Twin-Roll Casting of Aluminum-Steel Clad Strips: Static and Dynamic Mechanical Properties of the Composite

M. Stolbchenko, O. Grydin, and M. Schaper

Abstract

The manufacturing of thin aluminium-steel clad strips by means of twin-roll casting is a prospective trend of the progress in the light metals sheet production. The resulting composite possesses high bonding strength due to the presence of a continuous thin layer of intermetallic phases at the bonding interface of metallic constituents. At the same time, for the application of twin-roll cast clads, the evaluation of their properties is of great importance. In order to determine the behavior of twin-roll cast aluminum-steel clad strips under loading, monotonic tensile and fatigue tests were carried out. Therefore, strips in the as-cast condition as well as after a heat treatment, stimulating the growth of the intermetallic phases, were subject for the characterization. In addition, the specimen's fracture surfaces were analyzed using scanning electron microscopy to obtain information on the type of fracture, the location and source of the crack nuclei.

Keywords

Twin-roll • Casting • Clad strip • Aluminum-steel • Fatigue

Introduction

Clad products made of dissimilar materials finding a wide application in the different branches of modern industry. Among them can be highlighted the transport machine building, chemical industry, offshore and civil building. The main feature of clad materials is a set of properties typical for its constituents combined in a single product. In case of aluminum-steel composite these properties are high strength and ductility, excellent corrosion resistance, and heat and electric conduction, good weldability.

Besides the well-known technologies for production of flat clad products, such as roll bonding, explosion bonding and welding, the twin-roll casting [1] can be used to manufacture clad strips directly from the melt. This technology is used over the last years for production of strips of different steel grades [2], aluminum [3, 4], magnesium [5] alloys and other metals. The main advantage of twin-roll casting is possibility to exclude the intermediate heating steps from the thin strip production chain. This allows reducing of construction and production costs, energy and material consumption as well as decreases harmful pollutions. Application of the twin-roll casting for production of clad strips gives in turn additional advantage consisting in minimization of surface treatment of bonding materials.

Nowadays, the manufacture of clad strips by means of twin-roll casting is limited on the laboratory scale. The investigations of this process are mostly carried out for the one group of materials or for materials having similar melting points. In this case, all the layers of clad strip are consequently twin-roll cast from their melts. Haga et al. [6, 7] show the use one-, twin- and triple-roll casters for production of clad strips consisting of different aluminum alloys. Two- and three-layer strips are produced at the casting

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speeds up to 40 m/min. The strips have a good bonding strength due to the thermal activation of diffusion processes between aluminum alloys during the casting.

In [8] a manufacture of clad strip of high manganese steel with an austenitic stainless steel by means of twin-roll casting is shown. A sound bonding between the strip layers is reached by partial melting of material at the contact interface. The application of dissimilar materials for manufacturing of clad strips by means of twin-roll casting is demonstrated in [9]. Molten magnesium alloy was fed between two 50 µm thickness foils of pure aluminum in a horizontal twin-roll caster. Metallographic analyses showed the presence of a layer of intermetallic phases at the interface of the heterogeneous materials and a partial melting of the aluminum foils occurred. The first studies on cladding of materials with significantly different melting points by means of twin-roll casting were carried out by Grydin et al. [10]. Thin aluminum-steel clad strips possessing a total thickness of 3 mm were produced using a vertical twin-roll caster. Analysis of the metals bonding zone showed the presence of a thin continuous layer of intermetallic phases. Bonding strength exceeding 70 MPa were measured based on tensile adhesive strength tests results.

Along with the properties of the composite layers the high characteristics of the product are ensured by the tough bonding between them. This allows the layers to resist together under different loading conditions during production and service life. For the complex characterization of new composite material and evaluation of its application potential the mechanical tests have to be carried out. The tensile tests can give conclusions about material's use limits determining the ultimate strength and elongation at fracture. In turn, the testing under cyclic loading can complement the material characterization while in application dynamic loads are usually dominant.

The fatigue resistance is one of the most important features of construction materials. For conventional materials, such as aluminum and steel, this has already been extensively studied, for example in works [11, 12]. However, the combination of two different materials in a flat product under cyclic loading differs substantially from the theoretical prediction and the behavior of the individual materials. Such effect was mentioned in works dedicated to the investigation on fatigue behavior of multilayer structures [13–17]. The composition of materials as usual has higher mechanical characteristics than its constituents apart. Evaluation of servicing features, i.e. the fatigue strength and life prediction, for the multimaterial structures made by means of thermal or deformational methods is seen to be one of the important tasks in modern science [18, 19].

It was investigated [20] that the structure of bonding zone between two steel grades in an explosive bonded strip cardinally changes the character of crack propagation in the clad under the cyclic loading. The growth of the intermetallic phases on the bonding interface between dissimilar materials also leads to changes in the crack propagation mechanism. On the example of friction-stir welded aluminum and steel plates was shown [21] that the layer of Fe–Al intermetallics plays a decisive role in the strength of the joint. Moreover, dependent on the layer thickness of intermetallics the crack propagated either in the bonding zone or in the base material. The intermetallic phases of Fe–Al system [22–24] due to their brittleness can initiate the formation of cracks at the inner surfaces of the strip layers [25]. Moreover, in aluminum-steel joints the crack will probably propagate through the brittle layer of intermetallic phases than across the base material [26]. Pores, inclusions, inhomogeneity and other defects at the contact surface between the bonded metals can serve as nuclei for the formation of cracks [15, 27, 28]. On the other hand the soft and ductile interlayer can serve as a crack stopper in multilayer structures [13, 14].

An investigation of the fatigue behavior of roll bonded strips of 6016 aluminum alloy and FeP06 steel was carried out in [29]. The properties of clads were tested under static loading as well as under low- and high-cycle fatigue. The fatigue life of the composite was established comparing with its basic materials. The clad strip showed higher fatigue strength than the predicted value based on the rule of mixture. In all the tests the crack grew in steel from the bonding zone between two metals.

The microstructure of the aluminum layer also significantly affects the properties of the composite. First of all, the residual cast structure and casting defects that are characteristic for the twin-roll cast strips serve as crack nuclei and have a negative influence on the fatigue strength [11, 30].

Against this background, the more intensive study of the mechanical properties and fatigue behavior of the twin-roll cast aluminum-steel clad strips are of great scientific importance.

Experimental Procedure

Two-layer aluminum-steel clad strips were utilized for the experimental investigation. As strip materials technical pure aluminum EN AW-1070 and austenitic stainless steel 1.4301 were used. The strips were twin-roll cast using vertical caster of the Chair of Materials Science at Paderborn University [31]. The laboratory caster had two steel rolls, each with a diameter of 370 mm and a 200 mm barrel length. The experimental unit was additionally equipped with an uncoiler for the steel substrate, a device for its feeding, as well as with a puller for the finished clad strip. During the experiments, the melt of pure aluminum was fed into the twin-roll caster together with a solid substrate of stainless austenitic steel clasped to one of the casting rolls (see Fig. 1). After the complete solidification of the aluminum layer between two internally cooled rolls, the clad strip was plastic strained in the deformation zone (see Fig. 1) and left the caster. The main parameters of the twin-roll casting used in the experiment are listed in Table 1.

The twin-roll cast aluminum-steel clad strip with continuous bonding of layers and without significant casting defects was taken for the further analysis. The specimens for mechanical testing as well as for metallographic analysis were sampled from the clad strip at a distance of about 6 m from its emerging end. A section of the clad strip was subjected to heat treatment to initiate the diffusion between the aluminum and steel layers. Thus the composite material was annealed in a furnace at 400 °C for 2 h utilizing a protective gas atmosphere and subsequently cooled on the air. The annealing temperature was chosen based on the results of [32, 33]. Here the range between 400 and 450 °C was determined as a start temperature for the growth of Fe–Al intermetallic phases. At the same time the range of sensitization temperatures for austenitic stainless steel lies above 400 °C [34]. To avoid the reduction in the properties of steel layer, the lowest temperature of the diffusion process start range was chosen for the heat treatment.

For the characterization of intermetallic bonding between the clad strip's layers the microsections in the rolling direction were prepared both in the as-cast condition as well as after the heat treatment. The samples were stepwise grinded and fine polished using 1 µm silicon dioxide paste at the final stage. The prepared samples were analyzed using scanning electron microscope (SEM) Zeiss Ultra Plus, equipped with a secondary electron (SE) and energy-dispersive X-ray spectroscopy (EDX) detectors.

Evaluation of mechanical properties of the composite was carried out by means of uniaxial quasi-static tensile tests as well as fatigue tests. All the tests were performed at a room temperature using small dog-bone specimens having a width and a length of machined section of 3 and 8 mm

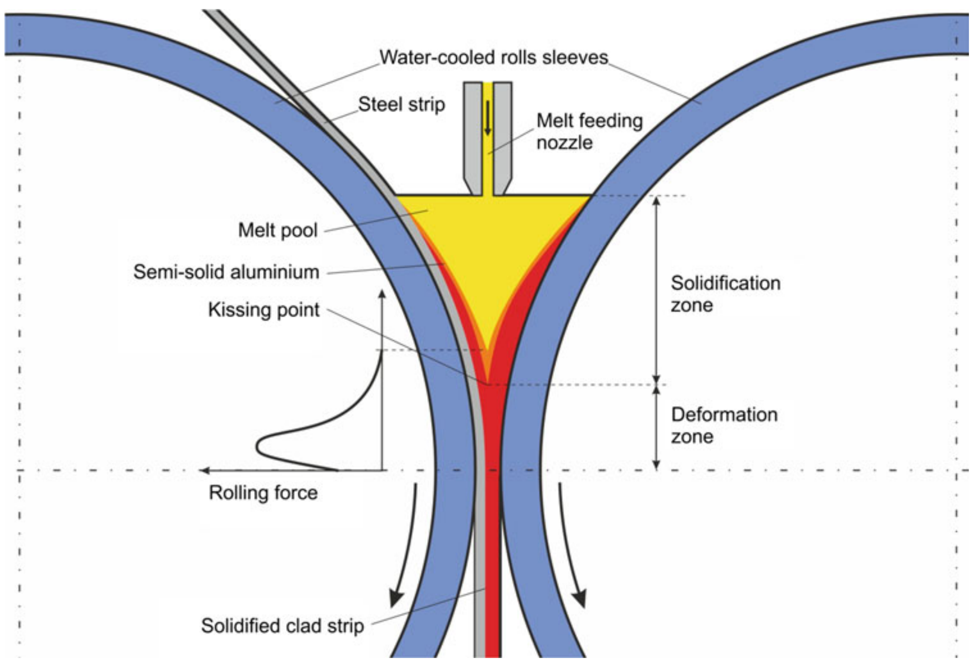

Fig. 1 Basic schematic of the twin-roll casting of aluminum-steel clad strips

Table 1 The main twin-roll casting process parameters

Process parameter	Value
Initial temperature of the steel substrate (°C)	20
Aluminum melt temperature (°C)	700
Steel substrate thickness (mm)	0.5
Total thickness of the clad strip (mm)	2.1
Casting speed (m/min)	5.1
Clad strip reduction in twin-roll caster (%)	40
Coolant flow rate (l/min)	110
Coolant temperature (°C)	14

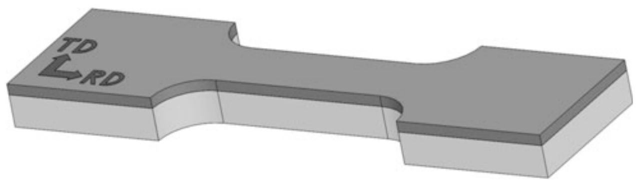

Fig. 2 26 mm length dog-bone specimen used in the mechanical testing: *RD*, *TD* rolling and transversal direction at twin-roll casting

respectively. The specimens were sampled from the clad strip sections by means of electro-discharge machining. The loading direction of all specimens coincided with the initial twin-roll casting direction (see Fig. 2). In order to remove surface unevenness and defects, the edges of samples were ground down to a grit size of 5 µm prior to the actual experiments. The tests were conducted on a MTS 858 table top system allowing maximal loading of 15 kN in both tension and compression directions.

In the first series of experiment the tensile tests at a constant strain rate of 0.001 s^{-1} were carried out. The specimens of the clad strip in as-cast condition and after the heat treatment were tested. For the comparative analysis, the specimens of constituent materials, twin-roll cast pure aluminum and austenitic steel 1.4301, were also subjected to the tensile testing.

In the second series of the experiments the strain-based low-cycle fatigue analysis of the clad strips was made. The specimens in as-cast conditions and after the heat treatment were used in the series. The fully reversed cycle loading with $R = 0$ at a constant strain rate of 0.006 s^{-1} was applied to the specimens. The total strain amplitude $\Delta\varepsilon/2$ was equal to ±0.25 and ±0.5%.

In the third series the stress-based high-cycle fatigue analysis of the clad material was performed. The specimens were tested using relation $R = \sigma_{min}/\sigma_{max} = 0$, so the stress was fluctuating from zero to its maximum. Such relation was conditioned by the unstable behavior of thin strip material under the high values of compression loading. The stress amplitude σ_a was varied from 50 to 90 MPa during the experiments. The frequency of cyclic loading amounted 5 Hz.

After the quasi-static and fatigue tests the fracture surface of the specimens was analyzed by means of electron microscopy. The scanning electron microscope Zeiss Ultra Plus with SE-detector was used for this purpose.

Results and Discussion

Twin-Roll Casting of Clad Strips

The SEM microsection in Fig. 3a obtained using SE-detector shows the bonding zone of the clad strip after the twin-roll casting. Neither large oxide particles in the fusion zone nor any delamination between the layers are discernable. Corresponding distribution of the relevant chemical elements, as determined by EDX, is shown in Fig. 4. The EDX analysis of bonding zone reveals presence of a thin uniform layer with a thickness less than 1 µm in the interface, indicative of an intermetallic phase of the Fe–Al. Such bonding character indicates on the good interaction between aluminum and steel and ensures a high bonding strength between the strip layers [10]. The microsection of the strip after the heat treatment is depicted in Fig. 3b. As can be seen, no delaminations or active growth of the intermetallic phases observed in the bonding zone comparing with a strip in as-cast condition. It can be concluded that for the intensive growth of the Fe–Al phases between pure aluminum and stainless steel 1.4301 the temperatures above 400 °C are strongly required. At the same time the negative effect of formation of the brittle intermetallics layer above 5 µm thickness by annealing at 400 °C can be excluded.

Quasi-Static Tensile Testing

The influence of the heat treatment on the mechanical properties of the clad strips was analyzed during the tensile tests. The averaged values of mechanical properties of the strips in as cast condition and after the heat treatment are given in Table 2. The corresponding stress-strain curves of the composite material in the both conditions as well as of its constituents are shown in Fig. 5.

An atypical form of the initial section of the stress-strain curves of composite material can be noticed in Fig. 5. The transition from the elastic to plastic strain passes in two stages. At a low stress the both layers are elastic strained together. After reaching the ultimate tensile strength of aluminum the curve makes a deviation and passes into another straight section. This section corresponds to the beginning of the plastic strain in the steel layer. After reaching of yield strength of the steel the curve flows further showing strain hardening of the whole composite to the maximum values of 228 MPa of tensile strength and 39% elongation at fracture. The heat-treated material shows a slightly lower strength but simultaneously a higher ductility. This can be explained as withdraw of work-hardening in composite during annealing.

The fracture surfaces of the specimens in as-cast as well as annealed conditions after the tensile tests obtained using SEM are shown in Fig. 6a, b.

The fractured surface of both layers have characteristic dimple path indicating the ductile fracture. A difference between the end cross section prior to the fracture of specimen can be also mentioned. Such necking in the annealed material ensures its higher elongation at fracture measured during the experiments. At the same time, a clear

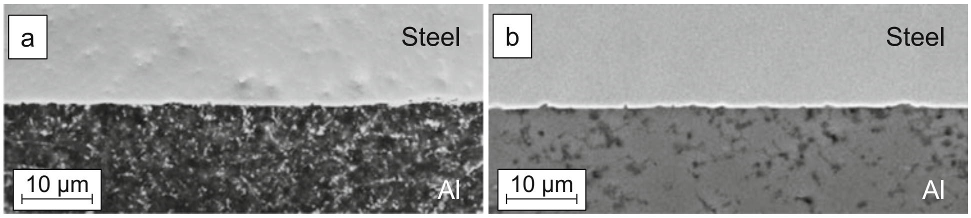

Fig. 3 SEM micrographs of the bonding zone of the twin-roll cast clad strip: **a** in as-cast and **b** in annealed condition

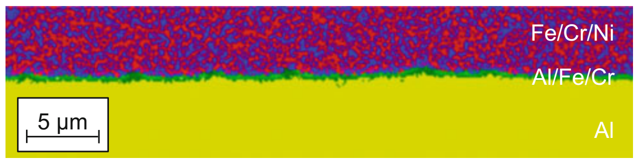

Fig. 4 Distribution of the chemical elements in the bonding zone between the layers of clad strip in as-cast condition obtained using EDX analysis

Table 2 Mechanical properties of the twin-roll cast strips obtained during the tensile tests

Specimen condition	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation at fracture (%)
As-cast	86	228	48
Cast and annealed	63	220	56

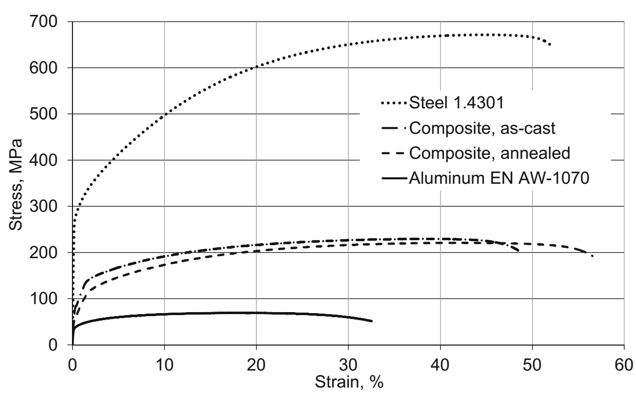

Fig. 5 Stress-strain diagram of the twin-roll cast strips and their constituent materials under the monotonic tensile loading

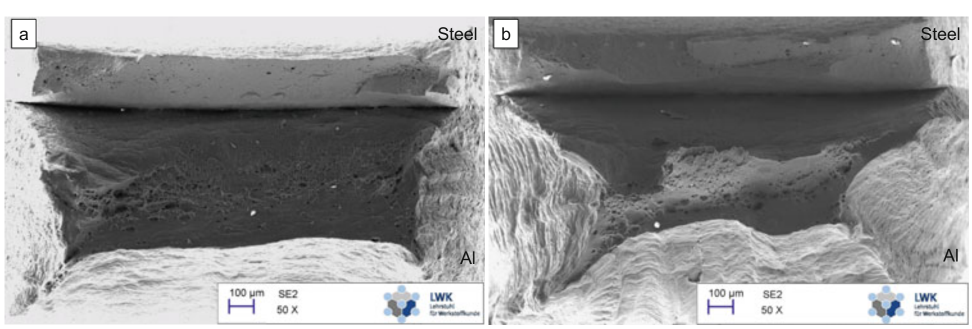

Fig. 6 Fracture surface of the composite material after the tensile test in as-cast (**a**) and annealed (**b**) conditions

delamination of the strip layers can be seen on the both specimens. However, the propagation of delamination crack is restricted only in the fracture zone and the clad material in whole retains its stability.

Low-Cycle Fatigue Testing

For the investigation of material behavior under cyclic loading in the range above the yield strength the low-cycle fatigue tests were performed. The obtained hysteresis loops at the half-life cycles for the material in as-cast and annealed condition are shown in Fig. 7.

The annealed material shows poorer ductility that can be seen from the hysteresis loop width. During the initial stage of LCF tests the specimens showed facility to the strain hardening. In the second stage, approximately after reaching of half-life loading cycle all the specimens softened and broke showing ductile fracture behavior.

In order to determine the crack initiation point as well as crack propagation direction a fracture surface analysis was performed using the specimens after the fatigue tests. The specimens in as-cast condition after the LCF-tests with total strain amplitude of ±0.25 and ±0.5% are shown in Fig. 8a, b correspondingly. The areas of both fatigue and forced fracture can be detected on the specimens' surfaces. In both samples in Fig. 8 the crack in the steel layer was initiated at the edge of the bonding interface with aluminum layer. No delamination occurred in the clad material prior to the forced fracture. Due to the tough bonding in the specimens in as-cast condition the crack overcame the bonding zone and propagated simultaneously in the both layers. Analyzing the form of striations in aluminum layer, the crack growth direction was determined. The striations on the fracture surface of aluminum show the crack propagation from the specimen's outer surface to its core. Moreover, numerous striations were detected indicating the crack propagation in aluminum layer towards the bonding zone (see Fig. 9). Simultaneously, with cracks that overcame the bonding zone they origin from

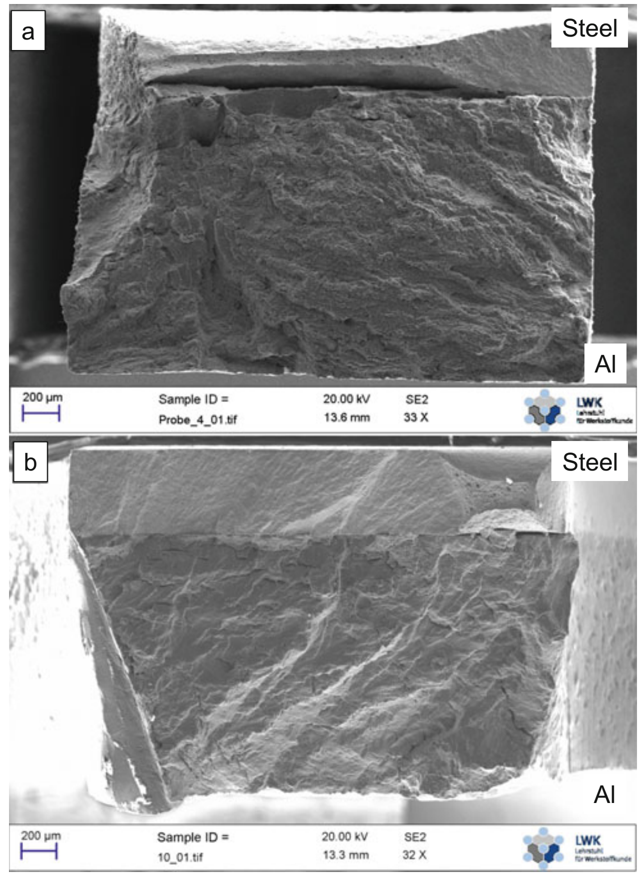

Fig. 8 Fracture surface of the composite in as-cast condition after the low-cycle fatigue test with total strain amplitude of $\Delta\varepsilon/2 = \pm 0.25\%$ (**a**) and $\Delta\varepsilon/2 = \pm 0.5\%$ (**b**)

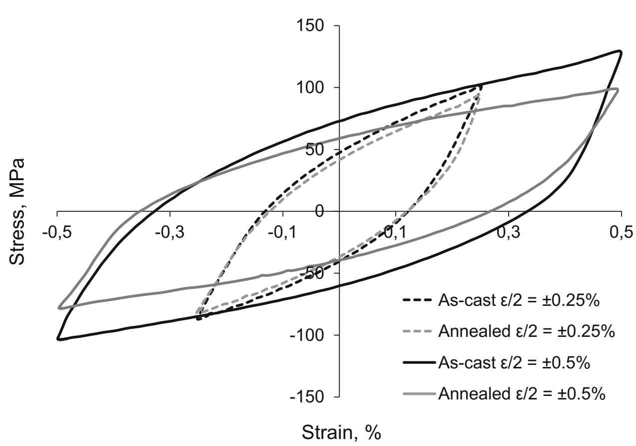

Fig. 7 Half-life hysteresis loops for the aluminum-steel composite in as-cast and annealed conditions under cyclic loading with total strain amplitudes of $\Delta\varepsilon/2 = \pm 0.25\%$ and $\Delta\varepsilon/2 = \pm 0.5\%$

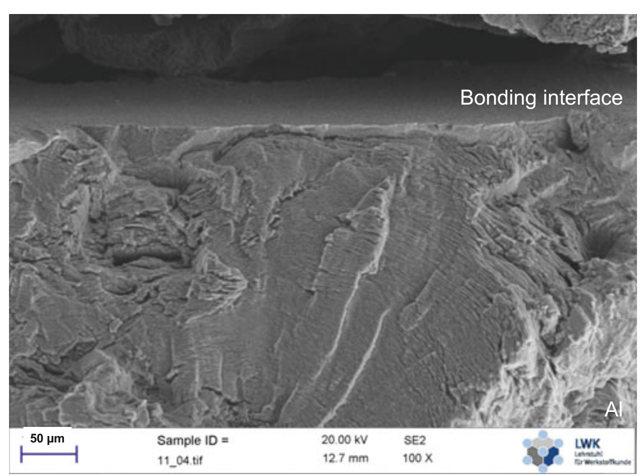

Fig. 9 Striations on the fractured surface of aluminum layer showing the crack propagation towards the bonding zone

numerous sources on the aluminums' outer surface. Analyzing the form of fractured specimens, it was established that the forced fracture occurs first in the aluminum layer and at least in the steel layer.

An intensive delamination between the layers can be observed in the annealed clad strips (see Fig. 10) comparing with the specimens in as-cast condition. This affected the independent crack propagation in each of the strip layers. The crack in steel layer grew from the bonding interface, whereas the cracks in the aluminum layer started from the outer surface of the specimen. Analogous to the as-cast strips, the fracture of steel layer followed after the complete partition of aluminum layer.

The crack sources and their growth direction were studied in detail. The image in Fig. 11 shows the bonding surface in the specimen in as-cast condition fractured under cyclic loading with stress amplitude of ±0.25%. From Fig. 11a can be seen that the transversal crack in the steel layer served as an additional fracture initiator. In Fig. 11b numerous crack propagations into the steel layer from the bonding interface can be observed.

So the intermetallic bonding layer between the clad strip layers can serve as a source for cracks under the cyclic loading. At the same time, a delamination between the layers during loading leads to the independent crack propagation in the strips layers. So influencing the thickness and morphology of the bonding layer, and consequently the bonding strength, the conditions for minimal crack initiation and joint resistance of the layers to the loading can be achieved in the clad strips.

High-Cycle Fatigue Testing

Further material characterization was made under the cyclic loading with low stresses. Due to the minor change in the properties of composite after annealing only strips in the as-cast condition were subject of this experiment. On the

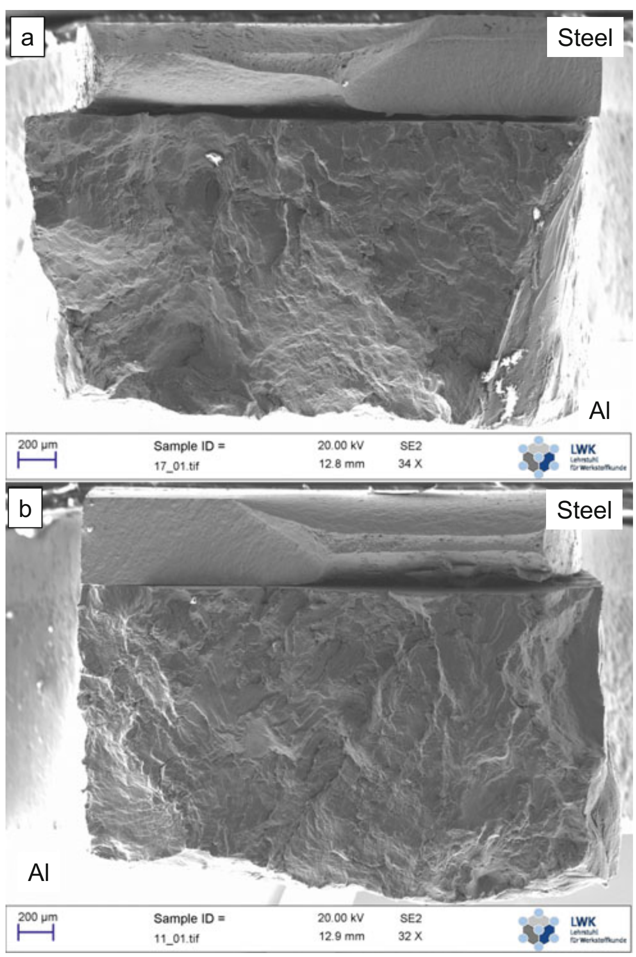

Fig. 10 Fracture surface of the composite in annealed condition after the low-cycle fatigue test with total strain amplitude of $\Delta\varepsilon/2$ = ±0.25% (**a**) and $\Delta\varepsilon/2$ = ±0.5% (**b**)

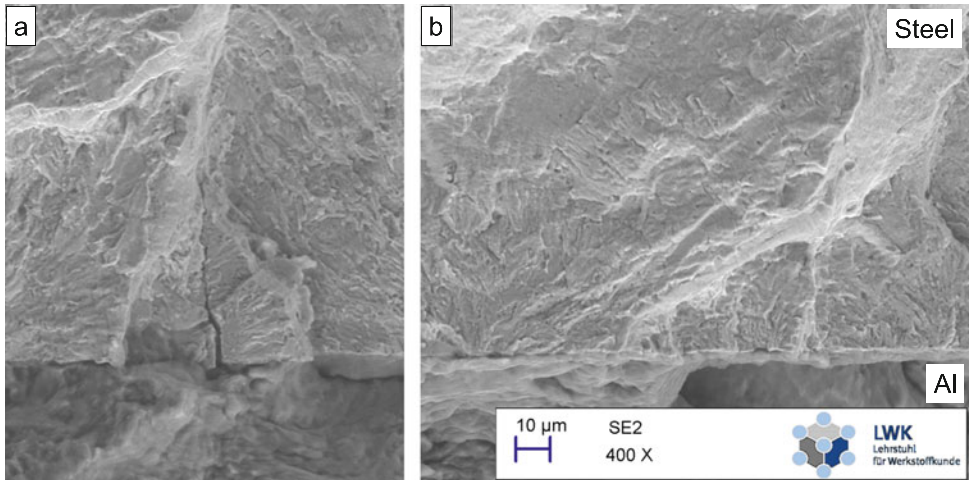

Fig. 11 Fractured surface near the bonding zone of the clad strip in as-cast condition after the cyclic loading with strain amplitude of ±0.25%. **a** Transversal crack, **b** crack sources

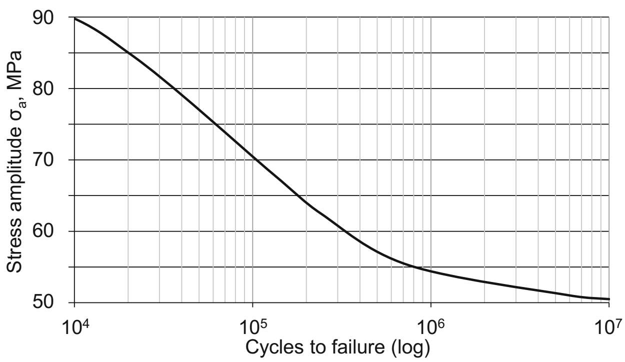

Fig. 12 S-N diagram of aluminum-steel composite under pulsating tensile stress

results of performed HCF-tests the S-N diagram was built (see Fig. 12).

As can be seen from the S-N diagram, the fatigue life of composite increases with reduction of stress amplitude and at $\sigma_a = 51$ MPa material reaches the fatigue limit by $N = 10^7$ load cycles.

Conclusions

Two-layer aluminum-steel clad strips were manufactured by means of twin-roll casting. The strips have a continuous strong bonding between the layers provided by thin diffusion layer on the bonding interface. The properties of the bonding layer can be influenced during heat treatment at the temperatures of 400 °C and higher. Under the tensile tests the clad strips reached the highest ultimate tensile strength at 228 MPa in as-cast condition. At the same time, the best value of elongation at fracture at 56% was reached by composite after annealing. The same tendency was observed during the low-cycle fatigue testing. The as-cast strips show higher strength than the ones in annealed condition. The fracture surface analysis showed that in the as-cast strips the crack propagates in the both layers consequently. In the annealed strips due to the lamination between the layers the cracks grow independent in the steel and aluminum layer. The sources of the crack initiation were found in a bonding layer as well as at the aluminum surface. The fatigue limit for the twin-roll cast clad strip determined during high-cycle fatigue tests corresponds to stress amplitude of 51 MPa.

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