DE GRUYTER DOI 10.1515/secm-2013-0136 — Sci Eng Compos Mater 2015; 22(5): 511–515

Peng Li, Jinglong Li*, Jiangtao Xiong, Fusheng Zhang and Li Liang

# Investigations on interface microstructure and strength properties of dissimilar tin bronze/ superalloy diffusion bonded joints

**Abstract:** Diffusion bonding of dissimilar metals QSn4-3 and GH34 by using a QSn6.5-0.1 interlayer has been conducted in this study. The purpose of the study is to investigate the interface microstructure and strength of the joints, and to demonstrate the feasibility of using another high Sn content tin bronze interlayer to fabricate a typical microstructure joint. Microstructure examinations show that a penetration structure is formed by using a QSn6.5-0.1 interlayer, and its feature is apparent. Also, prolonging the holding time is conducive to the forming of the penetration structure. Shear testing results show that the penetration structure formed in a diffusion bonded joint of QSn4-3 and GH34 enhances the joint strength to almost the same as the QSn4-3 base metal. The mechanism forming the penetration structure is as follows: Sn atoms diffuse faster than Cu atoms into GH34 causing more Sn atoms to aggregate at the GH34 grain boundary. When the bonding temperature reaches 950°C for a short time, the aggregated Cu alloys having higher content of Sn than 5.3wt.% will melt, and penetrate and disrupt some grains from GH34 base metal.

**Keywords:** diffusion bonding; dissimilar joint; interface microstructure; interlayer; penetration structure.

---

***Corresponding author: Jinglong Li,** State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, P.R. China; and Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, P.R. China, e-mail: lijinglg@nwpu.edu.cn
**Peng Li:** State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, P.R. China; and Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, P.R. China
**Jiangtao Xiong, Fusheng Zhang and Li Liang:** Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, P.R. China

## 1 Introduction

Tin bronze has been found to have wide applications in aerospace and chemical industries due to its excellent heat conduction and wear resistance. Steel is widely used as a structural material for its superior mechanical properties and comparatively low price. In some cases, bonding them together to form a bimetallic component that benefits from both of their advantages, is a vital necessity for engineering applications in space, aviation, nuclear, automobile and rail industries. The plunger pump of an aircraft engine, the heat exchanger, dynamic pressure bearing and the first wall of the International Thermonuclear Experimental Reactor [1–3], are examples.

Joining copper alloy to steel has been investigated using several methods such as brazing [4], friction welding [5], explosive welding [6], fusion welding [7] and diffusion bonding [8–10], Of these methods, diffusion bonding has been widely used and its effectiveness has been successfully demonstrated in other dissimilar metals.

However, Cu-Fe is a typical immiscible system which needs a high bonding temperature and a long holding time to form a bond, but as the strength of a direct bonded joint achieves up to one third of the strength of copper alloy, the joint cannot meet the requirements for commercial specializations. In order to further improve the joint strength and thereby meet the constantly increasing demands of Cu-Fe bimetallic components, new manufacturing concepts and technologies could be introduced. Recently, researchers found that using an interlayer between the two metals, a penetrative structure could form on the steel side that can significantly enhance the joint strength [11, 12]. The core of this method is that the lower melting point components within the interlayer could aggregate and form liquid phase at the grain boundaries of the steel base. Based upon the above analysis, our research used a widely recognized tin bronze and superalloy to form a sound joint, with the intention of providing some ideas on dissimilar metal component fabrication, especially for copper-steel couples.

This investigation reports on vacuum diffusion bonding of dissimilar metals using tin bronze (QSn4-3) and superalloy (GH34). The main objective of this work is to evaluate the interface microstructure and strength of the joints, to demonstrate the feasibility of using another high Sn content tin bronze interlayer to form a typical microstructure joint and discuss the joining mechanism.

**Table 1** Chemical composition of GH34 (wt.%).

| Material | C | Fe | Cr | Ni | W | Mo | V | Mn | Si | P | S |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GH34 | 0.16–0.24 | Bal. | 2.4–3.3 | ≤0.50 | 0.3–0.55 | 0.35–0.55 | 0.60–0.85 | 0.25–0.60 | ≤0.40 | ≤0.03 | ≤0.02 |

## 2 Materials and methods

Commercially available tin bronze (QSn4-3 type) and a typical superalloy (GH34 type) were used as base metals for bonding, machined into 20 mm×10 mm×5 mm and 40 mm×10 mm×5 mm blocks, respectively. The interlayer was tin bronze foil (QSn6.5-0.1 type), 100 μm thick. The chemical compositions of the metals are listed in Tables 1 and 2. The samples were polished, ultrasonically cleaned in ethanol, and dried in air. A series of four samples were assembled in the sequence of QSn4-3/QSn6.5-0.1/GH34 as shown in Figure 1, and loaded into a vacuum diffusion bonding furnace (FJK-2, Northwestern Polytechnical University, Xi'an, China) under pressure of 10 MPa. When the vacuum reached $4.5\times10^{-3}$ Pa, the temperature was raised to 950°C and samples from each series subjected to this temperature for 15 min, 30 min, 1 h and 3 h, respectively, for comparison tests. The selections of the bonding process parameters were based on the literature relating to the diffusion bonding of several Cu-Fe couples [8, 10, 13, 14], and on results of a prior trial of the diffusion bonding process. The samples were cooled down in the furnace. After bonding, the samples were cut, ground and polished for metallographic examination and the shear strengths of the joints evaluated by a testing machine (Instron 3382, Instron, MA, USA) at a crosshead speed of 0.5 mm/min.

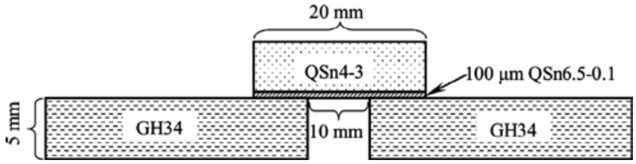

**Figure 1** Assembly of the bonded joint.

## 3 Results and discussion

### 3.1 Direct diffusion bonding interface examination and joint strength evaluation

Figure 2 shows the evolvements of interfacial microstructure of the direct bonding joints bonded under different conditions. Figure 2A shows the microstructure of joint at 950°C, 1 h, 10 MPa, where it is observed that a common flat interface was formed between the two base metals. When the holding time is increased to 3 h, the joint interface changes to a rough structure, as shown in Figure 2B. This interface, which appears like a "saw tooth wave" could produce a small interlocking effect between the base metals and lead to some enhancement of the joint strength [15]. The shear strength testing shows that by increasing the holding time, the joint strength reaches about 182 MPa, which remains too weak for commercial application. Moreover, the physical and chemical properties of QSn4-3 base metal are sharply altered as a 3 h holding time at 950°C is too long for a Cu alloy. In addition, dimensional accuracy as well as the strength of the joints is affected by creep deformation and grain coarsening of the Cu alloy. Therefore, when using the indirect bonding method, it is proposed that to enhance joint strength, the longer holding times should be avoided.

**Table 2** Chemical composition of QSn4-3 and QSn6.5-0.1 (wt.%).

| Materials | Cu | Sn | Zn | P | Pb | Fe |
|---|---|---|---|---|---|---|
| QSn4-3 | Bal. | 3.5–4.5 | 2.7–3.3 | ≤0.03 | ≤0.02 | ≤0.05 |
| QSn6.5-0.1 | Bal. | 6.0–7.0 | 0.30 | 0.1–0.25 | 0.02 | ≤0.05 |

### 3.2 Indirect diffusion bonding interface examination and joint strength evaluation

Figure 3 shows the interface microstructures of the joints bonded for different holding times by using a QSn6.5-0.1 interlayer. It can be seen that the width of diffusion zone grows rapidly as the holding time increases. The joint interface in Figure 3A, at 15 min holding time is relatively smooth compared to longer holding times. When the holding time exceeds 30 min a choppy joint interface is seen, where some dispersed oxide impurities were formed between the base metals and the original interfaces of interlayer with the two base metals disappears. This is shown in Figures 3B and 3C.

It was noted that the tin bronze penetrated into GH34 base and disrupt some grains (the largest size is about 20 μm) from the GH34 base, which we named as

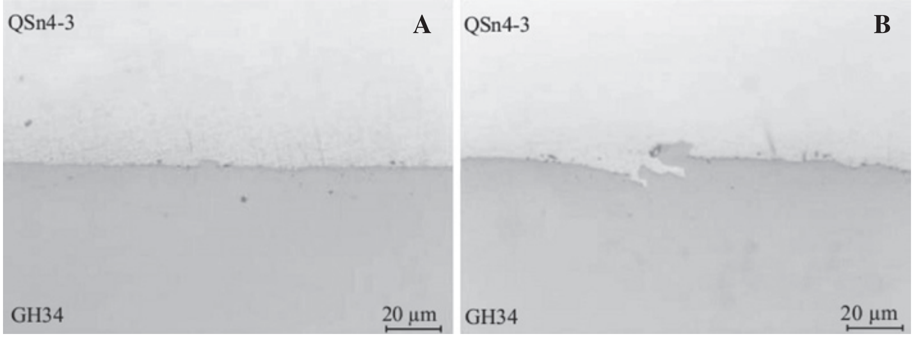

**Figure 2** Interface microstructure of the joints bonded at 950°C, 10 MPa for (A) 1 h and (B) 3 h.

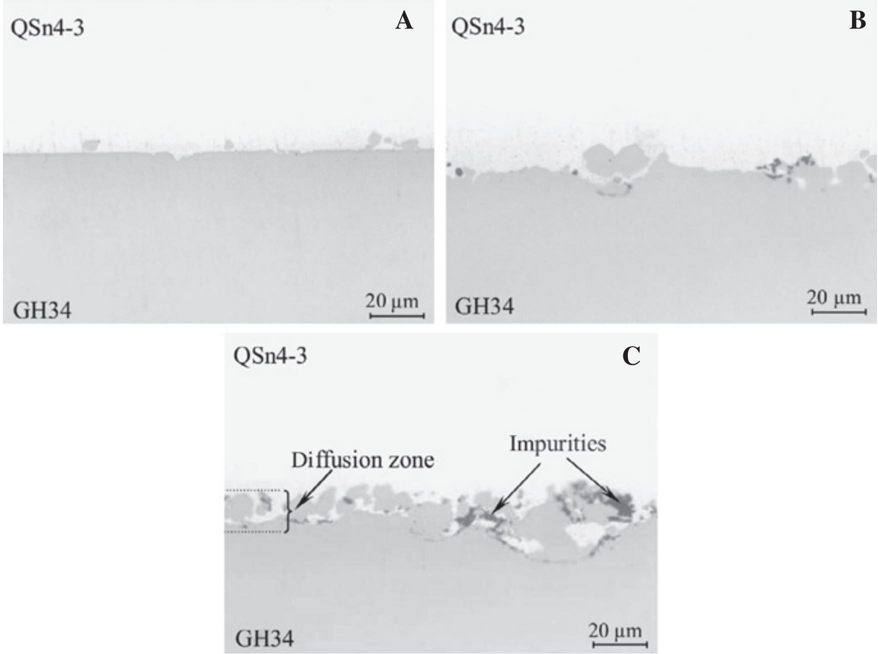

**Figure 3** Interface microstructure of the joint bonded at 950°C, 10 MPa with a QSn6.5-0.1 interlayer for (A) 15 min, (B) 30 min and (C) 1 h.

"penetration structure". This penetrating phenomenon forms a strong interlocking effect that contributes to joint strengthening. This contrasts with direct bonding joints, when a penetration interface structure can be achieved at a shorter holding time (30 min) by using the QSn6.5-0.1 interlayer, with joint strengthening being apparent. The shear testing result shows that the strength of the indirect bonding joint bonded at 1 h reaches 220 MPa, which is almost the same as that of QSn4-3 base metal.

## 3.3 Mechanism of formation of the penetrations structure

It is well known that the mutual diffusion of the base metal plays the most important role in the diffusion bonding process. And the diffusion coefficient, $D$, of the element obeys Arrhenius law

$$D=D_0\exp(-Q/RT) \tag{1}$$

$D_0$ is the pre-exponential factor, $Q$ is the activation energy, $R$ is the gas constant and $T$ is the absolute temperature.

In the case of a bonding temperature of 950°C, the pre-exponential factor $D_0$ and the activation energy $Q$ for Cu in Fe is 0.19 cm$^2$/s and 272.6 kJ/mol, and for Sn in Fe is 0.845 cm$^2$/s and 261.7 kJ/mol, respectively [16]. Thus, the diffusion coefficient for Cu in Fe ($D_{\text{Cu-Fe}}$) is $4.32\times10^{-13}$ cm$^2$/s, and for Sn in Fe ($D_{\text{Sn-Fe}}$) is $5.61\times10^{-12}$ cm$^2$/s. It can be seen that $D_{\text{Sn-Fe}}$ is greater than $D_{\text{Cu-Fe}}$, and Sn atoms can diffuse faster into GH34 than Cu atoms. In addition, it is easier to migrate into grain boundaries than into grain bodies for

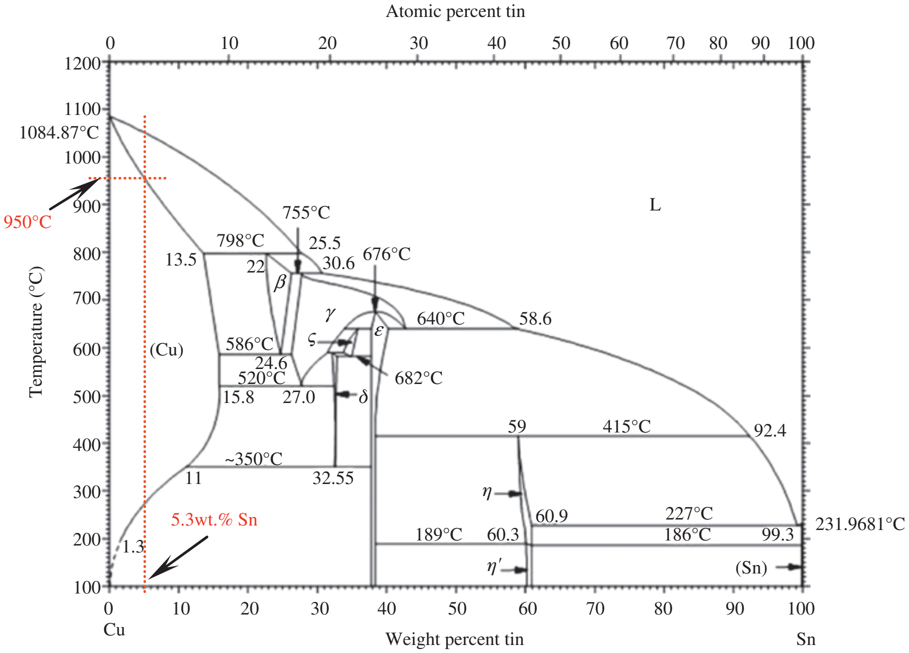

**Figure 4** Cu-Sn binary phase diagram [17].

the atoms. As the holding time increased, more Sn atoms will aggregate at the GH34 grain boundaries, so the Sn content of Cu alloys which aggregate at the GH34 grain boundaries are higher than that of QSn4-3.

Figure 4 shows the Cu-Sn binary phase diagram, which indicates that the solidus temperature for Cu-5.3wt.% Sn alloy is 950°C. In the discussion, the aggregated Cu alloys in the GH34 grain boundaries may have lower solidus temperature than 950°C due to the higher content of Sn. From this, the forming mechanism of the penetration structure can be deduced. When the bonding temperature reaches 950°C for a short time, the Cu alloy's liquid phase will form at the boundaries and then penetrate and disrupt some grains from GH34 base metal, which makes the joint interface uneven. This phenomenon will also appear at longer holding times without an interlayer, to a limited extent.

## 4 Conclusions

On the basis of the results obtained, we can conclude that a penetration interface structure can be achieved at a holding time of 30 min at 950°C by using a QSn6.5-0.1 interlayer, and results in joint strengths that can reach as high as the QSn4-3 base metal. When the bonding temperature is 950°C for this time, the aggregated Cu alloys having a higher Sn content than 5.3wt.% will melt and disrupt some of the grains of the GH34 base metal forming the penetration structure. Prolonging the holding time to 3 h at 950°C is conducive to forming a penetration structure but cannot be applied to direct bonding as the temperature for this duration can be detrimental to the base metals.

**Acknowledgments:** This work is supported by the National Natural Science Foundation of China (Grant No. 51071123), and the fund of the State Key Laboratory of Solidification Processing in Northwestern Polytechnical University, China (Grant Nos. 43-QP-2009 and 31-TP-2009) and 111 Project (B08040). The authors would like to thank Professor A.Vairis for English language polishing.

Received June 7, 2013; accepted March 5, 2014; previously published online April 4, 2014

## References

[1] Yilmaz O, Çelik H. *J. Mater. Process. Technol.* 2003, 141, 67–76.
[2] Kalinin GM, Abramov VY, Gervash AA, Zolotarev VB, Krestnikov NS, Mazul IV, Strebkov YS, Fabritsiev SA. *J. Nucl. Mater.* 2009, 386–388, 927–930.
[3] Leedy KD, Stubbins JF. *Mater. Sci. Eng. A* 2001, 297, 10–18.
[4] Nishi H, Kikuchi K. *J. Nucl. Mater.* 1998, 258–263, 281–288.
[5] Kimura M, Kusaka M, Kaizu K, Fuji A. *Sci. Technol. Weld. Joi.* 2010, 15, 590–596.

[6] Durgutlu A, Gülenç B, Findik F. *Mater. Design* 2005, 26, 497–507.

[7] Mai TA, Spowage AC. *Mater. Sci. Eng. A* 2004, 374, 224–233.

[8] Sabetghadam H, Zarei HA, Araee A. *Mater. Charact.* 2010, 61, 626–634.

[9] Batra IS, Kale GB, Saha TK, Ray AK, Derose J, Krishnan J. *Mater. Sci. Eng. A* 2004, 369, 119–123.

[10] Nishi H, Araki T, Eto M. *Fusion Eng. Des.* 1998, 39, 501–511.

[11] Xiong JT, Xie Q, Li JL, Zhang FS, Huang WD. *J. Mater. Eng. Perform.* 2012, 21, 33–37.

[12] Kozlova O, Voytovych R, Devismes MF, Eustathopoulos N. *Mater. Sci. Eng. A* 2008, 495, 96–101.

[13] Yilmaz O, Aksoy M. *J. Mater. Process. Tech.* 2002, 121, 136–142.

[14] Yilmaz O. *Mater. Sci. Tech.* 2001, 17, 989–994.

[15] Magnabosco I, Ferro P, Bonollo F, Arnberg L. *Mater. Sci. Eng. A* 2006, 424, 163–173.

[16] Gerhard N, Cornelis T, Eds., *Self-diffusion and Impurity Diffusion in Pure Metals: Handbook of Experimental Data*, 1st ed. Pergamon Materials Series, Pergamon: Oxford, UK, 2008.

[17] ASM Handbook, *Vol 3 Alloy Phase Diagrams*, ASM Intnl: Materials Park, OH, USA, 1992.