Article ID: 1003 - 6326(2004)01 - 0105 - 06

Formation process, microstructure and mechanical property of transient liquid phase bonded aluminium-based metal matrix composite joint ①

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Abstract: The formation process, microstructure and mechanical properties of transient liquid phase (TLP) bonded aluminium-based metal matrix composite (MMC) joint with copper interlayer were investigated. The formation process of the TLP joint comprises a number of stages: plastic deformation and solid diffusion (stage 1), dissolution of interlayer and base metal (stage 2), isothermal solidification (stage 3) and homogenization (stage 4). The microstructure of the joint depends on the joint formation process (distinct stages). The plastic deformation and solid diffusion in stage 1 favoure the intimate contact at interfaces and liquid layer formation. The microstructure of joint consists of aluminium solid solution, alumina particle, Al_2Cu and $MgAl_2O_4$ compounds in stage 2. The most pronounced feature of joint microstructure in stage 3 is the alumina particle segregation in the center of the joint. The increase of joint shear strength with increasing bonding temperature is mainly attributed to improving the fluidity and wettability of liquid phase and decreasing the amount of Al_2Cu brittle phase in the joint. The principal reason of higher bonding temperature (> 600 ℃) resulting in lowering obviously the joint shear strength is the widening of alumina particle segregation region that acts as a preferential site for failure. The increase of joint shear strength with increasing holding time is mainly associated with decreasing the amount of Al_2Cu brittle phase and promoting homogenization of joint.

Key words: metal matrix composite; transient liquid phase bonding; microstructure; mechanical properties
CLC number: TG 404 **Document code:** A

1 INTRODUCTION

The aluminium-based metal matrix composites (MMCs) are advanced materials that have superior properties, especially increased stiffness, high strength, good wear resistance and superior elevated temperature properties. They have received considerable attention as candidates for advanced industrial applications[1, 2]. But, their applications have been severely restricted by the lack of a suitable joining method[3].

Althougth fusion welding methods can be used to join the MMCs, the methods normally tend to result in unfavourable joints because of deteriorating the matrix, the reinforcement particles, and the metal/ceramic interfacial bonds[4, 5]. In comparison with the fusion welding, friction welding and solid diffusion bonding are more suitable for joining MMCs as there are no problems arising from the fusion welding[6, 7]. However, extensive plastic deformation at the bonding interface when using friction welding causes the breakup of reinforcement particles and the poor bond strengths, while solid diffusion bonding fails to produce reproducible bond strengths althougth satisfactory bonds are possible with greater plastic deformation[8]. In recent years, transient liquid phase (TLP) bonding has been applied to join alunminium-based MMCs with some success[9, 10]. The low temperature and pressure required by the TLP bonding process make it potentially suitable for joining aluminium-based MMCs. It has become one of the most active subjects in joining of advanced materials[11-13]. Up to now, the relation between microstructure and mechanical properties of TLP bonded aluminium-based MMC joint has not been fully understood, which has become one of the important factors restricting the property improvement of the joint.

The present work investigates the formation process, microstructure and mechanical properties of TLP bonded aluminium-based MMC joint. Its purposes are to reveal the relation between formation process, microstructure and mechanical property of joint and to provide the theoretical basis for further improving the mechanical properties of the joint.

2 EXPERIMENTAL

The 6061 aluminium-based MMC containing 19.

① **Foundation item:** Project (990241) supported by the Ministry of Education of China
Received date: 2003 - 05 - 30; **Accepted date:** 2003 - 08 - 08
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4% (volume fraction) alumina and the copper interlayer metal with 25 μm thickness were employed in this investigation.

Prior to TLP, the contacting surfaces of MMC base metal specimens (8 mm × 5 mm × 3 mm) were polished using 1 200 grade emery paper, and then the specimens were ultrasionically cleaned in an acetone bath. The copper interlayer was inserted at the joint interface and the test assemblies were fixed in place using a specimen holder. The TLP bonding was carried out in a vacuum furnace maintained at 1.33×10^{-3} Pa. The heating rate between room temperature and bonding temperature was 5 ℃/min and after known holding time at known bonding temperature, the specimens were quenched into water.

The liquid layer width and the copper concentration were measured using the image analyzing system and the energy dispersive X-ray spectroscopy (EDS) unit attached to the scanning electron microscope (SEM), respectively. The microstructures of TLP bonded joint were examined with SEM and X-ray diffractometer (XRD). The shear strength of the joint was determined by the average value over three joint specimen measurements.

3 RESULTS AND DISCUSSION

3.1 Formation process and microstructure of TLP joint

The experimental results show that the formation process of TLP bonded aluminium-based MMC joint comprises a number of stages: plastic deformation and solid diffusion (stage 1), dissolution of interlayer and base metal (stage 2), isothermal solidification (stage 3) and homogenization (stage 4).

3.1.1 Stage 1

Fig. 1 illustrates the initial assembly of joint with 25 μm thick copper interlayer inserted between both MMC base metals before heating. With increasing temperature from room temperature to 500 ℃, there was no evidence of dissolution in the joint, but the thickness of the interlayer decreased from 25 μm to 21 μm (Fig. 2), which means that the plastic deformation on loading occurred in solid heating process. At the same time, the interdiffusion of copper and aluminium across the interfaces is also present in this process, as shown in Fig. 3. As a result, it is called plastic deformation and solid diffusion stage in this article.

On a microscopic scale, surfaces of interlayer and base metal prepared mechanically are rough and the interlayer/base metal interfaces are the contact of points on loading in the initial assembly of joint. The plastic deformation produced in solid heating process is mainly associated with lowering the yield strength

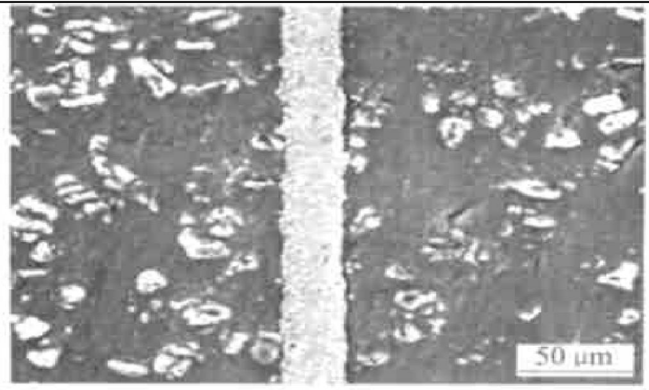

Fig. 1 Initial assembly of joint

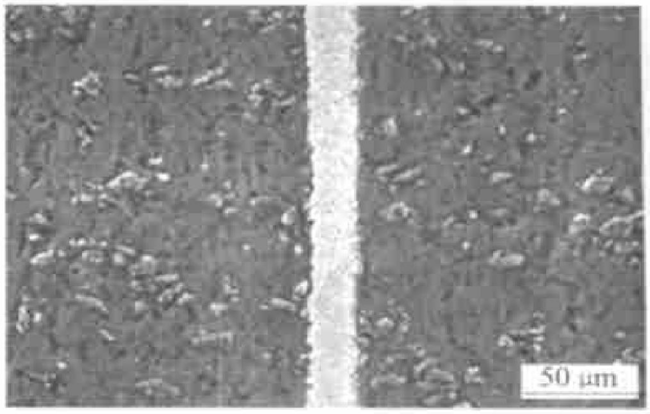

Fig. 2 Microstructure of joint at 500 ℃ for 0 min

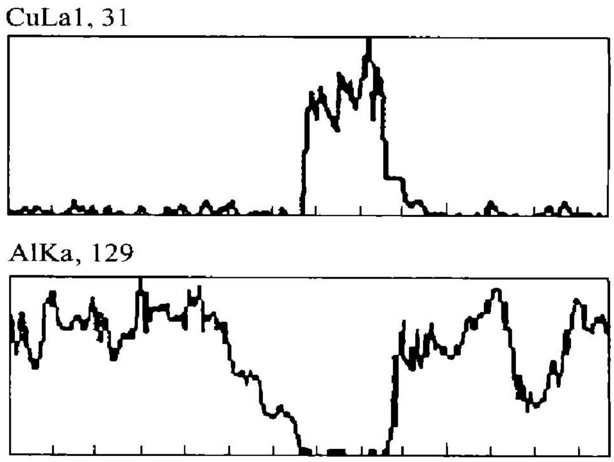

Fig. 3 Cu and Al profiles taken across joint at 500 ℃ for 0 min

at the bonding temperature and applying higher unit pressure on the points of contact for rough surfaces. It will increase the area in contact along the interfaces, result in an intimate contact at the interfaces, and accelerate diffusion bonding.

3.1.2 Stage 2

The most obvious feature of stage 2 is dissolution of interlayer and base metal[14, 15]. When the temperature reaches 550 ℃, the dissolution of copper interlayer occurs and the liquid layer forms, as shown in Fig. 4. The dissolution is so rapid that it is very difficult to observe the process of initial dissolution and as

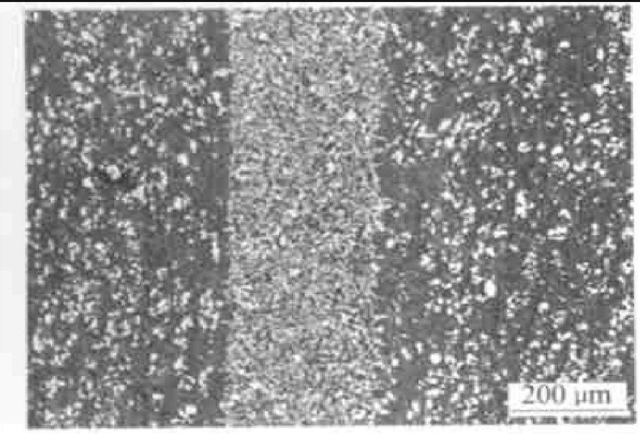

Fig. 4 Microstructure of joint at 550 ℃ for 0 min

can be seen, the liquid layer formed (210 μm) is much wider than original copper interlayer (25 μm). With further increasing temperature from 550 ℃ to 580 ℃ the liquid layer widens from 220 μm to 344 μm (Fig. 5) and the liquid layer reaches the maximum width (380 μm) when the holding time is 20 min at the bonding temperature of 580 ℃. The dissolution of copper interlayer results from the mixing of copper and aluminium at the interfaces by interdiffusion and the liquid layer widening is attributed to base metal dissolution because of the diffusion of copper in solid base metal and liquid layer. Fig. 6 shows the relation between the average copper concentration of liquid layer and the liquid layer width. The average copper concentration decreases from 37.7% to 20.4% with the liquid layer widening from 210 μm to 380 μm. Consequently, the completion of stage 2 can be determined by width and chemical composition of liquid layer.

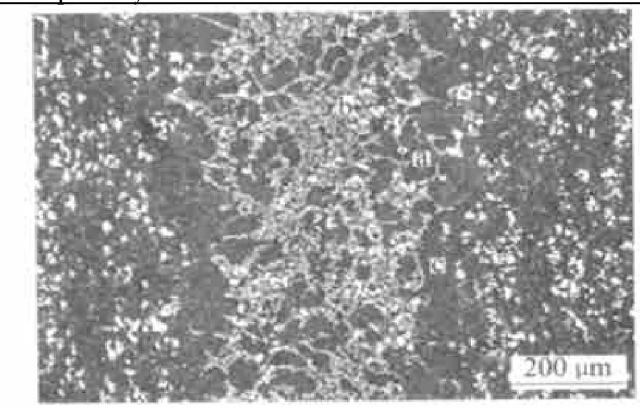

Fig. 5 Microstructure of joint at 580 ℃ for 0 min

In stage 2, the TLP joint is formed by the solidification of liquid layer on cooling to room temperature. From Fig. 5 it can be seen that microstructures of the joint mainly consist of aluminium solid solution, eutectic and alumina particles. XRD and EDS analyses reveal that the black areas (a) in the joint are the Al phase, the dark areas (b) of the eutectic are the Al and Al_2Cu phases, and the small light areas (c) are Al_2O_3 phase. In addition, there exists somewhat $MgAl_2O_4$ phase in the joint, as shown in Fig. 7. The amount of eutectic phases decreased with lowering the average copper concentration.

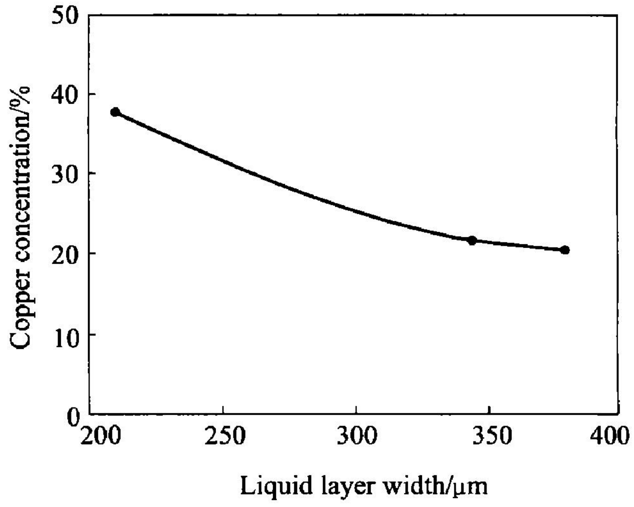

Fig. 6 Relation between average copper concentration and liquid layer width

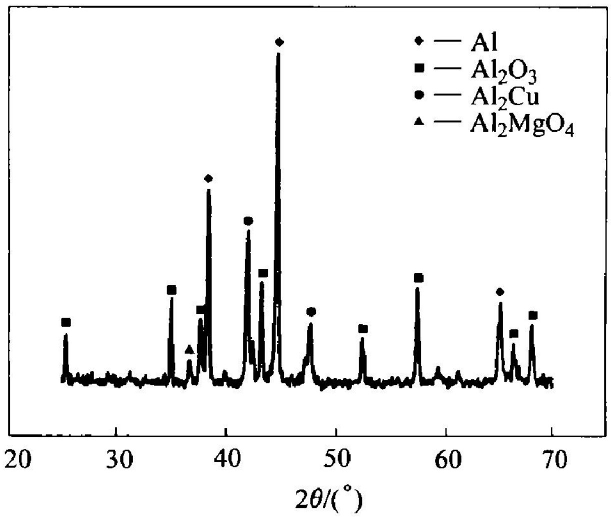

Fig. 7 X-ray diffraction patten of joint

3.1.3 Stage 3

With further increasing holding time from 20 min to 780 min at 580 ℃, the liquid layer width decreases from 380 μm to 0 μm (Fig. 8), which means that isothermal solidification occurs in this stage[14]. Since the isothermal solidification is controlled by the diffusion of copper in solid base metal, the completion time needed is very long.

In stage 3, the TLP joint is formed by isothermal solidification and solidification of liquid layer on cooling to room temperature. The microstructure of isothermal solidification zones immediately adjacent to base metals is mainly comprised of aluminium solid solution and alumina particles, whereas the cooling solidification zone in the center of joint contains not only aluminium solid solution and alumina particles but also eutectic. The amount of the eutectic in the joint decreases obviously compared with that in joint

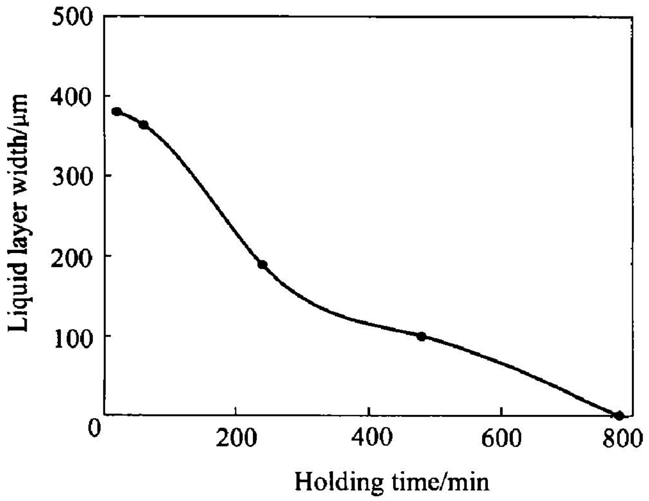

Fig. 8 Relation between liquid layer width and holding time at 580 ℃

produced in stage 2. Therefore, the completion of stage 3 can be determined by the disappearance of liquid layer and eutectic. As can be seen from Fig. 9, the most pronounced feature of the joint microstructure is the alumina particle segregation in the center of joint due to the pushing of particles ahead of the moving solid/liquid interface during isothermal solidification[16]. It is worth pointing out that the expulsion of liquid from the joint interface on loading also has effect on the particle segregation. Since the expulsion of liquid results in decreasing the liquid layer width, it may be one of reasons that there is the marked difference between experimental and calculated completion times for isothermal solidification.

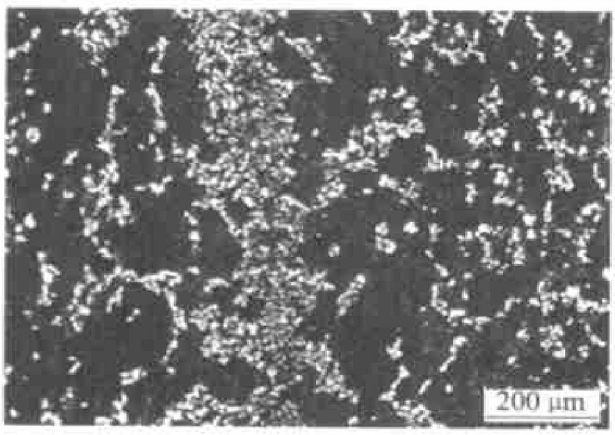

Fig. 9 Microstructure of joint at 580 ℃ for 240 min

3.1.4 Stage 4

After isothermal solidification stage, with further increasing holding time at 580 ℃, the average copper concentration of joint decreases and homogenization of joint occurs. The microstructure of the joint mainly consists of aluminium solid solution and alumina particles which segregate in the center of the joint.

Based on above experimental results, it can be concluded that the microstructures of TLP joint depend on joint formation process (distinct stages) controlled mainly by diffusion in the liquid phase and solid phase, and the factors affecting the formation process will affect not only the microstructure but also the mechanical properties of TLP joint.

3.2 Mechanical property of TLP joint

The experimental results indicate that the bonding temperature and holding time have an obvious effect on the shear strength of TLP bonded aluminium-base MMC joint.

Fig. 10 shows the relation between the joint shear strength and the bonding temperatures for holding time of 30 min. The joint shear strength increases from 68.9 MPa to 91.0 MPa with increasing the bonding temperature from 570 ℃ to 600 ℃ and the higher bonding temperature (> 600 ℃) results in lowering obviously the joint shear strength. Further studies reveal that the width of alumina particle segregation region in joint can be evaluated as a function of the bonding temperature (Fig. 11) and the segregation region acts as a preferential site for failure during shear testing, as shown in Fig. 12.

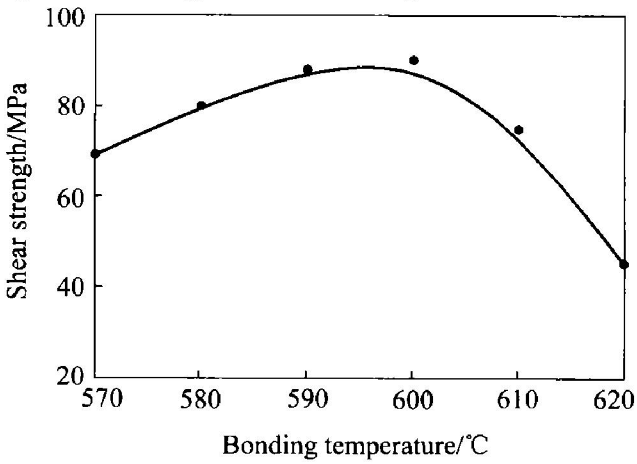

Fig. 10 Relation between joint shear strength and bonding temperature

The increase of joint shear strength with increasing the bonding temperature from 570 ℃ to 600 ℃ is mainly attributed to producing dense microstructure and increasing aluminium solid solution/alumina particle interface strength because of improving the fluidity and the wettability of liquid phase. In addition, it also has relation with decreasing the amount of Al_2Cu brittle phase in the joint. The principal reason of higher bonding temperature (> 600 ℃) resulting in lowering obviously the joint shear strength is the widening of alumina particle segregation region.

Fig. 13 shows the relation between the joint shear strength and the holding time at 600 ℃. The joint shear strength has an increased tendency from 78 MPa to 100 MPa with increasing the holding time from 5 min to 1 350 min, which is mainly associated

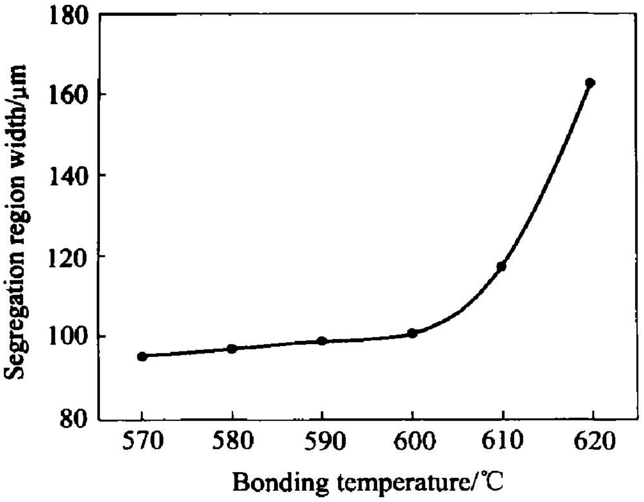

Fig. 11 Relation between segregation region width and bonding temperature

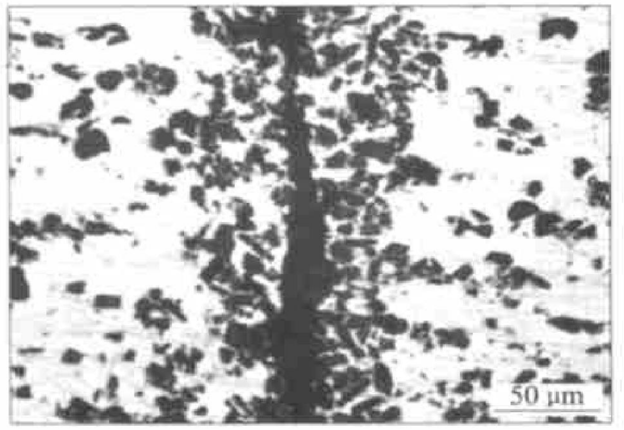

Fig. 12 Failure site of shear specimen

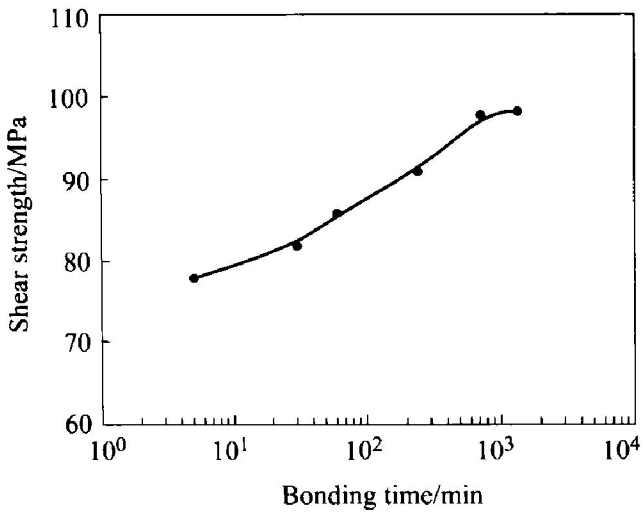

Fig. 13 Relation between joint shear strength and holding time

with decreasing the amount of Al_2Cu brittle phase and promoting homogenization of the joint.

Since the mechanical properties of TLP joint depend on the microstructure of the joint, and the alumina particle segregation and Al_2Cu brittle phase are principal reasons that joint shear strength impairs, it may be an effective way for further improving the mechanical properties of joint to use Cu-Al alloy interlayer in TLP bonding of alumimium-based MMC (It will be introduced in another article).

4 CONCLUSIONS

1) The formation process of TLP bonded aluminium-based MMC joint comprises a number of stages: plastic deformation and solid diffusion (stage 1), dissolution of interlayer and base metal (stage 2), isothermal solidification (stage 3) and homogenization (stage 4).

2) The microstructures of the TLP joint depend on the joint formation process (distinct stages). The plastic deformation and solid diffusion in stage 1 favour the intimate contact at interfaces and liquid layer formation. The joint consists of aluminium solid solution, alumina particle, Al_2Cu and $MgAl_2O_4$ compounds in stage 2, and most pronounced feature of joint microstructure in stage 3 is the alumina particle segregation in the center of the joint.

3) The increase of joint shear strength with increasing bonding temperature is mainly attributed to improving the fluidity and wettability of liquid phase and decreasing the amount of Al_2Cu brittle phase in the joint. The principal reason of higher bonding temperature($>$ 600 ℃) resulting in lowering obviously the joint shear strength is the widening of alumina particle segregation region. The increase of joint shear strength with increasing holding time is mainly associated with decreasing the amount of Al_2Cu brittle phase and promoting homogenization of the joint.

4) Since the alumina particle segregation and Al_2Cu are prinicipal reasons that the joint shear strength impairs, it may be an effective way for further improving the mechanical properties of joint to use Cu-Al alloy interlayer in TLP bonding of aluminium-based MMC.

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(Edited by YUAN Sai-qian)