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Abstract

Asymmetrical and lower heat transport caused by the cladding strip during twin-roll casting (TRC) of clad sheet makes the process window narrow compared with traditional TRC. The effect of pouring temperature on process stability is more remarkable when it is relatively high under high casting speed and casting speed becomes a leading factor when its value is low. The inter-diffusion zone width at the Al/Fe interface depends on the solid/semi-solid contacting time. The longer the time is, the wider the inter-diffusion zone. A widest zone of 3.8 μm is attained under condition of casting speed of 1.25 m/min and pouring temperature of 720 °C. Bonding strength of clad sheet by TRC depends on inter-diffusion zone width and rolling reduction. Proper combinations of inter-diffusion zone width and rolling reduction can result in same high bonding strength. The highest bonding strength of 16 N/mm is attained under a combination of rolling reduction of 29% and inter-diffusion zone of 3.7 μm . The wetting of aluminum melt on steel surface is uneven and insufficient as a result of short contacting time in TRC. As a result, same rolling reduction in TRC induces lower bonding strength than in roll bonding process. Bonding strength of clad sheet by TRC decreases when the surface of the steel strip is brushed, as a result of decrement of actual contacting area.

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Bonding Process and Interfacial Reaction in Horizontal Twin-Roll

Casting of Steel/Aluminum Clad Sheet

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Abstract: Asymmetrical and lower heat transport caused by the cladding strip during twin-roll casting (TRC) of clad sheet makes the process window narrow compared with traditional TRC.

The effect of pouring temperature on process stability is more remarkable when it is relatively high under high casting speed and casting speed becomes a leading factor when its value is low.

The inter-diffusion zone width at the Al/Fe interface depends on the solid/semi-solid contacting time. The longer the time is, the wider the inter-diffusion zone. A widest zone of 3.8 μm is attained under condition of casting speed of 1.25 m/min and pouring temperature of 720 $^{\circ}\text{C}$.

Bonding strength of clad sheet by TRC depends on inter-diffusion zone width and rolling reduction. Proper combinations of inter-diffusion zone width and rolling reduction can result in same high bonding strength. The highest bonding strength of 16 N/mm is attained under a

combination of rolling reduction of 29 % and inter-diffusion zone of 3.7 μm . The wetting of aluminum melt on steel surface is uneven and insufficient as a result of short contacting time in

TRC. As a result, same rolling reduction in TRC induces lower bonding strength than in roll bonding process. Bonding strength of clad sheet by TRC decreases when the surface of the steel strip is brushed, as a result of decrement of actual contacting area.

Keywords: clad sheet; horizontal twin-roll casting; process stability; interfacial reaction; bonding strength

1. Introduction

Stainless steel/aluminum clad sheet is widely used in various industrial fields because it combines high strength, excellent corrosion and abrasion resistance of stainless steel (SS) with high thermal/electrical conductivity and low density of Al alloys (Akramifard et al., 2014). At present, the most widely utilized method to produce SS/Al clad sheet is rolling (Jin et al., 2014). Compared with rolling, producing clad sheet by twin-roll casting (TRC) has many advantages, such as energy and space saving, short procedure and lower investment and cost (Grydin et al., 2013). However, the process window in TRC is relatively narrow because proper heat balance should be built (Zhang et al., 2015). As a result, clad sheet produced by TRC technique has not been put into use due to lack of process stability and low sheet quality (Stolbchenko et al., 2014). Moreover, the bonding mechanism during cladding TRC is not very clear until now. As pointed out by Kim et al. (2014), a good bonding can be designed and attained in clad sheet by analyzing the relationship between process parameters and interface properties. Thus, it is necessary to investigate the bonding process during cladding TRC and the effects of casting parameters on it.

Bonding mechanism in rolling clad sheets has been deep investigated and several theories have been put forward, among which the thin film theory is most widely accepted (Eizadjou et al., 2008). However, the investigations on bonding process in TRC of clad sheets are rare until now and no general theory is presented. Unlike in roll bonding process, a solid/solid contact as well as hot rolling happens during TRC, which makes the bonding process more complicated. Haga et al. (2003) experimentally studied the effects of cooling distance for base metal, pouring

temperature of cladding metal, casting speed and liquidus temperature of alloys on strip shape and bonding condition in a twin-roll caster made up of a melt drag caster and a downward melt drag caster. The results showed that when the cooling distance was 150 mm and melt temperature of the overlay strip was 600 °C, the overlay strip could not connect to the base strip. Higher roll speed resulted in shorter contacting time and the overlay strip could not connect to the base strip. Besides, Haga et al. (2004) also studied the technological feasibility for a wire-inserted composite on a downward melt-drag twin-roll caster. Results showed that the insertion of the wire did not affect the casting process and the bonding was more reliable when the wire was thin and the roll speed was slow as well as when the melt temperature was higher. The interface reaction decreased as the roll speed became higher and the melt temperature became lower. No separating force was built in Haga et al.'s experiments. Bae et al. (2011) investigated the technology of Al/Mg clad sheet by horizontal twin-roll casting. Results showed that the cladding strip is in contact with the base sheet without any visible defects along the Mg/Al clad interface. The proper parameters and their effects on bonding strength were not studied in their work. Grydin et al. (2013) studied twin-roll casting of aluminum/steel clad sheet on a vertical twin-roll caster. No surface treatment on the steel strip was carried out before casting. A 3 µm thick intermetallic layer was found at the interface. Effects of process parameters such as melt temperature and casting speed on the bonding process were not investigated in the study. Hadadzadeh et al. (2014) simulated the TRC process of a clad magnesium strip. Different cladding metals were used to identify their effects on the process feasibility. The results showed that pure Zn was not a feasible clad material due to pre-melting and aluminum alloy was feasible to be clad material. It was also found that the effect of clad thickness and clad material chemical composition on the thermal

history (temperature distribution) of the clad strip was negligible. Park (2016) numerically analyzed two types of cladding process by vertical TRC using a 2D model: Mg-AZ31 sheet was cladded on both sides with molten AA3003 and molten Mg-AZ31 was cladded with AA1100 sheets on both sides. Results showed in the first case Mg-AZ31 sheet was pulled in tension under roll pressure and thinned with a risk of fracture and in the second case Mg-AZ31 melt was incompletely solidified because of low interfacial heat transfer between the roll and the AA1100 sheet. The effects of casting parameters on bonding process were also not carried out.

In this paper, a stainless steel/aluminum clad sheet was produced on a horizontal twin-roll caster under different conditions of pouring temperature (temperature of melt in the nozzle, T_p), casting speed (v) and surface roughness of the cladding strip. Process stability, interfacial reaction and bonding strength of the clad sheet under these conditions were investigated to examine the bonding process during cladding TRC. The paper aims at finding out the mechanism in relation to bonding process in TRC.

2. Experimental and simulation

2.1 Experimental

The horizontal TRC process for steel/aluminum clad sheet and the materials have been described elsewhere (Chen et al., 2016). The horizontal caster has two rolls 500 mm in diameter and 500 mm in width. The roll is composed of a roll shell and a core with many channels for cooling water on it. The thickness of the roll shell is 40 mm. The roll gap and maximum rolling force are 3.8 mm and 2000 kN respectively. A refractory nozzle was used to direct AA1100 (composition in wt% was Al- 0.47Si- 0.26Fe) melt into roll gap. SS 409L (composition in wt% was Fe- 11.87Cr- 1.15Si- 0.21Al- 0.13Ti- 0.13Mg- 0.13Ni) strip 0.25 mm in thickness was used

as cladding strip and inserted through the seam between upper roll surface and the nozzle. To make the strip contact tightly with the roll surface, a pinch roll was used to exert tension on it. To

investigate the effect of surface roughness of steel strip on bonding strength, in one experiment the strip surface was circumferentially brushed with a stainless steel wire brush operating at a rotation speed of 2500 rpm. In other experiments, the strip surface was remained as-delivered without any treatments.

After TRC experiments, the bonding interfaces of the clad sheets were investigated under a Leica DMR optical microscope (OM). The inter-diffusion of Al and Fe across the interfaces was studied on a JEOL JXA-8530F electron probe micro-analyzer (EPMA) with an acceleration voltage of 20 kV and a sample current of 2×10^{-8} A. The bonding strength of the clad sheets was investigated with T-type peeling test, which has also been described in previous work (Chen et al., 2016). The samples were cut from the parts without misruns or wrinkles on the sheet surface. To make the results reliable, three samples were prepared for each sheet. The after-peeling morphology was studied on a SHIMADZU SSX-550 scanning electron microscope (SEM) equipped with energy dispersive spectrometer (EDS).

2.2 Simulation

To find out the temperature distribution in the cast-rolling zone as well as at the Al/steel interface, a 2D model was built using the commercial software ANSYS based on the process described above. Based on previous experiments (Li et al., 2015), three values of T_p (680 °C, 700 °C, 720 °C) and three values of v (1.0 m/min, 1.25 m/min, 1.5 m/min) were used in the simulation. In all, nine simulations were carried out based on different combinations of the above parameters. Several assumptions in the analysis were made as follow: (1) The AA1100 melt is an

incompressible Newtonian fluid and its flow in the calculation domain is laminar; (2) The deformation of the rolls is negligible and the roll speed is constant; (3) The deformation heat of AA1100 alloy is negligible compared with the heat of the melt; (4) No relative slip exists at the interfaces between steel strip and upper roll, AA1100 alloy and steel strip, AA1100 alloy and lower roll, respectively; (5) Physical properties of AA1100 alloy are only functions of temperature and that of 409L strip are constants; (6) Heat exchange mode at all interfaces is convection.

Governing equations in the simulation include energy conservation equation, momentum conservation equation (Navier-Stokes equations) and mass conservation equation (equation of continuity) and are listed as follows:

Energy conservation equation

$$\rho c \left(v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial T}{\partial y} \right) \quad (1)$$

Momentum conservation equation

$$\frac{\partial(\rho v_x v_x)}{\partial x} + \frac{\partial(\rho v_y v_x)}{\partial y} = \rho g_x - \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(\mu_e \frac{\partial v_x}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_e \frac{\partial v_x}{\partial y} \right) \quad (2)$$

$$\frac{\partial(\rho v_x v_y)}{\partial x} + \frac{\partial(\rho v_y v_y)}{\partial y} = \rho g_y - \frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left(\mu_e \frac{\partial v_y}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu_e \frac{\partial v_y}{\partial y} \right) \quad (3)$$

Mass conservation equation

$$\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} = 0 \quad (4)$$

where ρ is the density (in kg/m^3); c the specific heat ($\text{J}/(\text{kg}\cdot^\circ\text{C})$); T the temperature (in $^\circ\text{C}$); v_x, v_y the velocity at x and y directions (in m/s); K_x, K_y the thermal conductivity at x and y directions ($\text{W}/(\text{m}\cdot^\circ\text{C})$); g_x, g_y the components of acceleration due to gravity (in m/s^2); μ_e the dynamic viscosity (in $\text{Pa}\cdot\text{s}$); P the pressure (in Pa).

Thermal conductivity (K), specific heat (c), density (ρ), viscosity (μ_e) of AA1100 alloy and

409L are shown in Table 1 and Table 2, respectively. The values are cited from the books of Iida and Guthrie (1988) and ASM International (1990) and determined by interpolation. The method of equivalent specific heat (Li et al., 2015) was used to account for the release of latent heat during solidification. The latent heat was added to the specific heat of AA1100 alloy with equation (5):

$$c_e = c_0 + \frac{L}{T_L - T_S} \quad (5)$$

where c_e is the equivalent specific heat; c_0 the specific heat; L the latent heat of solidification; T_L and T_S the liquidus and solidus temperatures respectively of AA1100 alloy. The values of L , T_L and T_S are 3.874×10^5 J/kg, 657 °C and 643 °C, respectively.

Table 1. Physical properties of AA1100 alloy under different temperatures

T (°C)	50	100	200	300	400	460	560	600	646	657	660	700
K (W/(m•k))	231	230	230	225	220	211	208	204	200	90	92	93
T (°C)	25	127	227	327	427	527	627	645.9	646	657	657.1	700
c (J/(kg•k))	900	1111	1161	1209	1258	1328	1423	1423	36606	36606	1176	1176
T (°C)	20	100	200	300	400	500	600	607	649	670	700	750
ρ (kg/m ³)	2680	2675	2670	2665	2660	2655	2640	2635	2350	2345	2340	2330
T (°C)	20	200	300	400	500	600	607	632	649	690	750	-
μ_e (Pa•s)	100	100	100	100	100	99	10	0.0017	0.00129	0.00124	0.0012	-

Table 2. Physical properties of stainless steel 409L

K (W/(m•k))	c (J/(kg•k))	ρ (kg/m ³)	μ_e (Pa•s)
20	460	7900	1000

Quadratic element was used to mesh the calculation domain, i.e. the steel strip, the AA1100 alloy, the upper and lower roll shells. After meshing, the steel strip contained 280 elements, the

AA1100 alloy 1961 elements and the roll shell 9883 elements. The meshed AA1100 alloy is shown in Fig. 1. The upper and lower inwalls of the nozzle (surfaces 6 and 7 in Fig. 1) and the vertical walls of the nozzle exit (surfaces 4 and 5) were stationary walls and the velocities in both X and Y directions on these surfaces were zero. Peripheral speeds were loaded to the roll shells, the steel strip and the upper and lower surfaces (surfaces 2 and 3) of the AA1100 alloy in cast-rolling zone. The peripheral speeds were calculated from the relationship of v and coordinates. The velocity in Y direction at the inlet (surface 8) and outlet (surface 1) was set to zero while the X velocity at the outlet was set to v . The melt pressure and temperature in the inlet were set to 0.001Pa and T_p respectively. The initial value of temperature, pressure, X velocity and Y velocity of AA1100 alloy was set to T_p , zero, v and zero, respectively. The outlet speed and initial temperature of steel strip were set to v and 25 °C, respectively.

Fig. 1. Meshed AA1100 alloy in the simulation

The interfacial heat transfer coefficients (IHTCs) were decided according to the contacting tightness at the interfaces and the state of the surfaces during TRC, based on the works of Wang et al. (2014) and Park (2016). The values of IHTC are shown in Table 3, where Fe refers to steel surface; Roll_{up} refers to upper roll surface; Al refers to AA1100 alloy; Roll_{low} refers to lower roll surface and Roll_{shell} refers to inner surface of the roll shell.

Table 3. IHTCs for different interfaces in the simulation, unit: kW/ (m²•K)

Position	Before kiss point			After kiss point			-
Interfaces	Fe/Roll _{up}	Fe/Al	Al/Roll _{low}	Fe/ Roll _{up}	Fe/Al	Al/ Roll _{low}	Water/Roll _{shell}
IHTC	0.5	5	3	9	20	10	3

3. Results and discussion

3.1 Process stability

Fig. 2 shows the temperature field of AA1100 alloy in the cast-rolling zone under different conditions. The intervals on the legend were so set that the mushy zones (from 643 °C to 657 °C) could be shown in detail. The sumps are presented with the yellow wedge-shaped zones in the figures. The temperature fields are not symmetrical about X axis, which is different from that in ordinary TRC (Li et al., 2015). This is caused by the low heat transfer at the interface between steel strip and upper roll before kiss point (point where solid shells from upper and lower roll surfaces first meet). Both the sump depth and solid-liquid coexisted zone enhance with increasing of T_p and v . Notice that small low-temperature zones appear on the top right side in all cases, which happen as follow. When the melt comes out of the nozzle and contacts with the cold steel strip, it will suffer a chilling. Because of the low heat transfer between steel strip and upper roll surface before kiss point, the heat transferred to the strip is not completely removed by the roll and the strip is further heated by the melt and the chilling disappears.

Fig.2. Temperature field of cast-rolling zone under different combinations of casting speed (m/min) and pouring temperature (°C)

The sump depth ratio to set-back distance (SDR) and rolling reduction under different conditions are calculated and shown in Fig. 3 (a) and Fig. 3 (b), respectively. The rolling reduction was determined by taking the fully solidified and the exit thicknesses as the before-rolling and after-rolling thicknesses respectively according to Hadadzadeh et al.'s work (2014). The SDR increases with the increasing of T_p and v , whereas the rolling reduction decreases with the increasing of the two parameters. The slope of the 680 °C and 700 °C curves nearly remains constant. However, the slope of the 720 °C curves is higher for v section from 1.0 m/min to 1.25 m/min than for v section from 1.25 m/min to 1.5 m/min. As a result, the values of SDR and reduction for T_p of 720 °C are much higher than that of 680 °C and 700 °C cases under v of 1.25 m/min and 1.5 m/min whereas the value differences are relatively small at v of 1.0 m/min. It can be concluded that the effect of T_p is more remarkable when it is relatively higher under higher v whereas v becomes a leading factor when its value is small.

Fig.3. Sump depth ratio (SDR) (a) and rolling reduction (b) under different combinations of casting speed and pouring temperature

Zhao et al. (2011) found that a SDR of 20 %~25 % is necessary for steady TRC of magnesium

alloys. Stolbchenko et al. (2015) took the minimal required plastic strain as the determining factor for steady TRC of aluminum and found the corresponding reduction is 25 %~30 %. Based on these results, the 1.0 m/min +680 °C condition seems to be the best. However, the casting process failed as a result of pre-solidification in the nozzle after a short length and some wrinkles appeared on the steel side as shown in Fig. 4 (b). These wrinkles occurred as a result of the uneven deformation of the steel strip, which means the rolling reduction was too large. Although no pre-solidification happened in the 1.0 m/min +700 °C and 1.0 m/min +720 °C cases, some wrinkles still appeared on the steel surface, which indicates the rolling reduction was still too large. The 1.25 m/min +700 °C sheet is with relatively intact shape and good appearance without misruns or wrinkles as shown in Fig. 4 (a). Middle misruns as shown in Fig. 4 (c) appear in the 1.25 m/min +720 °C, 1.5 m/min +680 °C and 1.5 m/min +700 °C sheets, which were caused by alloy not fully cooled and solidified in the roll-casting zone. The misruns on the two 1.5 m/min sheets were even severer than that on the 1.25 m/min sheet. The stable casting condition should be 1.25 m/min +700 °C.

Fig.4. Steel/aluminum clad sheet with different sheet shapes (with steel surface on the top side): (a) good sheet shape with slight side leakage (T_p of 700 °C and v of 1.25 m/min); (b) sheet with wrinkles on the cladding steel (T_p of 680 °C and v of 1.0 m/min); (c) sheet with middle misruns

(T_p of 680 °C and v of 1.5 m/min)

The heat input and output in cast-rolling zone mainly depend on T_p and v respectively. Higher T_p under constant v means more heat input and higher v under constant T_p means the cooling time is shorter and less heat was removed by the rolls. When T_p or v is too low, the before rolling thickness is too large as shown in Fig. 3(b). As a result, the separating force and the tensile stress in the sheet are too large (Zhang et al., 2012), which causes wrinkles on the steel surface as shown in Fig. 4(b). When T_p or v is too high, the melt may not fully fill the casting zone or even cannot finish solidification before coming out of the roll gap and as a result, middle misrun forms, as shown in Fig. 4(c). According to reference (Iida and Guthrie, 1988), the relationship between melt viscosity and temperature is as follow:

$$\mu v^{\frac{1}{3}} = A \exp\left(\frac{c}{vT}\right) \quad (6)$$

where μ is the viscosity, v is the specific volume, T is the temperature and A and c are constants.

With temperature increment the melt viscosity decreases and this can help explain the more remarkable effect of higher T_p under higher v . That is, the inlet flow rate increases besides more heat input at higher T_p because of smaller viscosity. When v is too low, the heat output dominates the heat balance and the effect of T_p weakens as a result. Under such conditions, the solid proportion in the cast-rolling zone nearly remains constant, which can be seen from Fig. 2.

The corresponding SDR and rolling reduction for 1.25 m/min +700 °C case are 32.1 % and 23.8 %, respectively. Compared with traditional TRC, the suitable SDR increases whereas the suitable reduction slightly decreases in clad TRC. The suitable solid proportion decreases to avoid the convexity in the cladding sheet. Moreover, the cladding strip makes the cooling in roll-casting zone asymmetrical and weakened. As a result, the possibility of forming misruns

increases. Thus it can be speculated that compared with traditional TRC, the process stability of clad TRC decreases and the process window narrows.

3.2 Interface morphology and atom inter-diffusion

Fig. 5 shows the OM morphology of Al/steel interface under different conditions. The small inset on each figure shows an enlarged view of the interface. It can be seen that steel and Al bond with each other tightly at the interface under all conditions. In the two 1.0 m/min sheets shown in Fig. 5(a) and Fig. 5(b), the bonding interfaces show a wavelike shape as can be seen from the insets. The other interfaces are somewhat flat except for the brushed condition under 1.25 m/min +700 °C (abbreviated to 1.25 +700 +B, “B” stands for brush) in Fig. 5(d), in which steel and aluminum has embedded in each other at the interface as can be seen from the enlarged inset. The interface in the 1.25 m/min + 720 °C sheet in Fig. 5(e) is not so clean-cut compared with the two 1.5 m/min cases. The steel layer thickness is also indicated out for the 1.25 m/min +700 °C, 1.5 m/min +680 °C and 1.5 m/min + 700 °C sheets shown in Fig. 5(c), Fig. 5(f) and Fig. 5(g), respectively. The original steel strip thickness is 250 μm. Thus the rolling reductions of steel layer for the above three cases are 22.4 %, 9.6 % and 10.8 %, respectively. In Akramifard et al.’s work (2014), it was found that the total rolling reduction was almost evenly distributed in the commercial Al and 304L steel layer in rolling bonding. As the yield strength of 409L is slightly lower than that of 304L, it can be speculated that the total reduction was also evenly distributed in the Al layer and 409L layer. Thus the total reduction for the above three cases can be speculated to be 22.4 %, 9.6 % and 10.8 % respectively. Compared these values with the simulation results in Fig. 3(b), it can be seen the differences are relatively small. This indicates that the simulation results are somewhat credible.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig.5. OM morphology of steel/aluminum interface in clad sheet under different casting conditions (v in m/min, T_p in °C): (a) 1.0, 700; (b) 1.0, 720; (c) 1.25, 700; (d) 1.25, 700, B (“B” stands for brush); (e) 1.25, 720; (f) 1.5, 680; (g) 1.5, 700

Fig. 6 shows the EPMA results. The green lines in the backscattered electron images (BEI) on the left show the canning positions and the corresponding atom fraction curves of Al and Fe are on the right, with the inter-diffusion zones indicated out by two vertical lines in each and the width values marked out. It can be seen from **Fig. 6(a2)** and **Fig. 6(b2)**, the inter-diffusion zone width for the 1.0 +700 and 1.0 +720 sheets is 3.6 μm and 3.7 μm , respectively. The value for the 1.25 +700 +B sheet in **Fig. 6(c2)** is 3 μm , equals to that in the 1.25 +700 sheet without the steel strip being brushed (Chen et al., 2016). The 1.25 +720 sheet in **Fig. 6(d2)** has the largest width of 3.8 μm , nearly equals to that in the 1.25 +700 sheet suffered a 480 °C annealing for 1.5 h (Chen et al., 2016). The width for the two 1.5 m/min sheets is both 2.8 μm , as shown in **Fig. 6(e2)** and **Fig. 6(f2)**. The wavelike shape interfaces in 1.0 +700, 1.0 +720 and 1.25 +700 +B sheets can also be noticed in the BEIs in **Fig. 6**. To make the difference of inter-diffusion zone more apparent, the width values under different conditions are plotted in **Fig. 7**.

(b1)

(b2)

(c1)

(c2)

(d1)

(d2)

(e1)

(e2)

Fig. 6. Scanning position in EPMA (left) and corresponding atom distribution of Al and Fe across Al/Fe interface (right) in clad sheet under different conditions (v in m/min, T_p in °C): (a) 1.0, 700; (b) 1.0 720; (c) 1.25, 700, B; (d) 1.25, 720; (e) 1.5, 680; (f) 1.5, 700

Fig. 7. Inter-diffusion zone width in clad sheet under different conditions

Compared with solid-state diffusion, when one of the metals is liquid, the inter-diffusion is much enhanced as a result of the high temperature, high atomic activity and large interatomic distance (ASM International, 1990). Thus the mutual diffusion of Al and Fe atoms mainly happened during the solid/semi-solid contact, after the spreading wetting of Al melt on steel surface. According to the Fe-Al phase diagram (ASM International, 1990), solid solution, intermetallic and eutectic will form during the Fe-Al contacting. However, due to the short contacting time in TRC, no intermetallic forms at the interface and the inter-diffusion zone is a

solid solution zone in nature. Also from the phase diagram, it can be seen the solid solubility of Al in Fe is much higher than that of Fe in Al. This may help explain the smooth curves on Al side in Fig. 6. To explain the variation of the inter-diffusion zone width under different conditions, the bonding interface temperatures are extracted and plotted in Fig. 8, where Al side in Fig 8(a) and steel side in Fig. 8(b). From nozzle exit to roll exit, the interface temperatures on Al side first decrease until valleys reach and then increase back to platforms followed by sharp drops. The valleys' temperature is lower than solidus of AA1100 while that of the platforms is higher than the solidus. These valleys are consistent with the low temperature zones in Fig. 2. The temperatures on the steel side increase from very low values around 100 °C sharply to values higher than AA1100 solidus and form platforms followed by slight drops, from nozzle exit to roll exit. Notice the platforms' temperature is nearly same under all conditions on both Al side and steel side respectively and what varies is the platforms' length. The length for the 1.0 +700 and 1.0 +720 is nearly same and the shortest on both Al side and steel side. The length in 1.25 +720 and 1.5 +700 sheets is nearly same and the longest on both Al side and steel side. The values in the 1.25 +700 sheet come after that in the 1.0 +720 sheet on both Al side and steel side and are followed by the values in the 1.5 +680 sheet.

Fig. 8. Temperature at bonding interface of steel/aluminum clad sheet under different casting conditions: (a) Al side; (b) Steel side

As the platform lengths are calculated under different casting speed and the temperature values are nearly same, what really functions is the contacting time of steel surface and semi-solid AA1100 alloy (abbreviated to solid/semi-solid contacting time in the following text). The time values under different conditions are calculated and shown in Fig. 9. The value for the 1.0 +700 and 1.0 +720 sheets is 1.69 s and 1.75 s respectively. The value for the 1.25 +700 and 1.25 +720 sheets is 1.57 s and 1.88 s respectively and latter is the highest. The two 1.5 m/min sheets have the shortest time, which are 1.44 s and 1.49 s for the 1.5 +680 and 1.5 +700 sheets respectively. Comparing the time values under different conditions with the corresponding inter-diffusion zone widths in Fig. 7, it can be seen they are consistent with each other. That means the inter-diffusion zone is mainly caused by the solid/semi-solid contacting during cladding TRC. Liu et al. (2000) also pointed out that contacting time is another important factor besides interface temperature in deciding solid/liquid bonding.

Fig. 9. Solid/semi-solid contacting time and rolling reduction under different conditions

3.3 Bonding process

The peeling curves and average peeling strength (APS) of the clad sheets under different

conditions are in Fig. 10(a) and Fig. 10(b), respectively. The dash lines on the peeling curves indicate the APS. The APS of 1.0 +700 and 1.0 +720 sheets is 13.5 N/mm and 16 N/mm, respectively. The value of 1.25 +700 and 1.25 +720 sheets is 12 N/mm and 13.8 N/mm, respectively. The APS of 1.5 +680 and 1.5 +700 sheets is 11 N/mm and 6 N/mm, respectively. The 1.25 +700 +B sheet has an APS of 9 N/mm, lower than the un-brushed condition under the same condition. The 1.0 +720 sheet has the highest whereas the 1.5 +700 sheet the lowest APS.

Fig. 10. Peeling curves (a) and average peeling strength (APS) (b) under different casting conditions

According to Liu et al. (2015), in clad sheets the interface region can be solid solution strengthened by the inter-diffusion effect. The larger the inter-diffusion zone is, the stronger the strengthening effect. However, the 1.25 +720 sheet has the biggest inter-diffusion zone whereas a lower APS than the 1.0 +720 sheet. The reason lies in the different rolling reductions in these conditions, which are also shown in Fig. 9. In the work of Akramifard et al. (2014) it was found that in rolling bonding of commercial pure Al/STS, the APS increases with rolling reduction. The same rule also held for the TRC clad sheet as the rolling temperature is much higher. Thus the highest APS in the 1.0 +720 sheet is caused by the relatively high rolling reduction together with

the long solid/semi-solid contacting time. The relatively high APS of the 1.0 +700 sheet is also caused by the large reduction and the long contacting time. The wave-like shape of the interfaces in Fig. 6(a) and Fig. 6(b) is also the result of large reductions. Notice the APS of 1.0 +700 sheet is slightly lower than the 1.0 +720 sheet, which might indicate that the effect of inter-diffusion surpasses that of the rolling reduction on bonding. The relatively high APS in the 1.25 +720 sheet is mainly a result of the longest contacting time, which causes the largest inter-diffusion zone in the sheet. Notice the corresponding reduction for the sheet is 11.1 %. From the nearly equal APS in the 1.0 +700 and 1.25 +720 sheets, it can be concluded that proper combination of rolling and solid/semi-solid contacting can result in a same high bonding strength during cladding TRC. However, the selection of the parameters is restricted by the sheet shape, as discussed in the 3.1 part.

Fig. 11 shows the after-peeling morphology of Al and steel surfaces in the 1.0 +720 sheet. Fig. 11(a) shows the Al surface morphology and an enlarged image of the box is in Fig. 11(b). Many bright salient can be seen on the surface, the composition of which is Al, as marked out by “A” and shown in Fig. 11(e). Fig. 11(c) shows the steel surface morphology and an enlarged image of the box is in Fig. 11(d). Like on the Al surface, many salient also appear on the steel surface. The composition of these salient marked out by “B” is shown in Fig. 11(f) and contains 33.3 at% Fe, 66.3 at% Al and 0.4 at% Cr. Thus it can be concluded the salient are the bonding zones formed by rolling and inter-diffusion, suffering some deformation and fracturing during the peeling test. The results also show that the strength of the bonding zones is higher than the tensile strength of AA1100. The same result has also been found in Akramifard et al.’s work (2014).

Fig. 11. After-peeling morphology on Al side and steel side in 1.0 +720 sheet: (a) Al side; (b) an enlarged zone in Fig. 11(a); (c) steel side; (d) an enlarged zone in Fig. 11(c); (e) composition of point “A” in Fig. 11(b); (f) composition of point “B” in Fig. 11(d)

Fig. 12 shows the after-peeling morphology in 1.25 +720 sheet. Fig. 12(a) and Fig. 12(b) show the Al surface and Fig. 12(c) and Fig. 12(d) the steel surface. Many salient also appear on the Al and steel surfaces and compared with that in the 1.0 +720 sheet, they are a little bit scarcer. The

composition of the salient marked as “A” is mainly Al and these marked “B” contains 14.4 at% Al, 77.4 at% Fe and 8.1 at% Cr, as shown in Fig. 12(e) and Fig. 12(f), respectively. This means the salient are mainly the inter-diffusion zone that deformed and fractured during the peeling test. This is consistent with the proportions of inter-diffusion zone and rolling reduction in the sheet.

Fig. 12. After-peeling morphology on Al side and steel side in 1.25 +720 sheet: (a) Al side; (b) an enlarged zone in Fig. 12(a); (c) steel side; (d) an enlarged zone in Fig. 12(c); (e) composition of

point “A” in Fig. 12(b); (f) composition of point “B” in Fig. 12(d)

The after-peeling morphology in the 1.5 +700 sheet is shown in Fig. 13. Al surface is shown in Fig. 13(a) and Fig. 13(b) and steel surface in Fig. 13(c) and Fig. 13(d). It can be seen the salient on both Al surface and steel surface are very scarcer and smaller than that in the 1.0 +720 and 1.25 +720 sheets. The EDS results show that the composition of the salient is mainly Al. Also notice that on the Al surface the salient distribution is very uneven. There are large zones where no salient can be seen. This may indicate that the wetting and distribution of aluminum melt on steel surface is very uneven under this casting condition. The 1.5 +680 sheet shows the same after-peeling morphologies.

Fig. 13. After-peeling morphology on Al side and steel side in 1.5 +700 sheet: (a) Al side; (b) an enlarged zone in Fig. 13(a); (c) steel side; (d) an enlarged zone in Fig. 13(c)

Thus, the reasons for the lowest bonding strength in the two 1.5 m/min sheets are the short solid/semi-solid contacting time, lower reduction and the uneven bonding zone distribution on the surfaces. The relatively high casting speed causes the melt distribution, especially the transverse distribution, very uneven. This is clearly shown in Fig. 13(a). As a result, the thin inter-diffusion zone is discontinuous along the bonding interface. According to Rübner et al. (2011), another necessary condition for the successful bonding in clad sheet is a continuous metallic layer between base metals. Actually, during cladding TRC, the melt wetting and distribution on the steel surface is not totally even under all conditions, which can be seen from the peeling surfaces in Fig. 11 and Fig. 12. The areas without any salient maybe the insufficiently wetted zones as a result of surface tension and very short contacting time in TRC. Liu et al. (2014) also pointed out that a good wettability of solid substrates during solid/liquid bonding is essential in achieving good metallurgical bonding at the interface. Under the rolling after the completely solidification, bonding will also occur at these un-wetted zones. This can explain the intact interfaces without visible defects in Fig. 5. However, the bonding of these un-wetted zones also depends on rolling reduction. When the reduction is too small, the steel/Al contacting is still not very tight after coming out of the roll gap, which can be seen in Fig. 13. Actually, compared with rolling bonding, same reduction in TRC results in a lower bonding strength as the result of the uneven wetting. This can be assured by comparing the results of Akramifard et al. (2014) and the results in this paper.

3.4 Steel strip surface roughness effect

Fig. 14 shows the after-peeling morphology in the 1.25 +700 +B sheet. Fig. 14(a) and Fig. 14(b) show the Al surface and Fig. 14(c) and Fig. 14(d) the steel surface. Compared with the

above cases without the steel surface being brushed, apparent differences are observed. First, the salient on the surfaces are scarcer and smaller. From Fig. 14(e) and Fig. 14(f), it can be seen the salient compositions are mainly Al. What's more, many grooves can be seen on both the surfaces as a result of the brushing. At the bottom of these grooves no salient are found. Some fragments on the Al surface can also be seen in Fig. 14(b). These changes can help explain the low bonding strength in the sheet compared with the 1.25 +700 sheet with the as-received steel surface (Chen et al., 2016). In the works of Moujekwu et al. (1995) and Bouchard et al. (2001), it was found that the coarser surface of the solid substrate contained higher peaks and deeper valleys and the surface tension of the melt might have prevented a proper contact inside the valleys. That means, the aluminum melt cannot reach the bottom of the valleys as a result of the surface tension because the contacting time is rather short during TRC. This is verified from the peeling surfaces in Fig. 14, where no bonding found at the bottom of the grooves.

Fig. 14. After-peeling morphology on Al side and steel side in 1.25 +700 +B sheet: (a) Al side; (b) an enlarged zone in Fig. 14(a); (c) steel side; (d) an enlarged zone in Fig. 14(c); (e) composition of point “A” in Fig. 14(b); (f) composition of point “B” in Fig. 14(d)

The contacting of Al melt and brushed steel surface during TRC is schematically shown in Fig. 15. The actual contacting area decreases when the steel surface is brushed, compared with the un-brushed case. The air gaps formed at the bottom of the valleys exert a pressure on the melt and further on the solidified alloy when the separating force gradually builds, which makes the bonding harder. Moreover, it will be harder for the melt to flow on a rough surface, which may also contribute to the lower bonding strength. Notice in Fig. 5(d) and Fig. 6(c1), the interface also shows a wavelike shape. However, the formation of the shape is different from that in Fig. 5(a) and Fig. 5(b). That is, the former forms during the melt/steel contacting while the latter after the complete solidification and during the rolling. As a result, the latter bonding is tighter without air

gaps at the interface. Some small air gaps between the two flat surfaces are also shown in Fig. 15. These gaps are also the result of surface tension of the melt on the steel surface. However, they can be eliminated by the rolling following the complete solidification.

Fig. 15. Schematic diagram of contacting of aluminum melt on a burnished steel surface.

4. Conclusions

Bonding process and interfacial reaction in twin-roll casting of steel/aluminum clad sheet are investigated with the aid of simulating temperature field in cast-rolling zone.

(1) Asymmetrical and lower heat export caused by the cladding strip during TRC makes the process window narrow compared with traditional TRC. The effect of pouring temperature on process stability is more remarkable when it is relatively high under high casting speed and casting speed becomes a leading factor when its value is low.

(2) The inter-diffusion zone width at the Al/Fe interface depends on the solid/semi-solid contacting time. The longer the time is, the wider the inter-diffusion zone. A widest zone of 3.8 μm is attained under condition of 1.25 m/min +720 $^{\circ}\text{C}$.

(3) Bonding strength of steel/aluminum clad sheet by twin-roll casting depends on inter-diffusion zone width and rolling reduction. Proper combination of the two factors can result in same high bonding strength. The highest bonding strength of 16 N/mm is attained under a combination of 29 % and 3.7 μm .

(4) The wetting of aluminum melt on steel surface is uneven and insufficient as a result of short contacting time in TRC. As a result, same rolling reduction in TRC induces lower bonding strength than in rolling bonding.

(5) Bonding strength of clad sheet by twin-roll casting decreases when the surface of the steel strip is brushed, as a result of decrement of actual contacting area.

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