

Effect of Enhanced Atomic Diffusion on Microstructure Evolution of Heterogeneous Friction Welded Joints

Yanni Wei^{1,*} and Fu Sun²

¹Department of Materials Science and Engineering, Xi'an University of Technology, 5 South Jinhua Road, Xi'an 710048, P.R. China

²Shaanxi Zhituo Solid-State Additive Manufacturing Technology Co., Ltd., 70 west of chaoyang street, Weinan 714000, P.R. China
Email: weiyanni@xaut.edu.cn

Abstract. In this paper, the dissimilar pure metal diffusion couples with different metallurgical compatibility (Cu/Ni miscible couple, Mg/Ti immiscible couple) were designed and a physical simulation apparatus of rotation friction welding was used to investigate the diffusion of the heterogeneous interface during severe plastic deformation. The experimental results showed that an interface layer which presented the gray gradient transition characteristics appeared at Cu/Ni interfaces. The diffusion rate was calculated and was 10^4 times of that of thermally activated at the same temperature for Cu/Ni couple. The enhanced diffusion was also observed on the Mg/Ti friction welded joints. The diffusion coefficients under different strain rate were obtained and the phenomenological law between diffusion coefficient and strain rate were analysed. A linear relationship between diffusion coefficient and strain rate was obtained.

1. Introduction

The joining of dissimilar metals has always been a hot topic in modern manufacturing industry [1]. A sound joint may provide interesting combinations of structural and functional properties [2]. Friction welding (FW) is the most promising method to join dissimilar materials. In previous works, dissimilar metals such as Al/Fe [3], Al/Ti [4], Al/Cu [5], and Ti/Fe [6] of the friction welding have been carried out by many researchers. It is generally known that the materials near the joint have simultaneously encountered high temperature ($0.5 \sim 0.7 T_m$) and severe plastic deformation (SPD) (strain rate $10 \sim 1000s^{-1}$) during FW process [7]. The metallurgical interactions on the heterogeneous interface during the SPD of FW are critical for the joint strength and stability, which has become a key issue in the field of friction welding research [8-9]. In particular, the diffusion behaviour has a very important significance on the understanding of the metallurgical bonding mechanism, since it is the smallest scale of dynamic behaviour.

The phenomenon of the deformation promoting the diffusion has been concerned by Balluffi et al in 1963 [10]. Since then, it was found in the process of the mechanical alloying [11], accumulated rolling welding and friction stir welding [12] and a series of SPD process. Experimental data show that the diffusion coefficient is $10^3 \sim 10^8$ times of the thermal activation diffusion under the condition of same temperature, which called superdiffusion in physics. There were two perspectives on the generation mechanism of the superdiffusion generally. Xu et al [13] think that the surge of vacancy defects in the process of SPD is the primary reasons of super-diffusion. Another perspective suggests that the deformation process is a ballistic relocation of atoms and independent of temperature. Bellon and Odunuga et al [14~15] proposed the analytical expressions of ballistic activated diffusion coefficient with the aid of richardson marked particle in fluid mechanics, as thus given by:



$$D_b = \frac{C'}{3\pi} bR \dot{\epsilon} \quad (1)$$

Among them, the D_b , b , R is the ballistic diffusion coefficient, burgers vector and the atom spacing on both sides the dislocation respectively, C' is a constant related to the system. These conclusions are well tested and verified based on molecular dynamics and monte carlo method in numerical simulation at the same time [16~17]. However, the physics mechanism of superdiffusion during the friction welding process and its influence on joint microstructure evolution has not been clarified.

In this paper, the dissimilar pure metal with different metallurgical compatibility (Cu/Ni miscible couple, Mg/Ti immiscible couple) were designed and a physical simulation apparatus of rotation friction welding was used to investigate the interface diffusion during processing of SPD provided by FW. The phenomenological law between diffusion coefficient and strain rate were analysed. The effects of superdiffusion on joint microstructure evolution were analysed.

2. Experimental procedure

Commercially available bars of Cu (99.9 wt. %), Ni(99.9 wt. %), Mg(99.95 wt. %) and Ti(99.7 wt.%) were used. The specimens were machined with a dimension of 20 mm in joining part and 14 mm in clamping part. The rotation friction welding process was carried out on a physical simulation apparatus which shown in Figure 1. During the friction welding operations, the rotation speeds of friction welding was 1900rpm for Cu/Ni and 1200rpm for Mg/Ti couple, the different axial pressure was used as 20, 28, 36, 44, 52 MPa, with friction time 5s. In the meanwhile, the interface temperature was observed by the thermocouple embedded in the fixed bar 1.5mm from the interface.

After joining, the welded sample for metallographic examination was cut perpendicular to the welding interface. The samples were subjected to metallographic characterization employing scanning electron microscopy (SEM, JEOL, JSM-6700) equipped with an energy-dispersive spectrum (EDS) and transmission electron microscope (TEM, JEM-3010).

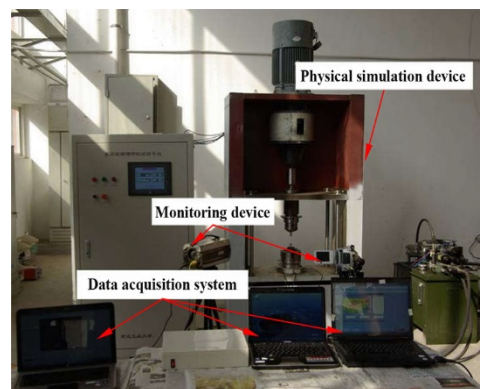


Figure 1. The real time illustration

3. Results and discussion

3.1 The morphologies of joint cross section

The defects free joints were obtained by the friction welding simulation experiments. The typical interface morphology of Cu/Ni and Mg/Ti rotary friction welding joints were shown in Figure 2. The Cu/Ni interface shows the gray gradient transition characteristics with a thickest diffusion layer, as shown in Figure 2a. This reflects the coupling effect of thermally activated and deformation activated diffusion in this miscible alloy systems. For Mg/Ti joints, the good bonding on the interface was formed although the interface transition region was not obvious as shown in Figure 2b.

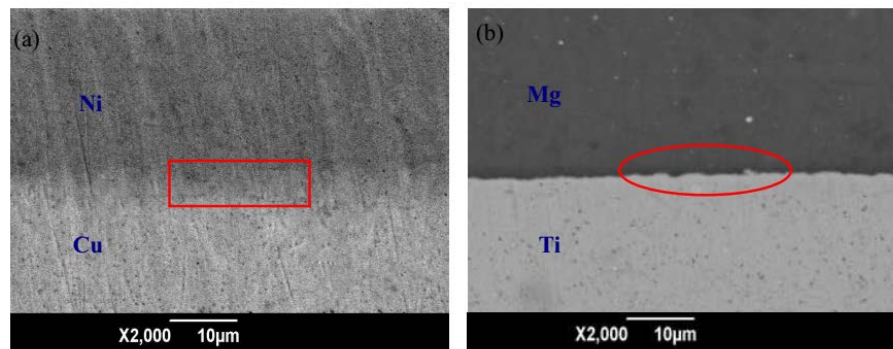


Figure 2. The typical interface morphology of joint: (a) Cu/Ni; (b) Mg/Ti

3.2 The superdiffusion in the SPD process of FW

3.2.1 The atom concentration distribution. In order to obtain more detailed microstructures of the interfacial transition layer, the images of larger magnification were used and the line scan and point scanning component analysis across the interface were been detected. Figure 3 shows the typical micro-morphology and the concentration profiles of elements of the Cu/Ni joining interface. Figure 3a and 3c show the detailed microstructures by SEM and TEM. The interface shows gradient transition characteristics in gray scale with different element content. A continuous solid solution was formed between Cu and Ni element. Figure 3b and 3d show the compositions and the concentration profiles of Cu and Ni element across the interface by EDS measurements with the electron beam diameter about 25 nm. The scanning positions and path were shown in Figure 3a. The composition analysis shows an obvious interdiffusion between Cu and Ni element occurs during FW process. The compositions obtained by point scan were consistent with the concentration profiles across the interface obtained by line scan, as shown in Figure 3a. The interdiffusion layer width could be roughly calculated according to concentration profiles, with the 8~10% content of solute elements as starting position of the measurement. Figure 4 shows the typical micro-morphology and the concentration profiles of elements of the Mg/Ti joining interface. The micro-morphology of Mg/Ti couples shows obvious interfaces in SEM image, as shown in Figure 4a. Further analysis obtained by TEM proved the existence of atomic diffusion in Mg/Ti joining interfaces. The microstructures of Mg/Ti interface present more clear boundaries in Figure 4b.

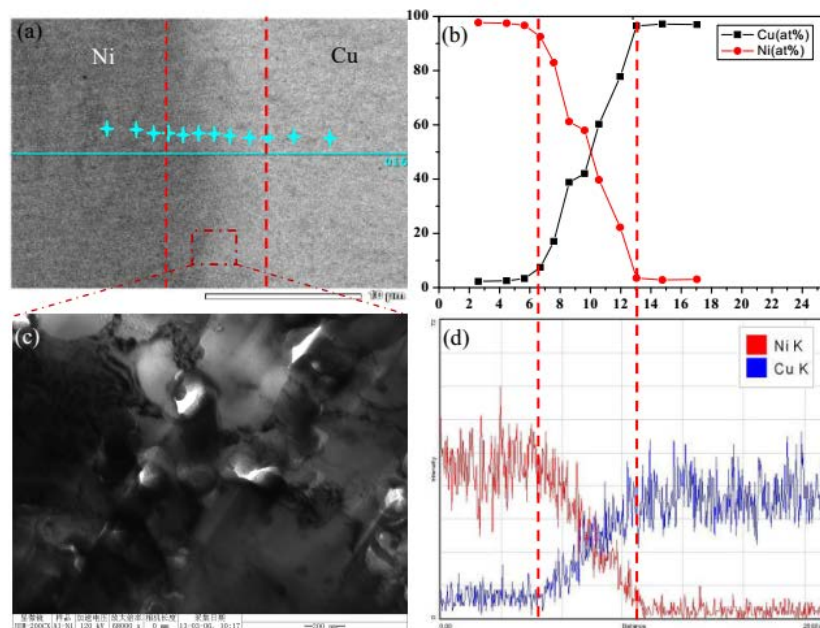


Figure 3. The microstructures and qualitative analysis of Cu/Ni interface: (a) SEM image; (b) composition; (c) TEM image; (d) line scanning results

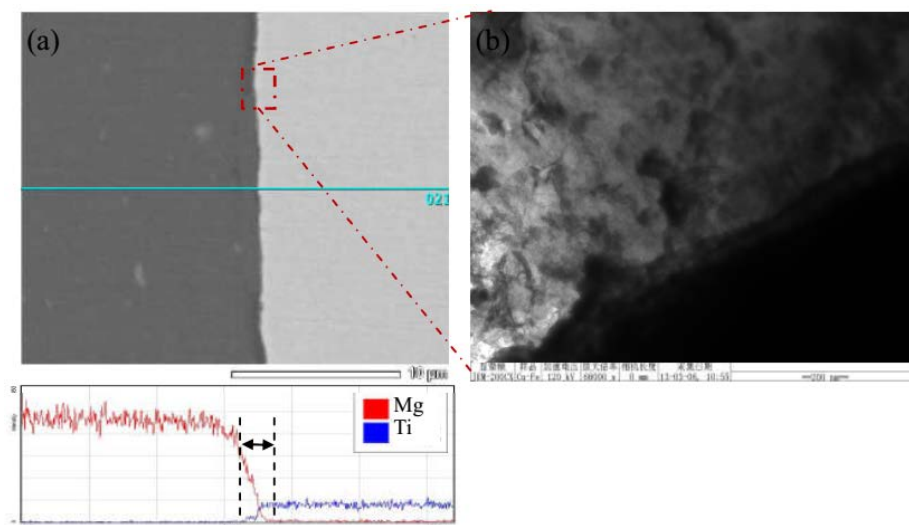


Figure 4. The morphology and qualitative analysis of Mg/Ti interface: (a) SEM and (b) TEM image

3.2.2 The interface temperature and the strain rate of the plastic region. During the FW process, the temperature of the interface region during the FW process was detected by the thermocouple embedded in the fixed bar 1.5mm from the interface. The temperature curves have an unsteady ascent stage and then become relatively stable stage. The average temperatures (shown in Table 1) were regarded as the diffusion temperature used in the calculation below. The strain rate of diffusion region was calculated according to the friction welding thermal coupling analytical model in references [18].

3.2.3 The interdiffusion coefficient of heterogeneous friction welding interface. It is reasonable that the atomic mixing during the severe plastic deformation may be enhanced by the following three factors during the FW process: increase of temperature due to plastic deformation and shear friction; a reduction in atomic diffusion distance by microstructural refinement; and an increase in the density of lattice defects such as vacancies, dislocations and grain boundaries. When the surface concentration

constant in the Semi-infinite diffusion couple. The relation between the diffusion distance, x , and interdiffusion coefficient, D , is generally described for a given period of time, t , as Eq. (2) [19]:

$$x = \sqrt{Dt} \quad (2)$$

According to the Eq (2), the interdiffusion coefficients and the strain rate under different parameters for Cu/Ni and Mg/Ti systems were calculated, as shown in Table 1.

Table 1. The diffusion coefficient, strain rate and average temperature for Cu/Ni and Mg/Ti couples

Diffusion	Strain rate (s^{-1})	Average temperature ($^{\circ}C$)	Diffusion coefficient ($10^{-12}m^2/s$)
Cu/Ni	878	607	1.99
	1087	612	2.09
	1429	634	3.24
	1969	645	4.11
	2803	659	6.01
	708	392	0.79
Mg/Ti	959	415	1.17
	1180	427	1.36
	1484	438	1.62
	1705	450	2.03

It can be seen that as the strain rate increases, the interdiffusion coefficient is continuously increasing. By fitting the data in Table 1, the curve of the interdiffusion coefficient as a function of strain rate is obtained as shown in Figure 5.

By analyzing the effect of different strain rate on the thermal-mechanical coupled diffusion coefficient D_s of Cu/Ni, Cu/Fe and Mg/Ti, a linear relationship of the form $y=A+Bx$ between D_s and strain rate was obtained. By extrapolating this formula, the contribution of thermally activated diffusion during friction severe deformation can be estimated when the strain rate is equal to zero. In other words, the first part A in the formula presents the thermally activated diffusion coefficient D_t' . The second part Bx can be considered as the contribution of deformation activated diffusion.

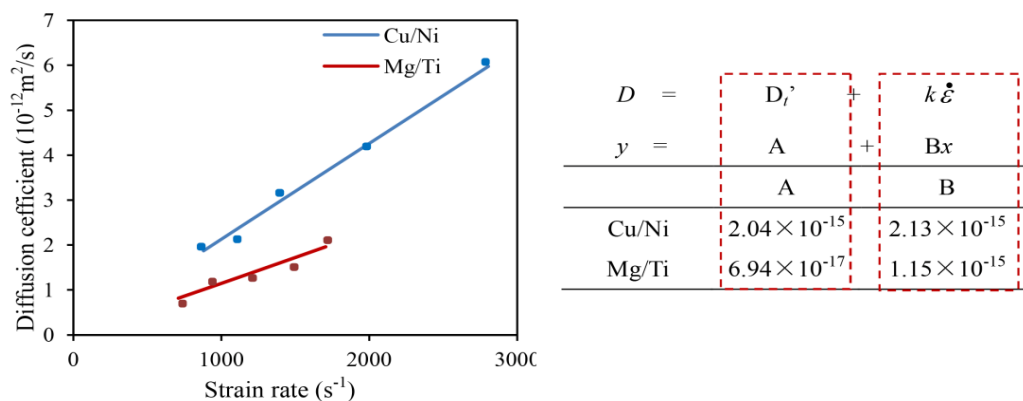


Figure 5. Interdiffusion coefficients as a function of strain rate and the fitting coefficient

From the perspective of non-equilibrium thermodynamics, the thermal-mechanical coupled diffusion process can be regarded as a driven system in a nonlinear non-equilibrium state. The dislocation-related micro-regions can be dealt with as a non-equilibrium steady-state based on the local equilibrium hypothesis. The new defect in deformation results in the arrangement of atomic space more disorder, but the heat activated diffusion induce the arrangement of atoms tends to be ordered. Under the influence of this pair of contradictory and mutually offsetting factors, the moving speed of the movable defects (mainly dislocations) in the micro system is kept constant, while the

temperature and strain rate remains constant in the macro system. Therefore, the movement speed, v , of defects (particularly dislocations) is proportional to the deformation activation diffusion, D_b , it can be expressed as:

$$D_b = k_1 v \quad (3)$$

where k_1 is the proportionality constant. In addition, since the relationship between v and strain rate can be expressed as [20]:

$$\dot{\varepsilon} = b \rho_m v \quad (4)$$

where b and ρ_m are the Burgers vector and the moving dislocation density, respectively. The expression of D_b can be obtained by substituting Eq. (4) into Eq. (3):

$$D_b = \frac{k_1}{b \rho_m} \dot{\varepsilon} \quad (5)$$

Comparing Eq. (1) with Eq. (6), it can be found that the deformation activation diffusion, D_b , is proportional to strain rate despite the differences in the representation of the proportional constants, which shown as:

$$D_b = k_2 \dot{\varepsilon} \quad (6)$$

where k_2 is the proportionality constant. Based on the thermal-mechanical coupled diffusion law of the Cu/Ni and Mg/Ti systems in Figure 5, it can be found that their diffusion coefficient D_s and strain rate follow the linear distribution although the systems have different metallurgical compatibility. This thermal-mechanical coupled superdiffusion actually involves thermal activation diffusion and deformation activation diffusion. And the presence of a linear additive relationship indicates that the existence of two types of diffusion in thermal-mechanical coupled superdiffusion is a linear combination. Therefore, the superdiffusion coefficient D_s can be expressed as:

$$D_s(T, \dot{\varepsilon}) = D_t' + D_b = D_t'(T) + k_2 \dot{\varepsilon} \quad (7)$$

4. Conclusions

The defects free joints were obtained by the friction welding simulation experiments. The interface of the Cu/Ni appears thickest diffusion layer with the gray gradient transition characteristics. The enhanced diffusion was also observed on the Mg/Ti friction welded joints. The diffusion coefficients under different strain rates were obtained.

A linear relationship between the thermo-mechanical diffusion coefficient and strain rates was obtained. This thermal-mechanical coupled diffusion actually involves thermal activation diffusion and deformation activation diffusion. A theoretical model of atom diffusion in the SPD interface of friction welding was established.

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