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Advanced rolling technologies for producing ultra-finegrain/nanostructured alloys

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Abstract

Ultrafine-grained materials show high strength at ambient temperature, high-speed superplastic deformation at elevated temperatures, and high corrosion resistance. Such materials have attracted increasing attention in the past twenty years. A number of severe plastic deformation techniques, such as equal-channel angular press, high pressure torsion, groove pressing, twist extrusion, asymmetric rolling, and accumulative roll bonding have been used to develop ultrafine-grained bulk materials. The equal-channel angular press, high pressure torsion, twist extrusion and groove pressing techniques suffer from some drawbacks: firstly, forming machines with large load capacities and expensive dies are indispensable for these processes; secondly, the productivity is relatively very limited; thirdly, the techniques are only suitable for small samples. Compared with equal-channel angular press, high pressure torsion, twist extrusion and groove pressing, the accumulative roll bonding and asymmetric rolling techniques can be used to produce continuous ultrafine-grained sheets in large quantities. In this paper, a survey of relatively recent rolling technologies is presented. The merits and drawbacks of each technique are examined. These techniques are: (1) Asymmetric cryorolling, which has potential for large-scale industrial production of nanostructured materials; (2) Four-layer accumulative roll bonding, which has potential to produce nanostructured materials at room temperature with high bonding quality, used for fabrication of ultrafine material sheets; (3) Asymmetric Rolling of accumulative roll bonding-processed sheets, which has potential for large-scale industrial production of nanocomposite foils.

Keywords

ultra, finegrain, nanostructured, technologies, rolling, alloys, producing, advanced

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Abstract

Ultrafine-grained materials show high strength at ambient temperature, high-speed superplastic deformation at elevated temperatures, and high corrosion resistance. Such materials have attracted increasing attention in the past twenty years. A number of severe plastic deformation techniques, such as equal-channel angular press, high pressure torsion, groove pressing, twist extrusion, asymmetric rolling, and accumulative roll bonding have been used to develop ultrafine-grained bulk materials. The equal-channel angular press, high pressure torsion, twist extrusion and groove pressing techniques suffer from some drawbacks: firstly, forming machines with large load capacities and expensive dies are indispensable for these processes; secondly, the productivity is relatively very limited; thirdly, the techniques are only suitable for small samples. Compared with equal-channel angular press, high pressure torsion, twist extrusion and groove pressing, the accumulative roll bonding and asymmetric rolling techniques can be used to produce continuous ultrafine-grained sheets in large quantities. In this paper, a survey of relatively recent rolling technologies is presented. The merits and drawbacks of each technique are examined. These techniques are: (1) Asymmetric cryorolling, which has potential for large-scale industrial production of nanostructured materials; (2) Four-layer accumulative roll bonding, which has potential to produce nanostructured materials at room temperature with high bonding quality, used for fabrication of ultrafine material sheets; (3) Asymmetric Rolling of accumulative roll bonding-processed sheets, which has potential for large-scale industrial production of nanocomposite foils.

Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Asymmetric cryorolling; Accumulative roll bonding; Asymmetric rolling; Nanostructured materials; Sheet

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1. Introduction

In recent years, nanostructured materials have been attracting a great deal of attention due to their special properties. Bulk fabrication of metallic materials using the severe plastic deformation technique has probably brought us closer to enabling the use of nano-materials for structural and functional applications. Variants of the severe plastic deformation technique, such as high-pressure torsion, equal channel angular pressing, asymmetric cryorolling, accumulative roll bonding, asymmetric rolling, etc. have been developed to enable bulk fabrication of nanostructured or ultrafine-grain samples of different metals. Among these, the high pressure torsion and equal-channel angular press techniques are more suitable for small samples, so that the material quantities which can typically be produced are rather limited. However, asymmetric cryorolling, accumulative roll bonding, and asymmetric rolling are techniques that have potential application in production of continuous products.

In this paper, we present a survey of some advanced rolling techniques for fabrication of nanostructured sheets/foils such as asymmetric cryorolling, four-layer accumulative roll bonding, and a combination of accumulative roll bonding and asymmetric rolling.

2. Asymmetric cryorolling

In the asymmetric rolling process, sheets or foils are passed between rolls that either have different diameters or rotate at different angular speeds. Asymmetric rolling has significant potential for a variety of industrial applications because it involves a reduction in the rolling pressure and an improvement in the sheet shape. Asymmetric rolling is different from conventional rolling processes in terms of parameters such as rolling load, shear strain, and minimum permissible thickness.

Cryorolling is a simple low-temperature process that requires a relatively lower load to induce severe strain for producing the sub-microcrystalline structural features in materials. A method involving rolling under liquid nitrogen temperature was used to improve the materials properties. Wang et al. (2002) carried out experiments to process pure Cu samples by cryorolling. The matrix grains impart high strength, the inhomogeneous microstructure induces strain hardening mechanisms that stabilize the tensile deformation, leading to high tensile ductility and high resistance to failure, and 30% uniform elongation. Cryorolling has been identified as one of the potential techniques to produce bulk ultrafine grained Al alloys form its bulk alloys at cryogenic temperature.

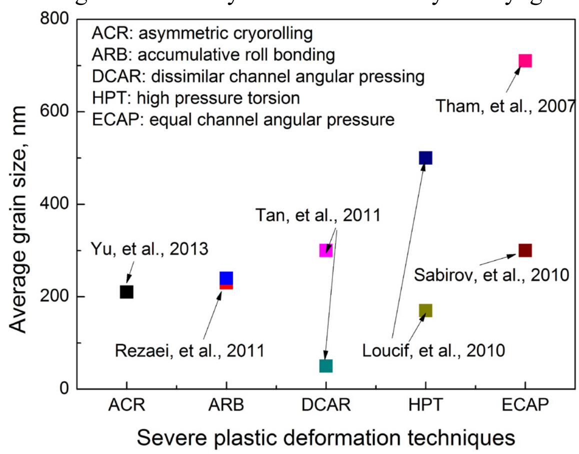

Fig.1. Grain size of Al 6061 alloy by different severe plastic deformation techniques.

Asymmetric cryorolling is a new technique that combines the features of asymmetric rolling and cryorolling. We carried out experiments on the asymmetric cryorolling process for AA1050 (Yu et al., 2012) and Al 6061 (Yu et al., 2013b) alloys in a multifunction rolling mill of a 50 mm diameter work roll under dry friction condition. For

AA1050, when the ratio of upper-to-lower rolling speeds is 1.4, the grain lattice dimension was seen to be 211 nm. This is much smaller than the 500 nm obtained by traditional asymmetric rolling. Both the strength and ductility of AA1050 increase with increase in the upper-to-lower rolling speed ratio from 1.1 to 1.4. When this ratio is 1.4, the tensile stress reaches 196 MPa, which is 22.3% greater than that with a rolling speed ratio of 1.1. Fig. 1 (Yu et al., 2013b) shows the grain size of Al 6061 alloy resulting from a number of severe plastic deformation processes. It is clear that the asymmetric cryorolling can result in greater grain refinement compared to the other techniques.

3. Four-layer accumulative roll bonding

Accumulative roll bonding is a severe plastic deformation technique that has been widely used to produce nanostructure materials in bulk. However, the accumulative roll bonding has drawbacks: as the reduction ratio in each pass is fixed at 50%, the bonding quality between the two layers is difficult to control, and it is difficult to manufacture the product from most metallic materials at ambient temperature. To produce good interface bonding during cold rolling of most metals requires a reduction ratio of more than 70%, as shown in Fig. 2 (Li, et al., 2008).

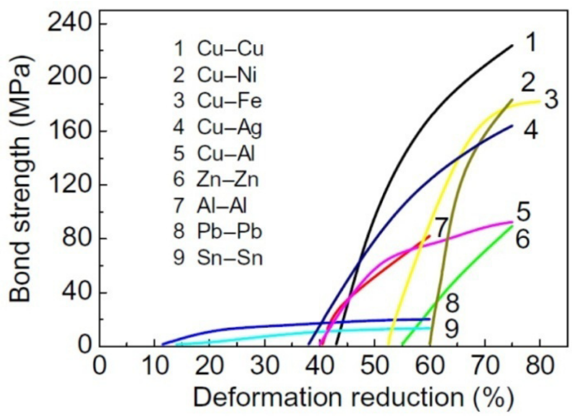

Fig. 2. Bond strength vs. reduction in deformation during cold rolling.

Recently, we presented a newly developed 'Four-layer accumulative roll bonding' technique (Yu et al., 2014a). The four-layer accumulative roll bonding technique has been successfully used to produce ultrafine-grained pure aluminum sheets. In the four-layer accumulative roll bonding process, a sheet is cut into four pieces of equal size, which are then neatly stacked. The interfaces between the any two adjacent sheets are surface-treated with steel brash in advance for improvement of the bond strength. The four layers are bonded together through a conventional roll bonding process, using a 75% reduction ratio. The rolled product is again cut into four parts lengthwise. The pieces are repeatedly surface-treated, stacked and roll-bonded. The whole process is repeated a number of times. Compared with the traditional accumulative roll bonding technique, the main advantages of the four-layer accumulative roll bonding technique are: (a) an improvement of the interface bonding with a higher rolling reduction ratio in each pass, and (b) potential application at room temperature.

Fig. 3 (Yu et al., 2014) shows the average grain size of pure aluminum samples attained with different severe plastic deformation techniques. With the equal-channel angular press technique, the average grain size of the pure aluminum reaches 660 nm, with the equivalent strain reaching 9.2 (Hockauf and Meyer, 2010). Using the accumulative roll bonding technique, Saito (1998) and Pirgazi et al. (2008) developed ultrafine-grained bulk pure aluminum with an average grain size of 670 nm and 500 nm after six and ten passes respectively. The groove pressing technique was used to reduce the grain size to 1000 nm after four passes for commercially pure aluminium (Krishnaiah, 2005). Using a semi-constrained groove pressing process, Morattab et al. (2011) obtained an average grain size of 300 nm in pure aluminum after four passes. Twist extrusion technique was used to reduce the average

grain size to about 1600 nm at the outer edge after 4 passes (Orlov, 2009). The high pressure torsion technique could be used to produce a grain size of about 100-200 nm at the sample edge, while at the sample center it is 600 nm for AA1050 when the equivalent strain is in the range 4.2 ~ 5.8 (Zhang et al, 2010). Zuo et al. (2008) observed extremely fine 500 nm grains in pure aluminum at room temperature using the asymmetric rolling technique. Yu et al. (2012) obtained samples with grain size in the range 211 nm ~ 360 nm at cryogenic temperatures. When using the four-layer accumulative roll bonding technique, the average grain size was seen to be 380 nm. With the exception of the twist extrusion technique, all the other techniques mentioned above can produce ultrafine-grained samples with a grain size less than 1000 nm.

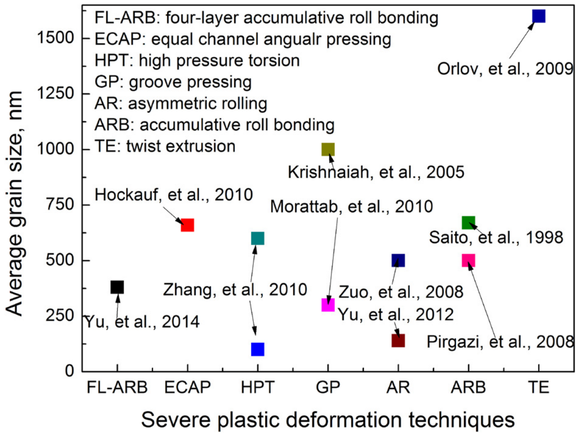

Fig.3. Grain size of pure aluminum after various severe plastic deformation techniques.

4. Accumulative roll bonding & Asymmetric Rolling

Metal laminates have become increasingly popular for engineering applications since they usually possess desirable properties to enable special service performance. Amir et al. (2013) studied the deep drawing of bimetallic materials. They found that laminated deep-drawn metal sheets can be used in manufacturing parts with different ‘inner’ and ‘outer’ conditions such as resistance to corrosion and wear, and thermal and electrical conductivities. Products with such features have been increasingly used in various fields such as the automotive, aerospace and vessel industries, medical instruments, and electrical industries. Meanwhile, micro-forming is fast emerging as a manufacturing process for fabrication of products from ultra-thin foil material. The thickness of the foil material may range from 0.001 mm to 0.3 mm.

Recently, we combined the features of accumulative roll bonding and asymmetric rolling to produce the nanostructured bimetallic foils (Yu et al., 2013a, 2004b). Sheets of commercial aluminium alloys (AA6061 and AA1050) of dimensions 60 mm (width) ×1.5 mm (thickness) were used to fabricate the bimetallic foils. The AA1050 sheet was annealed at 450 °C for 1 h and the AA6061 sheet was annealed at 500 °C for 2 h to achieve a fully homogeneous microstructure. First, the two sheets were stacked together and welded at one end (total thickness 3.0 mm). The composite sheet was pre-heated to 200 °C for 3 min in a furnace and then subjected to one accumulative roll bonding pass. The rolled 1.5 mm thick sheets were cooled to room temperature, and subjected to asymmetric rolling to reduce the thickness progressively from 1.5 mm to 0.04 mm. Asymmetric rolling was carried out on a multi-function rolling mill. The rolling speed ratio between the upper and lower rolls was set as 1:1.3. During the rolling process, the AA6061 side of the bimetallic sample was in contact with the lower roll.

Fig.4 (Yu et al., 2013a) shows TEM images of the interface zone in the rolled samples: Fig. 4(a) is for the accumulative roll bonding-processed sample, and (b), (c) and (d) for these after the first, third, and fourth asymmetric rolling pass respectively. It is clearly seen in Fig. 4(a) that the interface between the AA1050 layer and the AA6061 layer is not bonded well through the accumulative roll bonding process. After the first asymmetric

rolling pass, there are still some residual voids in the interface zone. Meanwhile, with the severe plastic deformation in this pass (using a 75% reduction ratio), the grain boundary becomes fuzzy, as shown in Fig.4(b). After the third asymmetric rolling pass, the two layers are bonded quite well, and residual voids are virtually eliminated from the test samples. In addition, the grain size of the materials has been refined, as shown in Fig. 4(c). With further asymmetric rolling passes, the grain sizes in the two layers increase slightly, and they become more uniform, as shown in Fig. 4(d). This may be the reason for greater ductility in the samples in the tensile test. Fig. 5 (Yu et al., 2013a) shows the log-normal distribution of grain size in the AA1050 and AA6061 layers. The average grain size of the AA6061 layer is refined to about 140 nm, and the grain size of the AA1050 layer is refined to about 235 nm.

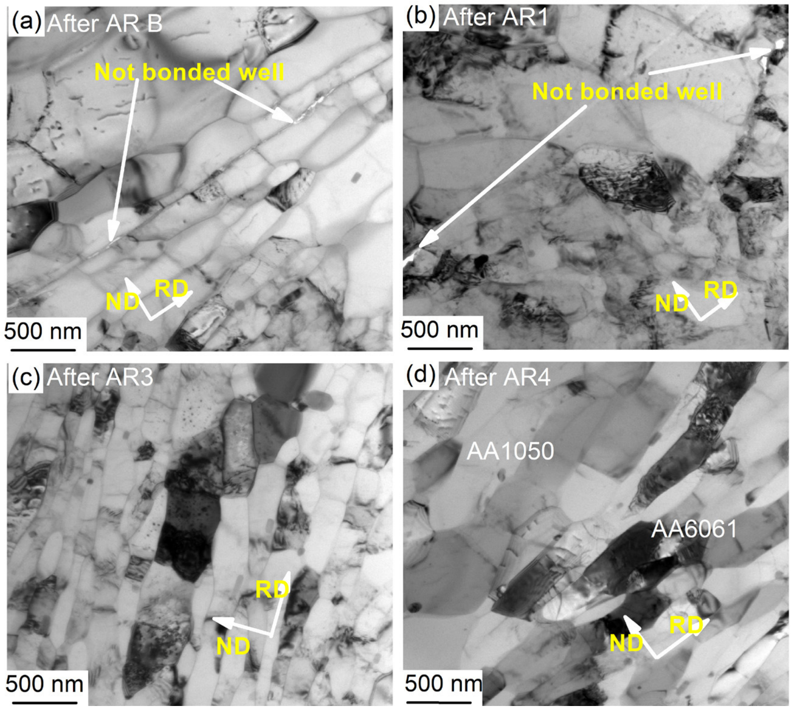

Fig.4. TEM images: (a) accumulative roll bonding processed sample, (b) after the first asymmetric rolling pass, (c) after the third asymmetric rolling pass, (d) after the fourth asymmetric rolling pass.

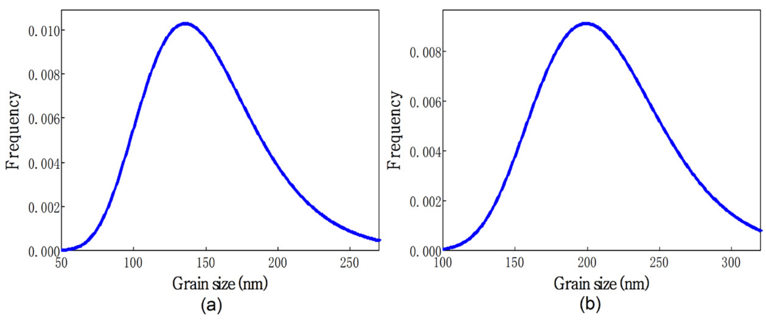

Fig.5. Log-normal distribution of grain size after the third asymmetric rolling pass, (a) AA6061 layer, (b) AA1050 layer.

5. Conclusions and future work

Compared with the equal-channel angular press, high pressure torsion, twist extrusion, groove pressing techniques, the techniques based on the roll forming have advantages such as the production of continuous products and potential application in industry. This paper presents a review of the recent progress in the fabrication of nanostructure sheet/foils by rolling techniques, including asymmetric cryorolling, four-layer accumulative roll bonding, and a combination of accumulative roll bonding and asymmetric rolling. These three techniques have been successfully used to fabricate nanostructured aluminium sheets and foils. Further investigations are being carried out to further assess the suitability of these techniques for different materials such as other Al grades, Ti.

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