Light Metals 2015
Edited by: Margaret Hyland
TMS (The Minerals, Metals & Materials Society), 2015

COMPARISON OF TWIN-ROLL CASTING AND HIGH-TEMPERATURE ROLL BONDING FOR STEEL-CLAD ALUMINUM STRIP PRODUCTION

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Keywords: Clad strips, Twin-roll casting, Roll bonding, Microstructure, Intermetallic phases, Aluminum-steel

Abstract

A conventional process chain for the manufacturing of steel-clad aluminum strips using roll bonding comprises many auxiliary operations. These steps include the surface preparation of steel and aluminum strips as well as heat treatment for an interfacial diffusion control. Twin-roll casting provides an efficient alternative way to join these metals. In this process a thin solid steel strip is fed between two revolving rolls together with an aluminum melt. The melt solidifies rapidly to a thin layer which is subsequently deformed in the roll gap. For a comparison of the mechanisms and conditions of joining using these two methods, a series of experiments of roll bonding at a temperature near the melting point of aluminum were carried out. The minimal hot deformation strain necessary for a satisfying bonding quality was identified. The results of roll bonding experiments and twin-roll cast trials related to clads' microstructure and mechanical properties were compared.

Introduction

Clad metallic materials are widely used in many fields of industry and research due to superior mechanical, physical and chemical properties in comparison to conventional mono-materials. Thus, the application of, e. g. bimetallic clad materials, becomes increasingly important in transport engineering where lightweight materials are vital for economic service. Consequently, they are applied as structure elements in many technical applications from car bodies and chassis via aircraft construction and shipbuilding to heat exchangers.

Among other bimetallic compositions, aluminum-steel compounds are of greatest interest. This is due to the fact that steel and various aluminum alloys are the most widely used materials in modern engineering enabling for using the latest developments in the field of steel production, such as advanced high-strength steel, and the newest aluminum alloys [1]. The combination of the materials allows for achieving unprecedented product characteristics beyond the ones of each single metal. Thus, particular high specific strength and ductility at likewise good thermal conductivity and capacity can be attained.

Widely used types of bimetallic products are double-or multi-layered aluminum-steel strips with a continuous bonding of the layers. The most common production methods are cold or hot roll bonding, welding and explosion cladding, with the latter providing the highest bonding strength between the layers. However, the application of explosion cladding is restricted due to high costs, low productivity and strict regulations for the explosion process. More than 90 % of flat clad products are manufactured using roll bonding, although this technology has severe drawbacks as well. Most prominent in this context is the high effort for substrate preparation in terms of cleaning, grinding and protection of joining surfaces. Moreover, the quality of the final clad product is not just depending on the cladding procedure itself, but also highly sensitive towards subsequent heat treatments and post-processing [2]. Finally, the high cost of the substrates, especially when manufactured by conventional production technologies using direct chill casting and hot reduction in multi-stand rolling mills, account for a large share of the final product cost. Eventually, the efficient application of multi-materials in practical engineering is highly restricted.

One technology allowing for overcoming the mentioned disadvantages of the currently used techniques for clad strip production is twin-roll casting. This method enables for manufacturing multi-layered clad strips directly from melts of different metals or by using a melt together with a solid substrate. By waiving intermediate heating, that is characteristic to the conventional sheet manufacturing technologies, the energy and material consumption as well as detrimental impurities can be significantly reduced [3, 4]. High cooling rates during solidification as well as high deformation strains during metal forming in the twin-roll caster provide a fine-grained microstructure and good mechanical properties of the produced strips.

Clad strips production

Production of clad strips by twin-roll casting was realized on laboratory scale by T. Haga et al. [5-7] in the form of multi-layers of different aluminum alloys. The strip layers were formed from separate melts and subsequently bonded in roll casters with equal or unequal roll diameters as well as in a tandem twin-roll casting unit. Clad strip casting using a melt and a solid flat substrate was performed for magnesium-aluminum strips by A.R.P. Rao et al. [8, 9] and for thin aluminum-steel clads by O. Grydin et al. [10]. Subject of the latter work was, besides the actual material combination, the effect of high plastic deformation directly induced in the twin-roll mold on the resulting bonding quality. The results revealed favorable properties of the produced strips, with intermetallic phases on the bonding surface and bonding strengths of the bimetallic composite of more than 90 MPa [10]. Other works showed that high bonding strengths can be achieved, when the layer thickness of the intermetallic phase is in the range of 1 μm – 5 μm [11-13]. However, at present twin-roll casting of aluminum-steel clad strips stays on laboratory scale and the actual state of the art is still represented by roll bonding.

The parameters dominating the formation of the fusion between two dissimilar metals are the initial temperature of the materials, the duration of high-temperature interaction, the rolling force and the strip reduction. Thus, a distinction between two types of influencing parameters can be made: thermal and force factors.

The force factors have a decisive influence on the formation of bonding sources during the roll bonding process. Material reduction and plastic flow lead to formation of micro-cracks on the oxidized surfaces of the bonding materials activating the diffusional interaction. In combination with the applied rolling force the bonding between two layers is enforced [14]. The expansion and growth of intermetallic phases is then governed by thermal effects with temperatures ranging from 300 °C to 650 °C [12, 15-17]. This is realizable in course of cladding by means of hot rolling or by an additional heat treatment after deformation. Another parameter allowing for altering the formation kinetics of intermetallic phases is the time of material soaking [12].

Thermal factors considerably affect the formation of diffusion bonding, when one of the bonded materials remains in the liquid state, as present during welding or twin-roll casting. The bonding quality is then determined by the peak temperature in the fusion zone [18]. However, in order to obtain a high bonding strength compressive stresses between the materials are required as well. Yahiro et al. [19] showed for aluminum and steel, that preheating of the aluminum substrate to 550°C in combination with high deformation and friction during roll bonding results in contact zone temperatures exceeding the melting point of aluminum. This provides an active and uniform contact between the steel substrate and a thin layer of partly liquid aluminum. The particles of oxides are uniformly scattered across the aluminum-steel interface. Moreover, the preheating of the aluminum substrate leads to a reduction of the deformation ratio necessary for formation of a durable diffusion fusion.

As shown above, the initial bonding is highly affected by thermally and mechanically activated processes. Thus, the fusion mechanisms of high-temperature roll bonding might be similar to the layer formation during twin-roll casting. However, literature on high-temperature roll bonding of steel and aluminum with preheating temperatures above 550°C is scarce. Consequently, the aim of the current work is to compare the effective mechanisms and reveal the conditions of intermetallic bonding of clad strips, processed via twin-roll casting and high-temperature roll bonding.

Experimental procedure

<u>Twin-roll casting</u>

For production of thin aluminum-steel clad strips two methods, twin-roll casting and high-temperature roll bonding, were applied. In case of the latter aluminum strips were preheated close to the melt point. The experiments on twin-roll casting were carried out using a laboratory twin-roll caster with internally water-cooled steel sleeves of 370 mm diameter (See Figure 1). A detailed description of the main dimensions and technical parameters can be found in [20]. The unit is equipped with a vertical melt feeding scheme, an uncoiler for the steel substrate, devices ensuring a controlled feeding of the steel substrate and a clad strip puller at the exit side of the machine. The uncoiler was placed as close as possible to the twin-roll caster, thus providing backward tension and stabilization of the steel strip during feeding. The experimental twin-roll casting unit enables for producing strips with 200 mm width and a total thickness of up to 5 mm at casting speeds of up to 6 m min^{-1}. The caster is sufficiently stiff to provide for in-situ plastic deformation of the aluminum layer of up to 50 %.

The austenitic steel 1.4301 was used as solid steel substrate, whereas the technologically pure aluminum EN AW-1070 provided the cladding melt. The steel substrate was uncoiled and directly, i.e. without any surface treatment, fed into the twin-roll caster. The aluminum melt was added simultaneously (See Figure 2). After solidification of the aluminum melt, assisted by two internally cooled rotating rolls, the clad strip was deformed to a total reduction of about 30 % resulting in a final thickness of 2.5 mm. The thickness ratio of the steel substrate to the aluminum cladding layer was 1:4. The roll separating force was measured throughout the experiment reaching values of about 250 kN. Table I shows the main technological and constructional parameters of the conducted experiments.

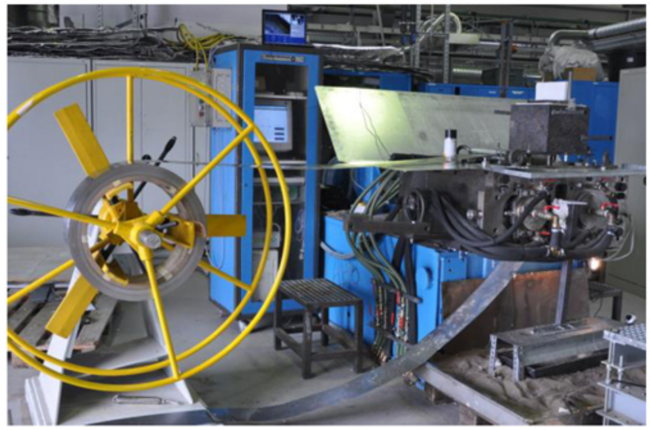

Figure 1. Twin-roll caster used for the clad strips manufacturing.

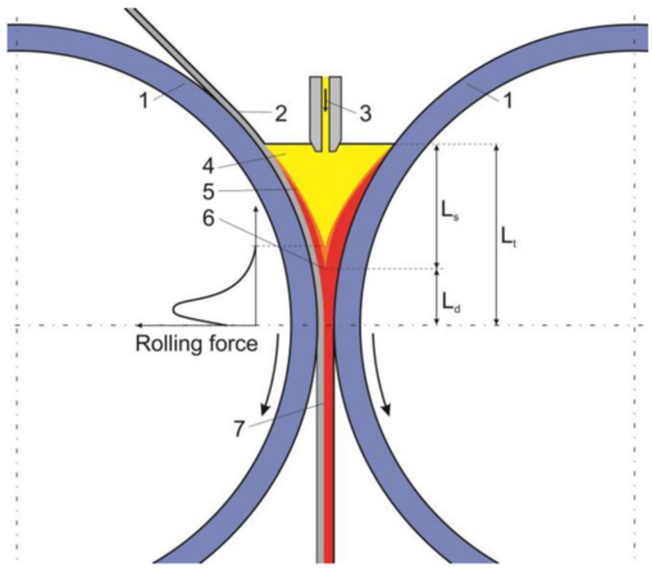

Figure 2. Basic schematic of the twin-roll casting of aluminum-steel clad strips: 1 – water-cooled rolls sleeves, 2 – steel strip, 3 – melt feeding system, 4 – aluminum melt, 5 – semi-solid metal, 6 – kissing point, 7 – clad strip; L_s – solidification zone length, L_d – deformation zone length, L_t – total length of the strip formation zone.

Table I. Main twin-roll casting parameters

Process parameter	Value
Aluminum melt temperature	700
Initial temperature of the steel substrate, °C	20
Casting speed, m min^{-1}	5.1
Total length of the strip formation zone, mm	35
Steel substrate thickness, mm	0.5
Total thickness of the clad strip, mm	2.5
Coolant flow rate, l min^{-1}	112
Coolant temperature, °C	14

It should be mentioned that the twin-roll casting process is unsteady until the working temperature of the roll sleeves is reached, which is after the first five roll rotations. This can lead to

casting defects of the aluminum strip as well as to local delamination between the layers. However, the clad strip produced at steady-state conditions is flawless without visible defects or delaminations. Thus, samples for further analysis were mainly extracted from the clads produced under steady-state conditions. Yet, some specimens were additionally taken from the strips produced in the beginning of the process.
Microsections of the clad strips were prepared for metallographic analysis by sequential grinding, polishing and etching with sulfur acid. For analyzing the aluminum layer by polarized light the microsections were electrolytically etched according to Barker [21]. Additional chemical analysis was performed in terms of electron probe microanalysis (EPMA). For this purpose the etched sample was fine polished down to 1 µm diamond paste. The measurements were carried out on a JEOL JXA-8900R using an acceleration voltage of 20 kV and a sample current of 2 x 10^{-8} A.

High-temperature roll bonding

For roll bonding preheated solid strips of the same aluminum and steel alloys as used for twin-roll casting were fed simultaneously to the rolling stand (See Figure 3). In zone I only the material with lower yield strength undergoes plastic deformation before the thickness of both materials is reduced in zone II. Bonding occurs due to high strain and compressive stresses present in the latter zone before the material leaves the roll gap in form of a clad strip. The employed equipment comprised a convection oven and a rolling stand with roll dimensions of 140 mm x 200 mm (diameter and length, respectively). The dimensions of the steel and aluminum substrates as well as other process parameters are given in Table II. Apart from degreasing no additional surface preparation was applied. The rolling scheme was symmetrical with synchronous roll speeds.

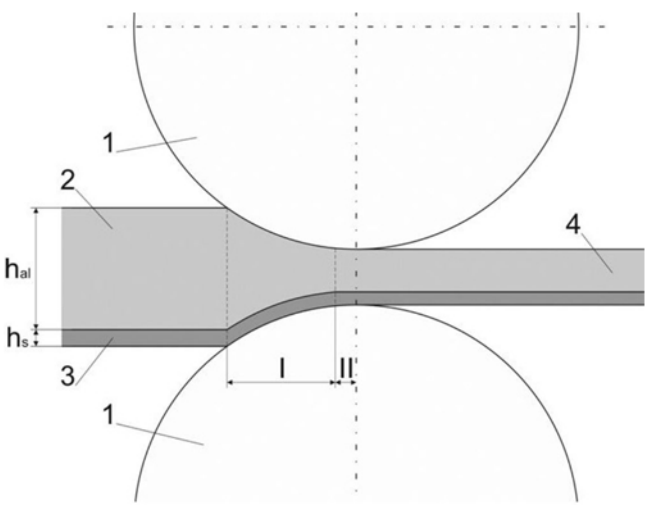

Figure 3. Basic schematic of the roll bonding of aluminum-steel clad strips: 1 –rolls, 2 – aluminum substrate, 3 – steel substrate, 4 – clad strip; h_{al} – initial thickness of aluminum substrate, h_s – initial thickness of steel substrate.

Table II. The main parameters of the high-temperature roll bonding experiments

Aluminum substrate dimensions, mm	4x80x200
Steel substrate dimensions, mm	0.5x60x120
Aluminum substrate temperature, °C	625; 650
Steel substrate temperature, °C	20; 350
Rolling speed, m s^{-1}	0.37

In order to evaluate the impact of the holding time on the bonding process the aluminum strips were soaked in the oven at 650°C without protective gas atmosphere for holding times of up to 225 min. Microstructural and surface analysis in terms of optical microscopy were carried out subsequently.
The first series of the experiments on hot roll bonding were carried out using the aluminum strips preheated to 650 °C and steel strips with a temperature of 20 °C. The reduction during one-pass rolling was gradually increased from 45 % to 70 % with 5 % between each experiment. The threshold strain value necessary for formation of a satisfactory bonding was found to be at a reduction of 55 %.
For the second series the temperature of the aluminum substrate was reduced to 625 °C. Using a non-preheated steel substrate and unprepared surfaces a qualitative bonding was not obtained at reductions between 45 % and 75 %. Either separation of layers at the outlet of the deformation zone or adhesion between the aluminum strip and the roll followed by delamination of the steel strip were observed. Preheating of the steel substrate to 350 °C was then applied in order to optimize the bonding conditions, as proposed by [16]. By doing so local bonding was achieved at reductions of 45 %. Increasing the reduction to 75 % with steps of 5 % resulted in further improvement in the strip bonding.
For quantitative analysis of the bonding strength of the clads manufactured by both twin-roll casting and high-temperature roll bonding, tensile tests according to DIN EN 582:1994 were carried out. For this purpose disks of 25 mm were cut from the clad strips and subsequently flat milled in order to provide the necessary plane parallelism of the sample surfaces. After degreasing, they were joined by STC ULTRA BOND® 100 adhesive to two cylindrical dies enabling for mounting the samples to the tensile testing machine. To polymerize the adhesive and to achieve its maximum strength, the dies were clamped and heat treated at 180 °C for 50 minutes ensuring a bonding strength of the adhesive of 100 MPa. Tensile testing was carried out perpendicular to the bonding surface using a spindle driven Z250 made by Zwick GmbH, Germany.

Results and discussion

The microsection in Figure 4 shows the dendritic structure characteristic to low-strained surface layers of aluminum. At the same time recrystallized grains can be observed in the middle layers indicating high local plastic deformation of the material during twin-roll casting.

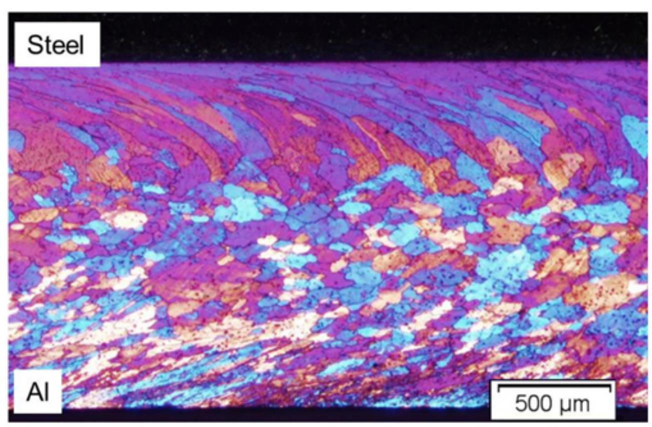

Figure 4. Grain microstructure of the aluminum layer of the twin-roll cast clad strip.

A more detailed view of the bonding zone showed presence of a thin uniform layer with a thickness of about 3 µm in the interface, indicative of an intermetallic phase of the Fe-Al system (See Figure 5). Neither large oxide particles in the fusion zone nor any delamination between the layers are discernable. The corresponding distribution of the relevant chemical elements, as determined by EPMA, is shown in Figure 6. The concentration gradient in the seam of the parent materials – iron and aluminum – confirms the presence of a diffusion bonding layer with a thickness of about 2.5 µm to 3 µm. In other works [10-12], uniform intermetallic layers of equal thicknesses were often found to be responsible for high bonding strengths. Consequently, high strengths were expected in this study as well. The formation of this diffusion layer is seen to be affected by the following factors: (1) the high temperature of the aluminum at the point of the initial contact to the steel substrate and concomitant active interaction in the solid-liquid system; (2) holding at high temperatures in the solidification zone for a time of about 0.5 s and growth of the intermetallic phases; (3) high pressure and plastic metal forming in the deformation zone after the complete solidification of aluminum.

Figure 5. Microstructure of the seam and the parent material of the twin-roll cast clad strip.

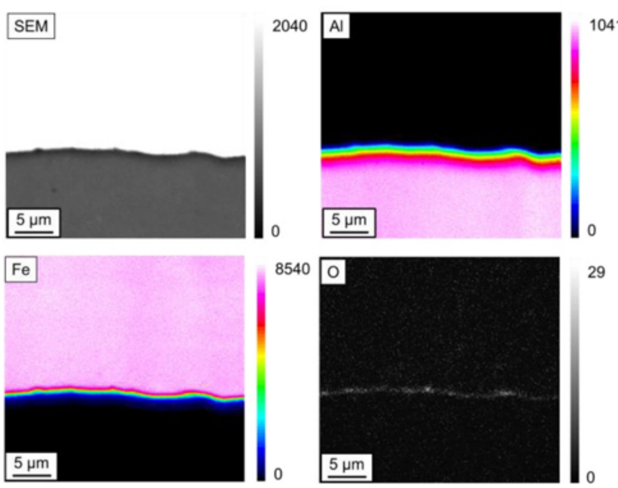

Figure 6. Distribution of the chemical elements in the seam of twin-roll cast clad strip (using EPMA measuring counts).

The exact estimation of the deformation strain value and its influence on the quality of the intermetallic bonding at twin-roll casting is complicated due to the high velocity and temperature of the process as well as the inaccessibility of the strip forming zone for direct observation. In order to compare the effective mechanisms cladding by roll bonding at high-temperature was carried.

The impact of different holding times on the formation of oxides during preheating is depicted in Figure 7. Obviously, thick oxide films evolve on the surface of the aluminum substrate when soaking duration exceeded 30 min. Additionally, the grains coarsen resulting in grain sizes of up to 1 mm due to longer holding times (See Figure 7 and Figure 8). In order to avoid severe changes in the microstructure and in the strip surface, but to ensure complete heating of the substrate, soaking of aluminum at 650 °C consequently should not exceed 30 min.

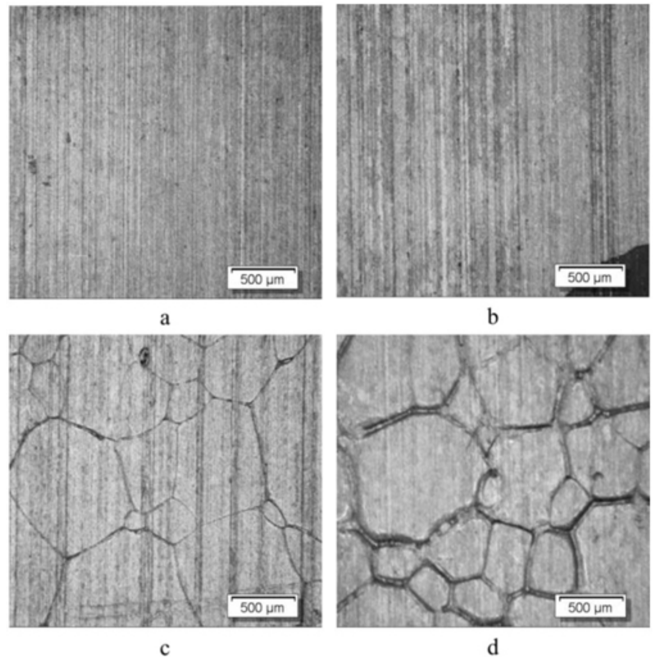

Figure 7. Surface of the aluminum substrates after holding in furnace at 650 °C without protective atmosphere for: 0 min (a), 30 min (b), 140 min (c), 225 min (d).

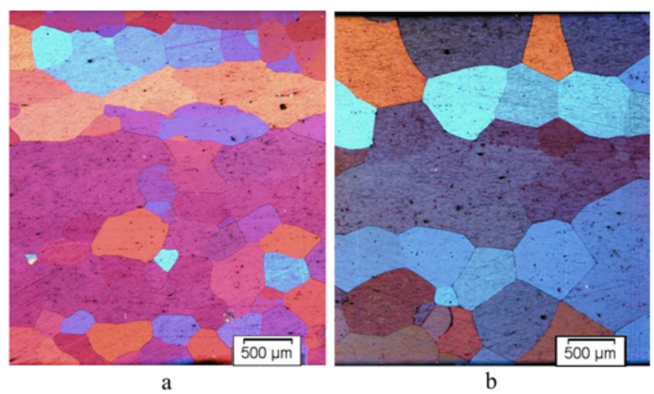

Figure 8. Grain microstructure of the aluminum substrate after 30 min (a) and 140 min (b) soaking at 650 °C.

A microsection of the aluminum-steel strip processed via roll bonding at a reduction of 65 % is shown in Figure 9 and Figure 10. Metallographic analyses of the clad strip samples roll-bonded at reductions ranging from 55 % to 75 % all showed a good bonding quality with formation of a continuous diffusion layer with a thickness between 2 µm and 4 µm (See Figure 10). Figure 9 shows an image taken of the aluminum surface etched according to Barker [21]. Clearly, single grains elongated along the rolling direction can be discerned, which is typical for metals undergone high plastic deformation. The EPMA analysis of the roll-bonded strips was carried out in analogy to the twin-roll cast clads, revealing a likewise pronounced formation of a thin intermetallic layer (See Figure 11).

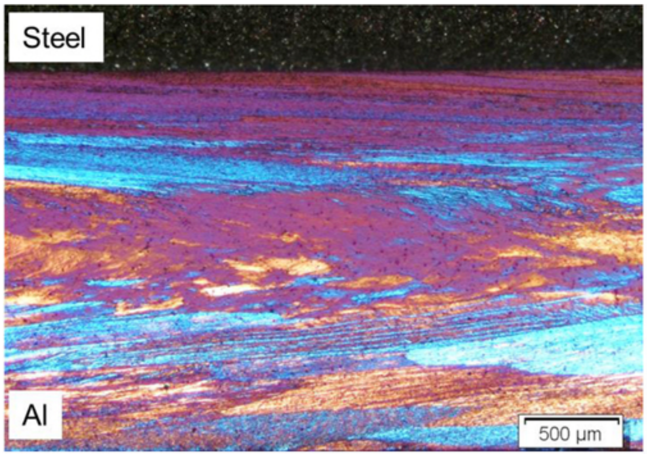

Figure 9. Grain microstructure of the aluminum layer of the hot roll-bonded clad strip.

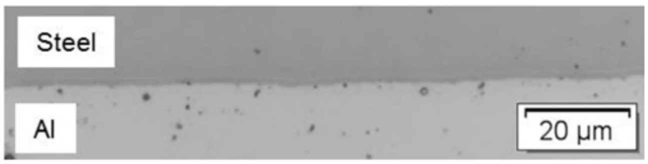

Figure 10. Microstructure of the seam and the parent material of the hot roll-bonded clad strip.

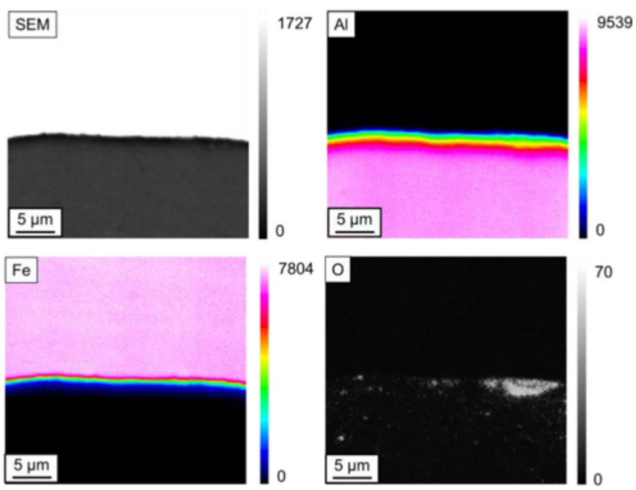

Figure 11. Distribution of the chemical elements in the seam of the hot roll-bonded clad strip (using EPMA measuring counts).

However, in dependence of the applied technique, i.e. twin-roll casting or roll bonding, significant differences are present in the microstructure of the aluminum as well as in the oxygen content of the bonding interface. Thus, the aluminum substrate after roll bonding is characterized by a fine and homogeneous microstructure, although the grains are slightly elongated. In contrast, the microstructure of the aluminum in the twin-roll cast strip is inhomogeneous due to non-uniform temperature distribution and consequently non-uniform plastic deformation. In most cases twin-roll cast aluminum strips need an additional thermo-mechanical treatment to optimize their mechanical properties [22]. The lower oxygen content in the bonding interface of the twin-roll cast clads is explainable by shorter exposure of the preheated bonding materials to ambient atmosphere and thus lower absorption of oxygen. In this case, oxygen is added in form of an oxide layer merely on the steel substrate. In contrast, during roll bonding an oxide layer forms on both the aluminum and steel strips and remains in form of particles in the bonding zone of the finished clad strip. The thick oxide layers on the interface impede their bonding and higher deformation strains are required in order to break them.

The results of the tensile tests revealed a bonding strength of about 95 MPa in case of the samples taken from the twin-roll cast strip at steady-state conditions. Bonding strength of specimens taken from the strip section at the beginning of the process was 50 % less. This effect can be explained by the low temperature of the caster rolls and the low outlet temperature in the beginning of twin-roll casting. Due to the interaction in the liquid-solid system the initial contact between the metals is achieved without any pressure in the bonded areas. Consequently, the formation of a continuous intermetallic layer is dominated by thermal factors, rather than by mechanical forces. Moreover the effect of the peak temperature on the thickness of the bonding layer is more than three times stronger than the duration of high-temperature influence, as known from [18]. Thus, the low temperature of the caster rolls leads to the formation of less intermetallic phases and strongly deteriorate the bonding properties. After the roll sleeves reach the working temperature, the temperature in the strip forming zone increases stimulating diffusion and formation of intermetallic phases on the interface of the bonded materials resulting in an improved bonding strength.

Although the high-temperature roll bonded strips have a continuous layer of intermetallic phases as well, their bonding strength does not exceed 48 MPa, even for strips without any visible delamination. Thus it is clearly lower than that of the twin-roll cast clads. Further decrease of the reduction close to the threshold value led to a decrease of the bonding strength to only 20 MPa – 25 MPa. The reduction during twin-roll casting usually does not exceed 40 % due to design limitations of twin-roll casters. Nonetheless the quality of bonding remains high. Thus, the formation mechanisms of intermetallic phases must be different in twin-roll casting and roll bonding. In case of the latter the initial contact between the bonding materials occurs in the solid-solid system impeding their interaction and the formation of intermetallic phases. Thus, additional pressure is required to obtain a strong bonding. The force necessary for breaking the oxide films and pressing the layers to each other is achieved only at high strains. However, an increase of the bonding strength was not observed, despite high absolute strain values, suggesting a highly detrimental effect of oxide particles present in the bonding zone.

As could be shown by this series of experiments, the primary factor for the formation of a durable bonding is the general temperature in the process, which was induced either from the aluminum substrate or from both cladded materials. As is shown in other works dedicated to cladding by roll bonding [15, 16, 23-25], also deformation induced heat or frictional heat due to asymmetrical rolling can be used for this purpose. With decrease of the rolling temperature, the influence of the thermal factors decreases and significance of the force factors naturally increase. Thus at low temperatures, as present during cold roll bonding, merely force factors are responsible for obtaining a durable bonding. Though higher forces and strains as well as additional surface preparation is needed [16, 26, 27]. However, the strength of a purely mechanically induced bonding is low and intermetallic layers are rather uneven and discontinuous. For increasing the bonding quality additional heat treatments are necessary for stimulating the growth of intermetallic phases.

Conclusions

Experiments on production of clad strips by means of twin-roll casting and high-temperature roll bonding were carried out. The mechanisms and conditions of bonding between stainless steel and pure aluminum during cladding are compared with respect to the different techniques.

For twin-roll casting with a laboratory casting unit optimized process parameters were established. It is shown that the thermal conditions in the casting system become steady after five roll rotations resulting in formation of a bonding with a maximum strength of 95 MPa.

For high-temperature roll bonding a threshold value for the reduction leading to a maximum bonding strength of 48 MPa was determined at 55 % for aluminum preheated to 650 °C and a steel temperature of 20 °C. For the aluminum strips preheated to temperatures close to the melting point an optimal soaking time, which does not significantly affect the microstructure and surface oxidation, was established at 30 min.

Microstructural analysis of the manufactured clad strips showed the presence of thin uniform diffusion layers on the interface of two metals with a thickness of about 2.5 μm – 3 μm. These were found in strips produced by both twin-roll casting and hot roll bonding. Intermetallic layers of such a thickness provide high bonding strength. However, the conditions of bonding formation are different in dependence of the technique applied. The formation of diffusion bonding during twin-roll casting is influenced mostly by thermal factors, such as the overall process temperature and duration of holding at high temperatures. In contrast, the bonding in case of roll bonding is more affected by force factors, such as the roll separating force and the total reduction of the strips during cladding. However, as the increased temperature during the process exerts an influence as well, the impact of the force factors is lower than in case of roll bonding at temperatures below 500 °C.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for their financial support for the scientific work carried out here within the scope of the project SCHA1484/21-1 "Production of aluminium-steel clad strips by means of twin-roll casting".

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