Study of Different Surface Pre-treatment Methods on Bonding Strength of Multilayer Aluminum Alloys/Steel Clad Material

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***Abstract*—*Metallic composite materials, as part of a large group of materials, are well known to design materials properties to the customers' demands. Due to its unique service performance features in comparison with other methods the cold roll bonding process for producing clad metal material has witnessed a rapid growth and development in recent years. The solid state joining technique in the CRB can be applied to a large number of metals, which may be the same or similar, possessing identical attributes, or different, possessing widely varying mechanical or metallurgical property. Here, bonding is caused by adhesion requiring specially prepared surfaces. However, surface cleanliness is difficult to achieve without a controlled atmosphere. In this work the effect of the surface roughness and the initial thickness of the sheets on the bonding strength of Al/St-clad materials were studied using wire brush and belt grinding to reach surfaces of different but defined roughness on the steel. Different Al thicknesses were used, as well. Highest roughness on the surface was achieved using grinding with a grit size of 40. Al-sheet thickness also showed influence on the green bonding strength with the thicker the Al-sheet the better the green bonding strength was. The adhesion between the clad partners exhibited higher when the steel surface was belt grinded.*

***Keywords*—*Cold rolling, bending, Al/St clad, roughness, bonding strength, surface pre-treatment.*

I. INTRODUCTION

1.1 Cold Roll Bonding (CRB)

CRB is a solid phase welding process establishing bonding by joint plastic deformation of different metal partners [1]. Bonding is obtained when the surface expansion exposes the surfaces of the virgin metal or when the pressure reaches a value large enough to extrude the virgin material through the cracks of the fractured layer resulting in the establishment of contact and bonding between opposing virgin surfaces [2]. The schematic illustration of CRB for the production of layered materials is sketched in Fig. 1 [3]. Before roll bonding, the surfaces to be bonded must be properly cleaned, so to remove surface layers, here especially grease and carbon-based components [4]. During bonding, a high reduction in thickness of the materials (up to 40% or more in one rolling pass) has to be achieved [5]. The high reduction generates a great amount of heat and creates virgin surfaces on the materials to be bonded. To increase the bond strength, an annealing treatment is performed after rolling [6, 7].

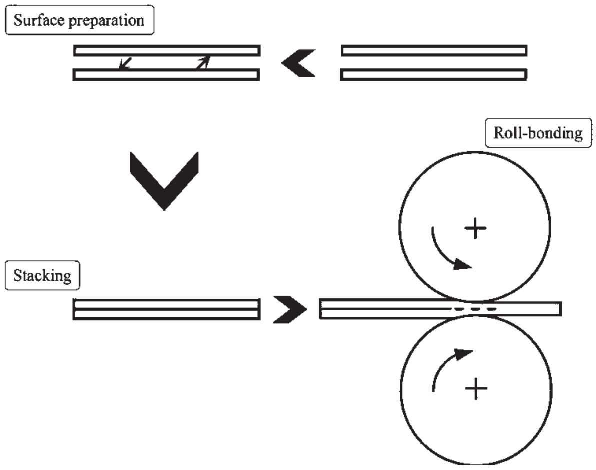


Fig. 1 Schematic illustration of the CRB process[3].

Many research studies on the parameters governing bonding have been carried out to understand the complex nature of the bonding mechanisms, and the conditions of the process have been well defined empirically. So, parameters affecting the CRB process - especially the bond strength - are namely the surface preparation [8, 9], deformation conditions [10], specimens sizes [5], the bonding temperature [11], the storage time between surface preparation and bonding [5], the geometry of the deformation zone (shape factor) [12], the stacking sequence [13], the post-heat treatment [14], the number of layers [15], the layer thicknesses [16], and the time during which the normal pressure is applied.

1.2 Evaluation of bonding quality

There are several methods used for quantifying the bond strength of layered materials, such as tension test, tensile shear test [17, 18], slide shear test [19], multistep shear test [20], peeling test, roller drum peel test [21], or T-peel test [22]. Also, there are some methods used for the qualitative evaluation of the bond, such as bending test, torsion test, impact test and fatigue test [23]. In this work, as the Al layers produced were too thin, it was not possible to use the peeling test because of permanent failure in the thin Al-layer. Therefore, the tensile shear test was used for characterization.

1.3 Shape factor in rolling

The geometry of the deformation zone or the shape factor in rolling has a meaningful effect on the bond formation and therewith the bond strength. Abbasi et al [19] defined the shape factor as

$$\Delta = \frac{h}{L} = \frac{(2-r)}{2}\sqrt{\frac{h_0}{rR}}, \tag{1}$$

where L is the chordal length of the roll contact arc, $h = (h_0 + h_f)/2$ is the mean thickness of the strip, $r = (h_0-h_f)/h_0$ is the reduction in thickness, R is the roll radius, and h_0 and h_f are the initial and final thicknesses of the strip, respectively. In cold rolling it is possible to provide various shape factors by changing the parameters. An investigation of the effect of varying the initial thickness of aluminum showed that the bond strength decreases with increasing initial thickness. However, it was found that the strength increased until the width/thickness ratio attained a value of about 6, and thereafter, the bond strength remained more or less constant [4].

1.4 Surface conditions

Metal surfaces are typically rough, and when two absolutely clean surfaces are pressed together, contact is expected. In practice, metal surfaces are covered with oxide films and other surface contaminants, such as grease, chemical compounds, remaining after pickling, and adsorbed moisture, which inhibits bonding, at least at room temperature. Consequently, the significance of the surface before CRB is another important variable factor influencing the bond strength.

1.5 Surface preparation methods

To produce a satisfactory bond in CRB, it is essential to remove impurities on the surfaces of the two metals to be bonded [24, 25]. A large number of surface preparations have been investigated [24], which can be classified into three groups: (a) chemical cleaning (b) mechanical cleaning and (c) the establishment of a brittle cover layer [9].

The effects of different types of surface preparation on bonding of aluminum composites was analyzed by [4]. It was found that degreasing followed by scratch brushing gave the best bonding conditions.

In this work, the main goal was to study the bonding strength of Al/St clad materials. For this reason, the surface of the steel plates was prepared using belt grinding and wire brushing. The initial thickness of the Al plates was found to have also a considerable effect on the bonding strength. Therefore, three different starting Al thicknesses (1, 2, 4 mm) were chosen to study this effect, too.

II. EXPERIMENTS

2.1 Material

Al 1050 plates with an initial thickness of 20 mm were hot and cold rolled to the required thickness for cladding (4 mm, 2 mm, 1 mm) and heat treated (see Fig. 2) before been roll bonded with steel plates of 4 mm thickness. The chemical composition of the different materials is shown in Table 1.

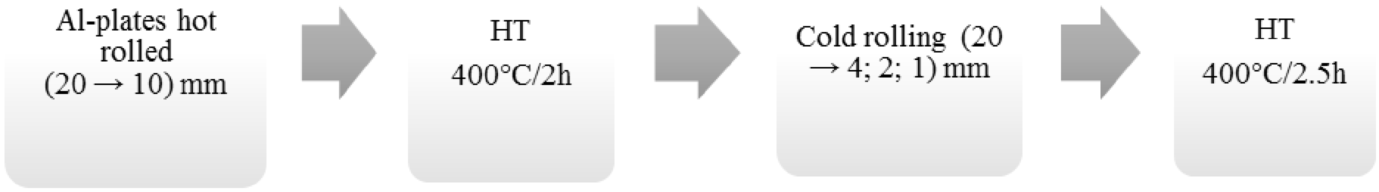


FIG. 2: AL-STRIPS PROCESSING (HT: HEAT TREATMENT, HR: HOT ROLLING)

TABLE 1
CHEMICAL COMPOSITION OF THE STEEL AND ALUMINUM PLATES IN WT%

Element (wt %)	C	Fe	Al	Si	Mn	Ti	P	N	others
Al 1050	-	0.33	bal	0.88	0.004	0.037	-	-	0.049
08Al Steel	0.017	Bal.	0.003	<0.002	0.240	-	0.013	0.039	0.234

2.2 Surface pre-treatment

To prepare the surface of the strips for cladding, the aluminum sheets of 750 x 70 mm (L x w) in three different thicknesses (1, 2, and 4 mm) were cleaned using acetone. The steel sheets of 750 x 70 x 4 mm (l x w x h) were pickled using 15% HCl acid at room temperature for 12 min, followed by acetone cleaning for 2 min and drying in air. Since one aim of this work was to analyze the effect of the steel surface topography on the quality of the clad product, the steel surface then was processed using

- Wire brushing WB (D: 0.2 mm, 0.3 mm and 0.5 mm) or
- Belt grinding BG (abrasive 120, 60 and 40 grit)

2.3 Roughness measurement

For roughness analysis a Hommel-Etamic W10 device was used and the roughness of the steel and Al plates were measured on samples with a traversing length (Lt) of 15 mm. Fig. 3 sketches the measured areas on the surfaces.

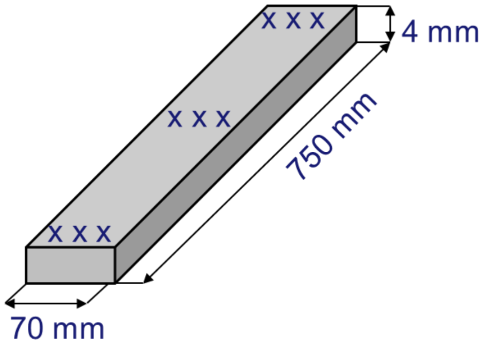


Fig. 3: Schematic representation of roughness measurement points on the sheets

2.4 Cladding

The tests were performed at the 12"-2-high rolling mill at the IMET with a roll speed of 0.2 m/s. The pre-treated materials were clad with thickness reductions between 40% and 50% as shown in 0. Additionally, the rolling parameters are listed. As no green bonding strength could be determined by peeling or tensile shear tests with thin Al 1050 (0.4 mm) material, Al-strip (Al 1050) with thicknesses of 1, 2, and 4 mm was used. As pre-treatment, the Al-strips were wire brushed at IMET after cleaning with acetone as described before.

TABLE 2
PARAMETERS FOR CLADDING PROCESS; STEEL WITH 4 MM AND 1-LAYER AL WITH 1, 2, 4 MM WITH H: THICKNESS OF THE MATERIAL, ε: REDUCTION, INDICES 0 OR 1: STARTING OR FINAL CONDITION, ST: STEEL, AL: ALUMINUM, TOTAL: VALUE OF THE COMPLETE SET

Clad No.	Surface pre-treatment (Steel)	$h_{0,St}$ (mm)	$h_{0,Al}$ (mm)	$h_{0,total}$ (mm)	$h_{1,total}$ (mm)	ε_{total} (%)	Rolling Force (kN)
C1	WB 0.3	4	1	5	2.90	42	810
C2	WB 0.3	4	1	5	2.51	50	950
C3	WB 0.3	4	2	6	3.50	42	800
C4	WB 0.3	4	2	6	2.98	50	940
C5	WB 0.3	4	4	8	4.70	41	800
C6	WB 0.3	4	4	8	4.02	50	920

III. RESULTS AND DISCUSSION

The microstructure of as-received materials was analyzed using by light optical microscopy. Typical structures are shown in Fig. 4. Grain size measurements were performed using the intercept line method. The as delivered materials exhibited grain sizes of (24±4) µm for the steel and (25±4) µm for the Al 1050 sheets.

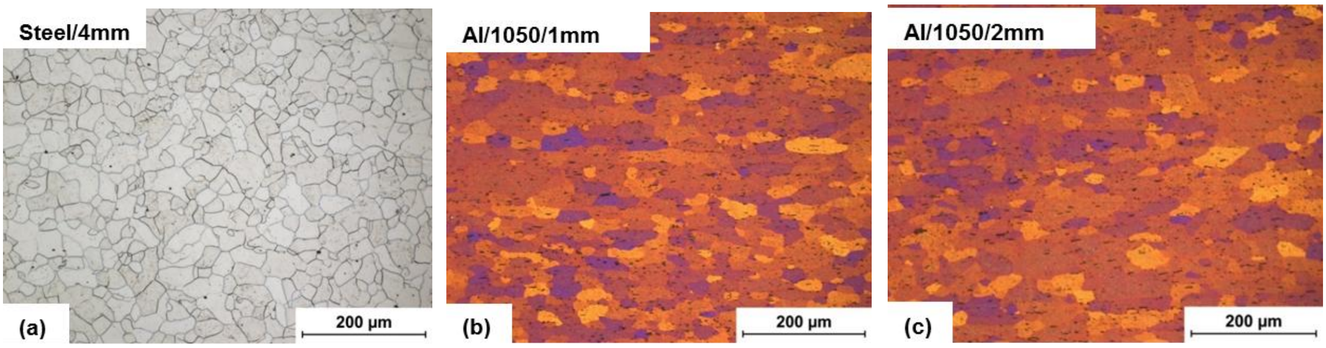


Fig. 4: Optical micrographs of as-received materials (a) Steel/4mm, (b) Al-strip 1 mm, Al/1050, (c) Al-strip 2 mm, Al/1050.

After rolling the materials and preparing the required strips for cladding, the mechanical properties of the materials were analyzed. Table 3 shows the mechanical properties and grain sizes of the materials.

The resulting values after pre-treatment under different conditions are given in Table 4 for steel and Table 5 for the aluminum surfaces, respectively with R_a: arithmetic roughness index and R_z: average surface roughness. The highest roughness values for steel (R_a = 5.8 µm) were achieved using belt grinding (abrasive 40 grit), the lowest ones for steel (R_a = 1.7 µm) using a wire brush with fine wire diameter.

TABLE 3
MECHANICAL PROPERTIES AND GRAIN SIZES OF AS-RECEIVED AND PROCESSED AL-MATERIALS; AVERAGE OUT OF FIVE TESTS

	Steel, 4 mm	Al, 1 mm	Al, 2 mm	Al, 4 mm
R_m (MPa)	345±2	100±1	98±1	95±1
$R_{p0.2}$ (MPa)	274±6	38±1	40±1	50±1
EL (%)	27±1.0	25±0.4	31±0.8	32±0.5
St:HV20, Al:HV1	130±5	28±1	28±1	27±1
Grain size (µm)	24±4	26±5	24±5	22±4

TABLE 4
ROUGHNESS OF THE STEEL SURFACE AFTER WIRE BRUSHING (WB) OR BELT GRINDING (BG) WITH DIFFERENT BRUSHES AND GRIDS

	Steel sheets	
Surface pre-treatment	**R_a (µm)**	**R_z (µm)**
WB ∅ 0.2mm	1.7±0.1	10.1±0.4
WB ∅ 0.3mm	1.8±0.1	10.3±0.8
WB ∅0.5mm	1.9±0.2	12.8±0.9
BG 40#	5.8±0.5	49.3±2.8
BG 60#	4.2±0.4	33.0±1.9
BG 120#	3.6±0.3	26.6±1.2

TABLE 5
ROUGHNESS VALUES OF THE ALUMINUM STRIPS

Wire bushing ∅ 0.2 mm	**R_a (µm)**	**R_z (µm)**
1 mm	2.4±0.2	14.2±1.2
2 mm	2.5±0.3	14.5±1.3
4 mm	2.5±0.3	14.6±1.5

A comparison of St/Al layer thicknesses after cladding with different Al layer thickness is given in Table 6. The total reduction was set between 41% and 50%. Based on these values, the results are shown graphically in Fig. 5. As expected, aluminum exhibits a higher thickness reduction compared to steel. Nevertheless, the ratio between the two partners depends on the starting thickness values.

TABLE 6
THICKNESS REDUCTIONS OF ST/AL CLAD MATERIAL BY USING OF 1, 2, 4 MM AL AND 4 MM STEEL

Clad No.	**St layer h_0 (mm)**	**Al layer h_0 (mm)**	**ε_{total} (%)**	**ε_{St} (%)**	**ε_{Al} (%)**
C1	4.0	1.0	42	39	56
C2			50	48	62
C3		2.0	42	39	49
C4			50	47	57
C5		4.04	41	35	48
C6			50	43	57

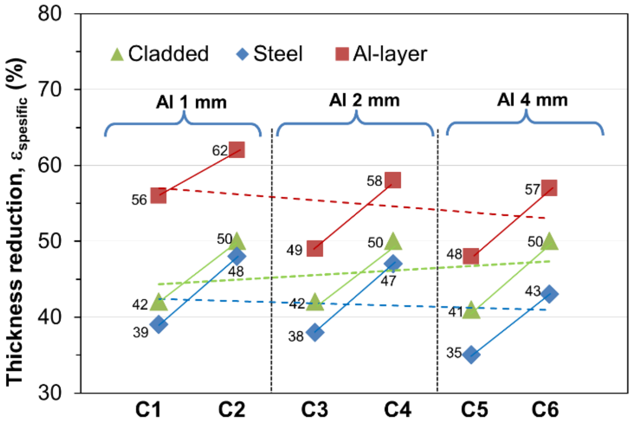


Fig. 5: Comparison of St/Al layer thicknesses after cladding process with thicker Al

In order to define the bonding strength of the green clad material, tensile shear tests were performed. As the samples with the standard thin Al layer always failed in the Al before deboning, these tests were performed with thicker Al material, so to bare the load. The tensile shear specimens were cut in rolling direction in the middle of the green clad material and prepared in accordance to GB/T 6396-2008. Fig. 6-a) and b) show schematically the sample geometry and the tensile shear sample at the UTS universal testing machine, respectively.

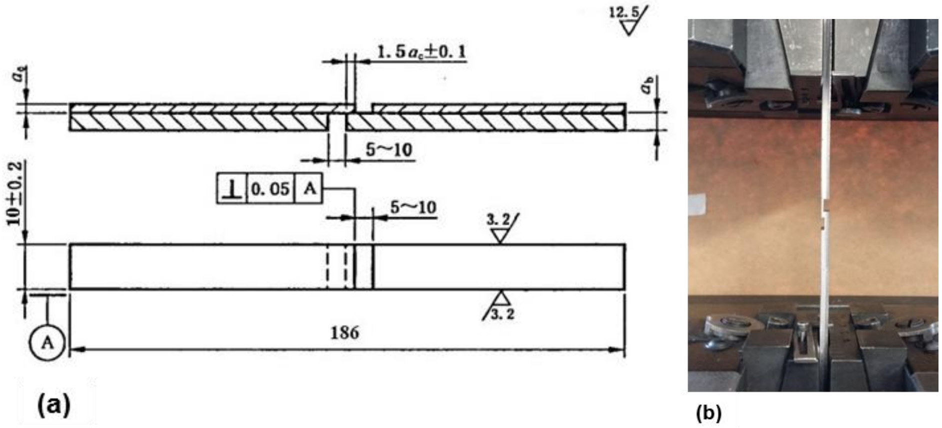
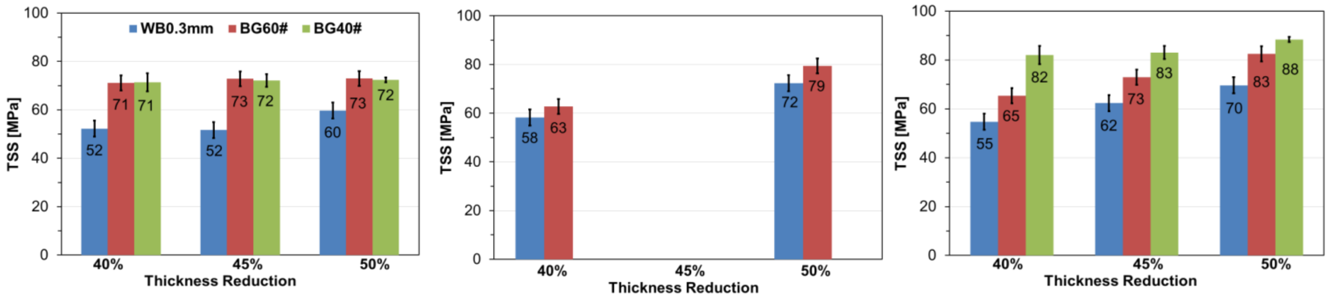


Fig. 6: Tensile shear test sample (a) schematically and (b) during testing

To determine the tensile shear strength (TSS), different thickness reduction ratios, surface pre-treatment methods, and Al thicknesses were selected, as pointed out in Fig. 7. The total reduction ratios for cladding with 1 and 2 mm Al sheets were 40, 45, and 50 %, for the 4 mm Al sheet 40 and 50 % were chosen. For surface pre-treatment wire brushing with 0.3 mm wire diameter, belt grinding with 60 grit and belt grinding with 40 grit were taken, except for the 4 mm Al sheet where wire brushing as before and belt grinding with 60 grit were performed. The highest TSS for green clad material was achieved for 2 mm Al thickness with belt grinding (40 grit). Cladding 1 mm Al, belt grinding with different grit didn't show clear effects on TSS. Increasing the thickness reduction for belt grinding and cladding with 1 mm Al, a slight increase in TSS up to 45% thickness reduction can be stated. However, increasing the reduction up to 50% doesn't show an effect in TSS. In general, the lowest TSS for all Al thicknesses and thickness reductions could be seen using wire brushing.



(A) (B) (C)

Fig. 7: Comparison of tensile shear strengths for green clad material, with Al thickness of (a) 1 mm, (b) 2 mm, and (c) 4 mm.

Surface analyses in the interface area of Al and St were performed with SEM investigations for three different preparation methods and two different thickness reductions. The results are shown in Fig. 8 to 10. For all SEM investigations Al with a thickness of 2 mm was used. In Fig. 8 the samples were wire brushed, the thickness reductions were 40 % in Fig. 8 (a) and (b) and for Fig. 8 (c) and (d) 50%. Fig. 8 (a) and (c) show the shear surface in Al and Fig. 8 (b) and (d) the one on steel. Comparing (a) and (c) it can be stated that the Fe adhesion at low thickness reduction (a) is clearly smaller than at higher thickness reductions (c). Moreover, it can be seen that, with the lower reduction, only some small cracks appear, increasing with increasing the reduction. Comparing Fig. 8 (b) and (d) shows the reduced Al adhesion on steel at lower reductions (a) compared to the higher ones (c).

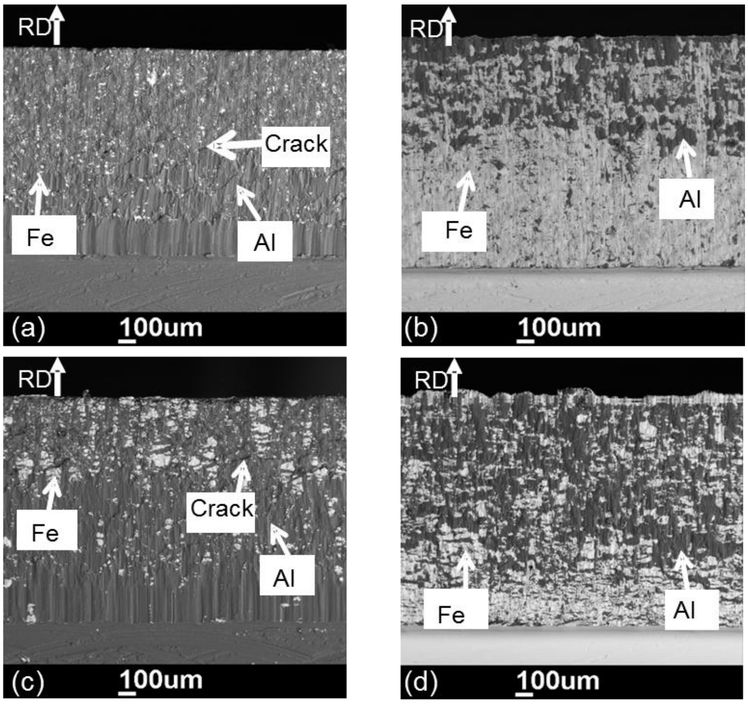


Fig. 8: Comparison between the green clad materials for samples with 40% and 50% total thickness reductions.

The samples in Fig. 9 were belt grinded with 60 grit. The thickness reductions for Fig. 9 (a) and (b) were 40 %, for Fig. 9 (c) and (d) 50 %, respectively. The Al-sheared surface can be see in Fig. 9 (a) and (c), Fig. 9 (b) and (d) show the shear surface of the steel. Comparing (a) and (c) it looks (for all samples investigated) as if the Fe adhesion at low thickness reductions (a) is higher than at high thickness reductions (c). Moreover, some big cracks at low reduction appeared, not visible at high reductions. Comparing Fig. 9 (b) and (d) shows that the Al adhesion at low reductions (a) is less than at high reductions (c). Comparing Fig. 9 (d) with Fig. 8 (d) shows that the Al on the St shear surface seems to be more compact for the belt grinded sample than for the wire brushed one.

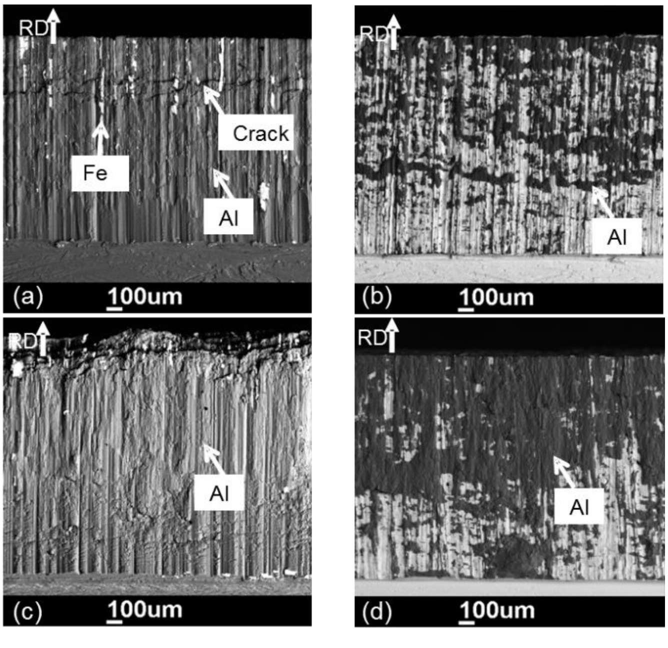


Fig. 9: The comparison shear surfaces between the green clad materials for sample with 40 % and 50 % total thickness reductions.

In Fig. 10 belt grinding with 40 grit was chosen as preparation method. Again, the thickness reduction was 40 % Fig. 10 (a) and (b)) and 50 % (Fig. 10 (c) and (d)). The Al shear surface is given in (a) and (c), (b) and (d) display the one of the steel. The Fe adhesion at lower reductions (a) appears higher than at the higher ones (c). Comparing Fig. 10 (b) and (d) shows that the Al adhesion at low reductions appears smaller than at higher reductions. The adhesion of Al on the St shear surface appears more compact for a 40 % reduction in the sample prepared with belt grinding with 40 grit compared to the sample prepared with a 60 grit. With 50 % reduction, the Al covers more or less completely the St shear surface.

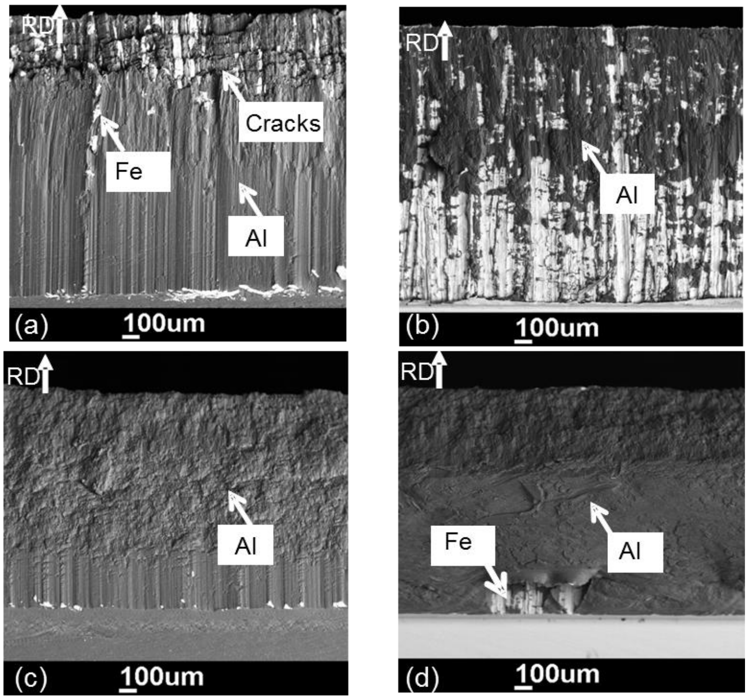


Fig. 10: Green clad materials for sample with 40 % and 50 % total thickness reductions.

IV. CONCLUSION

The bonding strength of cold roll bonded aluminum on steel can be controlled with the combination of surface roughness of the steel and the total deformation. Best results were achieved using belt grinding with 40 grit for steel surface preparation. Wire brushing only let to a low roughness. Due to this higher roughness, a bigger contact area between the steel and aluminum was available and subsequently adhesion could be improved. The adhesion of Al on the steel sheets in cold roll bonded materials was investigated on the shear surface of the test´s samples after shear tensile test using SEM. The Al adhesion to the steel surface was improved with a rougher steel surface and – of course – with increasing the thickness reduction by cold roll bonding.

ACKNOWLEDGMENT

We acknowledge the financial support of the Chinese Government within this project and Yinbang Clad Material Co. Ltd for providing the materials. Personally we thank the project partners Tang Chaolan (Guongyu University of Technology), Gao Kunyuan (Beijing University of Technology and Zhou Dejing (Yinbang Clad Material Co. Ltd) for their helpful discussions.

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