Residual Stress Study of Al/Al Laminates Processed by Accumulative Roll Bonding

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Keywords
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Keywords: Accumulative Roll Bonding, Residual Stress, Neutron Diffraction, Finite Element Model

Abstract. In this work accumulative roll bonding (ARB) was used to combine AA1050 and AA6061 sheets to produce AA1050/AA1050, AA6061/AA6061 and AA1050/AA6061 laminates with ultrafine grained (UFG) structure. Two sheets of starting materials were roll bonded with 200 °C preheating for 180 s before rolling. The through-thickness residual stress distribution of these laminates processed up to two cycles of ARB was determined by neutron diffraction with spatial resolution of 0.2 mm through 1.5 mm thickness. The measurements also required high accuracy of only few MPa since residual stresses in the laminates peaked at only about 15 MPa. The laminates composed of the same material (AA1050/AA1050 and AA6061/AA6061) showed symmetric residual stress profile with tensile stress at the centre of the sheets and compressive stress at the surfaces. The AA1050/AA6061 laminates showed asymmetric distribution with residual tensile stress in the AA1050 layer and compressive stress in the AA6061 layer. A finite element model (FEM) was used to simulate the residual stress distribution and the results were in agreement with the measured results qualitatively.

Introduction

Aluminium sheets are widely used as structural components in aircraft and automotive which has strict requirements of strength/weight ratio. Accumulative roll bonding (ARB) is an effective process to produce aluminium sheets with high strengths and it is also possible to bond two types of aluminium sheets in the hope that the properties of the original sheets would combine in the bonded laminates [1-3]. The materials processed by ARB generally experience larger strain magnitudes compared to traditional rolling. Furthermore, the ARB process includes rolling, cutting, surface grinding and stacking in different order, which makes the strain history complex in the bonded laminates. Microstructure, texture and mechanical properties distributions through the thickness of the laminates are non-uniform. This is especially true if different starting materials are used.

In addition, layers of different materials or materials at different thickness positions perform differently upon further deformation developing residual stress which is strongly dependent on the thermomechanical processing history of the materials. Residual stresses of traditional rolled sheets have been well reported [4-6]. Typical residual stress distribution of a rolled sheet material is tensile at the sheet centre and compressive at the sheet surfaces [6]. Residual stress of ARB processed sheets has not been evaluated up to now and it can be inferred that the residual stress distribution of the ARB processed sheets should be more complex than that of conventional rolling since the strain history of the ARB processed sheets is complex due to the cutting and stacking procedure.

For performance evaluation (e.g. fatigue), it is important to know the type and magnitude of the residual stress distribution in the laminates processed by ARB, especially the laminates.
composed of two different materials. The present work studied the through-thickness residual stress distribution of aluminium laminates produced by ARB using neutron diffraction techniques.

**Experimental**

Commercial aluminium alloy AA1050 and AA6061 sheets with initial thicknesses of 1.5 mm were used as starting materials. Three types of laminates AA1050/AA1050, AA6061/AA6061 and AA1050/AA6061 were produced by combining two sheets in a combination and rolling them together with 50% reduction so that this results in a laminate of the same 1.5 mm thickness after each ARB cycle. The as-received sheets were annealed to recrystallised condition and strips with size 400 × 50 × 1.5 mm$^3$ were cut from the annealed sheet for ARB processing. The rolling was performed on a rolling mill with 125 mm diameter rolls at a speed of 0.2 ms$^{-1}$ under dry conditions. Pre-heating at 200 °C for 180 s was performed to the strips prior to each rolling cycle. To ensure good bonding, the surface for bonding of each strip was wire-brushed and cleaned before stacking. The details of the ARB process and the microstructure and mechanical properties of the ARB processed laminates can refer to Ref. [7].

Neutron diffraction residual stress measurements have been carried out at the ANSTO OPAL research reactor using the KOWARI strain scanner. The laminates used for residual stress measurements were 1-cycle roll bonded AA1050/AA1050, AA6061/AA6061 and AA1050/AA6061 laminates and 2-cycle roll bonded AA1050/AA6061 laminate. Residual stress distributions were measured through the entire thickness in the central part of all samples. A gauge volume of 0.4 × 0.4 × 25 mm$^3$ was used for measurements of 1-cycle roll bonded laminates with 7 through-thickness positions. The step size between each position was 0.2 mm. A gauge volume of 0.2 × 0.2 × 25 mm$^3$ was used for 2-cycle roll bonded AA1050/AA6061 laminate to resolve its 4-layer structure. The step size was 0.1 mm and the measurements were taken at 13 thickness positions. 5 measurements at different locations of the same depth were taken to achieve better averaging (schematically illustrated in Fig. 1). With the matchstick-like gauge volume a high spatial resolution was achieved in the thickness direction while providing sufficient scattering intensity. It should be noted that there was an overlap between each thickness position and there was an edge effect for all the measurements. The measurements were achieved with high accuracy of ~5 MPa for the 1-cycle laminates and ~10 MPa for the 2-cycle laminate.

A Si(400) monochromator with a take-off angle 79° was used to provide neutron wavelength of 1.73 Å. The Al (311) reflections at 2θ ~90.3° was used for the strain measurements.

At each position, d-spacings along three principle directions, rolling direction (RD), transverse direction (TD) and normal direction (ND) were measured. Residual stresses along two principle directions RD and TD and d$_0$ was calculated according to the method described in Ref. [8] by assuming that the normal stress is zero and there are no shear components.

![Fig. 1 Schematic illustration of specimen and gauge volume.](image)

The residual stress of the laminates processed by ARB was simulated by finite element modelling (FEM) using Abaqus/Standard v.9. The current simulation was designed to match the experimental conditions. The starting sheets had the properties of fully annealed AA1050 and AA6061 by fitting the true stress-true strain curves of the experimental results. A two-dimensional model assuming plain strain deformation was used. The initial strip thickness, roll diameter, rolling speed and nominal
reduction was set the same as in the experiment. The friction between the sheet and the roll surfaces was described by Coulomb’s friction law with a friction coefficient of 0.25.

FEM of the real ARB process is difficult to achieve because the two sheets are separate prior to ARB and are joined together as one piece during roll bonding. However, for FEM, the two sheets will either be pre-joined as one piece or deform separately as two sheets during and even after ARB. In the current work, both cases were simulated. The case with two sheets deform separately was achieved by assuming a larger friction coefficient of 0.4 between the sheets.

**Results and discussions**

Fig. 2 shows the through-thickness residual stress distribution profiles of the ARB processed laminates. It can be seen from Fig. 2(a) and (b) that the through-thickness residual stress distribution for 1-cycle roll bonded AA1050/AA1050 and AA6061/AA6061 are similar to each other and are in accordance with the residual stress profile in rolled aluminium solid plate [6]. The profiles of the residual stresses in both RD and the TD are symmetric in general, with tensile residual stress zone at

![Image](361)
resolution and accuracy of the neutron diffraction technique and the absolute values of stresses are extremely small, even small experimental uncertainties ~5-10 MPa that were not accounted for, e.g. local stress variations, can lead to distortions affecting the real stress profile. In addition, the stress calculations were based on isotropic $d_0$ model, which in general is a good approximation, but it can also lead to a relatively significant and experimentally noticeable shift due to anisotropic microstresses because of the delicate stress distribution in our case. The distortion of stress profile must be more pronounced in AA6061/AA6061 due to its ability to acquire higher density of dislocations, thus the stress profile for this alloy tends to have more unbalanced stress distribution affected by biases.

The residual stress distribution of dissimilar AA1050/AA6061 laminates is quite different from that of the AA1050/AA1050 and AA6061/AA6061. It can be seen in Fig. 2(c) and (d) that tensile residual stress exists in the AA1050 layer and compressive residual stress exists in the AA6061 layer in general for both the 1-cycle and 2-cycle roll bonded sheets. Since the two alloys have different plastic properties (i.e. yield stress), residual stress arises as a result of the different deformation behaviours in the two alloys. After non-uniform deformation of the layers, a permanent curvature occurs (even though the curvature is very small) bringing stress momentum balance and finally shaping the stress profile. It is difficult to predict the residual stress distribution theoretically because of the complexity of the bonding process.

The measured residual stresses for all the laminates are in a range of ±15 MPa. This is also in accordance with the values reported in rolled aluminium [6, 9]. The residual stresses in rolling direction and transverse direction show similar characteristics but the absolute values are slightly smaller in transverse direction due to difference in constrain conditions. Since the laminates are only 1.5 mm thick and 0.2 mm spatial resolution of the neutron diffractometer is on its limit as well as accuracy of less than 5 MPa, any improvement of data in the neutron diffraction experiment is hardly possible.

Since FEM simulation cannot exactly reproduce the bonding process, two extreme cases were simulated: one with two sheets pre-joined as one piece and one with two sheets deform separately the entire process. Fig. 3 shows the FEM simulation results for the 1-cyle roll bonded AA1050/AA6061. The distorted FEM elements illustrate well the deformation behaviour and material flow during deformation. For the case with two sheets pre-joined as one piece, the interface deforms coherently. The mesh flows faster at the surfaces due to the friction between the sheet and the rolls. It can be seen that the mesh of AA1050 flows faster than AA6061. The thicknesses of the AA1050 layer and the AA6061 layer are the same and both have gone through 50% reduction from the initial state. The residual stress of the AA1050 layer is compressive and the AA6061 layer is tense. For the case with two sheets deform separately, there is relative displacement between the mesh of the AA1050 layer and the AA6061 layer. The mesh also flows faster at the surfaces. The thickness of the AA1050 layer is slightly smaller than the AA6061 layer and the reduction ratios of the AA1050 and the AA6061 layer are 51.6% and 48.4%. The residual stresses of the two layers are different and are quite complex.

Fig. 4 shows the FEM simulated through-thickness distribution of residual stress along RD for 1-cycle roll bonded AA1050/AA1050 and AA1050/AA6061 in comparison. The simulated through-thickness residual stresses along TD (not shown here) have similar trend to those along RD and have slightly lower absolute values. It can be seen from Fig. 4(a) that the FEM predicted residual stress of AA1050/AA1050 along RD matches the experimental results in general and reproduce symmetric profile. This is not surprising, since for the laminates with the two starting sheets of the same alloy, the deformation is similar to conventional rolling. Although the two sheets also experienced bonding during the rolling, there was no relative movement between the two sheets since they have the same properties.
Fig. 3 FEM mesh and residual stress in rolling direction of 1-cycle roll bonded AA1050/AA6061, prior to roll bonding (a), and after roll bonding (b) two sheets pre-joined as one piece and (c) two sheets deform separately.

Fig. 4 FEM simulated through-thickness distribution of residual stress along RD for 1-cycle roll bonded (a) AA1050/AA1050 and (b) AA1050/AA6061 with two sheets pre-joined as one piece and two sheets deform separately.

For the laminates with two starting sheets of different alloys, the two sheets are expected to deform differently because they have different plastic properties. In fact, they experience slightly different degree of reduction (larger reduction was observed for AA1050; it was slightly longer after the first cycle ARB). The FEM simulations are able to demonstrate this asymmetry in case of AA1050/AA6061 joint, However, the two extreme cases (pre-joint vs. separated) result in very different residual stress distributions, especially at the areas around the interface. This demonstrates that proper modelling of the contact phenomenon (e.g. amount of constraint versus amount of sliding) is the most critical element of the simulation. Qualitatively, the result of the two sheets deform separately (marked as Separated in Fig. 4(b)) agrees better with the experimental result. The absolute values of both cases are significantly larger than the values measured in experiment and also larger than the values of the simulated AA1050/AA1050.

The fact that the simulation results of the two sheets deform separately matches the experimental results better indicates that the two sheets deform more freely in the roll bonding process. Bonding
must occur in the very later stage of rolling deformation. The residual stress induced by the thermomechanical misfit of dissimilar materials is significantly larger in magnitude according to the simulation. The experimentally measured values, however, are very low. This may be because the simulation overestimates the difference in deformation resistivity of the two alloys and there may be a softening effect in the experiment due to the pre-heating before roll bonding.

**Summary**

Residual stress investigation was conducted on ARB processed AA1050/AA1050, AA6061/AA6061 and AA1050/AA6061 laminates of 1.5 mm thickness. Through-thickness stress profiles were determined with high spatial resolution (0.2 mm) and high measurement accuracy (<5 MPa). The results showed that the laminates composed of the same alloy (AA1050/AA1050 and AA6061/AA6061) showed symmetric residual stress profile with tensile stress at the centre and compressive stress under the surfaces. The AA1050/AA6061 laminates showed asymmetric distribution with residual tensile stress in the AA1050 layer and compressive stress in the AA6061 layer. FEM simulation of the laminates composed of the same alloy showed similar residual stress distribution as the experiment. The simulation results of the residual stress distribution in laminates composed of dissimilar alloys can only match the measured result qualitatively.

**References**


