by hot rolling. The laminated composite is about 10 mm in thickness, 450 mm in length, and about

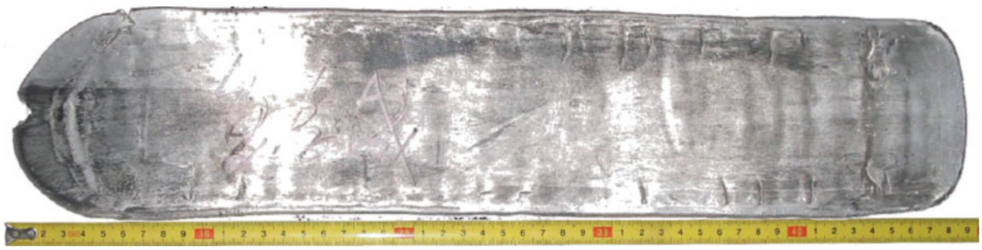

Fig. 5 Appearances of Al/Mg/Al laminated composite fabricated by hot rolling

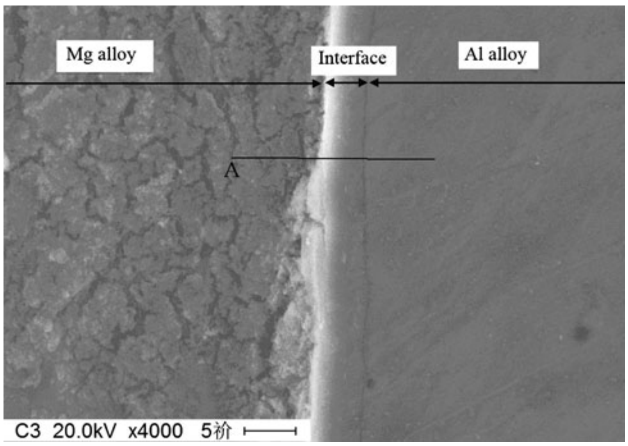

Fig. 6 Microscopic cross section of the experimental laminated composite

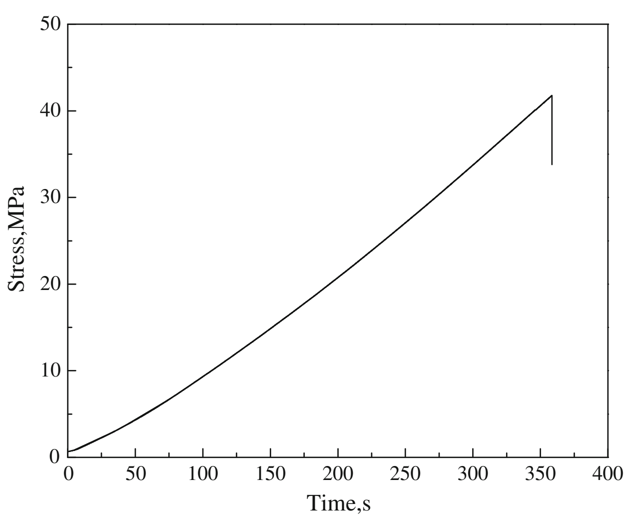

Fig. 7 Typical bond strength curve of the experimental laminated composite obtained at room temperature

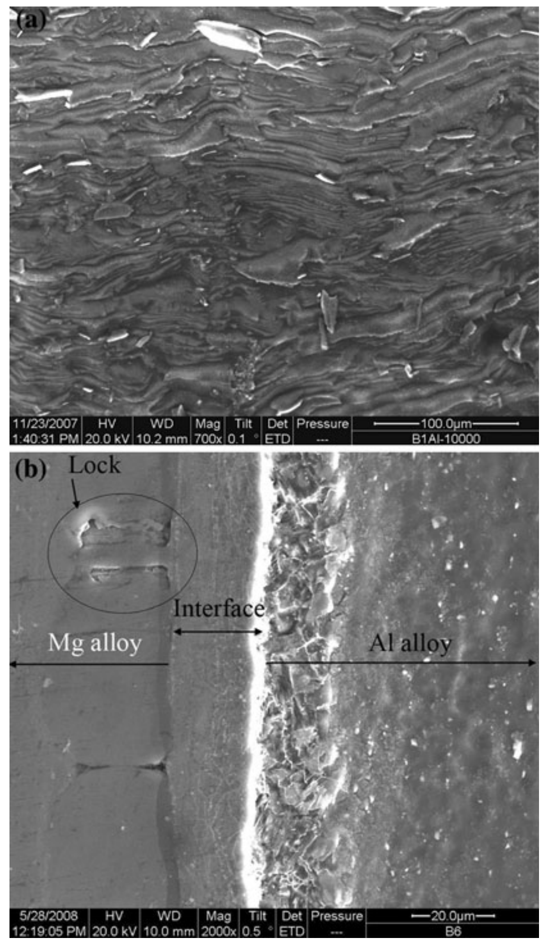

Fig. 8 Separated surface of the 7075 aluminium alloy after bonding strength test (**a**) and locks among the interface (**b**)

100 mm in width. Microscopic cross section of the laminated composite is shown in Fig. 6. No debonding is observed at the Mg/Al interfaces. A typical curve for the measurement of bonding strength is shown in Fig. 7. The shear stress necessary to separate the bond is about 40 MPa. It is somewhat less than expected but still indicating that reasonably successful bonding is achieved. The separated surface of 7075 aluminium alloy is shown in Fig. 8a. There are many significant permanent deformations of the asperity tops, giving rise to relatively large true areas of contact. The tendency of the separated surface of magnesium alloy was the similarity. In addition, there are some locks along the interface of aluminium alloy and magnesium alloy, as shown in Fig. 8b. The locks will increase the bonding strength of the laminated composite. The oxidized surface layers on both the Al and Mg alloy plates have little ductility, and there is also a hardness

difference between underlying virgin metal and the brittle surface layers. The brittle surface layers were broken under rolling deformation, resulting in cracks on the surfaces and broken chips of brittle surface layers. The brittle chips may penetrate into the virgin metals around the interface region during hot rolling [9], leading to the formation of "locks" we called.

The bonding strength and the structural quality of the interfaces depend on the thermomechanical processing of the laminated composite. There are two types of solid-state bonding, i.e., diffusion bonding and mechanical bonding. Diffusion bonding occurs in a considerable amount of time, and it involves the application of temperature and pressure. Mechanical bonding occurs instantaneously or over a very short time and depends on the forces of attraction between the atoms.

It is our contention that mechanical bond plays a major role in the quality of the interfaces in the research. In the first stages of hot rolling, the interfaces touch each other roughly leaving pores. As roll bonding starts at a high temperature, elements concentration gradients play a role in driving suited elements from the layers to the interfaces. However, the roll time, only 116 ms in the study, is too short to generate strong inter-diffusion. However, EDS linear analysis shown in Fig. 9 revealed that the elemental distribution at the interfaces is not strictly steep, indicating the occurrence of physical mixing and/or atomic inter-diffusion at the Mg/Al interfaces.

As described by Bowden and Tabor [10], the mechanical bond process causes bonding by adhesion requires the surfaces to be clean and to be an interatomic distance apart. Under industrial or laboratory conditions without the provision of protective environments and significant plastic deformation, complete cleanliness is simply not achievable.

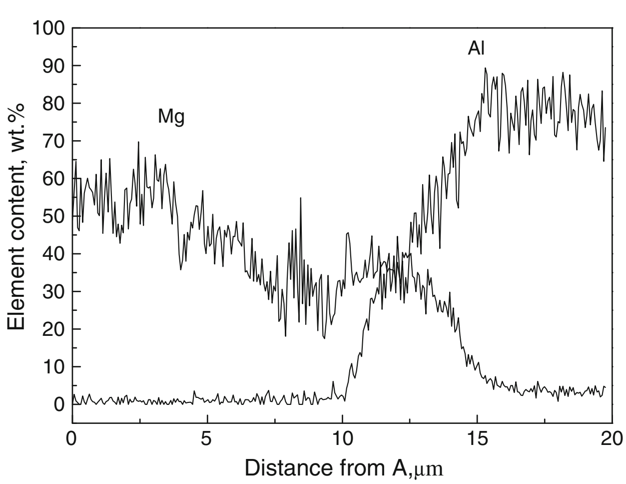

Fig. 9 Elemental distributions cross a Mg/Al interface of the laminated composite

There are the layers of oxides and adsorbed films on the surface of a metal. A large magnitude of surface expansion is required to cause the oxide layer to break up and to allow the fresh metal in between the cracks to make contact and thus, adhere to one another.

The first layer failure strength of Al/Mg/Al laminated composite

The typical tensile test curves of 7075 aluminium alloy layer and Mg–12Gd–3Y–0.5Zr magnesium alloy are shown in Fig. 10, and the mechanical properties of the alloys are listed in Table 1. The ultimate tensile strengths of 7075 aluminium alloy layer parallel to rolling direction are close to those vertical to rolling direction, thus 7075 aluminium alloy layer can be considered homogeneous during the calculation. Mg–12Gd–3Y–0.5Zr magnesium alloy layer is treated in the similar way.

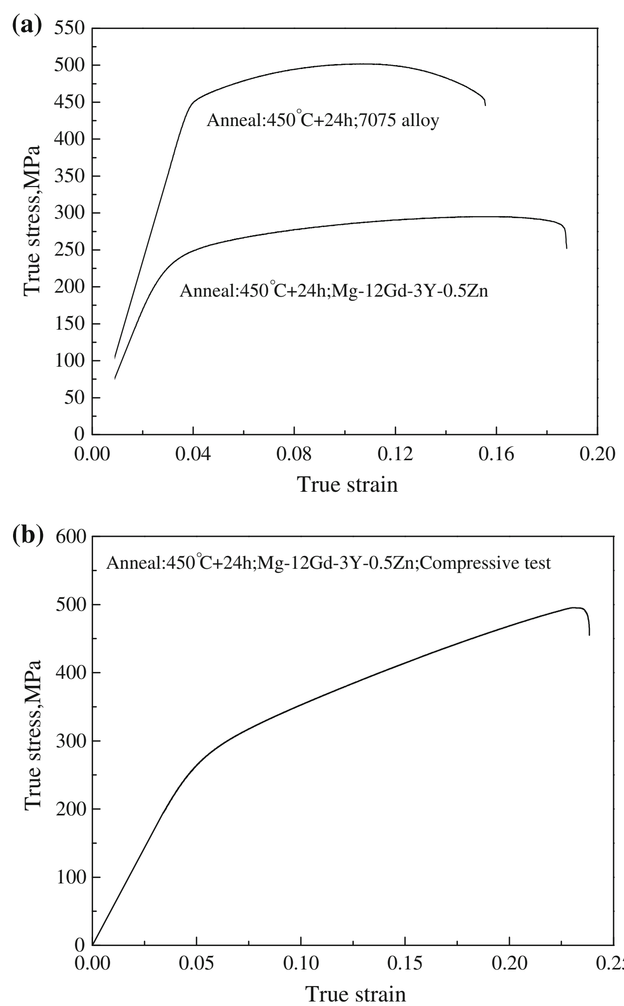

Fig. 10 Typical strain–stress curves of the 7075 aluminium alloy: **a** tensile test, **b** compression test

Table 1 Properties of 7075 aluminium alloy plate and Mg–12Gd–3Y–0.5Zr magnesium alloy plate

Alloy	Density (kg/m^3)	*E* (GPa)	*v*	*G* (GPa)	UTS (MPa) (parallel to rolling direction)	UTS (MPa) (vertical to rolling direction)	UCS (MPa)
7075	2810	71.70	0.33	26.9	495	502	560
Mg–12Gd–3Y–0.5Zr	2000	45.0	0.35	17	290	300	502

UTS ultimate tensile strength, *UCS* ultimate compression strength, *G* shear modulus, *E* Young's modulus, *v* Poisson's ratios

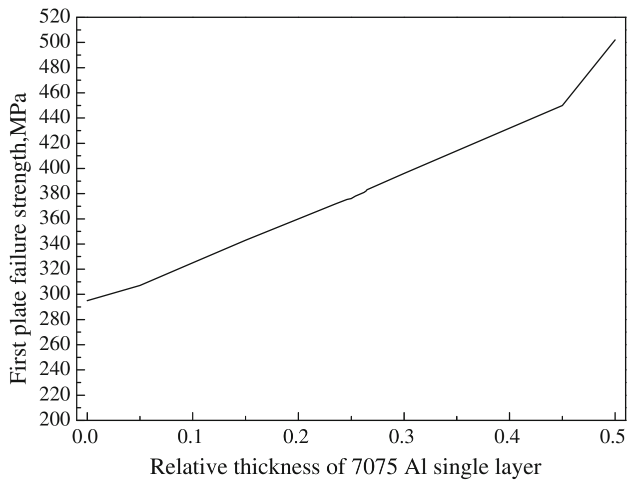

Fig. 11 Variation of first plate failure strength of the Al/Mg/Al laminated composites with the relative thickness of 7075 Al plate

The calculated first layer failure strength of Al/Mg/Al laminated composite varied with the relative thickness of aluminium alloy layer is shown in Fig. 11. The first layer failure strength of the laminated composite increases with the relative thickness of aluminium alloy layer.

A comparison of the experimental first layer failure strength and the calculations with the maximum stress criterion is shown in Table 2. The calculations agree with the experimental results in the error of 2.9–18%. Thus, the first layer failure strength of the Al/Mg/Al trilaminated composite fabricated by hot rolling can be calculated by CLT with the maximum stress criteria in a tolerable discrepancy.

The basic assumptions of CLT are [7, 8]: (1) the layers of the laminated composite are perfectly bonded together; (2) the material properties of each layer are constant through the thickness of the layer; (3) the stress–strain relations of the layers are linear-elastic; (4) the laminated composite is in plane stress state; (5) lines originally straight and normal to the midplane of the laminated composite remain straight and normal in extension and bending; (6) laminated composite in-plane strains and curvatures are small in comparison to unity. A laminated composite has to be flat out to meet the requirements listed above. The macrographs of 7075 Al/Mg–12Gd–3Y–0.5Zr/

Table 2 The calculated and experimental of first plate failure strength of Al/Mg/Al laminated composites

Sample	$t_1/(2 \times t_1 + t_2)$	Calculated (MPa)	Experimental (MPa)	Error (%)
1	0.235	372	305	18
2	0.246	375	349	6.9
3	0.254	378	349	7.7
4	0.262	381	363	4.7
5	0.264	382	370	3.1
6	0.265	383	372	2.9

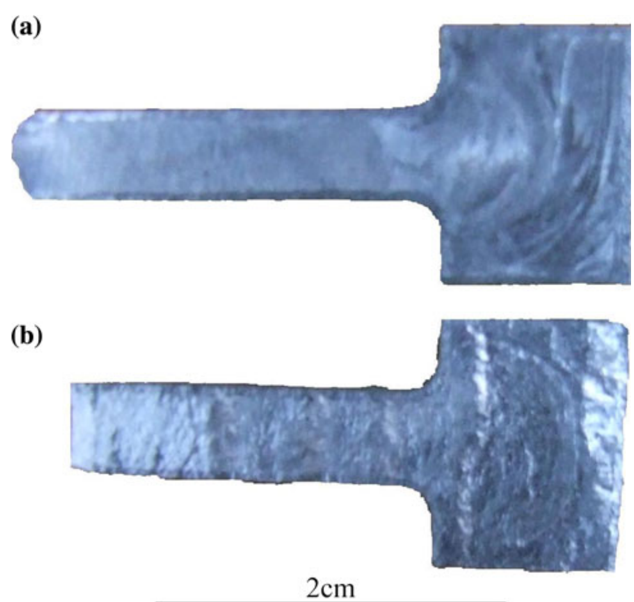

Fig. 12 Macrograph of Al/Mg/Al laminated composites fabricated by rolling with different bonding strength. **a** The experimental first plate failure strength is 370 MPa and the differences between calculation and the experimental is 3.1%; **b** the experimental first plate failure strength is 305 MPa and differences between the calculated results and the experimental ones is 18%

7075 Al laminated composites made by hot rolling with different first layer failure strength are shown in Fig. 12. There are many swings on the surface of the layers. The protrusions on the surface of the layer will lead to the stress concentration. In addition, the residual stresses will be the presence in the layer after hot rolling, and have a great influence on the first layer failure strength. Similar results have also been reported by Jeronimidis and Parkyn [11] and Kim and Hahn [12] following tests on thermoplastic and thermosetting composite materials, respectively. The material properties of the laminated composite are always subject to a certain amount of scatter. Such uncertainties are because of many causes, for example, the imperfect bonding between the layers, and their influence on the stiffness or strength of laminate. Thus, for safe and reliable designs, such uncertainties should not be ignored when calculating the constraint equations.

Tensile modulus and stiffness matrix of Al/Mg/Al laminated composite

Beside tensile strength, mechanical properties such as the tensile modulus and the stiffness matrix, for the applications of such laminated light-metal composites. Using the CLT, we calculated tensile modulus, tensile rigidity, bending rigidity, specific tensile rigidity, and specific bending rigidity. The tensile modulus and the stiffness matrix of the laminated composite varied with the relative thickness of aluminium alloy layer are shown in Fig. 13,

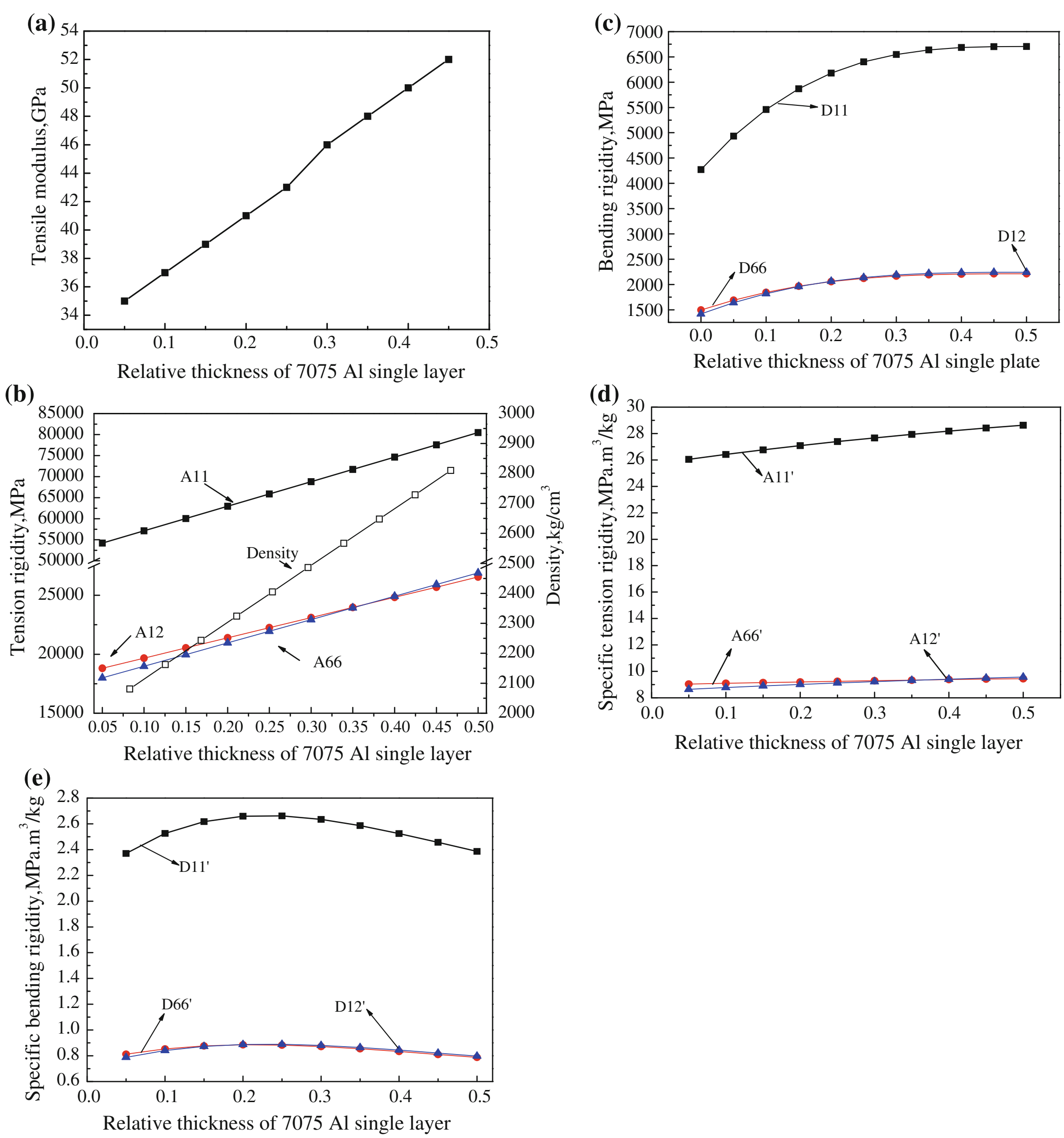

Fig. 13 Variation of **a** tensile modulus, **b** tensile rigidity, **c** bending rigidity, **d** specific tensile rigidity, **e** specific bending rigidity of Al/Mg/Al laminated composites with the relative thickness of 7075 aluminium layer for a stationary laminated composite thickness of 10 mm

while the laminated composite total thickness is fixed. The tensile modulus, the tensile rigidity, and the specific tensile rigidity increase almost linearly with the relative thickness of aluminium alloy layer. The bending rigidity of the laminated composite increases exponentially with the relative thickness of aluminium alloy layer and then it levels off when the relative thickness of aluminium alloy layer above 0.3. It is interesting to note that the specific bending rigidity increases with the relative thickness of aluminium alloy layer, and it reaches a maximum value when the relative thickness of aluminium alloy layer is 0.25.

In addition, an examination of the figure shows that tensile modulus of the laminated composite is in the range of 35–52 GPa. The minimum tensile modulus, 35 GPa, is less than that of Mg–12Gd–3Y–0.5Zr magnesium alloy, and the maximum, 52 GPa, is less than that of 7075 aluminium alloy.

Conclusions

An Al/Mg/Al laminated composite was fabricated by hot rolling. The bonding strength of the laminated composite is about 40 MPa. The mechanical bond is the main bond mechanism in this work. The first layer failure strength increases with the relative thickness of aluminium alloy layer, and the first layer failure strength is from 305 to 372 MPa when the relative thickness of aluminium alloy layer is from 0.235 to 0.265.

The CLT was used to calculate the first layer failure strength of the laminates. The calculation results agree with the experimental data: first layer failure strength, the inaccurate is less than 20%. Thus, the first layer failure strength of the laminated composite can be the calculated used CLT with the maximum stress criterion.

The elastic modulus, the tensile modulus, the tensile rigidity, the specific tensile rigidity, and bending rigidity of the laminates were predicted by The CLT. The elastic modulus, the tensile modulus, the tensile rigidity, and the specific tensile rigidity increase almost linearly with the thickness fraction of the aluminium alloy layer. The bending rigidity of the laminated composite increases with the relative thickness of the 7075 aluminium alloy layer, and the bending rigidity approximates to a fixed value after the relative thickness above 0.3. The specific bending rigidity increases parabolic with the relative thickness of single 7075 aluminium alloy layer and the specific bending rigidity reached the maximum value when the relative thickness is 0.25.

Acknowledgements This work was supported by Project 50801038 supported by National Natural Science Foundation of China, the Scientific Research Foundation of CAST (CAST200742), and the Zijin Star Project of Nanjing University of Science and Technology.

References

1. Liu FC, Liang W, Li XR (2008) J Alloys Compd 461(1–2):399
2. Li YJ, Liu P, Wang J, Ma HJ (2008) Vacuum 82(1):15
3. Zhao LM, Zhang ZD (2008) Scripta Mater 58(4):283
4. Matsumoto H, Watanabe S, Hanada S (2005) J Mater Process Technol 169(1):9
5. Ueda TT, Tsukahara M, Kamiya Y, Kikuchi S (2005) J Alloys Compd 386:253
6. Takeichi N, Tanaka K, Tanaka H, Kikuchib S (2007) J Alloys Compd 446–447:543
7. Berthelot JM (1999) Composite materials mechanical behaviour and structural analysis. Springer-Verlag, New York
8. Jones RM (1998) Mechanics of composite materials, 2nd edn. Taylor and Francis Inc, London
9. Bay N (1986) Met Constr 18(6):369
10. Bowden FP, Tabor D (1950) The friction and lubrication of solids. Clarendon Press, Oxford, Gloucestershire
11. Jeronimidis G, Parkyn AT (1988) J Compos Mater 22(5):401
12. Kim RY, Hahn HT (1979) J Compos Mater 13(1):2