CIRP Annals - Manufacturing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Joining sheet metals by electrically-assisted roll bonding

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ARTICLE INFO

Keywords:
Joining
Rolling
Electrically-assisted forming

ABSTRACT

Roll bonding is a solid-state welding process performed by means of rolling. During the process, virgin metal is extruded to the surface from underneath the surface through micro cracks leading to the formation of new metallic bonds. Electrically-assisted roll bonding (EARB) was applied to roll bond $127\ \mu m$ aluminum sheet to $127\ \mu m$ aluminum or copper sheets. The quality of the bonds was examined through micrographs and peel tests. It was found that the Joule heating effect in EARB lowered rolling forces and increased the bond strengths of bonded sheets by as much as three times.

1. Introduction

Laminated metal composites (LMCs) have received considerable attention from aerospace, appliance, automobile and defense industries because of their improved material properties over single layer sheet metals and alloys, including lower weight [1], improved corrosion resistance [1], higher fracture toughness [2], and better damping capacity [3]. One LMC application example is the replacement of copper alloy sheets with Al/Cu clad sheets. Al/Cu clad sheets have comparable electrical and thermal conductivities to copper alloys while providing about 40% and 60% reductions in weight and cost, respectively [4]. The application of Al/Cu composites has been extended to the production of armored cables, air-cooling fins, TV set yoke coils and bus-bar conductor joints. Due to the strengthened properties, laminated metal bars have recently emerged in building construction [5]. As the application of LMCs increases for different industries, there is an increasing demand for developing more cost- and time-effective techniques for LMC production.

To manufacture LMCs, metal layers need to be joined. This can be accomplished by adhesive bonding or material deformation. In adhesive bonding, bond strength is limited by the properties of the adhesive. The sensitivity of adhesives to surface finish [6] and the environment, such as temperature and humidity, further affects their performance, resulting in variation of the bond strength. Joining by material deformation in comparison transcends these limitations [7]. This technique can be further classified into two categories: mechanical and metallurgical. In metallurgical joining by deformation, joining occurs when new metallic bonds are generated at the metal layer interfaces through deformation, as is in the cases of cold welding, friction welding, friction stir welding, and resistance welding [7]. As a variant of the cold welding processes, roll bonding (RB) enables joining over large areas and is effective in LMC production. During the RB process, metal sheets are compressed against each other and deformed. The compressive motion extrudes fresh or virgin metals out through micro cracks on the surface, subsequently, enlarges the micro cracks and generates new surfaces at the interface. The generated surfaces are merged under compression to form new metallic bonds. As a result, the sheets are permanently joined. Bay et al. joined different sheet metal pairs by roll bonding and studied the factors affecting bond strength [8]. Bambach et al. [9] presented a numerical framework to simulate the bonding process. It was reported that bond strength depended on the amount of surface expansion or thickness reduction. A threshold value of surface expansion shall be exceeded to achieve successful cold welding of different metal pairs [10].

Conventionally rolling temperature is increased by elevating the workpiece temperature in a furnace. As compared to furnace heating, heating by electric current is rapid with a localized heating effect. Electrically-assisted microrolling was used to heat and soften metals for enhancing surface texturing [11]. Additionally, an annealing process is often applied after roll bonding to further enhance the bond quality, in which the annealing temperature is one key factor [12]. Quadir et al. [13] and Movahedi et al. [14] studied Al/Al and Al/Zn bonds, respectively. Both studies have shown that increasing the annealing temperature increases bond strength and decreases the required threshold in thickness reduction for bonding. Furthermore, Xu et al. conducted electrically-assisted solid-state pressure welding to increase the bond

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http://dx.doi.org/10.1016/j.cirp.2015.04.131
0007-8506/© 2015 CIRP.

Please cite this article in press as: Ng M-K, et al. Joining sheet metals by electrically-assisted roll bonding. CIRP Annals - Manufacturing Technology (2015), http://dx.doi.org/10.1016/j.cirp.2015.04.131

strength at the same thickness reduction level as without current applied [15].

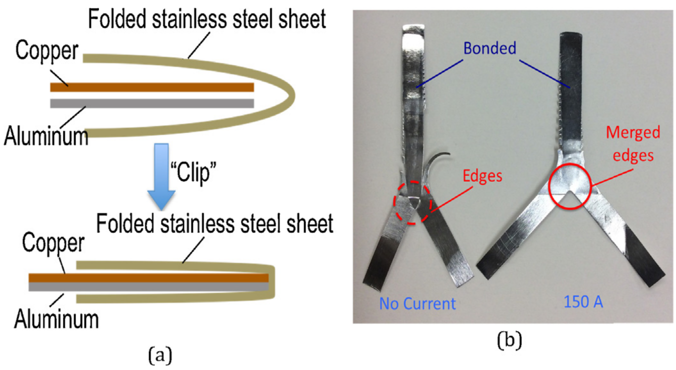
Unlike the static state bonding in Xu's work mentioned above, dynamic electrically-assisted bonding, i.e., electrically-assisted roll bonding (EARB), is conducted in this study. Leveraging the advantages of the electric current in material softening and in-process annealing, EARB is conducted and its capability and bonding mechanisms are investigated. Additionally, the bond strength of roll bonded LMCs is experimentally evaluated.

2. Experimental setup

2.1. Roll bonding

A desktop microrolling mill was utilized for roll bonding. Roll gap can be adjusted by a piezo actuator placed on the roll shaft bearing housing, with a resolution of 0.8 nm and stiffness of 360 N/μm. A load cell with 5 kN/μm rigidity and 30 kN capacity is used for rolling force measurement. Displacement of the bearing housing, which affects the roll gap, is measured by a pair of capacitive position sensors with a resolutions of 10 nm. The upper and lower rolls (65.62 mm and 27.58 mm in diameter, respectively) are driven by separate servomotors that provide independent control of the rolling speed (pre-set at 0.8 mm/s for bonding). During EARB, electric current was passed through the workpiece from one roll to the other. Two current levels, 50 A and 150 A, were investigated for the experiments. To protect the sensors and actuators from damage caused by current "leakage" to the mill structure, ceramic sleeves were applied on the roll shafts for electrical insulation.

Aluminum alloy sheets, i.e., Alloys 1100, 1145, and 1235, were roll bonded with either the same alloy or 110 Copper alloy sheets, all having a thickness of 127 μm. Both Al and Cu sheets were cut into strips of 5 mm width. Prior to roll bonding, they were degreased by acetone, immediately followed by wire brushing. Subsequently, the sheets were sandwiched and "clipped" between a reusable piece of folded stainless steel of 127 μm thick, as illustrated in Fig. 1a. The adoption of the stainless steel folding "clip" serves three purposes: (1) It increases the total thickness of the stack to 508 μm, which is thicker than the 400 μm minimum roll gap of the microrolling machine setup, thereby, facilitating the compression operation needed for successful bonding; (2) The stiffness of the stainless steel "clip" is higher than that of the Al or Cu alloys and therefore, effectively transferring the compression to the metal sheets being bonded; and (3) The folded steel "clip" effectively prevents relative slippage between the thin sheets as described below, which was a major challenge in bonding narrow strips.



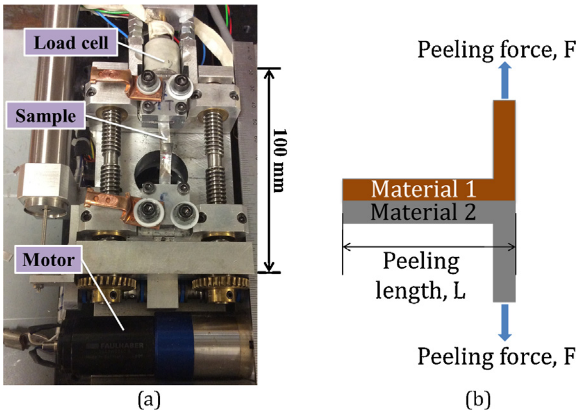
(a) (b)

Fig. 1. (a) Workpiece layout for roll bonding experiments, and (b) Al/Al sheets bonded by conventional and 150 A electrically-assisted roll bonding at 50% reduction.

The lengths of the strips were designed to be longer than the stainless steel folding clip, as illustrated in Fig. 1a, so that the unbonded ends can be used in the subsequent peel tests. The Y-shaped branches, as seen in Fig. 1b at the end of the bonding strips, represent the portion of the strips that exceeded the length of the stainless steel folding clip, and therefore, was unconstrained by the clip. The differentiation of frictional forces acting on multiple interfaces deviated the thin metal strips at the "unclipped" region and caused the formulation of branches as shown in Fig. 1b. Fig. 1b shows two Al/Al sheets bonded by RB and EARB. Both samples had the same thickness reduction of 50%. In the figure, the edges of the samples bonded by EARB with a 150 A current level were clearly merged. The merging of the edges may be due to the combination of the compression and the localized high Joule heating temperature.

2.2. Peel test

Peel tests were conducted to evaluate the bond strength of roll-bonded laminate composites. The test procedure follows the ASTM D1876 T-Peel Test Standard but a smaller sample size was used due to the constraint of the sample size in our current roll bonding process. A micro uniaxial tensile machine (SEMTest 1824 LM, MTI Instruments/Fullam Inc.), shown in Fig. 2a, was used in peel tests. During the test, the two ends of the bonded sheets were clamped and pulled by precisely aligned clamps at a pulling speed of 0.11 mm/s, as schematically shown in Fig. 2b. A load cell with a 100 N capacity and a 0.01 N resolution was incorporated for measuring the peeling force. The total peeling length was measured by a linear displacement transducer with a 1 μm resolution.



(a) (b)

Fig. 2. (a) A roll bonded sample being pulled by a micro tensile machine, and (b) illustration of the peel test.

3. Results and discussion

3.1. Rolling force

Cross-sectional images of the bonded interface along the sample width direction are shown in Fig. 3. These images were taken from the Al/Al and Al/Cu samples bonded by RB or EARB. The

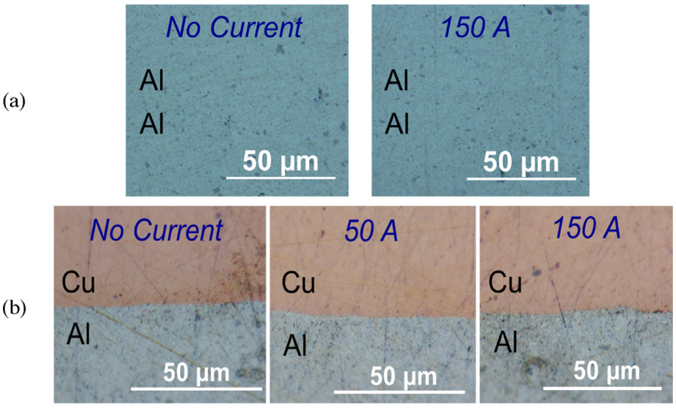


Fig. 3. Images of interface cross-sections in (a) Al/Al at 60% thickness reduction, and (b) Al/Cu at 40% reduction sheets bonded by roll bonding with or without current.

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