Article ID: 1003－6326(2004)05－0918－04

Effect of solid fraction on steel-mushy Cu-graphite pressing bonding①

ZHANG Peng(张 鹏)[1], DU Yun-hui(杜云慧)[1], LIU Han-wu(刘汉武)[1],
ZENG Da-ben(曾大本)[2], CUI Jian-zhong(崔建忠)[3], BA Li-min(巴立民)[4]
(1. Department of Mechanical Engineering, Beijing Jiaotong University, Beijing 100044, China;
2. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China;
3. Metal Forming Department, Northeastern University, Shenyang 110006, China;
4. Anshan Automobile Fittings Factory, Anshan 114014, China)

Abstract: The pressing bonding of steel plate to QTi3.5-3.5graphite slurry was studied. The bonding conditions were 620 ℃ for preheating temperature of steel plate, 530 ℃ for preheating temperature of dies, 50 MPa for pressure and 2 min for pressing time. The relationship between the solid fraction of QTi3.5-3.5graphite slurry and the interfacial mechanical property of bonding plate was obtained. The results show that when the solid fraction of QTi3.5-3.5graphite slurry is smaller than 45.8%, the interfacial shear strength of bonding plate increases with the increasing of solid fraction. When the solid fraction is larger than 45.8%, the interfacial shear strength decreases with the increasing of solid fraction. When the solid fraction is 45.8%, the largest interfacial shear strength of bonding plate 127 MPa can be got, and the interface is made up of Fe-Cu solid solution.

Key words: steel-mushy QTi3.5-3.5graphite; pressing bonding; interfacial shear strength; solid fraction
CLC number: TD 146 **Document code:** A

1 INTRODUCTION

The common steel-backed metal matrix bearing is steel-backed Al matrix bearing which mainly includes steel-backed Al-Sn bearing, steel-backed Al-Pb bearing and steel-backed Al-graphite bearing[1-4]. This bearing has perfect property under low load at low temperature[5]. However, under heavy load especially at high temperature, Al matrix whose melting point is 660 ℃ will soften[6], and the property of bearing deteriorates rapidly[7]. This limits the application of steel-backed metal matrix bearing greatly.

Copper alloys such as brass, bronze, have perfect abradability, embedability, high strength and higher melting point (higher than 880 ℃)[8]. Graphite has excellent lubricating property[9]. It is the most common solid lubricant, and its usage temperature can be higher than 400 ℃ without oxidization in the air[10]. It can be seen that steel-backed Cu-graphite composite will be very ideal for heavy-load high-temperature bearing.

Cu-graphite composite with uniform distribution of graphite particles was prepared using semi-solid processing technology[11, 12]. In this work, the pressing bonding of steel plate to QTi3.5-3.5 graphite slurry was conducted. The relationship between solid fraction of QTi3.5-3.5graphite slurry and interfacial mechanical property of bonding plate was established, and the condition for the largest interfacial shear strength was determined.

2 EXPERIMENTAL

The materials used in this experiment were 1.2 mm-thick 08Al steel plate, QTi3.5 and 230 mesh graphite particles (about 60 μm). QTi3.5 is a copper alloy containing 3.5%－4.0% Ti and the total amount of impurities such as As, Sb, Sn, Si, Al, Pb, P, Fe, Bi, Zn, Mn, are less than 0.5%. Its freezing range is 890－1 070 ℃.

The experimental procedures were as follows.

1) Surface treatment of the steel plate. Firstly degrease and descale the surface to get fresh surface. Secondly immerse the surface in aqueous solution of flux (No. 2 flux being patented). The concentration of solution was 7% (mass fraction). The temperature of solution was 90 ℃. The immersing time was 1.5 min. These conditions could form a 25 μm-thick flux layer on the surface of steel plate. This flux layer could prevent the fresh surface from oxidizing at high temperature during preheating. Thirdly stove the steel plate for 2 min at 250 ℃ in order to remove the water in flux layer.

2) Preparation of QTi3.5-3.5graphite (mass fraction) slurry. Electromagnetic-mechanical stirring technique was used to prepare QTi3.5-3.5graphite

① **Foundation item:** Projects (50274047; 50304001) supported by the National Natural Science Foundation of China; project supported by the Beijing Jiaotong University Foundation
Received date: 2004－01－05; **Accepted date:** 2004－04－27
Correspondence: ZHANG Peng, Professor, PhD; Tel: +86-10-51682226; E-mail: zhangp9@263.net

slurry[11]. The precision of solid fraction of slurry was ±0.5%.

3) Conducting steel-mushy QTi3.5-3.5graphite pressing bonding. The experimental equipment is shown in Fig. 1. The pressing equipment was a 100-ton oil hydraulic press. The bonding procedures were as follows. Firstly put the steel plate (620 ℃ of preheating temperature) into the lower die (530 ℃ of preheating temperature). Secondly delivere the QTi3.5-3.5 graphite slurry with required solid fraction onto the steel plate surface in the lower die through the slurry transfer. Ar gas shield must be used to prevent the slurry from oxidization. Thirdly cover the upper die (530 ℃ for preheating temperature) and descend the press head (50 MPa for pressure) to conduct pressing bonding for 2 min. The preheating temperature precision was ±1 ℃. The pressure precision was ±0.1 MPa. The thickness of bonding plate was 4.0 mm.

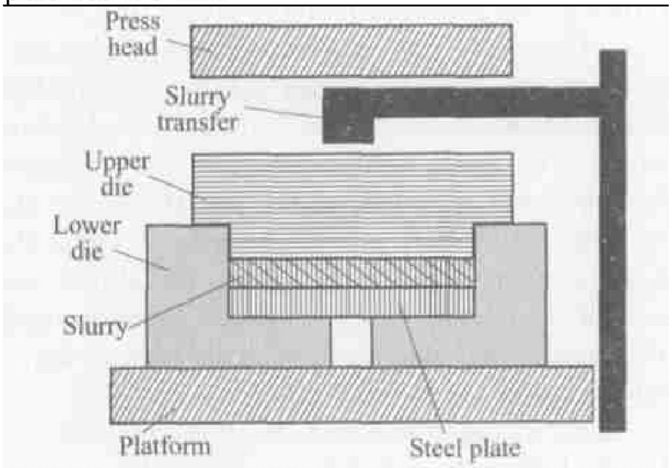

Fig. 1 Sketch of steel-mushy QTi3.5-3.5 graphite pressing bonding

4) Cutting the bonding plate into test samples for interfacial mechanical property experiment using linear cutting method. The samples for interfacial shear strength (as shown in Fig. 2) were sheared on universal material testing machine.

3 RESULTS AND DISCUSSION

3.1 Relationship between solid fraction of slurry and interfacial shear strength

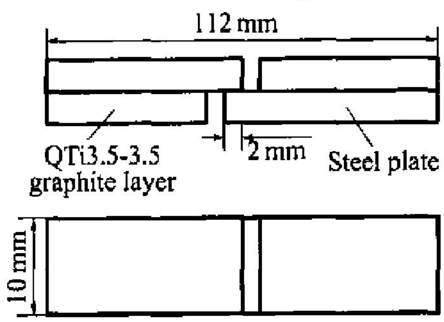

Fig. 2 Testing sample for interfacial shear strength

According to the experimental data, the relationship between solid fraction of QTi3.5-3.5graphite slurry and interfacial shear strength of bonding plate in steel-mushy QTi3.5-3.5 graphite pressing bonding was gotten (as shown in Fig. 3). Using nonlinear theory the regressive equation is obtained as:

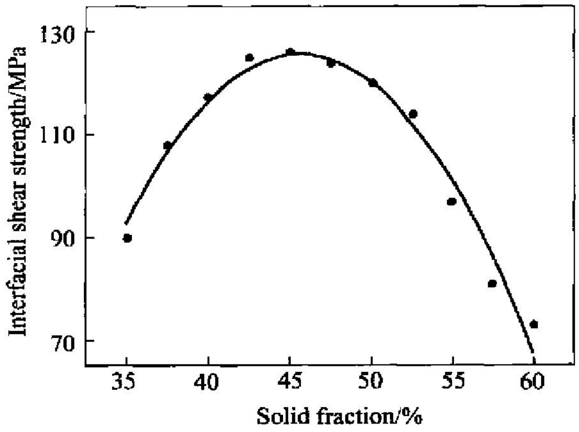

Fig. 3 Relationship between solid fraction and interfacial shear strength

$$S = -468 + 26\varphi_s - 0.284\varphi_s^2 \qquad (1)$$

where S is the interfacial shear strength, φ_s is solid fraction. The regression coefficient R_1 is 0.986 76. This illustrates that the regressive Eqn. (1) has built a correct relationship between solid fraction of QTi3.5-3.5graphite slurry and interfacial shear strength of bonding plate. Let the derivative of Eqn. (1) equal to zero, the condition for the largest interfacial shear strength is gotten: $\varphi_s = 45.8\%$, and the corresponding largest interfacial shear strength is 127 MPa. Therefore, in steel-mushy QTi3.5-3.5graphite pressing bonding, when the bonding parameters are 620 ℃ for preheating temperature of steel plate, 530 ℃ for preheating temperature of dies, 50 MPa for pressure and 2 min for pressing time, the solid fraction of QTi3.5-3.5graphite slurry should be 45.8% in order to obtain the largest interfacial mechanical property. This reasonable technology has been verified through further experiments. The experimental data is shown in Table 1. This interfacial shear strength value (127 MPa) is much larger than that of steel-backed Al matrix bearing (about

Table 1 Experimental data of largest interfacial shear strength

Sample No.	Solid fraction/ %	Interfacial shear strength/ MPa
1	45.8	127.3
2	45.8	126.8
3	45.8	126.6

70 MPa), and the steel-backed Cu-graphite composite is very safe and competent for heavy-load high-temperature bearing.

3.2 Discussion

For steel-mushy QTi3.5-3.5graphite bonding, when QTi3.5-3.5graphite slurry contacts with the steel plate surface, the bonding behaviors such as wetting, spreading, adsorption and diffusion will occur[13]. The inter-diffusion of Cu atoms and Fe atoms will result in the forming of interface which is made up of Fe-Cu solid solution (Fig. 4)[14]. In this experiment, the bonding behaviors such as wetting, spreading and adsorption could be accelerated due to the action of pressing and the flux layer on steel plate surface. However, this flux layer would need some energy to melt and decompose. Therefore, the inter-diffusion of Cu atoms and Fe atoms generated only after the removing of flux layer from the surface of steel plate. When the solid fraction of QTi3.5-3.5graphite slurry was too large (such as larger than 45.8%), the removing of flux layer was restricted because of the lower temperature and the hindering of primary solid particles in QTi3.5-3.5graphite slurry. Thus the inter-diffusion of Cu atoms and Fe atoms did not generate at the whole contact surface, and the remaining flux became an obstacle to steel-mushy QTi3.5-3.5graphite bonding. That is to say the effective bonding area became smaller. The larger the solid fraction, the more the remaining flux, and the smaller the effective bonding area between steel plate and QTi3.5-3.5graphite layer. Therefore, when the solid fraction of QTi3.5-3.5graphite slurry was larger than 45.8%, the interfacial shear strength of bonding plate decreased with the increasing of solid fraction (as shown in Fig. 3).

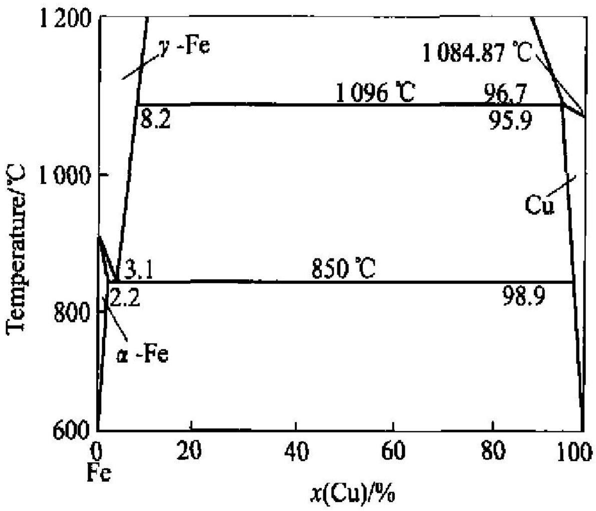

Fig. 4 Fe-Cu binary equilibrium diagram

For the bonding plate which is made up of different materials, the subsidiary stress will generate at the interface because of the difference of physical characters[15]. The subsidiary stress can be approximatively determined as:

$$\sigma = \Delta\alpha \Delta T E_1 E_2 t_1 / [(1-\upsilon)(t_1 E_1 + t_2 E_2)] \quad (2)$$

where σ is the subsidiary stress, $\Delta\alpha$ is the difference of thermal diffusivity, ΔT is the difference of temperature, E is the elastic modulus, υ is Poisson ratio, t is the thickness, subscript 1 and 2 represent the two bonding materials. This interfacial subsidiary stress can decrease the interfacial mechanical property of bonding plate. The larger the subsidiary stress, the lower the interfacial mechanical property. In this experiment, the difference of physical characters, such as expansion coefficient, elastic modulus, thickness and temperature, between steel and QTi3.5-3.5graphite resulted in the subsidiary stress at interface of bonding plate. When the solid fraction of QTi3.5-3.5graphite slurry was too small (such as smaller than 45.8%), the high temperature and the more liquid in QTi3.5-3.5graphite slurry guaranteed the removing of flux layer from the whole interface and the sufficient inter-diffusion of Cu atoms and Fe atoms. However, the larger difference of temperature between steel plate and QTi3.5-3.5graphite slurry resulted in larger interfacial subsidiary stress. The smaller the solid fraction, the larger the difference of temperature, and the larger the interfacial subsidiary stress. Therefore, when the solid fraction of QTi3.5-3.5graphite slurry was smaller than 45.8%, the interfacial shear strength of bonding plate decreased with the decreasing of solid fraction (as shown in Fig. 3).

Only when the solid fraction of QTi3.5-3.5graphite slurry not only ensure moderate inter-diffusion of Fe atoms and Cu atoms but also avoid the large interfacial subsidiary stress, for example, when the solid fraction is about 45.8%, the interfacial shear strength can reach its largest value (as shown in Fig. 3).

Fig. 5 shows the SEM micrograph of interface of bonding plate which is prepared according to the reasonable steel-mushy QTi3.5-3.5graphite bonding technology. The left side is 08Al steel plate, the right side is QTi3.5-3.5graphite layer. In QTi3.5-3.5graphite layer, the white round parts are the primary solid particles and the dark round parts are graphite particles. It can be seen that not only the primary solid particles but also graphite particles distribute rather evenly in QTi3.5-3.5graphite layer. The juncture of steel plate and QTi3.5-3.5graphite layer is the interface. QTi3.5-3.5graphite layer contacts with steel plate rather closely, and there is no defect at the interface. Fig. 6 and Fig. 7 show the line profiles of Cu and Fe at the midst of interface. It can be seen that there is a narrow inter-diffusion zone of Fe atoms and Cu atoms at the interface. Therefore, a firm metallurgical combination forms at the interface of steel-mushy QTi3.5-3.5graphite bonding plate.

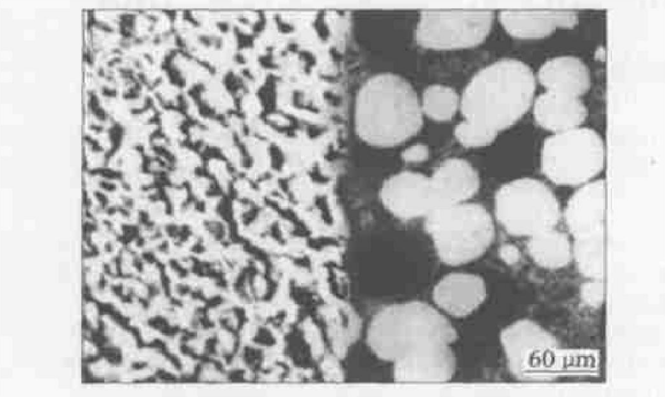

Fig. 5 Interface of bonding plate

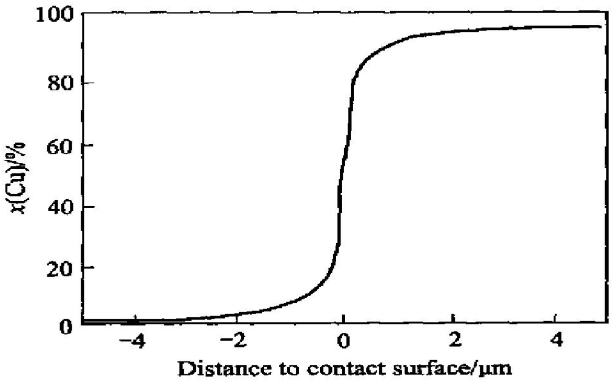

Fig. 6 Cu line profile near interface

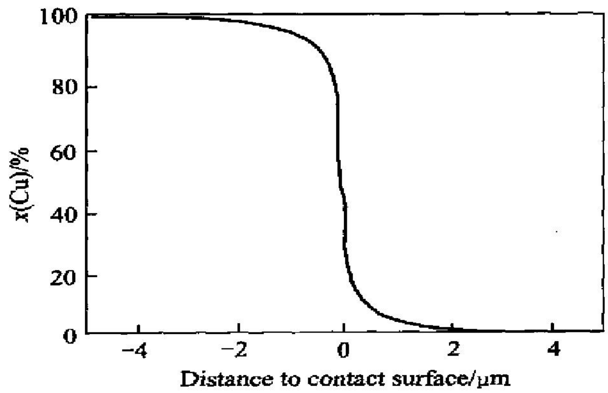

Fig. 7 Fe line profile near interface

4 CONCLUSIONS

1) Steel-mushy QTi3. 5-3. 5graphite pressing bonding is a new and effective technology for preparing steel-backed metal matrix composite.

2) For steel-mushy QTi3. 5-3. 5graphite pressing bonding, when the bonding parameters are 620 ℃ for preheating temperature of steel plate, 530 ℃ for preheating temperature of dies, 50 MPa for pressure and 2 min for pressing time, the relationship between solid fraction of QTi3. 5-3. 5graphite slurry and interfacial shear strength of bonding plate is

$$S = -468 + 26\varphi_s - 0.284\varphi_s^2$$

where S is the interfacial shear strength, φ_s is the solid fraction. When the solid fraction of QTi3. 5-3. 5graphite slurry is 45. 8%, the largest interfacial shear strength 127 MPa can be got. The interface is made up of Fe-Cu solid solution, and a firm metallurgical combination is obtained.

REFERENCES

[1] Kenneth B. Metal Base Composite Material[M]. Beijing: National Defense Industry Press, 1982. 45-68.

[2] ZHANG Peng, DU Yun-hui. Study on steel-mushy Al-20Sn alloy bonding[J]. J Mater Sci Technol, 2001, 17(2): 224-228.

[3] SUN Da-ren. Effects of cooling velocity and lead content on microstructure of cast Al-Pb alloy[J]. Trans Nonferrous Metal Soc China, 1998, 8(1): 142-146.

[4] ZHANG Peng, DU Yun-hui. Study on semi-solid processing of steel-Al-7graphite binding plate[J]. J Wuhan Univ Tech(Mater Sci Ed), 2002, 17(3): 46-49.

[5] ZHANG Huan. Composite Bearing[M]. Beijing: Science Press, 1996. 108-120. (in Chinese)

[6] Davis J R. Aluminum and Aluminum Alloys[M]. OH: ASM International Publications, 1993. 156-162.

[7] WANG Cheng-shou. Bearing[M]. Beijing: China Machine Press, 1986. 56-63. (in Chinese)

[8] ZHE Jiang-sheng. The Welding of Copper and Copper Alloy[M]. Beijing: Chemical Industry Press, 1979. 9-21. (in Chinese)

[9] LI Shi-xian. Graphite[M]. Beijing: Chemical Industry Press, 1991. 11-19. (in Chinese)

[10] Mackay M L. Innovation in powder metallurgy: An engine bearing material[J]. Metal Progress, 1997(6): 32-36.

[11] ZHANG Peng, DU Yun-hui. Study on QTi3. 5-10graphite slurry[J]. Trans Nonferrous Metal Soc China, 2004, 14(1): 148-151.

[12] ZHANG Peng, DU Yun-hui. Preparation QTi3. 5-3. 5graphite lubricant material with semi-solid casting technology[J]. J Mater Sci Technol, 2001, 17(suppl. 1): 155-158.

[13] FANG Jun-xin. Solid Physics[M]. Shanghai: Shanghai Science and Technology Press, 1980. 170. (in Chinese)

[14] LI Long-sheng. Casting Alloy and Melting[M]. Beijing: China Machine Press, 1989. 156-159. (in Chinese)

[15] Nakahashi M, Shirokane M. Bonding of different metals[J]. Composite Trans Jpn, 1986, 12(5): 223-232.

(Edited by YUAN Sai-qian)