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Sandwich rolling of twin-roll cast aluminium-steel clad strips

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Abstract

In the present study experimental results of twin-roll cast aluminium-steel clad strips of a thickness of 2.0 mm using the example of pure aluminium and an austenitic steel are presented. Electron probe measurements of the bonding area revealed the presence of a continuous interface layer of about 2 μm. To verify the formability of the twin-roll cast clad strips, sandwich samples were cold rolled with up to 66% strain. Furthermore, the sandwich samples were hot rolled at the temperature of 300 °C with different strain values. Mechanical properties, the microstructure and the surface quality of the deformed compound after rolling were analysed. To test ductility and formability of the rolled strips these were cold deep drawn.

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Keywords: Twin-roll casting; Aluminium-steel clad strips; Cold and hot rolling; Mechanical properties; Microstructure

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1. Introduction

Currently, flat clad aluminium-steel products are manufactured by roll bonding, explosion welding and fusing. However, these technologies have several disadvantages, such as a large number of secondary operations, low productivity and high requirements regarding of the bonding surfaces preparation quality. The application of the energy efficient technology of twin-roll casting to produce clad strips is one of the promising sheet production

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technologies. Manufacturing of clad strips by means of twin-roll casting has been presented by Haga et al. (2013) using the example of layered strips of different aluminium alloys, as well as by Bae et al. (2011) at the example of bonding aluminium with magnesium. Twin-roll casting for producing aluminium-steel clad strip was firstly implemented by Grydin et al. (2013). Here, the continuous feeding of the solid steel strip into the roll gap of the caster simultaneously with the aluminium melt is challenging (see Fig. 1). Diffusion bonding occurs between the clad strip components due to the short-term influence of high temperatures in the contact area of the bonded materials as well as the compressive stresses during plastic deformation of the solidified aluminium in the caster. Optimal process conditions during clad strips production should result in the formation of a continuous diffusion layer with a thickness up to 2 μm (Mukae et al., 1995) or up to 5 μm (Ryabov et al., 1984) at the contact interface between aluminium and steel. Ensuring these optimal thickness values of the diffusion layer reduces negative effects that occur due to the presence of hard and brittle intermetallic phases of the type Fe_xAl_y and induces a positive effect on the deformability of the resulting clad strip.

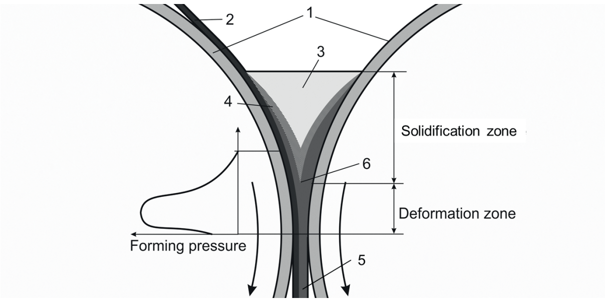

Fig. 1. Principal scheme of the twin-roll casting of aluminium-steel clad strips: 1 – water-cooled rolls, 2 – steel strip, 3 – aluminium melt, 4 – semi-solid aluminium, 5 – solidified clad strip, 6 – kissing point.

Presently, twin-roll casting of clad strips is carried out only under laboratory conditions and has not been realized commercially yet. This is due to the lack of process stability during the clad strip production and the low quality of the aluminium layer surface of the strips. Application properties of the clad compounds are defined by the bonding strength as well as by the microstructure and mechanical properties of its layers. The main drawback of twin-roll cast aluminium-steel clad strips is the presence of a partially cast microstructure in the aluminium layer. This is due to the inhomogeneous temperature distribution across the aluminium layer during rolling in the caster. The surface layer of the aluminium has a lower temperature and thus deforms less than the inner layers, so the cast structure formed during the solidification remains almost non-reworked (Grydin et al., 2014).

It is known that the presence of a cast structure reduces the quality of aluminium strips. As a consequence, the twin-roll cast material needs to be processed subsequently by a combination of rolling and heat treatment. During such processing the aluminium grains first obtain a stretched form. Subsequently, smaller grains form during recrystallization and the microstructure becomes more uniform. Cold deformation with a true strain of 0.1 to 0.25 increases the tensile strength and yield strength of aluminium by 1.5 to 2 times, but decreases the ductility about 3 to 5 times (Rangaraju et al., 2005; Kammer, 1990). Strain hardening is eliminated by a following annealing. It is known that during annealing at a temperature above 250 °C to 300 °C an intensive recrystallization occurs in pure aluminium. This results in the removal of strain hardening and an increase of ductility by 5 times (Altenpohl, 1994). During such a treatment the main drawbacks of strips like poor quality of the aluminium layer surface, porosity and unevenness are eliminated. Hot rolling in combination with heat treatment is widely used after twin-roll casting to improve the quality of monometallic strips of aluminium and its alloys, magnesium alloys and steels (Grydin et al., 2014; Hagemann, 2003).

The main task of the processing of clad strips is improving the aluminium layer properties while retaining the bonding strength of the compound as well as the steel layer properties. This imposes certain limitations on the use of conventional methods of cast strips processing. It has been shown that heating of clad aluminium-steel strips to a temperature of 350 °C to 400 °C leads to an intensive growth of the intermetallic phase layer (Bach et al., 2008; Manesh et al., 2003). Exceeding a critical thickness of 5 μm significantly reduces the strips bond strength. An analysis on the effect of plastic strain and heat treatment on the properties of aluminium-steel clad strips, obtained by means of roll bonding, is given in (Li Han et al., 2005). It has been shown that a cold strain of more than 33% and a subsequent annealing at a temperature of 350 °C results in a substantial improvement of the quality and durability of the clad strip at cyclic bending tests. However, these treatment conditions cannot be used for twin-roll cast clad strips since the thickness of the diffusion layer after the twin-roll casting is already within the optimal range of 2…5 µm, providing satisfying bonding strength, and any further growth of the brittle intermetallic phase layer will cause a decreasing bonding strength (Grydin et al., 2013). Similarly, an annealing of the strain hardened steel layer is not possible without reducing of entire compound quality.

Hence, the aim of this work is to determine the effect of a rolling treatment on twin-roll cast aluminium-steel clad strips regarding the mechanical properties, the microstructure and the surface quality. Furthermore, the critical value of cold strain resulting in a delamination of the clad strip shall be identified.

2. Twin-roll casting of clad strip

Twin-roll cast strips with a width of 160 mm and a total thickness of 2 mm were produced for the following experiments. As materials an austenitic steel (1.4401) with a thickness of 0.5 mm and the aluminium alloy EN AW-1070 were chosen. The experimental twin-roll caster of Chair of Materials Science of University of Paderborn (Grydin et al., 2010) was used to produce the clad strips. The following test parameters were employed for the investigations: temperature of the aluminum melt 690 °C, casting velocity 5.1 m/min and total pool length approx. 40 mm. Pre-treatment of the steel strip before feeding into the aluminium pool is not carried out.

Due to significant differences in the yield stress values of aluminium and the steel at the temperatures of twin-roll casting the plastic strain during rolling in the caster is localized in the aluminium layer. By usage of specified parameters of continuous forming plastic strain in the aluminium layer amounted to 30%.

As a result of the experiments of twin-roll casting aluminium-steel clad strips with a durable continuous bond of aluminium and the steel layer are obtained. To confirm the presence of a diffusion layer between aluminium and the steel, a chemical element analysis of the bonding area was performed by means of an electron probe microanalyser JEOL JXA-8900R. The corresponding distribution of the relevant chemical elements is depicted in Fig. 2. The results confirm that a thin diffusion bonding layer formed during the strip casting. Aluminium diffused into the steel strip as can be seen by the concentration gradient in the seam of the iron plot.

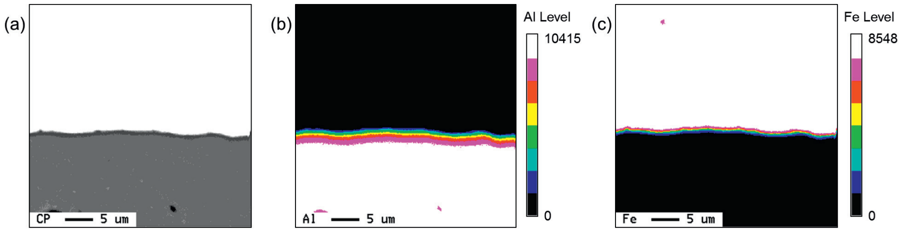

Fig. 2. Microscope image of the strip´s bonding zone (a) and distribution of Al (b) and Fe (c) in it obtained by means of electron measuring.

3. Rolling of twin-roll cast clad strips

To analyse the deformability of the twin-roll cast aluminium-steel clad strips during rolling a series of rolling experiments was carried out. Due to the yield strength difference of the aluminium and the steel and the corresponding deformation inhomogeneity in the layers of the clad strip during rolling a not desired bending in the direction of the steel layer is possible. As a consequence, tensile stresses occur in the contact area between two dissimilar materials leading to debonding of the intermetallic compound even at relatively low strain values. Hence, to ensure symmetric conditions during rolling the clad strip samples of about 25 mm width and 150 mm length were coupled in 8 symmetrical sandwiches with the aluminium layers outward. The strips in the sandwiches were joined at both ends with aluminium rivets. The prepared sandwiches were longitudinal cold rolled using a laboratory two-high rolling mill with a roll diameter of 140 mm and barrel length of 200 mm at a rolling speed of

0.37 m/s. Rolling of the aluminium-steel clad strip sandwiches was carried out in two passes to provide a variation of reduction by the individual passes and with an approximately equal value of the total plastic strain after two passes. The deformation parameters for the first and the second passes are given in Table 1.

Table 1. Deformational parameters of sandwich rolling of aluminium-steel clad strips.

Experiment number	1	2	3	4	5	6	7	8
Reduction at 1st pass (%)	49.9	41.9	33.3	59.1	33.3	63.6	37.1	52.4
Presence of delamination	-	-	-	-	-	±	-	-
Reduction at 2nd pass (%)	33.3	40.0	46.8	25.3	49.0	14.0	45.8	32.1
Total reduction (%)	66.6	65.0	64.6	69.4	66.0	67.8	65.9	67.7
Presence of delamination	-	-	-	-	-	±	-	-

After the first pass local delaminations were observed only on one sandwich that was rolled with the maximal deformation strain of about 64%. After the first pass and the analysis of the experimental data the clad strip sandwiches were rolled in the second pass with different reduction values to the final thickness of about 2 mm. After the second pass of cold rolling the front and rear ends of the sandwiches containing the rivets were cut off. The packages were split into the separated aluminium-steel clad strips and analysed. The final thickness of the single clad strip samples was 1 ± 0.2 mm. After the second pass one sandwich subjected to the maximum plastic strain in the first pass delaminated along the entire contact surface. Since total reduction in the experiment after two passes was approximately equal for all samples it is obvious that the maximum reduction at one single pass should be considered as the critical strain value. For the given type of twin-roll cast aluminium-steel clad strips it amounts to about 63%.

To analyse in detail the influence of the deformation treatment on the microstructure and mechanical properties of the twin-roll cast clad strips the following rolling experiments were performed. To ensure symmetry conditions during rolling the deburred twin-roll cast clad strips with 2 ± 0.2 mm thickness were formed in sandwiches of two samples with dimensions of 150x150 mm with the steel surface inside and fastened with four aluminium rivets in the corners. The initial sandwich thickness was about 4.5 mm. The rolling experiments were performed using the above mentioned two-high rolling mill at a rolling speed of 0.37 m/s. The rolling was carried out at temperatures of 20 °C and 300 °C, respectively, with a total plastic strain of 11 %, 20 % and 32 % in 1, 2, and 3 passes, respectively. The specified hot rolling temperature ensures recrystallization of the aluminium but prevents the growth of an intermetallic phase layer at the aluminium-steel interface.

4. Influence of rolling on quality of clad strips

After the experiments the sandwiches were split and specimen of the clad strips were prepared for mechanical testing and a metallographic analysis of the microstructure. As reference, samples of clad strips in the as-cast state and not subjected to rolling were prepared. Results of the uniaxial tensile tests from 6 samples for each plastic strain value and rolling temperature were averaged. As can be seen from Fig. 3, samples of the clad strips in the initial state feature a very high ductility, but their strength can be significantly improved after hot rolling at 300 °C using a plastic strain of about 10 %. Furthermore, hot rolling at 300 °C with up to 32% plastic strain increases the tensile strength and yield strength compared to the initial values by 20% and 90%, respectively. This also increases the bonding strength between the clad strip layers. Samples of the initial as-cast state show a slight delamination after uniaxial tension. For samples subjected to rolling such effect was not observed. During the tensile tests the aluminium and steel layers of these samples deformed and fractured simultaneously. Cold rolling at room temperature has a greater impact on the increase in tensile and yield strength of the clad strips. For example, rolling with 20% plastic strain doubles the strip strength. However, a negative effect of the strips deformation hardening is a significant reduction of its ductility.

For a quantitative evaluation of the effect of rolling on the surface quality of the strips optical measurements of the surface topography were carried out. The measurements were performed using a Keyence 9000 laser microscope. Both the steel and aluminium surface of the clad strips in the initial state and after rolling with 32%

strain were analyzed. Due to the rolling the aluminium surface roughness R_z was reduced by 4 times from 32 μm to 8 μm. For the steel surface a lesser reduction is observed due to the low surface roughness of the initial material. However, a decrease in the R_z value from 19 μm to 10 μm was measured. Thus, rolling has a positive effect on the strip surface quality.

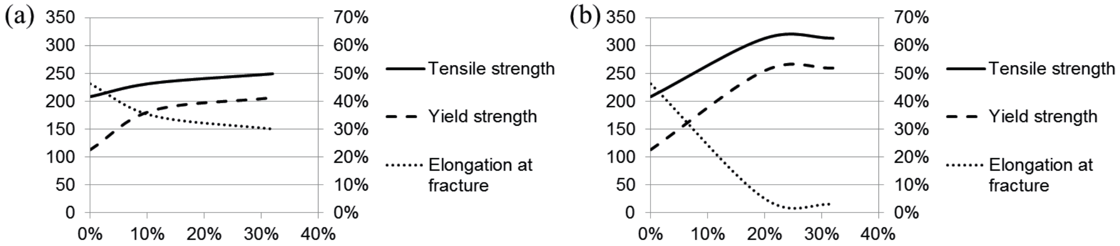

Fig. 3. Mechanical properties of the strips, deformed with different strain during hot rolling (a) and cold rolling (b).

To analyze the microstructure in the aluminium layer of the clad strips as well as the bonding zone micrographs in the rolling direction were prepared by polishing and etching according to Barker. Polarized light was used to analyze the grain structure of the aluminium as well as the bonding zone. As can be seen in Fig. 4, the microstructure of the aluminium layer of the strips in the initial as-cast state is inhomogeneous and contains residual cast grains. In the center of the layer a recrystallized fine-grained microstructure is observed. However, close to the bonding zone large grains dominate, formed as a result of the retarded crystallization and therefore subjected to a lessened deformation in the caster. This is due to the reduced heat transfer from the strip to the caster roll through the steel strip. The aluminium microstructure of the strips subjected to cold rolling depicted in Fig. 4 mainly consists of elongated and deformed grains and is more uniform than in the as-cast strip. It is obvious that the recrystallization process in the material occurs very slightly. This results in a high strength of the cold rolled strips and a low ductility. Fig. 4 reveals that during hot rolling at temperatures of 300 °C large dendritic aluminium grains are deformed as well, which favorably affects the microstructure uniformity across the layer. But unlike cold rolling recrystallization occurs with a formation of new fine aluminium grains. Such aluminium microstructure provides both high strength and plasticity of the clad strips.

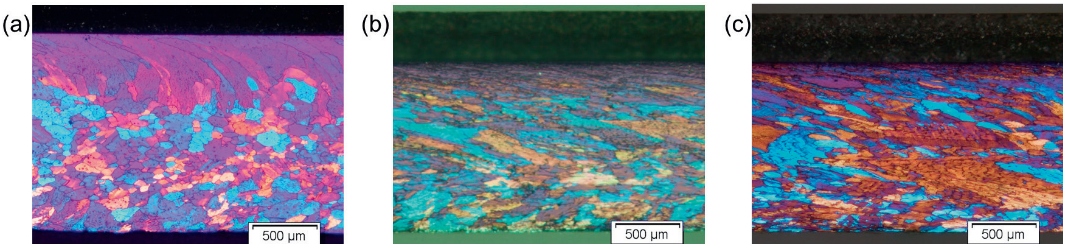

Fig. 4. Microstructure of aluminium layer in the clad strips in as-cast state (a) and after cold (b) and hot (c) rolling with 32% deformation strain.

To investigate a further plastic deformation of the clad strips after sandwich rolling with total reduction of 32% cold deep drawing of the strips was carried out. The deep drawing tests were performed on a 1000 kN hydraulic press using a circular cup as an example part. 100 mm diameter discs were cut out of the clad strip. The punch diameter was 50 mm with a corner radius of 5 mm. The internal diameter of the drawing ring was 54 mm. The pressure ring's force was set to 60 kN. The punch velocity during the deep-drawing was 20 mm/s. The discs were placed with the steel side facing downwards (inside of the finished cup) and deep-drawn up to a depth of approx. 40 mm (see Fig. 5). It should be noted that the bonding zone was subjected to a tensile stress between the aluminium and steel during the deep-drawing which could have resulted in cracking and delamination if the mechanical properties of the diffusion layer would have been too low. However, no damage or delamination was observed.

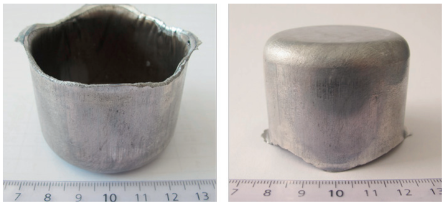

Fig. 5. Cold deep drawn cup.

5. Conclusions

Using the novel technology of twin-roll casting thin clad aluminium-steel strips were produced. The presence of a uniform thin layer of Fe_xAl_y intermetallic phases at the metals interface is confirmed by means of EPMA. The applicability of rolling to rework the residual cast microstructure of the aluminium layer has been shown. It has been revealed that the hot sandwich rolling with up to 32% strain increases both yield stress and tensile strength of the twin-roll cast clad strips by 1.9 and 1.2 times, respectively, though elongation at fracture decreases. Cold rolling of the clads increases their strength by 1.5 times, but lowers the ductility by 10 times. Rolling provides a positive effect on the quality of the intermetallic bonding and improves the quality of the strip surface. Thus, rolling with 32% strain reduces the aluminium surface roughness R_z of the strip by 4 times and almost by 2 times for the steel surface. After rolling the clad strips feature a satisfactory formability and high bonding strength, which is shown using an example of cold deep drawing of a cylindrical cup. No destruction of the strip and no delamination after deep drawing were observed. By means of sandwich rolling with a total plastic strain of 66% was determined that the critical deformation that leads to delamination of the composite is 63% in one pass.

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