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ACCUMULATIVE ROLL-BONDING (ARB) OF Al99.8%

WALCOWANIE AKUMULACYJNE ZE SPAJANIEM (ARB)

The Accumulative roll-bonding (ARB) process consists in rolling of the pack of two sheets to 50%. Then, the rolled materials is sectioned into two halves, stacked again and the procedure of roll-bonding can be repeated practically unlimitedly.

The paper presents the accumulative roll-bonding procedure applied to the Al 99.8% strips. The evolution of mechanical properties, microstructure and texture in dependence on number of passes are discussed.

Istotą procesu walcowania akumulacyjnego ze spajaniem (ARB) jest związanie blach w pakiecie, złożonym z dwóch blach, podczas walcowania ze zgniotem równym 50%. Po takim walcowaniu blacha jest dzielona na dwie równe części, składana i ponownie walcowana z takim samym zgniotem. Taki sposób walcowania ze spajaniem może być powtarzany teoretycznie bez ograniczeń.

W pracy przedstawiono zmiany własności mechanicznych, mikrostruktury i tekstury krystalograficznej Al 99.8% w zależności od liczby przepustów akumulacyjnego walcowania ze spajaniem.

1. Introduction

Severe plastic deformation (SPD) processes are more and more widely proposed as methods to produce materials of ultra fine grained (UFG) microstructure [1]. The main features of such materials which can be interesting for industry are the improved strength as well as the ductility, which shifts the temperature of super-plastic deformation towards lower temperatures [2].

SPD methods, like equal-channel angular pressing (ECAP) and high pressure torsion (HPT) should have been widely applied to produce bulk ultra-fine grained (nanocrystalline) materials because they both require special equipment. Moreover, the

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efficiency of such methods is rather low. The accumulative roll-bonding (ARB) process, invented a few years ago [3], seems to be more promising for introducing severe plastic deformation into industrial practice. The ARB process consists in rolling to 50% of the two sheets pack, of which the stacked surfaces were initially cleaned. Then, the rolled material is sectioned into two halves, stacked again and the procedure of roll-bonding repeated. Practically, the process can be repeated without limits. Generally, the severe plastic deformation methods like the ARB or the ECAP can produce bulk samples of relatively large dimensions and without pores compared to the powder metallurgy methods, in which the pores are difficult to remove. The ARB method, additionally, can supply final products in the form of sheets, which can be directly used for further work forming operation.

The paper is aimed at presenting the results of accumulative roll-bonding applied to Al 99.8% strips. The evolution of mechanical properties, microstructure and texture in dependence on number of passes are discussed.

2. Accumulative roll-bonding

Fig. 1 presents the scheme of accumulative roll-bonding (ARB) procedure. Two pieces of strip with clean and degreased surfaces are put together and after annealing joined by means of 50% consecutive rolling. The obtained strip which is composed of two bond layers is then sectioned in two pieces and after cleaning of two surfaces which are to be fixed together, consecutively heated and rolled 50% to perform roll-bonding. Due to 50% rolling reduction followed by stacking 2 halves and consecutive 50% rolling reduction the procedure can be continued practically without limits [3].

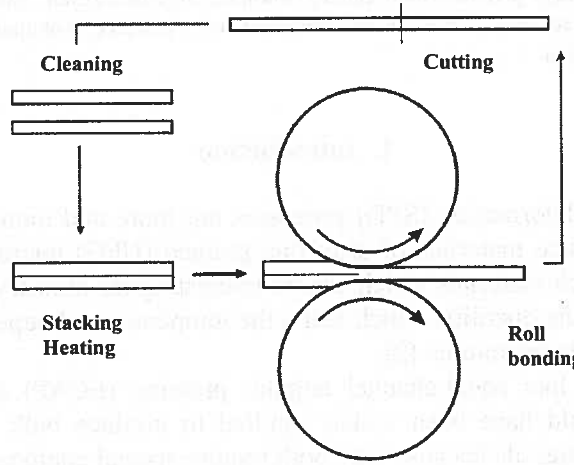

Fig. 1. Scheme of the accumulative roll-bonding (ARB) process

Suppose the strip with initial thickness t_o, rolled with 50% reduction in each cycle; the thickness t_n of individual layer, after n cycles, can be calculated according to the formula

$$t_n = t_o/2^n. \tag{1}$$

The total reduction z_n after n cycles is

$$z_n = 1-t/t_o = 1-1/2^n \tag{2}$$

and with the Huber-Hencky-v. Mises yield criterion of plasticity [4] and plane strain state of deformation under rolling the equivalent plastic strain ε is equal to

$$\varepsilon_n = \left\{\frac{2}{\sqrt{3}} \ln\left(\frac{1}{2}\right)\right\} * \mathrm{n} = 0.8\ \mathrm{n} \tag{3}$$

Assuming initial thickness t_o = 1 mm and performing exemplary n = 5 cycles roll- bonding, the thickness of layer was equal to t_5 = 1/32 mm = 31.25 μm, total reduction was z_5 = 96.875% and total equivalent deformation was ε_5 = 4; in the case of n = 10 cycles of roll-bonding the final thickness of layer is equal to t_{10} = 1/1024 mm = 0.98 μm, total reduction z_{10} = 99.9% and total equivalent deformation ε_{10} = 8 can be obtained.

Although relatively large deformation can be obtained, in practice the end parts of strip have to be prepared each time after roll-bonding and then, with increasing number of cycles, the length of roll-bonded strip decreases.

3. Material and experimental technique

The experiments were carried out on aluminium Al 99.8 [5] annealed 0.5 h at 400°C, with initial grain size d = 20- 30 μm (see *A* in Fig. 3). Roll-bonding was performed using laboratory roll mill with 150 mm diameter rolls at velocity equal to v = 4.33 m/min. Stack strips of 250 × 30 mm^2 dimension were heated before each pass (see the temperatures in Table 1). Strain marks induced by deformation on the lateral surface of a rolled sample as well traces of layers were observed by means of optical microscope.

The microstructure observations (TEM) were carried out using Philips CM20 electron microscope at chosen deformation step. Thin foils, parallel to sheet plane, were prepared by electrolytic thinning.

Tensile test were performed by means of INSTRON 6025 machine and specimens with the heads and gauge dimensions 20 × 4 mm^2 were cut out in RD direction of roll- bonded sheets.

The changes of crystallographic orientations were studied by the method of pole figures. The measurements of pole figures in middle layer of rolled strip were performed using Philips X- ray diffractometer and CoK$_\alpha$ characteristic radiation. The Orientation

Distribution Function (ODF), which expresses the density of probability of grains with the orientation g=g(φ_1, Φ, φ_2) and dg precision, where φ_1, Φ, φ_2 are Euler angles describing the orientation of the crystal system with reference to the sample system, was calculated [6] for processed sample.

4. Results and discussion

4.1. Tensile test and metallographic observations

Roll-bonding at ambient temperature usually does not give satisfactory final product. Then an initial heating was executed before the rolling at higher temperature. The results of tensile tests in dependence on temperature and number of passes are presented in Table 1. The mean values of strength and tensile elongation are visualized

TABLE 1

Tensile properties of Al 99.8% processed by accumulative roll-bonding; temperature, number of passes and sample number are marked i.e. A150-1 is for sample No 1 and 1 pass at 150°C, r — recrystallized

Sample	Yield Stress [MPa]	Ultimate Tensile Strength [MPa]	Elongation [%]
	$R_{0.2}$	R_m	A
	Mean values		
A150-1	127.0	140.85	6.3
A150-5	129.5	164.0	8.9
A150-10	130.0	159.5	8.0
A150-15	133.5	153.0	7.1
A200-1	125.0	137.2	6.5
A200-5	135.0	156.8	8.3
A200-10	127.5	147.1	8.0
A250-1	122.0	136.5	6.4
A250-5	125.0	151.6	7.5
A250-10	127.0	144.6	7.7
A-r	50.6	77.5	33.6

in Fig. 2. The most promising mechanical properties of ARB processed Al 99.8% were obtained during heating at 150°C and after 5 passes (ε = 4.0) of roll-bonding. The strength increased twice and elongation decreased down to 8%. Similar increase in strength equal to 1.8 and elongation decrease down to 8% was observed in the deformed aluminium AA 1100 up to ε = 8.0 [3]. Strength of 200 MPa for AlFeSi alloy was stabilized above ε = 4.0 and maximum elongation equal to 17% was observed above ε = 8.0 [6]. The metallographic observations of cross-sections of ARB processed strips demonstrated still existing central trace due to the last roll-bonding as can be observed in Fig. 3 and 4. The cross-sectional metallographic pictures for the best ARB

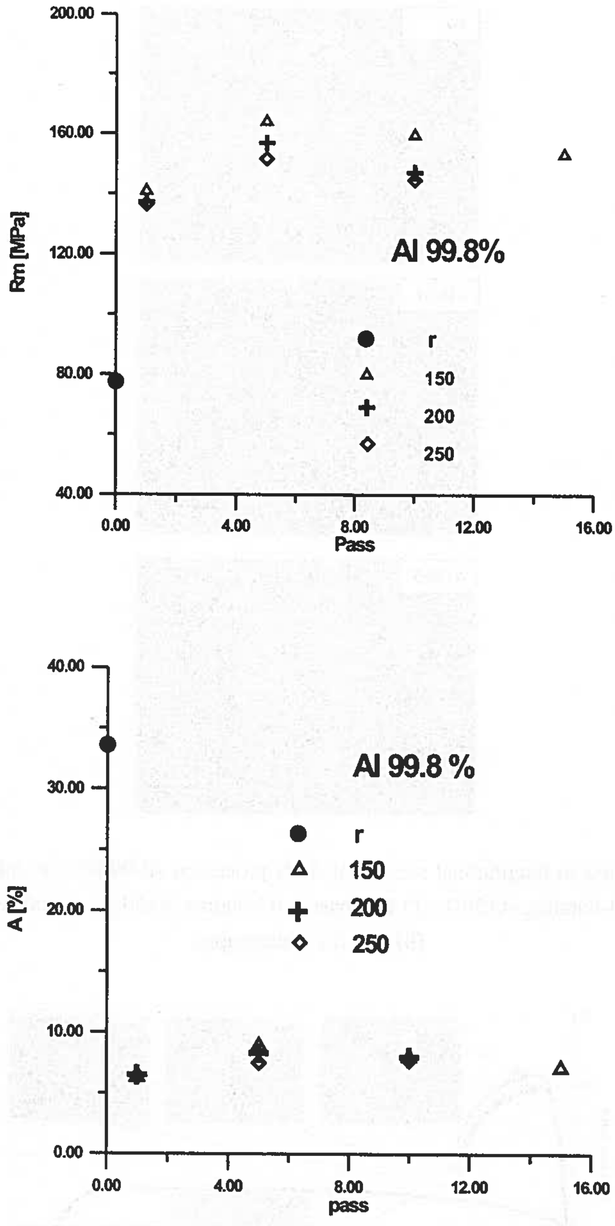

Fig. 2. Mean values of yield strength (a) and elongation (b) versus number of passes of Al 99.8% roll-bonded at different temperatures

parameters obtained are related additionally to tensile stress – strain dependences and are shown in Fig. 4.

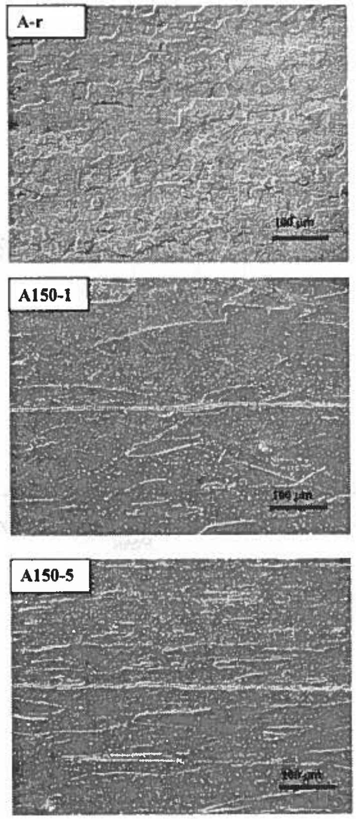

Fig. 3. Microstructure in longitudinal section of ARB processed Al 99.8%: (a) initially recrystallized A-r, (b) one pass roll-bonding A150-1, (c) five pass roll-bonding A150-5; central roll-bonding is seen in (b) and (c) photographs

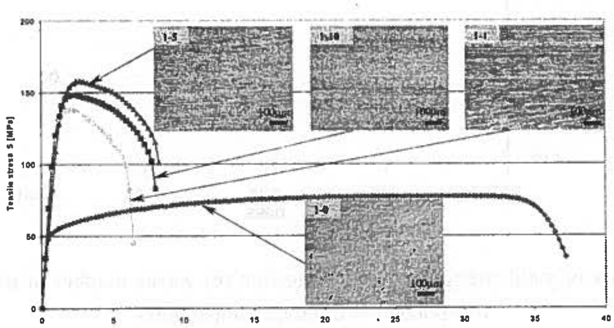

Fig. 4. Tensile stress versus elongation curves for samples after recrystallization (1-0) and roll-bonding at 150°C: 1 pass (1-1), 5 passes (1-5) and 10 passes (1-10) are presented

4.2. TEM observations

After the first pass of roll-bonding ($\varepsilon = 0.8$) and heating temperature 150°C of Al 99.8% strip, the microstructure with dislocation cells diameter of order 1 μm was observed; there were only a few cells with smaller size as can be seen in Fig. 5. Five passes at the same conditions ($\varepsilon = 4.0$) lead to considerable grain refinement

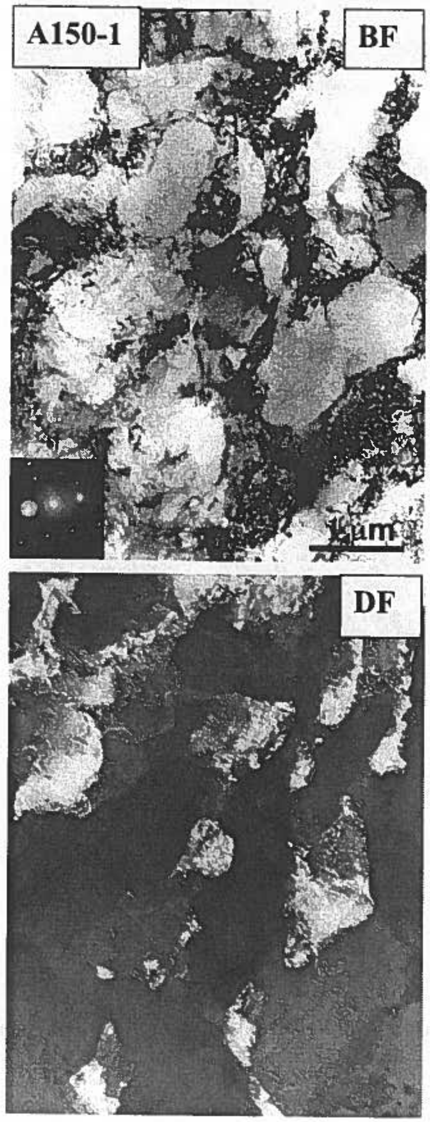

Fig. 5. Microstructure of Al 99.8% after 1 pass roll-bonding at 150°C (A150-1): bright field BF and dark field DF — 200 image

and we observe still numerous cells of 100 — 200 nm diameters; although some coarse cells can be encountered (Fig. 6). During ARB processing up to ε = 8 of

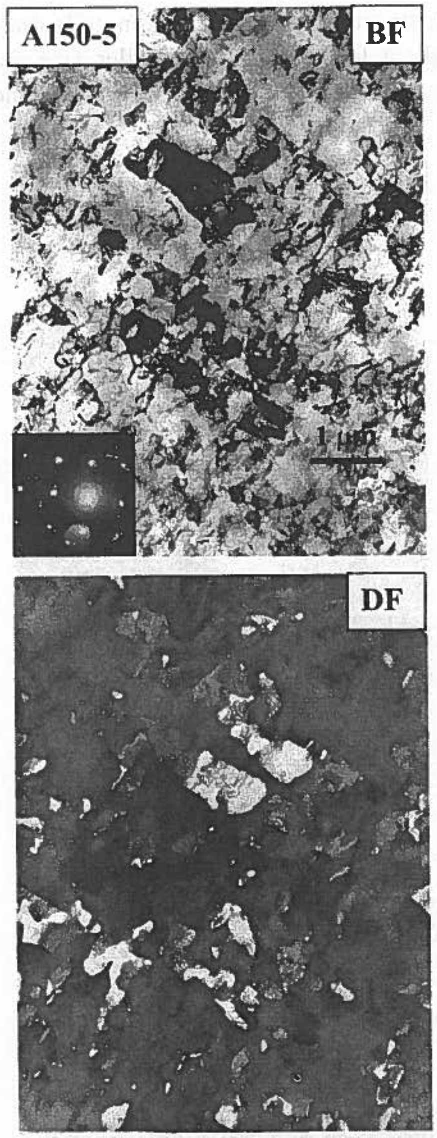

Fig. 6. Microstructure of Al 99.8% after 5 pass roll-bonding at 150°C (A150-5). Description — as in Fig. 5

aluminium AA1100, the grain size below 0.5 μm was noted. It is worth noting that at that deformation we registered in tensile test the maximum of strength accompanied by maximum of elongation in the tensile test. The increase of passes by the same ARB mode did not yield the grain refinement, on the contrary the microstructure after 10 passes (ε = 8.0) was similar to that one after the first pass (compare Fig. 7 and 5); also the strength as well the elongation were lower (compare Fig. 4 and Table 1). Although

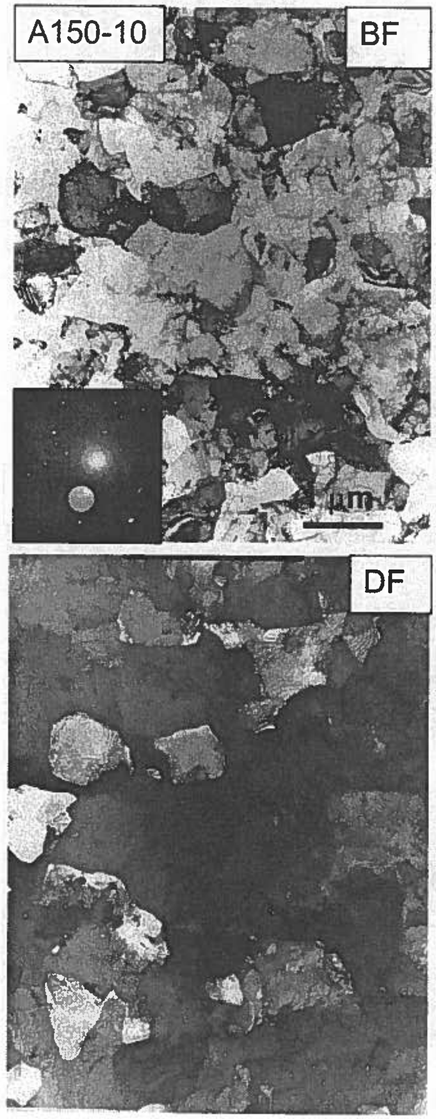

Fig. 7. Microstructure of Al 99.8% after 10 pass roll-bonding at 150°C (A150-10). Description — as in Fig. 5

the microstructure after 15 passes (ε = 12.0) continued to refine grain size (Fig. 8) but did not induce actually the improvement of mechanical properties as can be seen in Table 1.

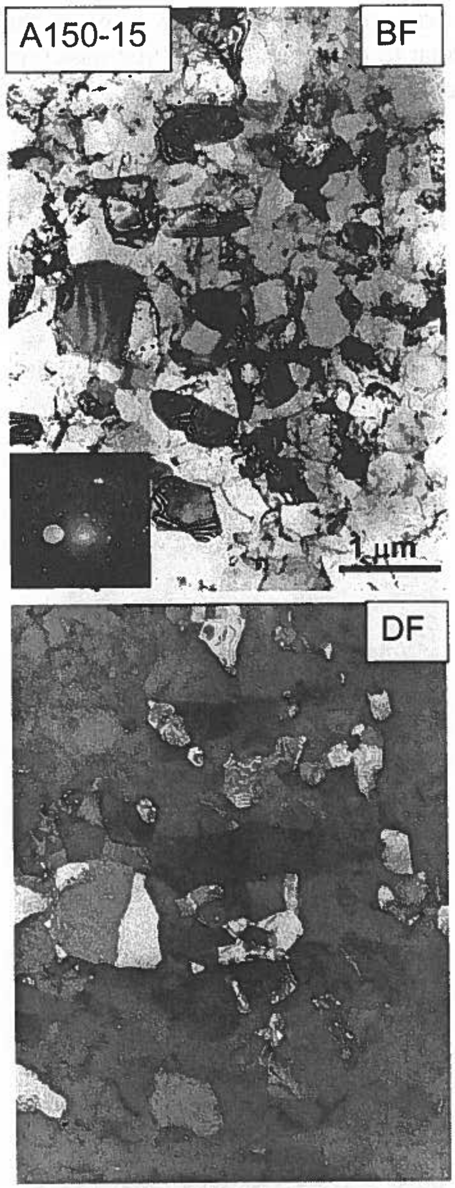

Fig. 8. Microstructure of Al 99.8% after 15 pass roll-bonding at 150°C (A150-15). Description — as in Fig. 5

4.3. Crystallographic texture measurements

Figures 9 presents the pole figures of roll-bonded strips after 5 and 10 passes. One can observe in the middle layer of ARB processed strip, very asymmetric rolling texture component (compare orientations in Table 2) namely: (41-2)[1-21] main orientation in

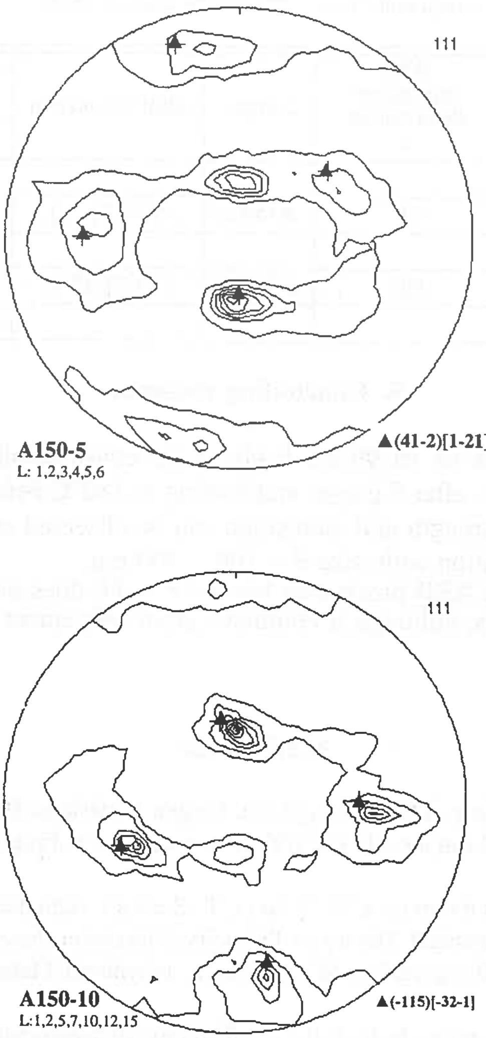

Fig. 9. {111} poles figures of Al 99.8% roll-bonded at 150°C; 5 passes (A150-5) and 10 passes (A150-10)

Al 99.8% ARB processed up to $\varepsilon = 4.0$ and (-115)[-32-1] main orientation in Al 99.8% ARB processed up to $\varepsilon = 8.0$. The strong Cu {112}< 111 > component was observed although the distribution of texture component was very inhomogeneous across the thickness of ARB processed aluminium [8,9].

TABLE 2

Ideal orientations of main components of ARB processed Al 99.8%; f — ODF value for ideal orientation, f_{max} — maximum value of ODF

Material	ARB equivalent deformation ε	Sample	Ideal orientation	ODF f/f_{max}
Al 99.8%	4.0	A150-5	(41-2)[1-21]	31/49
Al 99.8%	8.0	a150-10	(-115)[-32-1]	294/384

5. Concluding remarks

The ARB procedure of Al 99.8% leads to the considerable grain refinement at deformation $\varepsilon = 4.0$, i.e., after 5 passes and heating to 150°C before each roll-bonding.

The maximum of strength and elongation can be observed at equivalent deformation $\varepsilon = 4.0$ and dislocation cells size d = 100 – 300 nm.

The continuation of ARB processing beyond $\varepsilon = 4.0$ does not lead to the increase of mechanical properties, although it continues grain refinement.

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