Proposal of Novel Ultra-High Straining Process for Bulk Materials - Development of the Accumulative Roll-Bonding (ARB) Process -

Yoshihiro SAITO, Hiroshi UTSUNOMIYA, Nobuhiro TSUJI and Tetsuo SAKAI

Division of Materials Science and Engineering,
Graduate School of Engineering, Osaka University,
2-1 Yamada-oka, Suita, Osaka, 565-0871, JAPAN
E-mail: uts@mat.eng.osaka-u.ac.jp

ABSTRACT It is known that ultra-fine grain size can be achieved by special intense plastic straining processes. In this paper, the authors propose a novel intense plastic straining process named the *Accumulative Roll-Bonding (ARB)* for bulk materials. In the process, a strip is put on another strip neatly, at first. The two layered materials are joined together by rolling in the manner of a conventional roll-bonding process. Then, the length of rolled material is sectioned into two halves. The sectioned strips are again stacked and roll-bonded. The whole process can be repeated again and again. The achieved strain by the process is unlimited since repetition times are endless in principle. The detailed process is presented in this paper. The proposed ARB process has been applied to a commercial aluminum (1100) and an Al-Mg alloy (5083). After several cycles of ARB at 473K, ultra-fine (sub-micron) grain structure with large misorientations, i.e. polycrystal was formed and dramatic strengthening was attained.

Keywords: *sub-micron grain, ultra-high straining, accumulative roll bonding, super metal, mechanical property, texture, aluminum.*

1. INTRODUCTION

It has been reported that materials with ultra-fine (sub-micron) grains show outstanding strength at ambient temperature, high-speed superplastic deformation at elevated temperature and high corrosion resistance. These materials, so called *super metals*, have aroused much interest. Although they have been produced by various techniques such as rapid solidification, vapor deposition, mechanical alloying, cryogenic metalforming and intense plastic straining. Intense plastic straining is considered to be the most appropriate process for industrial application. As the intense plastic straining, some special processes such as Cyclic Extrusion Compression (CEC) [1], Equal Channel Angular Press (ECAP) [2] and Torsion Straining under high pressure (TS) [3] have been already proposed and applied to various materials. However these processes have two main drawbacks. Firstly, forming machines with large load-capacity and expensive dies are indispensable for these processes. Secondly, the productivity is relatively low and the lot size, i.e. the amount of materials processed is very limited. These processes are supposed to be inappropriate for practical application, especially for large structural materials.

The authors now propose an alternative novel intense plastic straining process named the *Accumulative Roll-Bonding (ARB)*[4, 5] for bulk-material manufacturing at high productivity. In this paper, the principle of the ARB process and some convincing results are presented.

2. ACCUMULATIVE ROLL-BONDING(ARB)

Figure 1 schematically represents the proposed ARB process. At first, a strip is put on another strip neatly. The interfaces of the two strips are surface-treated in advance in order to enhance bond strength, if required. The two layered materials are joined together by rolling in the manner of a conventional roll-bonding process. Then, the length of rolled material is sectioned into two halves. The sectioned strips are again surface-treated, stacked and roll-bonded. The whole process is repeated again and again. The roll-bonding process should be conducted at elevated temperature below recrystallization temperature because recrystallization cancels out the accumulated strain. Low temperature would result in insufficient ductility and bond-strength. There exists minimum limit of the reduction in thickness i.e. the *threshold deformation* to attain sufficient bond strength. It is well known that the threshold deformation decreases with temperature. Even if the homologous temperature of the roll-bonding is less than 0.5, the sufficient joining can be achieved by reduction greater than 50% [6]. It means that materials can be bonded together without recrystallization.

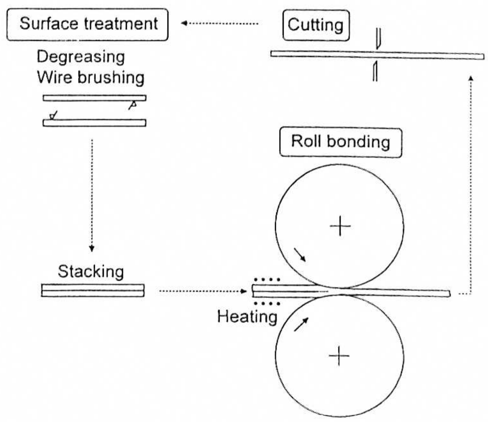


Fig. 1 Diagrammatic representation of the Accumulative roll-bonding process.

The process can introduce ultra-high plastic strain without any geometrical change, if the reduction in thickness is maintained to 50% in every rolling pass, because the increase in width is negligible in sheet rolling. The achieved strain is unlimited since repetition times are endless in principle. Arbitrarily large deformation is possible by the ARB process. For example, if the process is repeated 7 times, the initial thickness is reduced to 1/128. The initial thickness 1.0mm reduces to 7.8μm. The achieved total reduction is 99.2% and the estimated equivalent plastic strain is 5.6. In case of 10 cycles, the final thickness is 1.0μm, the total reduction is 99.9% and the strain is 8.0. It is easy to introduce ultra-high strain into materials by the ARB process.

3. EXPERIMENTAL

A commercial aluminum (1100) and an Al-Mg alloy (5083) were chosen to study the feasibility of the proposed ARB process. Materials were fully annealed before the ARB process. The mean grain sizes were 37 and 18μm for 1100 and 5083, respectively. The initial dimensions of the materials were 1.0mm in thickness, 20mm in width and 300mm in length. The width was limited by the load-capacity of used rolling mills. The interfaces between two strips were degreased by acetone and scratch-brushed by a 304 stainless-wire bevel brush. Two strips were layered to set brushed surfaces in contact and fixed each other closely. For this purpose, four holes, which had been drilled in the vicinity of four corners of strips were bound firmly by thin wires as shown in **Fig. 2(a)**.

The layered strips were held in a box-type electric furnace at 473K for 5min before roll bonding. Two rolling mills were used in this study. 1100 strips were rolled at 10m/min by a rolling mill with rolls 255mm in diameter. 5083 strips were rolled at 43m/min by the other mill with rolls 310mm in diameter. The thickness of the layered strips were reduced 50% under dry condition. Well-bonded bulk materials were successfully obtained. In case of 5083 alloy, however, excessively high total-reduction, i.e. repetition times, sometimes resulted in edge cracks or center fracture as shown in **Fig.2(b) and (c)**. It was due to tensile stress caused by lateral spreading near the edges, because the lateral spreading cannot be neglected when the aspect ratio (width/thickness) is less than 10 [7]. In order to avoid propagation of edge cracks in the following cycles, the both edges of roll-bonded strips were trimmed by shearing. The leading and trailing ends of strips were also cropped. These edge-cracks can be suppressed by materials with high aspect ratio or by lubricant.

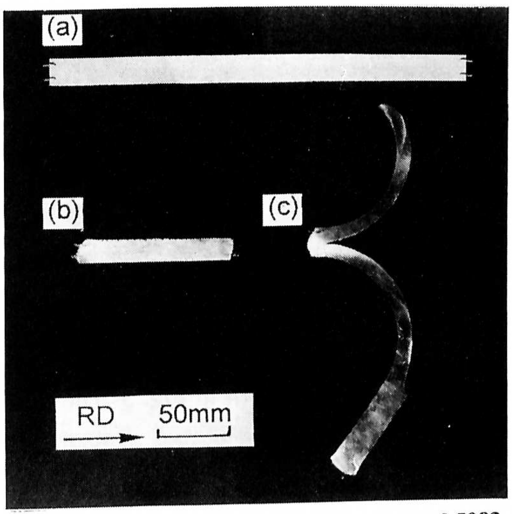


Fig. 2 Appearance of initial and ARB processed 5083 strips. (a),initial: (b) and (c), after three cycles.

The longitudinal cross-sections normal to transverse direction were observed with an optical microscope. The transmission electron microscopic (TEM) studies were also conducted using a HITACHI H-800 microscope operated at 200kV. For this purpose, thin foils parallel to the rolling plane were prepared by twin-jet polishing. The mechanical properties of initial and several-

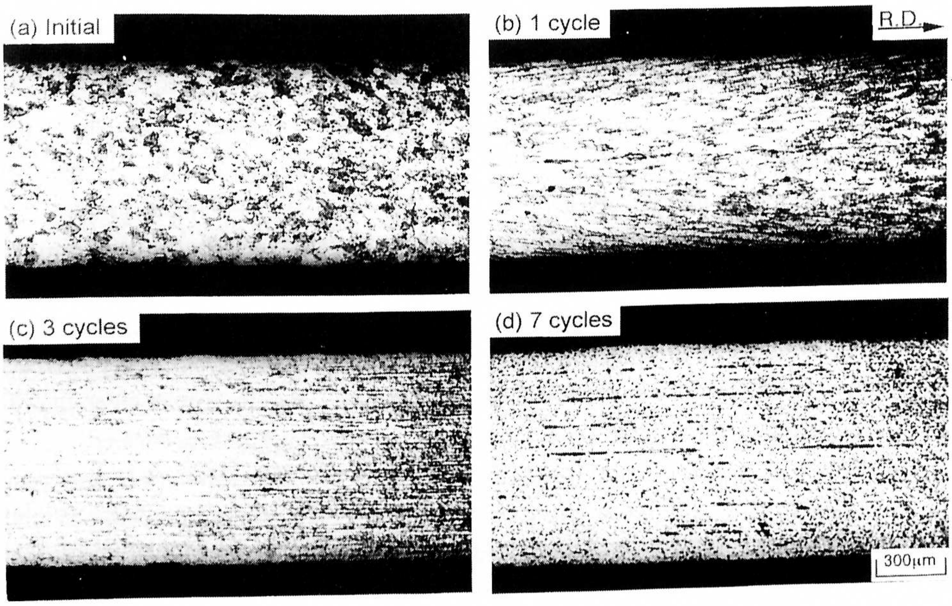
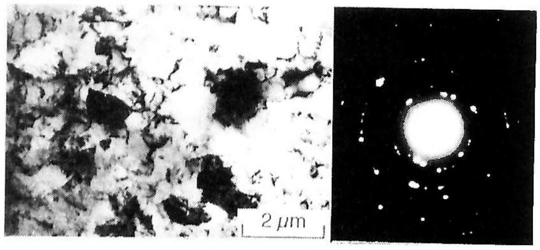
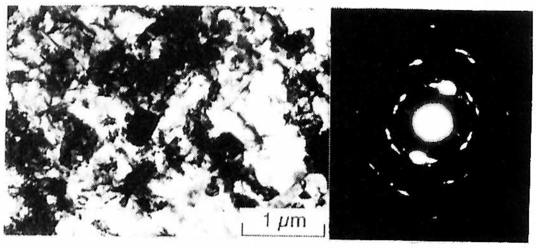


Fig. 3 Longitudinal cross sections of initial and ARB processed 1100 strips.

cycle processed strips were measured at ambient temperature by an Instron-type testing machine. Tensile-test specimens were spark-machined so that the tensile direction was parallel to the rolling direction. The gauge length was 10mm and the gauge width was 5mm. The cross-head speed was 0.5mm·min^{-1} so that the initial strain rate was 8.3 x 10^{-4}s^{-1}. {111} incomplete pole figures of obtained strips were measured by the Shulz reflection method with Cu-Kα radiation. The <h k l> //ND axis densities were determined from the ratio of integral X-ray diffraction intensities to that for a standard randomly oriented sample.



(a) 8-cycle processed 1100



(b) 7-cycle processed 5083

Fig. 4 TEM micrographs and SAD patterns of ARB processed strips.

Table 1 Mechanical properties of initial and ARB processed strips.

Material	No. of cycles	Tensile strength /MPa	Elongation /%
Al (1100)	0 (initial)	84	42
Al (1100)	8	304	8
Al-Mg (5083)	0 (initial)	319	25
Al-Mg (5083)	7	551	6

4. RESULTS

Optical micrographs of the ARB processed 1100 are shown in **Fig. 3**. The initial strip shows typical recrystallized structure with equiaxed grains. In the case of one-cycle processed material (**Fig. 3(b)**), the interface introduced is visible and sheared grains beneath surfaces are clearly observed. In case of 3-cycle or 7-cycle processed strips, some interfaces appeared partially by chemical etching. However, it is difficult to find all the interfaces introduced. It means that the introduced interfaces are bonded sufficiently. After three cycles, the whole thickness is covered by very thin and elongated grains and it is very difficult to distinguish individual grains by optical microscopy. **Figure 4** shows TEM micrographs of the ARB processed materials. The associated selected area diffraction (SAD) patterns taken from the center of the field by use of an aperture with a 1.6 μm in diameter are also shown in the figure. The structure is of a granular type with equiaxed grains. The mean grain sizes of them are smaller than 0.5 μm. The SAD patterns have numerous diffraction spots along circles. Such patterns indicate that large misorientations exist between the individual grains. Therefore, it is clear that ultra-fine (sub-micron) grain structure with large misorientations, i.e. polycrystal, were formed.

The mechanical properties of the initial and the ARB processed materials are compared in **Table 1**. In the case of the aluminum 1100, the tensile strength of commercially available full-hardened material (temper grade H18) is reported ~165MPa [8]. The tensile strength of the ARB processed 1100 (8 cycles) is 1.8 times higher than that of the 1100-H18. The ARB-processed 5183 also shows extremely high strength. On the other hand, the elongation decreased to 6 – 8 %. However, the materials show still some ductility, although the materials were strained heavily.

Figure 5 shows {111} incomplete pole figures of the 8-cycle ARB processed 1100 strip. It is clear that both pole figures do not show well-developed textures, although the strips were heavily strained (the total reduction is 99.6%). The surface texture is a typical shear texture [9-12], the main component of which is {001}<110>. The distribution of the pole intensities //ND through half thickness of the initial, 1-cycle, 2-cycle, 3-cycle and 7-cycle processed 1100 strips are shown in **Figure 6**. The <110>//ND or <111>//ND increases beneath the surface slightly with number of cycles. This is due to the redundant shear strain introduced by friction. On the other hand, no pole intensity increases around center of thickness. This is because the developed surface shear texture is destroyed at center by stacking and rolling. It is notable that sub-micron grains shown in **Fig.4** do not show well-developed texture. This redundant shear deformation may contribute in the formation of sub-micron grains.

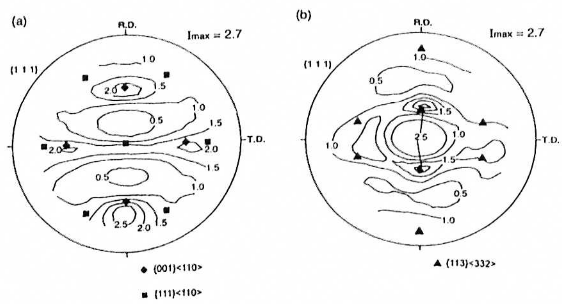


Fig. 5 {111} incomplete pole figures of the 8-cycle processed 1100 strips. (a),surface; (b) center

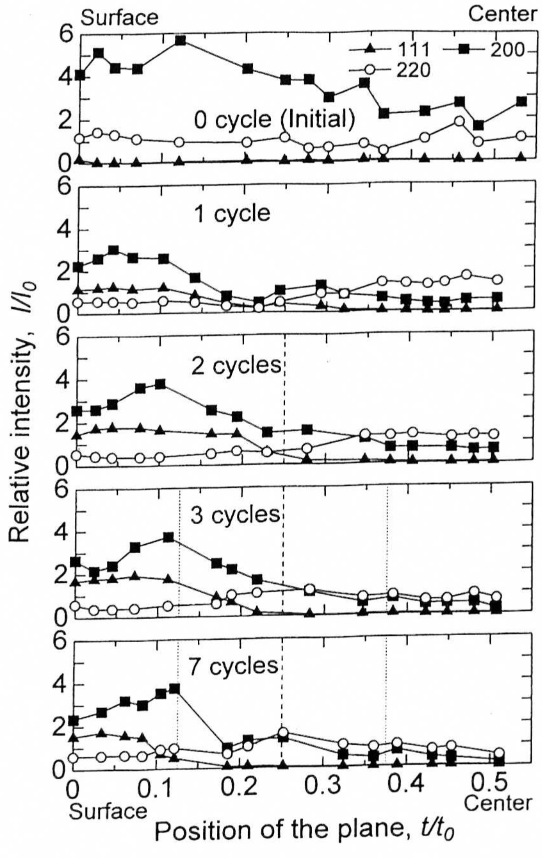


Fig. 6 Variations of preferred orientation through the thickness of 1100 strips.

5. DISCUSSIONS

It is made clear that the proposed accumulative roll-bonding (ARB) process causes ultra-fine (sub-micron) grains and surprising strength. These effects are confirmed experimentally by two materials, i.e. the commercial purity aluminum (1100), the Al-Mg alloy (5083). There are two possible additional mechanisms in the ARB process different from other high straining processes. The first possible mechanism is the effects of the severe shear deformation beneath surfaces. This redundant shear deformation significantly increases the equivalent strain and promotes grain refinement. Moreover the ARB process can introduce this severely deformed region into interior of material by repetition. The whole thickness of materials may be severely strained totally after several cycles. The other mechanism is the introduction of new interfaces. A large number of interfaces are introduced by several ARB cycles. These interfaces show well-developed fiber structure. The oxide films on surfaces as well as inclusions are dispersed uniformly by repetition. Those contribute the strength well and may act as obstacles for grain growth. The mechanism of the grain refinement during the ARB process is still unclear at this stage and some further discussions will be given in the other papers [13, 14].

Anyway, the advantages of this process against other high straining processes are its high productivity and feasibility of large-sized materials production. Although the experiments have been carried out with narrow 20mm wide materials in this study, it is supposed that application to bulk materials such as wide strips in coil is not difficult. The process does not require any special machines because the roll-bonding is widely adopted in clad metal production [15, 16]. The process may be readily to be industrialized.

6. CONCLUSIONS

A novel ultra-high straining process, *the accumulative roll-bonding (ARB)* process is proposed. The ARB process has been successfully applied to a commercial purity aluminum (1100) and an Al-Mg alloy (5083). Several-cycle ARB processed materials have structures with sub-micron grains and show very high strength. The proposed accumulative roll-bonding (ARB) is the promising process to manufacture high-strength bulk materials at high productivity.

ACKNOWLEDGMENTS

We are grateful to Mr. J. Miyamoto and Mr. R.G. Hong of Osaka University for experimental assistance. We also thank to Nakayama Steel Works, Ltd. for improvements in rolling mill and Sumitomo Light Metal Industries, Ltd. for material supply. This study was financially supported by the Japan Research and Development Center for Metals (JRCM).

REFERENCES

[1] J. Richert and M. Richert: Aluminium, **62**(1986), 604.
[2] R. Z. Valiev, N. A. Krasilnikov and N. K. Tsenev: Mat. Sci. & Eng., **A137**(1991), 35.
[3] Z. Horita, D. J. Smith, M. Furukawa, M. Nemoto, R. Z. Valiev and T. G. Langdon: J. Mat. Res., **11**(1996), 1880.
[4] Y. Saito, H. Utsunomiya, N. Tsuji and T. Sakai: applied to Japanese Patent.
[5] Y. Saito, H. Utsunomiya, N. Tsuji and T. Sakai: submitted to Scripta Mater.
[6] M. G. Nicholas and D. R. Milner: British Welding Journal, **8**(1961), 375.
[7] A. Helmi and J. M. Alexander: J. Iron and Steel Inst., **206**(1968), 1110.
[8] American Society for Metals: Metals Handbook, Ninth ed., **2**(1979), 65.
[9] T. Kamijo, K. Sekine, S. Kuba and T. Takeuchi: J. Jpn. Inst. Metals, **36**(1972), 33, (in Japanese).
[10] W. Truszkowski, J. Krol and B. Major: Metall. Trans., **11A**(1980), 749.
[11] T. Sakai, Y. Saito, K. Hirano and K. Kato: Trans. ISIJ, **28**(1988), 1028.
[12] N. Tsuji, Y. Nagai, T. Sakai and Y. Saito: Mat. Trans. JIM, **39**(1998), 252.
[13] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai and R. G. Hong: submitted to Scripta Mater.
[14] Y. Saito, N. Tsuji, H. Utsunomiya, T. Sakai and R. G. Hong: Proceedings of this conference.
[15] R. F. Tylecote: The Solid Phase Welding of Metals, Edward Arnold Ltd., London (1968).
[16] M. Ishio: J. Jpn. Soc. Tech. Plast., **32**(1991), 27, (in Japanese).