

**INVESTIGATION OF ASYMMETRIC ROLLING  
APPLIED TO TWIN-ROLL CAST Al-Mn ALLOY**POKOVÁ Michaela<sup>1</sup>, ZIMINA Mariia<sup>1</sup>, CIESLAR Miroslav<sup>1</sup>, GRYDIN Olexandr<sup>2</sup>

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**Abstract**

Twin-roll cast aluminium alloy from AA3003 series was subjected to several passes of asymmetric rolling at room temperature, which gradually led to a grain refinement. This process is more effective in the grain refinement than conventional cold-rolling. During subsequent annealing at elevated temperatures the deformed grains are replaced by new ones by a static recrystallization, which starts near the surfaces of strips. Higher strain imposed by rolling results in a decrease of temperature of recrystallization. Nevertheless, the rolling direction remains still apparent even after full recrystallization.

**Keywords:** Twin-roll casting, asymmetric rolling, microhardness, recrystallization

**1. INTRODUCTION**

Twin-roll casting (TRC) is an alternative method to direct-chill casting techniques for the production of aluminium alloys. To advantages of twin-roll casting belong mainly the high casting speed and more economical production [1]. Recently, many works were devoted to investigation of microstructure evolution in TRC alloys (eg. [2, 3]). However, new methods how to further improve strength of TRC sheets are under an intensive research. Main possibilities are modification of chemical composition or application of severe plastic deformation [4, 5].

Asymmetric rolling (ASR) is a method of severe plastic deformation (SPD) whose aim is to reduce grain size to submicron range and thus increase the strength of the material. Asymmetric rolling has greater economic efficiency than other SPD techniques such as accumulative roll bonding or equal channel angular pressing, since it produces large volumes of deformed material and can be easily implemented on industrial rolling mills [6].

Asymmetric rolling with different angular velocities of rolls gives rise to intense plastic shear strains, which result in grain refinement and hence improvement of mechanical properties. The most common implementation of different angular velocities is the use of rolls with the same diameter but different speed [7, 8]. The ASR gives rise to a simple shear and compressive strains and develops a shear texture [9].

**2. EXPERIMENTAL**

Aluminium alloy from AA3003 series was studied. The amount of main alloying elements is as follows: 1.02 wt.% Mn, 0.20 wt.% Fe, 0.53 wt.% Si and 0.17 wt.% Zr. This alloy was manufactured by twin-roll casting in industrial conditions to thickness 8.5 mm. Afterwards the sheet was ASR treated in laboratory conditions with higher speed of the upper roll and speed ratio 4. After each step the sheet was rotated by 180° around

the rolling direction. First step led to the thickness reduction to 5.3 mm, second one to 3.5 mm, third to 2.5 mm, fourth to 1.9 mm and the final thickness after fifth asymmetric rolling pass was 1.4 mm.

Mechanical properties of ASR sheets were tested by Vickers microhardness (HV) measurement with a load of 100 g at QNess A10+ microhardness tester. Microstructure changes were observed in polarized light by light optical microscope Olympus GX51 after electrochemical polishing by Barker solution [10]. The recrystallization process was monitored during isochronal annealing in an air furnace with the step 50 K/50 min.

### 3. RESULTS AND DISCUSSION

#### 3.1. Asymmetric rolling

The initial state of the studied alloy after twin-roll casting consists of grains elongated in the rolling direction (RD) and inclined towards the sheet surface, with their length in the order of 200  $\mu\text{m}$ . The grain structure is inhomogeneous through the sheet thickness – the grains are more flat near both sheet surfaces and a macrosegregation of particles of  $\alpha\text{-Al}(\text{Mn,Fe})\text{Si}$  phase [11] is present in the central part of the sheet (Fig. 1a).

During asymmetric rolling the thickness of the sheet is reduced and grains are flattened and elongated. The microhardness gradually increases with the number of ASR passes (Fig. 2). From the initial value of 55 HV0.1 the microhardness rises to 80 HV0.1 after the first pass and reaches 95 HV0.1 after five passes. The evolution of the microhardness is similar in both planes perpendicular to the rolling direction and to the transverse direction (TD).

The microhardness distribution is inhomogeneous through the sheet thickness, which is demonstrated on Fig. 3. This figure represents microhardness distribution in the plane perpendicular to the transverse direction in the sheet after three passes of ASR. Microhardness is higher near sheet surfaces, where grains are more flattened and also in the central part of the sheet, where the macrosegregation of primary phases occurs. The nonuniformity of microstructure after ASR is connected with the heterogeneous structure of the TRC sheet. This heterogeneity is demonstrated on the grain structure of the sheet deformed by one pass of ASR on Fig. 1b).

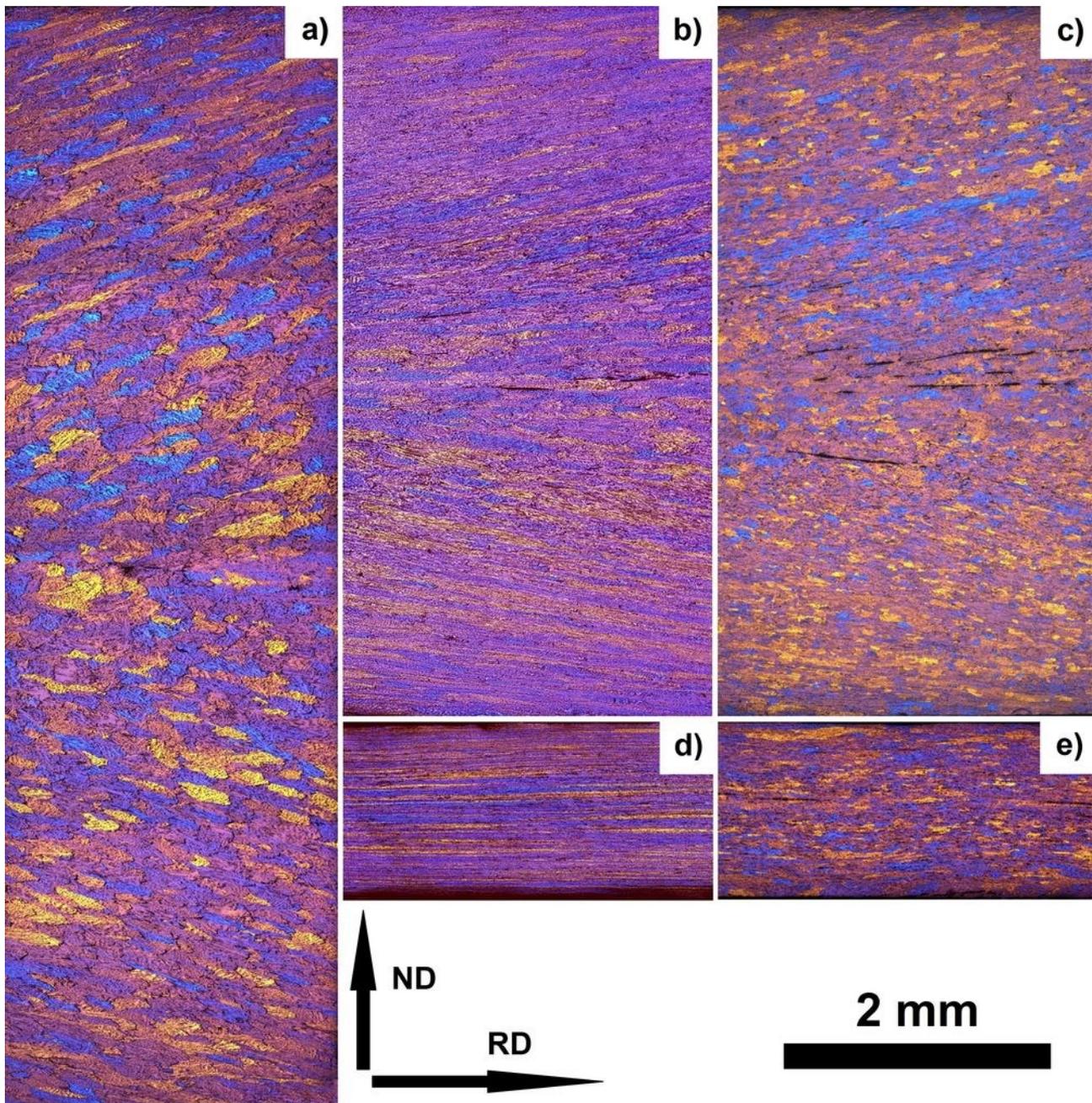
After further rolling to the thickness 1.4 mm the differences in the grain shape within the sheet thickness become less distinct, pancake grain structure develops and the grain length reaches several  $\mu\text{m}$  (Fig. 1d).

#### 3.2. Isochronal annealing

The high temperature stability of the asymmetrically rolled sheets is examined during isochronal annealing with heating rate 50 K/50 min from room temperature to 600 °C. The evolution of microhardness for different number of ASR passes during the annealing is shown on Fig. 4.

At annealing temperatures below 200 °C slight increase of microhardness is observed. Such augmentation of microhardness was described by Huang et. al. [12] in severely deformed aluminium and is attributed to depletion of the aluminium matrix from dislocations and formation of dislocation cells. In such materials with reduced dislocation density, there new dislocation sources have to be activated to enable further deformation; thus, a higher stress is required. Similar behavior was observed on the same alloy processed by equal channel angular pressing [13] and on similar material deformed by accumulative roll bonding [14]. This effect gets more significant with increasing deformation.

When annealing above 200 °C is applied on asymmetrically rolled sheets microhardness gradually decreases to values around 80 HV0.1 at 400 °C, regardless the number of ASR passes. At this stage the grains are still heavily elongated in the rolling direction.



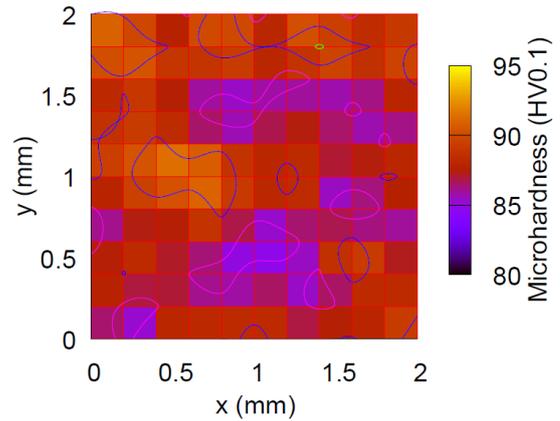
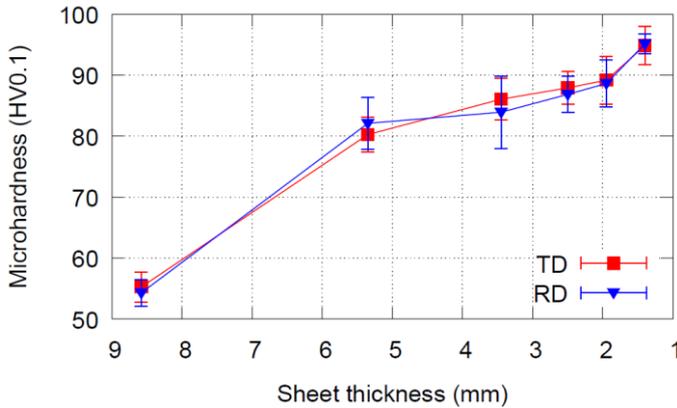
**Fig. 1** Light optical micrograph of grain structure of twin-roll cast alloy (a). Elongated grain structure after one (b) and five (d) passes of asymmetric rolling. Recrystallized grains after annealing to 600 °C of ASR sheets deformed by one pass (c) and after annealing to 450 °C of sheet deformed by five ASR passes (e).

Above 400 °C significant drop of microhardness takes place and recrystallization occurs in all sheets. Recrystallization starts near the sheet surface. The original grains are finer near the surface than in the central part and also the microhardness is higher, which is connected with a higher stored deformation energy. Thus, driving force for recrystallization is higher in these areas and recrystallization starts here. Some fractions of grains near the surface grow to a larger size as compared to the bulk of the sheet.

The temperature of recrystallization is highly dependent on the sheet thickness, which is closely connected with the stored deformation energy in the matrix. At 450 °C the sheet deformed by five passes of ASR is fully

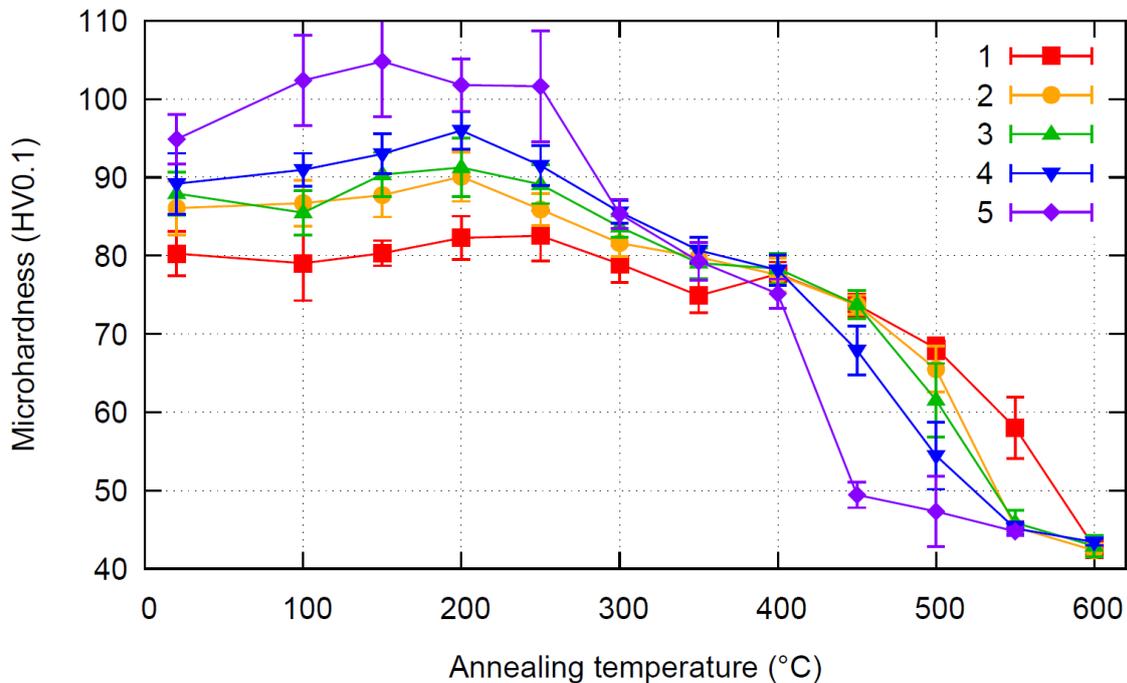
recrystallized (Fig. 1e). The newly formed grains are much shorter; however, the rolling direction is still apparent. The average size of recrystallized grains is 70  $\mu\text{m}$  in the rolling direction and 25  $\mu\text{m}$  in the normal direction and is not significantly influenced by the number of ASR passes (Fig. 5).

Recrystallization of sheets deformed to lower extent begins at higher annealing temperatures. Example of a partially recrystallized structure is given on Fig. 6a). Materials deformed by 2, 3 and 4 passes of ASR are fully recrystallized at 550  $^{\circ}\text{C}$  (Fig. 6b), material deformed by only one pass with the lowest stored deformation energy is fully recrystallized after annealing up to 600  $^{\circ}\text{C}$  (Fig. 1c).

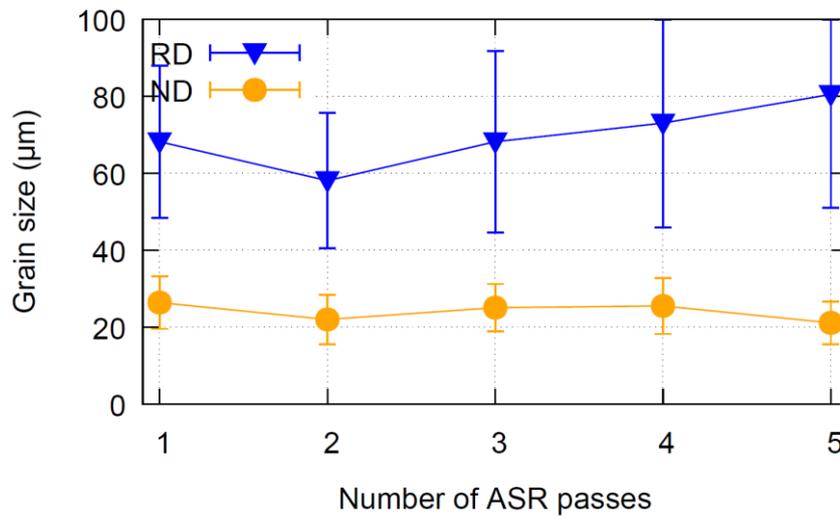


**Fig. 2** Microhardness evolution with decreasing of the sheet thickness during asymmetric rolling; values are measured in planes perpendicular to transverse direction (TD) and rolling direction (RD).

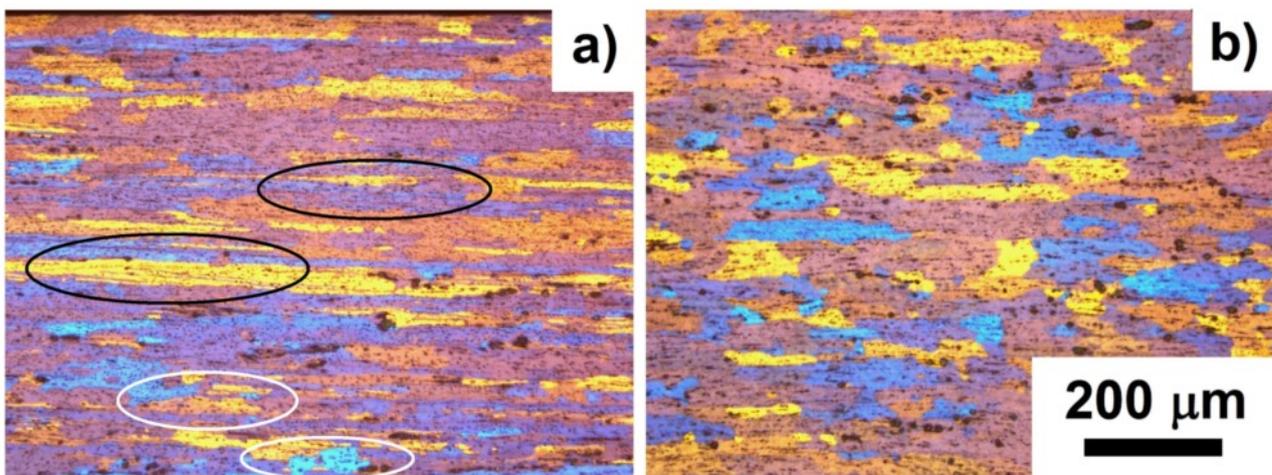
**Fig. 3** Microhardness distribution after 3 asymmetric rolling passes measured in the plane perpendicular to the transverse direction.



**Fig. 4** The evolution of Vickers microhardness of sheets asymmetrically rolled to various thicknesses during isochronal annealing with rate 50 K/50 min.



**Fig. 5** Recrystallized grain size after annealing up to 600 °C in normal (ND) and rolling direction (RD) for sheets after different number of asymmetric rolling passes.



**Fig. 6** Grain microstructure of sheet processed by three ASR passes and annealed to 500 °C (a) and 550 °C (b). Deformed parts in (a) are marked by black ellipses, recrystallized by white ones.

#### 4. CONCLUSION

Twin-roll cast aluminium alloy was subjected to severe plastic deformation by several passes of asymmetric rolling with the speed ratio of rolls being 4. ASR leads to formation of pancake grain structure and substantial increase of microhardness.

The higher is the stored deformation energy induced into the material during ASR, the lower is the thermal stability at elevated temperatures and sheets recrystallize at lower temperatures. The grain structure remained inhomogeneous after recrystallization with the average grain size 70 µm, which is lower than in twin-roll cast sheet.

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