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Modification of residual stress in Al-[AlBO]$_w$/Al compound plate①

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[Abstract] The application of compound parts of Al-[AlBO]$_w$/Al not only reduces the cost of the parts but also improves its properties. However, there is a large thermal residual stress between Al and [AlBO]$_w$/Al, and it is harmful for practical application. From the theoretical analyses and experimental results, it was found that by the compressive pre-plastic deformation perpendicular to the interface between Al and [AlBO]$_w$/Al, the interlayer residual stress of compound parts can be reduced, while the mechanical properties of compound parts can be improved.

[Key words] Al-[AlBO]$_w$/Al; compound plate; residual stress
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1 INTRODUCTION

The metal matrix composites take advantages of higher specific strength, higher specific module, lower thermal coefficient of expansion etc[1, 2], resulting in a typical engineering material with good prospects. Due to the high cost, the application and popularization of the composites are restricted in a great extent, although the fabricated techniques of the composites have been getting mature up to now. Actually, if the composite is only used in the key area of common alloy parts, the properties of parts in this area can be improved while fabricated cost do not increase in a great extent. So, it is the developing direction for the application and popularization of the composites. However, due to the coefficient of alloy is obviously larger than that of the composite, the thermal residual stress between two types of materials must be caused when the temperature cooled from high fabricated temperature to room temperature. The thermal residual stress can give a harmful effect to the material mechanical properties and dimensional stability[3, 4]. As an example of the plate-part in this paper, an [AlBO]$_w$/Al composite layer was fabricated on the aluminum alloy. The relationship of interlayer thermal residual stress with the pre-plastic deformation was theoretically analyzed, and it was experimentally verified at same time. In addition, the influence of pre-deformation on the mechanical properties of compound plate was also investigated.

2 MODEL AND ANALYSES

Fig. 1 gives the model of Al-[AlBO]$_w$/Al compound plat, in which the thickness of [AlBO]$_w$/Al layer is a, and the total thickness of the compound plate is b. The length (L) and width (L) of compound plate are enormously larger than its thickness. For simplicity, this model can be simplified as a problem of plane stress, and the X-axial rake, and Y-axial rake can be considered as the equivalent direction. The compressive stress is applied along the Z-axis, and certain plastic strain in this direction of compound plate is occurred. It is assumed that, the average compressive pre-plastic strain of compound plate along the Z-axis is $-\varepsilon_p$, meanwhile the compressive pre-plastic strain of Al layer and [AlBO]$_w$/Al layer in this direction is $-\varepsilon_{p,Al}$ and $-\varepsilon_{p,com}$, respectively. The relation among three plastic strains is as follows:

$$b \cdot \varepsilon_p = (b - a) \cdot \varepsilon_{p,Al} + a \cdot \varepsilon_{p,com} \quad (1)$$

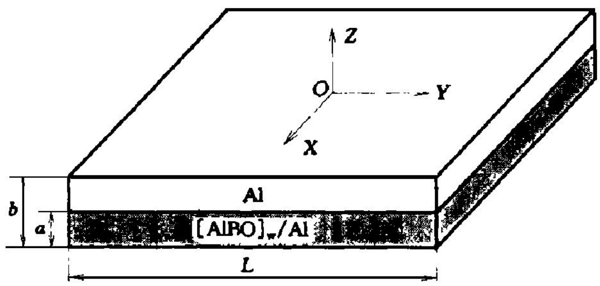

Fig. 1 Sketch of Al-[AlBO]$_w$/Al compound plate

Because the plastic volume of material can not be changed during compressive process, the tensile plastic strain along the X-axis and Y-axis in Al layer of compound plate are $\varepsilon_{p,Al}/2$, meanwhile the tensile plastic strain along the X-axis and Y-axis in [AlBO]$_w$/Al layer of compound plate are $\varepsilon_{p,com}/2$.

When the compound plate is unloaded after pre-plastic deformation, the relation between stress and strain in Al layer is

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$$\varepsilon_{X,\mathrm{Al}} = [(1-\upsilon_{\mathrm{Al}})/E_{\mathrm{Al}}]\sigma_{X,\mathrm{Al}} + \varepsilon_{\mathrm{p,Al}}/2 \quad (2)$$

where $\sigma_{X,\mathrm{Al}}$ and $\varepsilon_{X,\mathrm{Al}}$ are the stress and strain along the X-axis in Al layer respectively; E_{Al} and υ_{Al} are elastic modulus and Poisson ratio of Al layer respectively.

When the compound plate is unloaded after pre-plastic deformation, the relation between stress and strain in $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer is

$$\varepsilon_{X,\mathrm{com}} = [(1-\upsilon_{\mathrm{com}})/E_{\mathrm{com}}]\sigma_{X,\mathrm{com}} + \varepsilon_{\mathrm{p,com}}/2 \quad (3)$$

where $\sigma_{X,\mathrm{com}}$ and $\varepsilon_{X,\mathrm{com}}$ are the stress and strain along the X-axis in $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer respectively, and E_{com} and υ_{com} are elastic modulus and Poisson ratio of $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer respectively.

Due to the resultant force of Al layer and $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer becomes zero after unloading of compound plate, the stress balance equation is

$$(b-a)\cdot\sigma_{X,\mathrm{Al}} + a\cdot\sigma_{X,\mathrm{com}} = 0 \quad (4)$$

In addition, because the interfacial bonding between two layers of materials is good, the strains of two layer along X-axis are same. To make Eqn.(2) equal to Eqn.(3), the following equation can be obtained:

$$\frac{1-\upsilon_{\mathrm{Al}}}{E_{\mathrm{Al}}}\cdot\sigma_{X,\mathrm{Al}} + \frac{\varepsilon_{\mathrm{p,Al}}}{2} = \frac{1-\upsilon_{\mathrm{com}}}{E_{\mathrm{com}}}\cdot\sigma_{X,\mathrm{com}} + \frac{\varepsilon_{\mathrm{p,com}}}{2} \quad (5)$$

With Eqns.(1) ~ (5), we can get,

$$\sigma_{X,\mathrm{Al}} = -\frac{(\varepsilon_{\mathrm{p}}-\varepsilon_{\mathrm{p,com}})b/2(b-a)}{(1-\upsilon_{\mathrm{Al}})/E_{\mathrm{Al}} + (1-\upsilon_{\mathrm{com}})(b-a)/aE_{\mathrm{com}}} \quad (6)$$

$$\sigma_{X,\mathrm{com}} = \frac{(\varepsilon_{\mathrm{p}}-\varepsilon_{\mathrm{p,com}})b/2(b-a)}{(1-\upsilon_{\mathrm{Al}})a/E_{\mathrm{Al}}(b-a) + (1-\upsilon_{\mathrm{com}})/E_{\mathrm{com}}} \quad (7)$$

Eqns.(6) and (7) are the actual variation of residual stress in Al layer and $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer respectively. Eqn.(6) shows that, when the composite is unloaded after pre-plastic strain, the variation of thermal residual stress of Al layer is negative, that is to say the tensile residual stress of Al layer is decreased. Eqn.(7) shows that, when the composite is unloaded after pre-plastic strain, the variation of thermal residual stress of $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer is positive, that is to say the compressive residual stress of $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer is also decreased. In a word, the residual stresses in two layers of material can be decreased at same time when the pre-plastic deformation occurred perpendicular to the interface between two layers of the Al-$[\mathrm{AlBO}]_w/\mathrm{Al}$ compound plate.

3 MATERIALS AND EXPERIMENTAL

Three samples of 6061Al-25% (volume fraction) $[\mathrm{AlBO}]_w/6061$ alloy compound plate were fabricated by the method of squeeze cast. The dimension of compound plate is $L = 55$ mm, $a = 2$ mm and $b = 4$ mm. The molecular formula of $[\mathrm{AlBO}]_w$ whisker in compound plate is $\mathrm{Al_{18}B_4O_{33}}$, whose length and diameter is 5~ 20 μm and 0.5~ 1.5 μm respectively. The elastic modulus and Poisson ratio of Al layer is $E_{\mathrm{Al}} = 70$ GPa and $\upsilon_{\mathrm{Al}} = 0.33$ respectively, and the elastic modulus and Poisson ratio of $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer is $E_{\mathrm{com}} = 95$ GPa and $\upsilon_{\mathrm{com}} = 0.30$ respectively.

One as-cast compound was selected and did not make any pre-plastic deformation ($\varepsilon_{\mathrm{p}} = \varepsilon_{\mathrm{p,Al}} = \varepsilon_{\mathrm{p,com}} = 0$). By using MTS-810 mechanical tester, two of other compound plates were treated by compressive pre-plastic deformation. The direction of applied loading is along the Z-axis. The maximum compressive applied-loading of compound plate is 150 MPa and 250 MPa respectively. After unloading, the average plastic strain of compound plate is $\varepsilon_{\mathrm{p}} = 0.41\%$ and 0.83% respectively. The loading of 150 MPa and 250 MPa is close to $\sigma_{0.15}$ and $\sigma_{0.39}$ of 25% (volume fraction) $[\mathrm{AlBO}]_w/6061$ alloy composite, so the plastic strain in $[\mathrm{AlBO}]_w/\mathrm{Al}$ layer of compound plate is approximated as $\varepsilon_{\mathrm{p,com}} = 0.15\%$ and 0.39% respectively.

With X-300 X-ray stress analyzer and conventional method[5, 6] of $\sin^2\psi$, the residual stresses along X-axis in the Al layer of each compound plate were measured. Before measurement, the surface of Al layer of compound plate was chemically polished in a 20% NaOH solution. Typically, more than about 100 μm was removed from the studied surface of the specimen. After the stress measurement, the tensile specimens were made, and the tensile tests were carried out on MTS-810 mechanical tester.

4 RESULTS AND DISCUSSION

4.1 Residual stress

The relationship between the residual stress (σ_{R}) in Al layer of Al-$[\mathrm{AlBO}]_w/\mathrm{Al}$ compound plate and the compressive pre-plastic strain (ε_{p}) is shown in Fig. 2. According to Eqn.(6), the variation of residual stress due to pre-plastic strain can be calculated, and then it is added to the residual stress in the

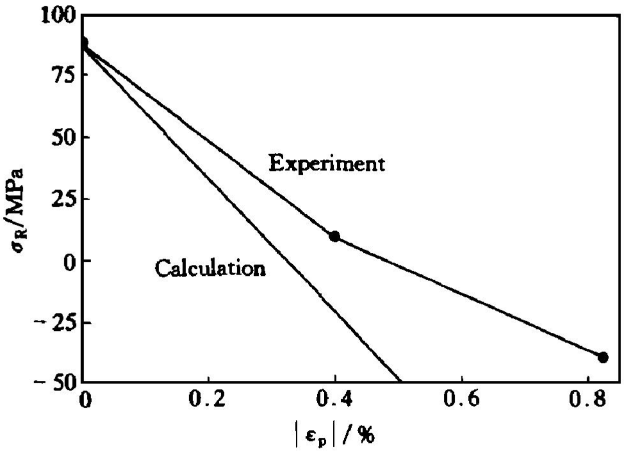

Fig. 2 Residual stress (σ_{R}) of 6061Al layer vs pre-compressive plastic strain (ε_{p}) in 6061Al-25% (volume fraction) $[\mathrm{AlBO}]_w/6061$ alloy compound plate

primary state ($\varepsilon_p = 0$), thus the calculated residual stress after pre-plastic deformation can be obtained.

Fig. 2 shows that, a large residual stress existed in the Al layer of compound plate. With increasing pre-plastic strain of compound plate, the residual stress has a monotonous decreasing tendency. In addition, the varying tendency of calculated value is similar to that of experimental, but both of them are not identical. The difference between theoretical values and experimental ones in Fig. 2 is mainly due to the too simple of theoretical model and the error of experiment in this paper. It should be explained that the residual stress between Al layer and [AlBO]$_w$/Al layer of compound plate belongs to the macro residual stress. Moreover, the thermal mismatch stress between [AlBO]$_w$ whisker and Al matrix in [AlBO]$_w$/Al layer does also exist, that is the micro residual stress[7,8]. The range of thermal mismatch stress in [AlBO]$_w$/Al layer is equivalent to the dimension of whisker, so it cannot bear on the Al layer of compound plate, and cannot affect the measuring result of residual stress of Al layer.

4.2 Yield strength

Fig. 3 gives the relation between tensile yield strength ($\sigma_{0.2}$) and compressive pre-plastic strain (ε_p) of Al-[AlBO]$_w$/Al compound plate. It can be seen that, the yield strength increases with increasing pre-plastic strain of compound plate.

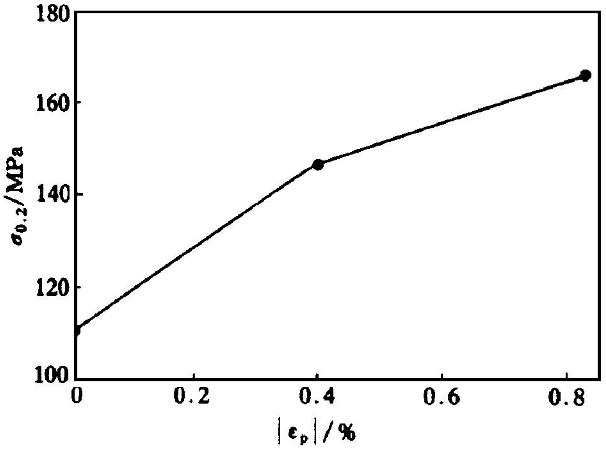

Fig. 3 Tensile yield strength ($\sigma_{0.2}$) of 6061Al-25% (volume fraction) [AlBO]$_w$/6061 alloy compound plate vs pre-compressive plastic strain (ε_p)

The effect of pre-plastic deformation on tensile yield strength of compound plate is mainly due to the decrease of residual stress and the increase of work-hardening[9,10]. The tensile residual stress of Al layer can decrease the yield strength of compound plate. On the contrary, the compressive residual stress of [AlBO]$_w$/Al layer can increase the yield strength of compound plate. However, because the yield strength of Al layer is obviously lower than that of [AlBO]$_w$/Al composite, the initial yield strain of compound plate must occur in the Al layer during tensile test. The tensile residual stress can enhance the plastic strain of Al layer, and induce the decrease of the tensile yield strength of compound plate. After pre-plastic deformation, the tensile residual stress of Al layer is reduced, it must lead to the increase of yield strength of compound plate. On the other hand, due to the plastic strain and work-hardening in Al and [AlBO]$_w$/Al layer during pre-plastic deformation, it is also beneficial to improve the yield strength of compound plate.

It is well known that the working environment of aerospace construction parts is very severe. These materials must have good dimensional stability except certain strength. The residual stress is harmful for the dimensional stability of material, so modification of residual stress is important in engineering. For the parts of Al-[AlBO]$_w$/Al in simple shape, they can be easily pre-plastic deformed, thus the residual stress is reduced. For the parts in complex shape, if the suitable technological processes are selected, the key position of parts can also be treated by pre-plastic deformation, thus the residual stress is reduced and the local properties of the parts is improved.

[REFERENCES]

[1] Nair S V. SiC-reinforced aluminum metal matrix composites [J]. International Materials Reviews, 1985, 30(6): 275-288.

[2] Lloyd D J. Particle reinforced aluminum and magnesium matrix composites[J]. International Materials Reviews, 1994, 39(1): 1-23.

[3] Marschall C W and Maringer R E. Dimensional Instability —an Introduction[M]. New York: Pergamon Press, 1977. 41-50.

[4] Neite G and Mielke S. Thermal expansion and dimensional stability of alumina fiber reinforced aluminum alloys [J]. Mat Sci Eng, 1991, A148: 85-92.

[5] Noyan I C and Cohen J B. Residual Stress Measurement by Diffraction and Interpretation [M]. New York: Springer-Verlag, 1989. 117-125.

[6] Lancu Otto T and Munz Dietrich. Residual stress state of brazed ceramic/metal compounds, determined by analytical methods and X-ray residual stress measurements [J]. J Am Ceram Soc, 1990, 73(5): 1144-1149.

[7] Arsenault R J and Taya M. Thermal residual stress in metal matrix composite [J]. Acta Metall, 1987, 35(3): 651-659.

[8] Ledbetter H M and Austin M W. Internal strain(stress) in an SiC-Al particle-reinforced composite: an X-ray diffraction study [J]. Mat Sci Eng, 1987, 89: 53-61.

[9] JIANG Chuan-hai, WANG De-zun, ZHANG Wen-long, et al. Effect of low temperature treatment on tensile yield strength of SiC$_w$/Al alloy composites [J]. Trans of Nonferrous Met Soc China, 2000, 10(2): 200-203.

[10] JIANG Chuan-hai, WANG De-zun and YAO Zhong-kai. Influence of pre-deformation on thermal residual stress and yield strength of SiC$_w$/Al composites[J]. Trans of Nonferrous Met Soc China, 2000, 10(3): 393-396.

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