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PAPER

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To cite this article: Hanwei Tian *et al* 2018 *Mater. Res. Express* **5** 126505

IOP Publishing Mater. Res. Express 5 (2018) 126505 https://doi.org/10.1088/2053-1591/aadfbe

Materials Research Express

RECEIVED
29 June 2018

REVISED
31 August 2018

ACCEPTED FOR PUBLICATION
7 September 2018

PUBLISHED
19 September 2018

PAPER

Numerical simulations of the Cu/Al composite plate continuous cast-rolling process

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Keywords: Cu/Al composite plate, cast-rolling forming, numerical simulation, pouring temperature, casting speed, temperature field

Abstract

A two dimensional steady state laminar flow model was established using finite volume software to study the effects of rolling speed and melt pouring temperature on the bonding performance of a copper/aluminum composite plate manufactured using a cast-rolling process. The boundary conditions were optimized in two aspects by writing C language programs. Meanwhile, outlet temperature was measured by thermocouple in the experiment, the maximum error of the simulation and experiment was 2.8%, so the reliability of the simulation analysis was verified. The study found that semi-solid/solid contact time and rolling reduction percentage are the key factors affecting bonding, with pouring temperature and rolling speed changing which factor plays a leading role. The calculated results show that the optimal pouring temperature and casting speed are 963 K and 0.5 m min^{-1}, respectively. Processing under these conditions results in semi-solid/solid contact time of 2.2 s and rolling reduction of 40% based on simulation results, with experimental peeling strength of 86 N mm^{-1}. Optical images of surface morphology after peeling show that the failure mechanism of the Cu/Al composite plate is plastic and brittle fracture. This study provides guidance for optimizing cast-rolling processing parameters.

1. Introduction

Multi-layer metal composites offer chemical, mechanical, and physical properties that may not be found in single metal materials. This is especially true for the laminated copper/aluminum (Cu/Al)composite, which is widely used in electrical power transmission and communications equipment due to its low weight, high thermal conductivity, and low electrical resistance [1–4]. However, defects formed at the Cu/Al interface cause deterioration of physical and electrical properties, reducing the advantages of the composite. Cu/Al composites are commonly manufactured using a solid-solid, liquid-liquid, or solid-liquid bonding process. In solid-solid bonding, solid Cu and Al layers are pressed together, which creates weak mechanical interfacial locking and requires annealing treatment to increase atomic diffusion and reaction diffusion [5–7]. In liquid-liquid bonding, the Al melt and Cu melt interact and solidify, creating a thick transition layer as well as Al_2Cu, Al_4Cu_9, and AlCu brittle intermetallic compounds, which reduce peeling strength and electrical conductivity [8, 9]. In solid-liquid bonding, aluminum melt flows onto and solidifies on the surface of solid copper, which not only ensures the mutual diffusion of copper and aluminum atoms, but also creates high bond strength [10, 11]. A popular method for solid-liquid bonding of Cu/Al is cast-rolling, which is a combination of twin-roll casting and high-temperature roll bonding.

To find conditions for optimal metal bonding, research has turned to simulations utilizing computer-generated models. Zhi *et al* [12] used finite element analysis to simulate roll-plate and thermo-mechanical coupling heat transfer after studying the mechanisms of interfacial heat transfer and the heat transfer characteristics at high temperature gradient interfaces during aluminum rapid casting. A two-dimentional

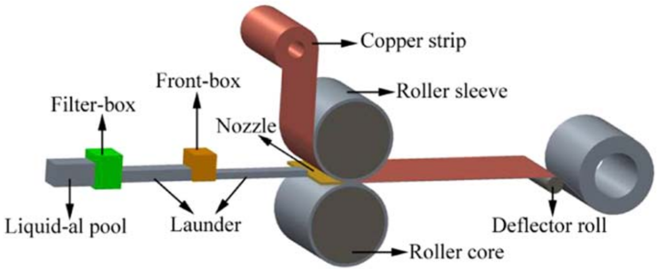

Figure 1. Process of preparing the Cu/Al composite plate by horizontal twin-roll casting.

finite-element simulation of the system 'clad strip –water cooled rolls' using the ANSYS software is proposed by M. Stolbchenko *et al* [13], the impact of operational and geometrical parameters of twin-roll casting on the thermal-strain conditions of aluminium-steel clad strips formation was studied, whose analysis is concrete and can provide beneficial references for us. However, some experiences should be done to certificate the reliability of the simulation. Xu *et al* [14] studied the cast-rolling process of steel-aluminum composites through numerical simulation as well as experimentation and discussed the influence of pouring temperature and casting speed on material properties. These simulations have been important for improving material processing, however, they can be enhanced with the addition of more accurate boundary conditions. Cu/Al composite plate were prepared using cast-rolling technique by Huang *et al* [10] with a $d160$ mm*150 mm twin-roll caster, the laws of interface evolution were summarized, and the extent of interfacial reactions and types of intermetallic compounds were investigated with SEM, DES and XRD, they provide an economical way to fabricate Cu/Al composite plate directly. However, it is fewer study about the influence of technological parameters on the Cu/Al bonding. In addition, the technological parameters of horizontal casting rolling and vertical casting rolling are quite different due to gravity. Therefore, this paper mainly studies the influence of technological parameters on horizontal cast-rolling.

In this paper, finite volume analysis software is used to establish a two-dimensional steady state model for the Cu/Al cast-rolling process. The boundary conditions are optimized by establishing thermal resistance formula and C language program, and the reliability of the simulation is verified by thermocouple measurement. Using this model, the aluminum melt temperature, the speed of the cast-rolling process, and the contact area of the copper sheet and the upper roll as well as the contact area of the aluminum cast and the lower roll are optimized.

2. Experiments and simulations

2.1. Experimental process

The horizontal twin roll caster used for making the Cu/Al composite is shown in figure 1. The 40 mm thick sleeve of each roll is cooled with a water flow rate of 200 t/h. The inner drum diameter is 920 mm, the roller gap is 10 mm, and the width of each roller is 1030 mm. A sheet of commercially available treated copper is uncoiled and fed directly into the twin roll caster without further preparation. However, the aluminum undergoes multistep processing since it must be delivered onto the copper sheet as a liquid. An aluminum ingot is first melted. Then, the aluminum melt enters the filter box for removal of impurities. After this, the clean aluminum melt enters the front box and remains for several minutes for slag deposition and temperature control. The melt then enters the nozzle, which allows liquid aluminum to be drawn into the twin roll caster along with the treated copper sheet. When the high temperature aluminum melt and the copper sheet enter the rolling area, liquid cooled rollers solidify the Al melt, bonding it to the solid Cu [15].

2.2. Physical models

Heat transfer in the cast-rolling process occurs in three ways: conduction, convection and radiation, and the energy conservation equation is as follows:

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{E}) + \nabla \cdot [\vec{v}(\rho \mathrm{E} + \mathrm{p})] = \nabla \cdot \left[\mathrm{k_{eff}} \nabla \mathrm{T} - \sum_{\mathrm{j}} h_{\mathrm{j}} \vec{J}_{\mathrm{j}} + (\overline{\tau}_{\mathrm{eff}} \cdot \vec{\mathrm{v}}) \right] + \mathrm{S_h} \tag{1}$$

where k_{eff} is the effective thermal conductivity and $\vec{J}_j$ is the diffusion flux of the material j. The first three items on the right side of the equation represent the conductive heat transfer, material diffusion and viscous dissipation. S_h isdefined as any volume heat source.

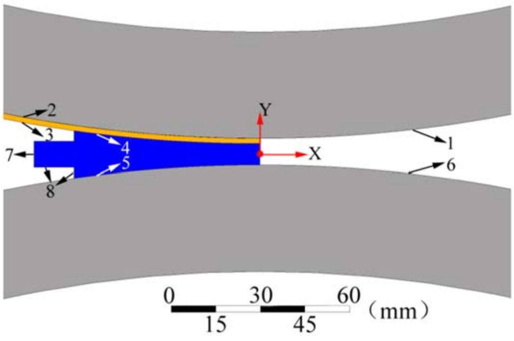

Figure 2. Horizontal cast-rolling geometry model of Cu/Al composite plate.

Table 1. Thermal physical material parameters.

	T, K	300	673	873	923	930	1073
1050Al	$c/(\mathrm{J \cdot kg^{-1} \cdot k^{-1}})$	906	1075	1429	42 100	1172	1173
	$\lambda/(\mathrm{w \cdot m^{-1} \cdot k^{-1}})$	225	218	205	158	90	94
	$\mu/(\mathrm{kg \cdot m^{-1} \cdot s^{-1}})$	100	100	8.323	1.002	0.001 33	0.000 997
		ρ, $\mathrm{kg \cdot m^{-3}}$		c, $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$		λ, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	
Roll sleeve		7830		560		31	
Copper T2		8920		386		398	

The finite volume software were used to create a simulation of the Cu/Al laminate composite cast-rolling process. The aluminum melt in the rolling area was treated as a viscous incompressible fluid, and the deformation of the copper sheet during the cast-rolling process was ignored [16, 17]. The laminar, solidification, and melting models were applied, and the semi implicit method of pressure coupling equations was chosen, the contact between each domain was set as coupling contact, and the boundary in contact with air was set to adiabatic wall [18].

2.3. Geometrical model

Figure 2 is the horizontal cast-rolling geometry model of the Cu/Al laminate, which is divided into the upper roll, copper sheet, aluminum melt, and lower roll regions [13]. The contact areas of the four regions are represented as points 1–6. Points 1 and 2 are the contact areas between the upper roll and the copper sheet, points 3 and 4 are the contact areas of the copper sheet and aluminum melt, and points 5 and 6 are the contact areas of the aluminum melt and the lower roll. The thickness of the copper sheet is 2 mm, and the length of the aluminum cast-rolling zone is 70 mm. Points 7 and 8 indicate the boundary of the aluminum melt inlet and the nozzle, respectively. The coordinate origin is on the outlet boundary of the cast-rolling zone.

2.4. Material parameters

For the simulation and experiment, 1050Al was used for aluminum, T2Cu was used for copper, and 32Cr3Mo1V was used for the material of the rolls. The thermal-physical parameters of the materials are calculated with JMatPro software, using chemical compositions given by GB/T3190-1996 (shown in table 1) [19, 20]. The latent heat is 397.92 $\mathrm{J \cdot g^{-1}}$, c is the specific heat coefficient ($\mathrm{J \cdot kg^{-1} \cdot k^{-1}}$), λ is thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot k^{-1}}$), and μ is viscosity ($\mathrm{g \cdot m^{-1} \cdot s^{-1}}$).

2.5. Boundary conditions optimization

Contact between the copper sheet and the upper roll is described as solid-solid. However, thermal contact resistance, surface roughness, the heat conduction medium, and the interface pressure are important factors affecting heat transfer between the two mediums. Thermal contact resistance is influenced by various factors, and mechanical surface interaction is difficult to fully model. Due to the limitations of software and theoretical research, all factors are converted into air gap thickness to measure during boundaries [20]. The formula is shown as follows:

$$R = \frac{\delta}{\lambda} = \frac{1}{k} \tag{2}$$

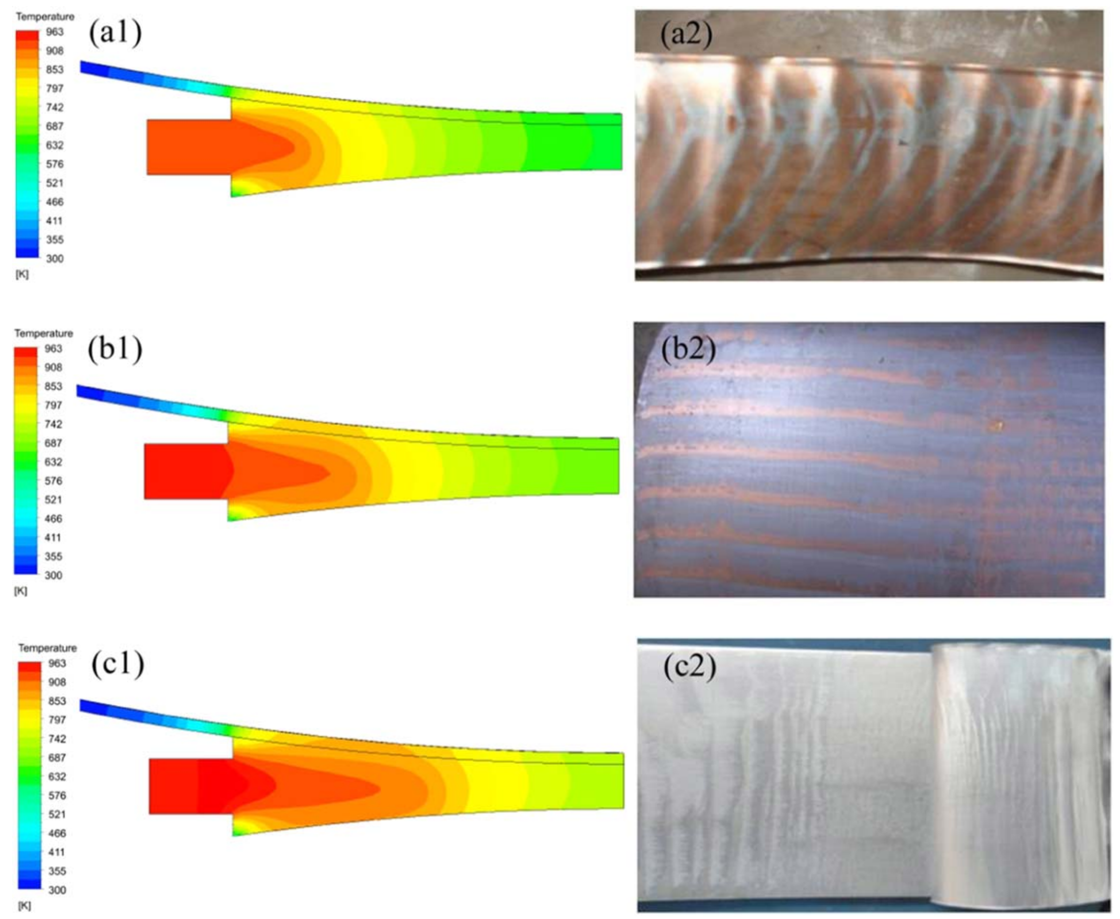

Figure 3. Distribution of temperature fields and physical drawings at different pouring temperatures at 0.5 m · min^{-1} rolling speed, (a)923 K; (b) 943 K; (c) 963 K.

$$\delta = \frac{\lambda}{k} \tag{3}$$

The δ and k are the air gap thickness during boundaries and the interface heat transfer coefficient respectively. R is the contact thermal resistance and λ is the thermal conductivity of the air.

Zhi *et al* [12] proposed that the interface thermal resistance of the casting zone and rolling zone is 8.33e–5 $\text{m}^2 \cdot \text{k/W}$ and 6.67e–5 $\text{m}^2 \cdot \text{k/W}$, respectively. In practical application, the interface thermal resistance is gradually reduced from the casting zone to the rolling zone. In order to model the contact of the cast-rolling zone and lower roll, this paper assumes that the contact thermal resistance in the cast-rolling zone behaves linearly. If the origin and coordinate points are the same as the geometric model coordinates in figure 2, the starting and ending coordinates of contact between the cast-rolling zone and lower roll are (8.33e-5, −8.9) and (6.67e-5, −4), respectively. The linear equation for contact thermal resistance is shown as equation 4, which was inserted into Fluent as a user defined function (UDF) by compiling C language.

$$R = 5.31 \times 10^{-5} - y \times 3.4 \times 10^{-6} \tag{4}$$

3. Results and discussion

3.1. Pouring temperature effects on Cu and Al bonding

The simulated and experimented effects of Al pouring temperature on Cu/Al solidification during cast-rolling are shown in figure 3. With Al pouring temperatures of 923 K, 943 K, and 963 K and a casting speed of 0.5 m min^{-1}, the coordinates of complete solidification are (−62.25, 0.71), (−57.52, 0.16), and (−51.7, −0.42), respectively. As pouring temperature is increased, these coordinates gradually move to the outlet and below of the cast-rolling zone, the proportion of liquid phase area increased gradually, it is beneficial for copper atoms to get energy and migrate, increased atomic diffusion of Cu and Al, enhanced metallurgical bonding, which can reduce the process of heat treatment. Moreover, longer liquid phase area helps to increase flow and grain refinement. The contact thermal resistance of the copper sheet and the upper roll is larger than that of the cast-

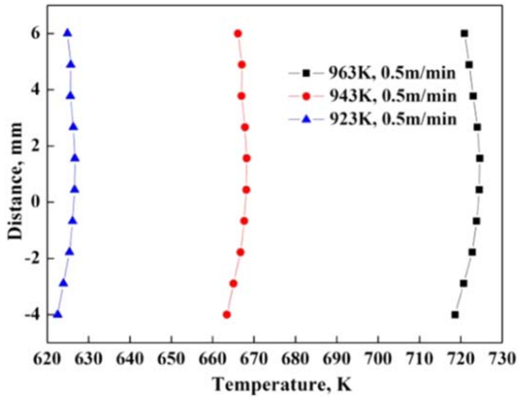

Figure 4. Simulated outlet temperature curves with varying pouring temperature.

Table 2. Comparison between measurement and simulation results.

Pouring temperature, K	Simulation, K	Measurement, K	Error, %
923	626	641	2.3
943	667	680	1.9
963	722	743	2.8

rolling zone and the lower roll, which results in low heat transfer speed. However, the high thermal conductivity of the copper sheet causes accelerated Al solidification near the Cu due to rapid heat transfer after initial Al/Cu contact. When pouring temperature and casting speed is 963 K and 0.5 m $\min^{-1}$, respectively, the area ratio of casting zone and rolling zone is moderate, which makes the heat and rolling force play a full role, the Cu/Al composite plate has better shape and bonding strength.

Simulated outlet temperature curves with varying pouring temperature are shown in figure 4. When the pouring temperature is increased from 923 K to 943 K, the outlet temperature increases by about 40 °C, and when the pouring temperature is increased from 943 K to 963 K, the outlet temperature increases by about 60 °C, When the pouring temperature is higher, the average outlet temperature varies greatly with the pouring temperature. The uniform temperature distribution at the outlet is beneficial to the later cooling treatment, which can also reduce the stress concentration caused by thermal expansion and contraction at the interface of Cu/Al composite plate, and debase the casting-rolling stress and cracking of the clad plate. To verify model accuracy, the temperature at the Al/Cu interface at the twin-roll outlet was physically measured by a thermocouple. The measured data compared with simulation results are shown in table 2.

Figure 5 shows the effect of different Al casting temperatures on the semi-solid/solid contact time and the rolling reduction percentage. The semi-solid/solid contact time is calculated as the time of contactbetween the aluminum meltand the copper sheetbeforecompleteAl solidification. When the pouring temperature is 923 K, the semi-solid/solid contact time is 0.9 s, which is too short foradequate Cu/Al atomic diffusion. In addition, the rolling reduction rate is 49%, which leads to uneven wrinkling and bulging of the Cu/Al composite during rolling as shown in figure 3(a2). When the pouring temperature is 963 K, the semi-solid/solid contact time is 2.2 s, which allows for full attomic diffusion. The rolling reduction rate is 40%, which produces mechanical occlusion formation as seen on the physical sample in figure 3(c2) as well as improved metallurgical bonding. Because the second derivative of the curve of contacting time is greater than 0, the change of contact time at high temperature is larger than that at low temperature. Thus, as pouring temperature is increased, semi-solid/solid contact time is a dominant factor in bonding Cu and Al.

3.2. Rolling speed effects on Cu and Al bonding

The simulated effects of rolling speed on Cu/Al solidification during cast-rolling are shown in figure 6, with corresponding temperature curves shown in figure 7. It is seen that increased rolling speed causes overall temperature to rise significantly. When rolling speed is increased from 0.3 m $\min^{-1}$ to 0.5 m $\min^{-1}$, the outlet temperature increases by about 105 °C. When the rolling speed is increased from 0.5 m $\min^{-1}$ to 0.8 m $\min^{-1}$, the outlet temperature increases by about 163 °C. According to the coordinates established in figure 2, complete

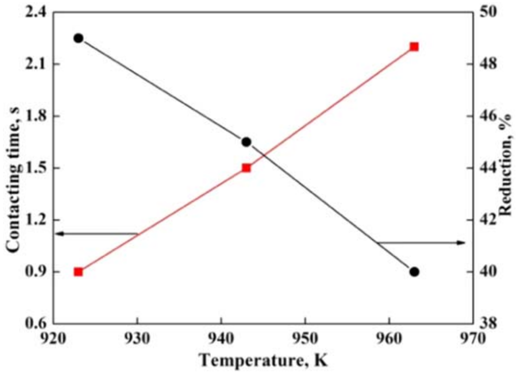

Figure 5. The effect of Al casting temperature on semi-solid/solid contact time and material reduction percentage.

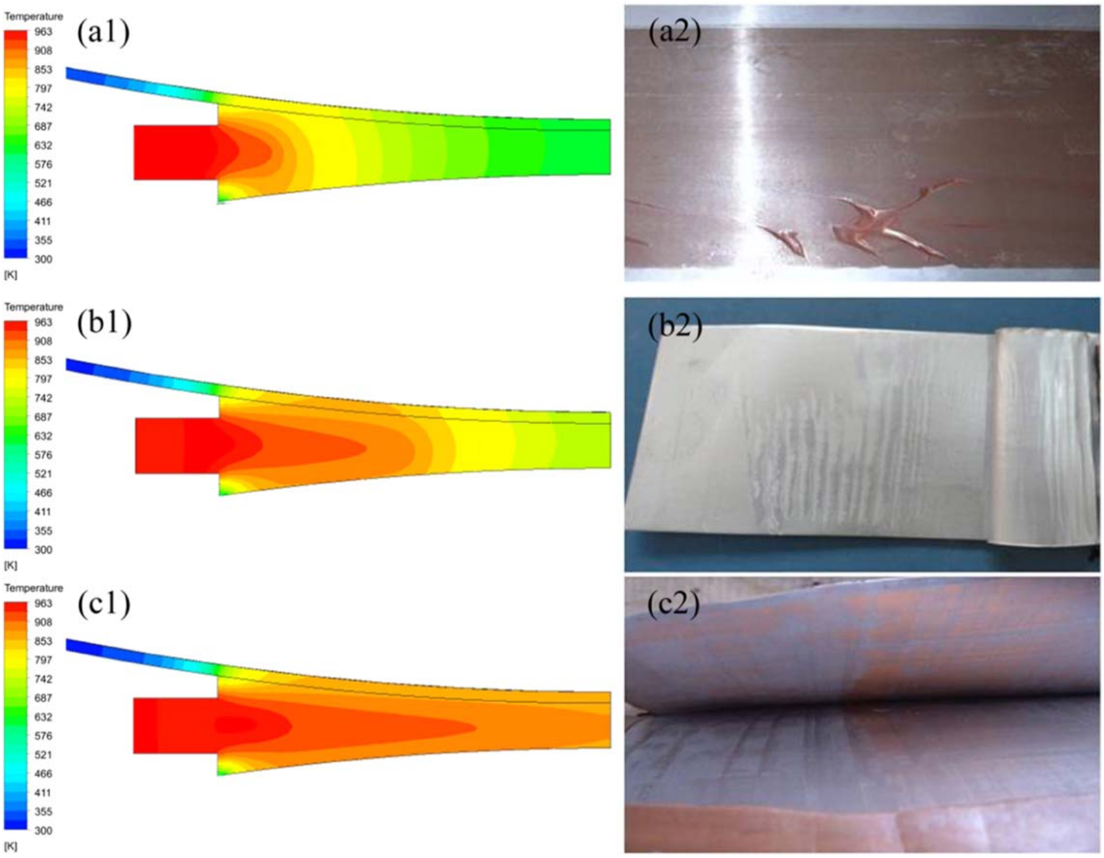

Figure 6. Temperature distribution and physical samples at different rolling speeds with 963 K pouring temperature, (a) 0.3 m $\min^{-1}$; (b) 0.5 m $\min^{-1}$; c) 0.8 m $\min^{-1}$.

solidification occurs at (−62.02, −0.27), (−51.7, −0.42) and (−37.6, −0.53) with rolling speeds of 0.3 m $\min^{-1}$, 0.5 m $\min^{-1}$, and 0.8 m $\min^{-1}$, respectively.

Physical samples created with different rolling speeds are shown in figures 6(a2), (b2) and (c2), and the effect of different rolling speed on semi-solid/solid contact time and material reduction percentage is shown in figure 8. Since the length of the cast-rolling zone upper boundary is 70.23 mm, the total contact time of the copper sheet and cast-rolling zone is 14 s, 8.4 s, and 5.4 s with rolling speeds of 0.3 m $\min^{-1}$, 0.5 m $\min^{-1}$ and 0.8 m $\min^{-1}$, respectively. When the rolling speed is 0.3 m $\min^{-1}$, the semi-solid/solid contact time is 1.6 s even though the total contact time is longer. This is important since it is easy to cause overheating of the copper sheet surface, resulting in surface darkening and the local peeling as shown by Figure 6(a2). When the rolling speed is 0.8 m $\min^{-1}$ the rolling reduction rate is 26%, which reduces fresh surface contact and atom diffusion, prevents

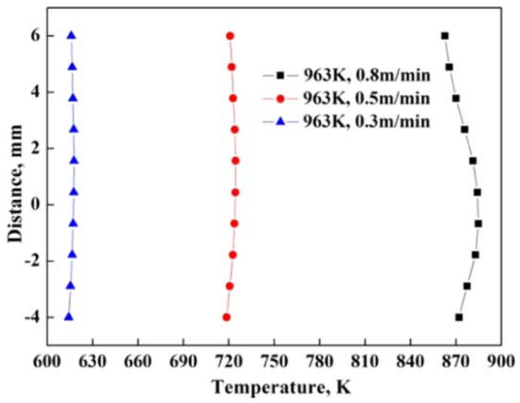

Figure 7. Simulated temperature curves with varying rolling speeds.

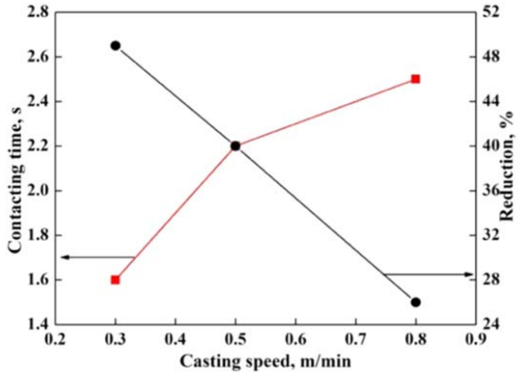

Figure 8. The effect of different casting speed on semi-solid/solid contact time and material reduction percentage.

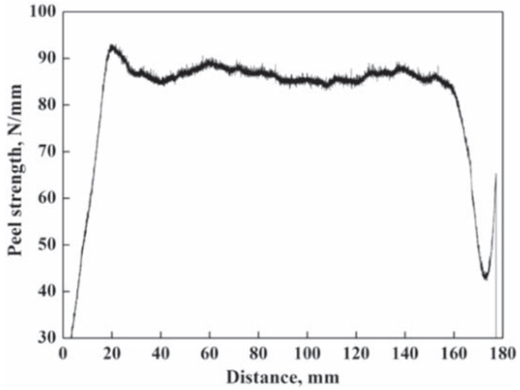

Figure 9. Peeling curve of material manufactured with 963 K pouring temperature and 0.5 m $\min^{-1}$ rolling speed.

mechanical occlusion formation, and causes local peeling as shown at Figure 6(c2). Thus, as rolling speed is increased, the rolling reduction rate is a dominant factorin Cu/Al bonding.

3.3. Analysis of peeling experiment

The peeling strength of Cu/Al composite plate manufactured with a pouring temperature of 963 K and rolling speed of 0.5 m $\min^{-1}$ was tested by a universal tensile tester at 180°. Figure 9 shows the peeling curve, where the peeling strength is seen to reach a stable value of 86 N mm^{-1}. Figure 10 illustrates the surface morphology of the Cu/Al after peeling. Signs of plastic fracture such as ridges and grooves as well as some tearing plat forms are seen on theAl side, indicating that the tear occured between the Al matrix and interface layer and the interface layer

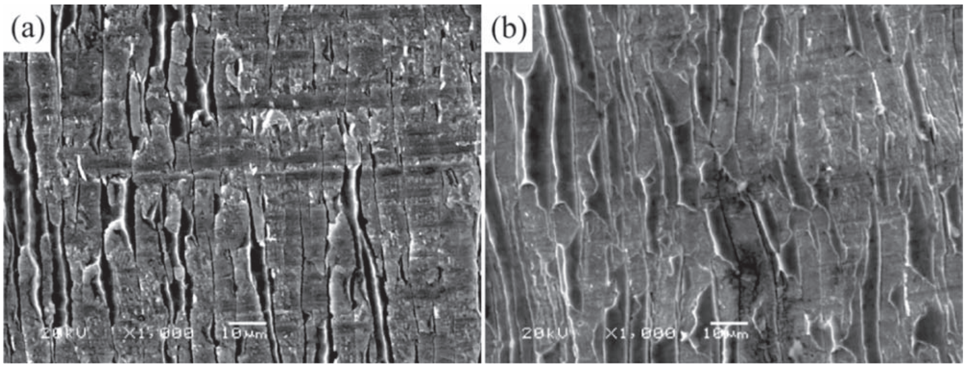

Figure 10. Surface morphology after peeling, (a) Al interface; (b) Cu interface.

has a higher bonding strength with the Cu matrix. Cracks on the Cu side indicate that brittle fracture occured on the interface layer, which reduces peeling strength. Thus, the failure mode of the Cu/Al composite plate is plastic fracture and brittle fracture.

4. Conclusions

(1) In the optimization process, the contact thermal resistance of the copper sheet and the upper roll is set to 8.33e-5 $\mathrm{m}^2 \cdot \mathrm{k} \cdot \mathrm{W}^{-1}$, and the formula of the contact thermal resistance of the cast-rolling zone and the lower roll is shown as follows:

$$R = 5.31 \times 10^{-5} - y \times 3.4 \times 10^{-6}$$

(2) By comparing the physically measured temperatures of samples with simulated cast-rolling results, the maximum error is 2.8%. This shows that the simulation results are in agreement with actual results.

(3) With increased pouring temperature, the semi-solid/solid contact time is an important factor in Cu/Al bonding. As rolling speed is increased, however, the influence of the rolling reduction rate also increases.

(4) The metallurgical bonding of the Cu/Al composite plate is best when the pouring temperature is 963 K and the casting speed is 0.5 m min^{-1}. This allows for semi-solid/solid contact time of 2.2 s and a rolling reduction rate of 40%. With this processing, peeling strength is about 86 N mm^{-1} and the failure mode is plastic and brittle fracture.

(5) By studying the influence of technological parameters on temperature field distribution and Cu/Al bonding, which provides theoretical guidance for actual production, reduces research and development costs, and provides a basis for further study of thermo-mechanical coupling in the Cu/Al composite plate continuous cast-rolling process.

Acknowledgments

This work was supportedby the National Natural Science Foundation of China(Grant No. U1604251).

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References

[1] Liu T *et al* 2016 An investigation into interface formation and mechanical properties of aluminum-copper bimetal by squeeze casting *Materials and Design* **89** 1137–46

[2] Honarpisheh M, Asemabadi M and Sedighi M 2012 Investigation of annealing treatment on the interfacial properties of explosive-welded Al/Cu/Al multilayer *Materials and Design* **37** 122–7

[3] Xinhua L *et al* 2018 Numerical simulation analysis of continuous casting cladding forming for Cu-Al composites *Acta Metall. Sin.* **03** 470–84

[4] Haga T *et al* 2003 A vertical-type twin roll caster for aluminum alloy strips *J. Mater. Process. Tech.* **140** 610–5

[5] Yu H *et al* 2013 Fabrication of ultra-thin nanostructured bimetallic foils by accumulative roll bonding and asymmetric rolling *Sci. Rep.* **3** 2373

[6] Kim H J *et al* 2001 Effects of Cu/Al intermetallic compound (IMC) on copper wire and aluminum pad bondability *IEEE Trans. Components and Packaging Technologies* **26** 367–74

[7] Rohatgi A, Vecchio K S and Gray G T 2001 The influence of stacking fault energy on the mechanical behavior of Cu and Cu/Al alloys: deformation twinning, work hardening, and dynamic recovery *Metallurgical & Materials Transactions* A **32** 135–45

[8] Pintore M *et al* 2018 Experimental investigations on the influence of the thermal conditions during composite casting on the microstructure of Cu–Al Bilayer compounds *International Journal of Metalcasting* **12** 1–10

[9] Haga T and Suzuki S 2003 A twin-roll caster to cast clad strip *Journal of Materials Processing Tech* **138** 366–71

[10] Huang H G *et al* 2017 Evolution of bonding interface in solid–liquid cast-rolling bonding of Cu/Al clad strip *Transactions of Nonferrous Metals Society of China* **27** 1019–25

[11] Jian-yu Z *et al* 2015 Kinetics analysis of liquid phase diffusion bonding between Cu and Al *The Chinese Journal of Nonferrous Metals* **25** 2478–83

[12] Zhi G and Gang X 2003 Simulation of heat transfer behavior of shaped interface in aluminum cast-rolling process *The Chinese Journal of Nonferrous Metals* **13** 1350–6

[13] Stolbchenko M *et al* 2014 Numerical analysis of the twin-roll casting of thin aluminum-steel clad strips *Forsch Ingenieurwes* **78** 1–10

[14] Chen G, Li J and Xu G 2017 Bonding process and interfacial reaction in horizontal twin-roll casting of steel/aluminum clad sheet *J. Mater. Process. Technol.* **246** 1–12

[15] Lee Y S, Kim H W and Cho J H 2015 Process parameters and roll separation force in horizontal twin roll casting of aluminum alloys *J. Mater. Process. Technol.* **218** 48–56

[16] Hadadzadeh A and Wells M A 2013 Thermal fluid mathematical modelling of twin roll casting (TRC) process for AZ31 magnesium alloy *Cast Metals* **26** 228–38

[17] Miao Y C *et al* 2006 Numerical simulation of the fluid flow, heat transfer, and solidification of twin-roll strip casting *J. Mater. Process. Technol.* **174** 7–13

[18] Kim W S, Kim D S and Kuznetsov A V 2000 Simulation of coupled turbulent flow and heat transfer in the wedge-shaped pool of a twin-roll strip casting process *International Journal of Heat & Mass Transfer* **43** 3811–22

[19] Stolbchenko M, Grydin O and Schaper M 2015 Twin-roll casting and finishing treatment of thin strips of the hardening aluminum alloy EN AW-6082 *Materials Today Proceedings* **2** S32–8

[20] Huang H-G *et al* 2016 Thermal-flow coupled numerical simulation and experimental research on bonding mechanism of Cu/Al composite strip by solid-liquid cast-rolling *The Chinese Journal of Nonferrous Metals* **26** 623–9