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Investigation of the Influence of Low Cycle Alternating Bending Loads on the Properties of Thin Sheets Possessing Different Crystal Lattice Structures

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Low cycle, alternating bending is a common type of forming during the manufacture and processing of thin sheets. This forming occurs during the rolling-up into and rolling-out from coils, whilst passing through rolling equipment during the etching process, washing, coating, straightening, bending and deep drawing. Investigations of the mechanical properties, the microstructure and texture of sheets made of the magnesium alloy AZ31, technically pure aluminium and low carbon steels were carried out following cyclic bending on a 3-roller bending machine and on an 11-roller straightening machine. A significant influence of this type of forming on the sheet's properties was established, in particular for materials possessinghcp crystal lattice structures. Pronounced anisotropic properties were observed in the latter material which can be explained by the effect of texture softening. This can be attributed to the activation of twin formation mechanisms in the bending direction. The influence of the prior rolling, the bending regime and the annealing was demonstrated on improving the properties of the sheets made of the magnesium alloy AZ31.

Keywords: ROLLING, BENDING, MICROSTRUCTURE, MAGNESIUM ALLOY, ANISOTROPIC, TEXTURE SOFTENING

Introduction

During the rolling of thin sheet, the material is subjected to multiple forming by means of alternating bending loads at different stages of the manufacturing process. This occurs during rolling-up into and rolling-out from coils, during the etching, washing, coating and straightening. These processes operate under conditions of single, low deformations and do not lead to geometric changes in the sheet's dimensions. However, they can influence the sheets properties. Previous investigations have shown that this type of forming can have a decisive influence on the stress-strain curves and the mechanical properties [1, 2]. In the current work, results are presented for investigations of the mechanical properties, the sheet's microstructure and texture for different materials which possess bcc, fcc and hcp crystal lattices. The corresponding materials include a low carbon steel DC01, a technically pure aluminium Al (99.9%) and the magnesium alloy AZ31.

1 mm thick sheets of low carbon steel 1.0312 (C ≤ 0.06%; Mn ≤ 0.35%; S ≤ 0.025%; P ≤ 0.025%), technically pure aluminium (99.9%) and the magnesium alloy AZ31 (Al 3.3%; Zn 0.9%; Mn 0.4%) were used as the initial materials. Specimens with the dimensions 95x95 mm were manufactured from these sheets. To eliminate the residual stresses, all the sheets were heat treated prior to being subjected to bending loads: Steel was heat treated at 600 °C for 1 hour, aluminium at 350 °C, also for 1 hour, and AZ31 at 330 °C for 30 min.

The cyclic bending was performed on a pipe bending machine using a bending radius of 25 mm and a fraction of the specimens was deformed on a straightening machine using 11, 25mm radius rollers of width 100 mm. One bending cycle consisted of bending in one direction, then bending flat to the horizontal position, subsequently bending in the other direction and then bending flat to the horizontal again. The number of cycles using the pipe-bending machine are varied between 1 and 18, and 5.5 cycles per pass can be realised using the straightening machine. A fraction of the specimens was subjected to cyclic, cruciform straightening where the sheets were rotated through 90° after each pass. Some specimens were annealed after bending. Following the tests, specimens were taken from the sheets for the tensile tests (longitudinal, transverse and at 45°), the metallographic examinations and the textural measurements using pole figures.

An analysis of the stress-strain diagrams shows that, in the case of the AZ31 magnesium alloy's deformation, the cyclic bending has a decisive influence on the diagrams' form. Subsequent to 3 bending cycles, a kink is formed in the curves, which accompanies a reduction in the yield strength within the forming range between 0.5 % and 1.0%. This effect can be observed in specimens which were manufactured in the bending direction (see **Figure 1a**). Under analogous conditions, the monotonic characteristic of the curves are not changed in the transverse specimens: Although the stress level is elevated. Generally, the level of the flow stresses in the longitudinal specimens is lower than those in the transverse specimens. Materials with fcc and bcc crystal lattices retain the monotonic character of their stress-strain curves following cyclic bending. Here, the stress level for aluminium tested in the longitudinal direction is more strongly elevated than for that tested in the transverse direction whereas for steel, the level is raised equally for both directions (see **Figure 1c**). It was generally possible to establish that the stress-strain curves' character had already stabilised after 3 bending cycles.

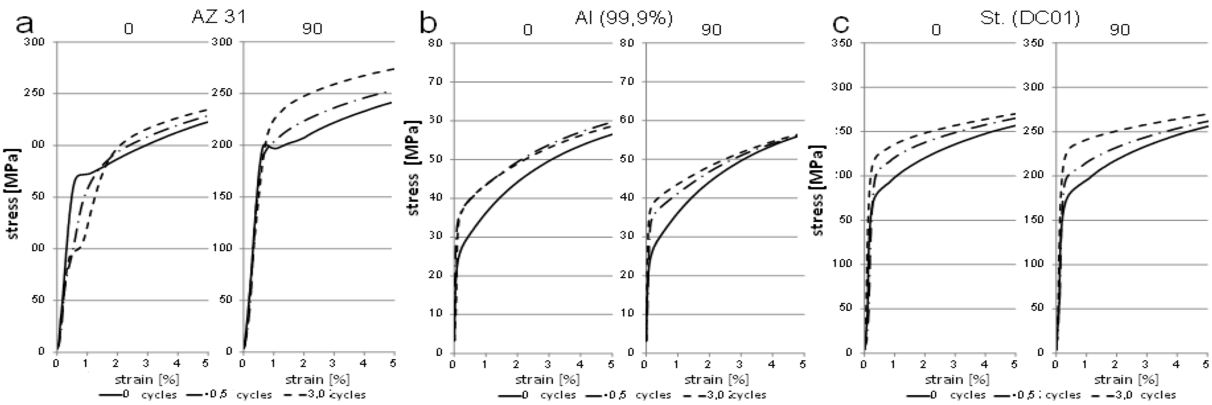

Figure 1. Stress-strain diagrams in the rolling (0°) and transverse (90°) directions following 0; 0.5 and 3 bending cycles: *a* – AZ31; *b* – Al; *c* – DC01

Investigations of the mechanical properties showed that cyclic bending has the largest influence on the yield point RP0.2, in which the influence significantly differs for both crystal lattices. For the magnesium alloy AZ31, which has ahcp crystal lattice, the work softening effect in the bending direction already attains its maximum after one bending cycle and remained constant in the course of further loading. In comparison to the initial material prior to the bending, the yield point RP0.2 is reduced by 40%, whereas a work hardening of 7% can be observed in the transverse direction after 3 bending cycles. This effect induces significant isotropy in the sheet's properties (see **Figure 2a**).

For the aluminium and the steel, the cyclic bending load leads to an elevation of RP0.2 but the anisotropy is minimal for both the longitudinal as well as for transverse specimens, (see **Figure 2c** and **2d**). The severest work hardening can be observed following 0.5 bending cycles in aluminium. In the course of further bending, the work hardening stabilises. In steel, the work hardening linearly rises also after one bending cycle. After 3 bending cycles, the aluminium and steel work harden to approx. 30%.

The influence of the cyclic bending is significantly smaller on the tensile strength Rm, which is determined at considerably higher levels of forming than the yield point RP0.2. Whilst, for the magnesium alloy AZ31, a work hardening of 5% to 6% is observed in the transverse direction following 3 bending cycles, this can not be established in the longitudinal direction (see **Figure 2b**). A change in the tensile strength Rm of aluminium and steel can not be observed following cyclic bending.

The values of the fracture strain A and the uniform strain Aglare isotropic and uniform in the longitudinal and transverse directions following cyclic bending. The largest reduction in the fracture strain A (by 15% to 20%) can be observed for the magnesium alloy AZ31 after 3 cycles. Here, the uniform strain is reduced by 10%. The corresponding reductions of these parameters are 5% and 10% for aluminium and 5% for steel.

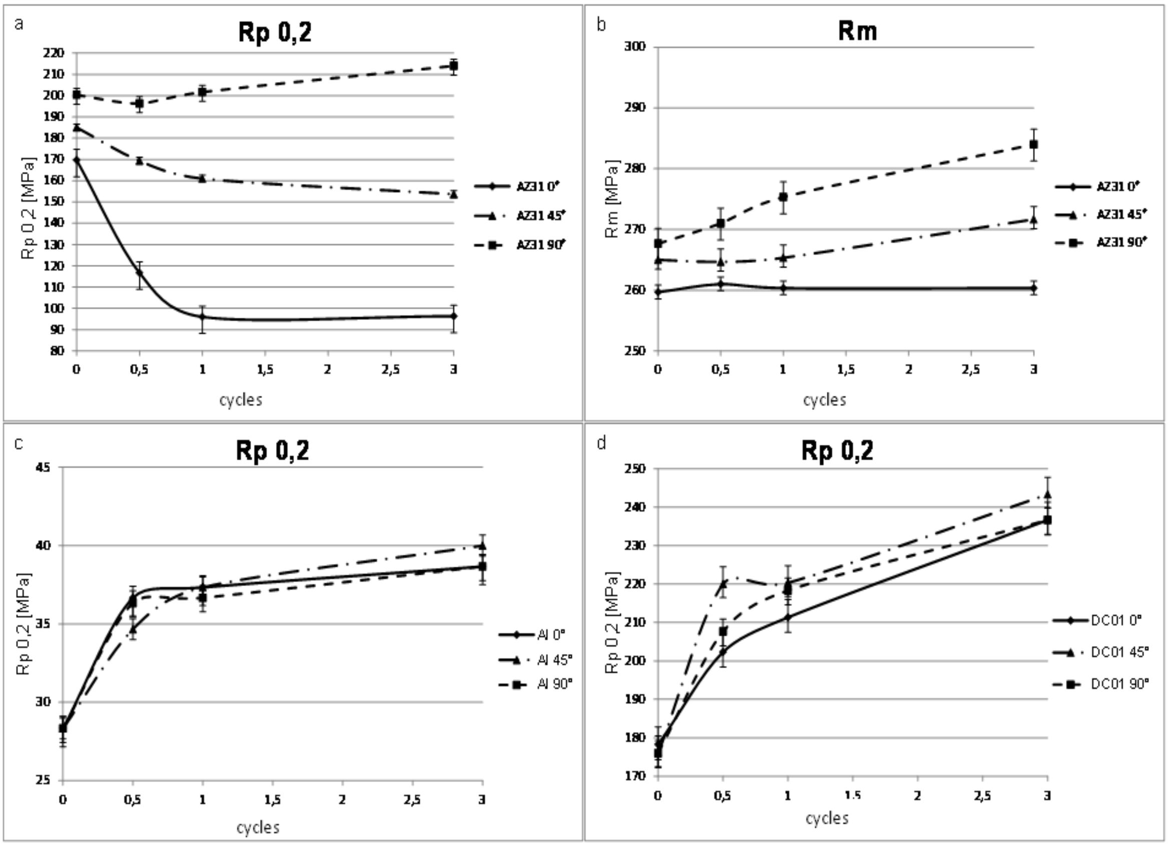

Figure 2. Changes in the yield point (*a*, *b*, *c*) and tensile strength (*b*) plotted against bending cycles as a function of the testing direction: *a*, *b* – AZ31; *c* – Al; *d* – DC01

The investigations of the texture carried out using the pole figure method showed that the alloy AZ31 exhibits a typical, ideal basal-orientation with a maximum intensity at the centre. Following 3 bending cycles, the pole figure exhibits a scattering (stretching) in the bending direction. In the same direction, the maximum intensity is translated and, in doing so, its amount decreases. Simultaneously, a change in the pole figure can be observed with increasing maximum intensities for the prismatic planes. In these planes, twins are formed in magnesium alloys, for which the required stress is considerably smaller than for deforming in the basal and the pyramidal planes. The formation of twins under cyclic bending conditions obviously has a large influence of the sheet's properties for the magnesium alloy AZ31. This is reflected in the change of the stress-strain curves' trajectories, within the range of small levels of forming, and in the level of the mechanical properties.

An analysis of the aluminium's and steel's pole figures shows almost no influence of the cyclic bending on the texture.

Metallographic examinations have shown that, following 3 bending cycles, a large number of twins can be observed in the surface layers of the alloy AZ31's sheet, whereas no twins are established in the region of the sheet's neutral fibres. For aluminium and steel, no changes can be observed either at the surface or in the deeper layers (see **Figure 3b** and **3c**).

Results of the performed investigations show cyclic bending exerts the largest influence on the properties of the sheet made of a material which possesses ahcp crystal lattice.

Investigations of the 1 mm thick sheets' texture for the magnesium alloy AZ31 (see **Figure 4**) show that the pole figures at the surface and at a depth of 0.25 mm are almost the same (see **Figure 4b** and **4c**). Adjacent to the sheet's neutral fibres, the pole figure exhibits a typical basal texture, such as that in the initial material prior to bending (see **Figure 4a**). Forming by means of alternating bending loads activate the system of twin formation which results in a texture with a deviation of the basal pole's angle of approx. 30°, (see **Figure 4b** and **4c**). The sheets are softened and their properties are anisotropic with respect to both the plane and the thickness.

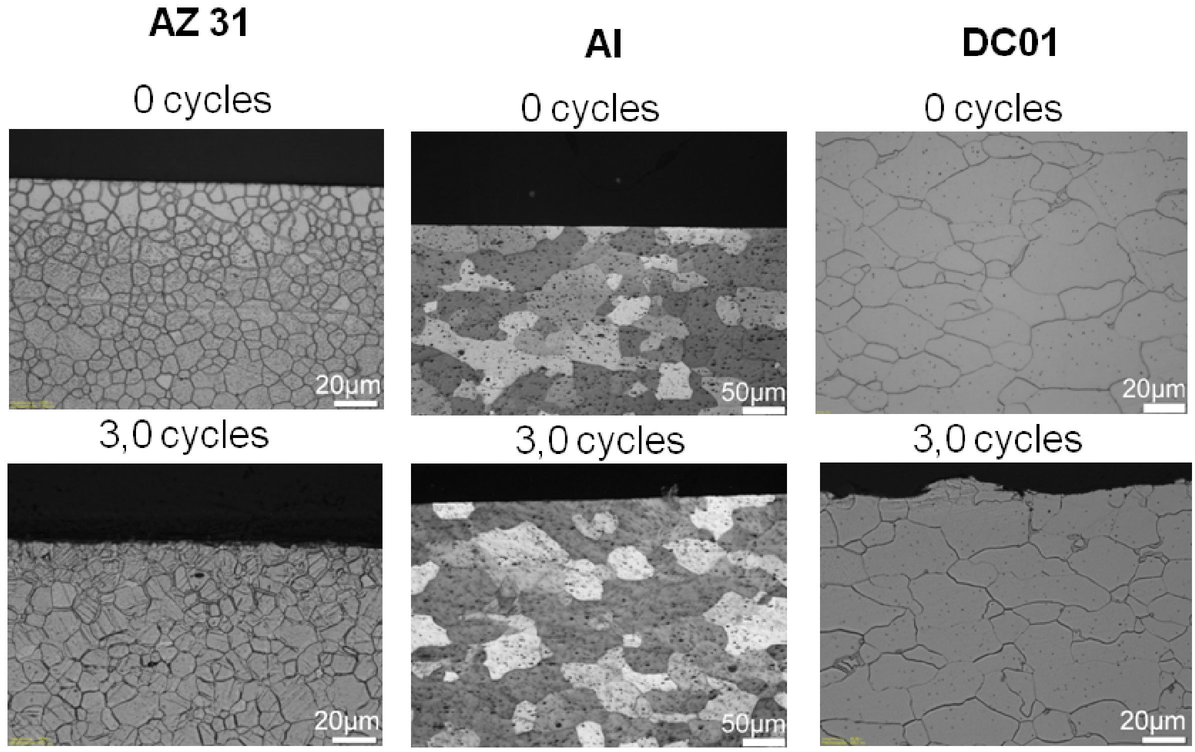

Figure 3. Microstructure longitudinal to the bending direction as a function of the number of bending cycles: *a* – AZ31; *b* – Al; *c* – DC01

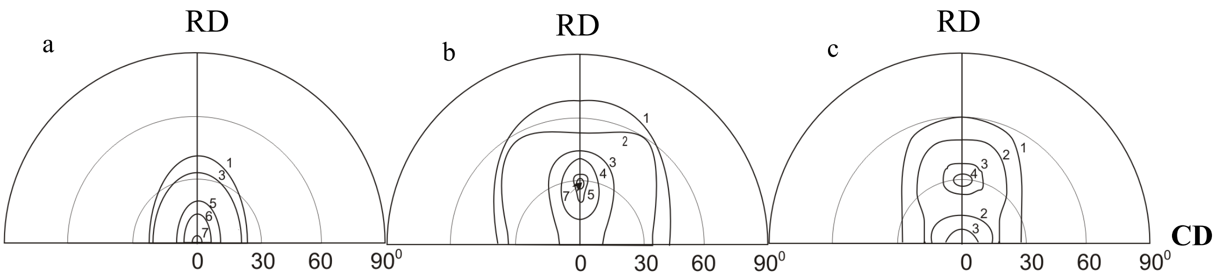

Figure 4. Pole figures (AZ31) for the initial material (*a*); of the bent sheet (1 bending cycle), on the surface (*b*) and at a depth of 0.25 mm (*c*)

The large influence of cyclic bending loads on the sheets made of the magnesium alloy AZ31 can be explained by the limited possibilities for basal slip subject to the conditions of low level cold forming. Here, a significant part of the deformation takes place by means of the mechanism of twin formation. For the sheets of aluminium and steel, the mechanism of twin formation plays a minor role. For this reason, isotropic work hardening with an elevated dislocation density can be observed for these materials subject to the conditions of cyclic bending.

The consequences of anisotropic properties can ensue during straightening which in turn affects the quality during the deep drawing process. Special experiments were carried out which demonstrate that the anisotropic properties of sheet material made of magnesium alloy AZ31, which arise due to monotonic forming (5 to10 %) during rolling followed by cruciform straightening, can be minimised by heating the metal from 200 °C to 250 °C during the final pass and then subsequently annealing [3].

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Исследование влияния малоцикловой знакопеременной гибки на свойства тонких листов из материалов с различной кристаллической решеткой

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Малоцикловая знакопеременная гибка является широко распространенным видом деформации при производстве и обработке тонких листов. Она встречается при прохождении через тянущие ролики в процессе травления, промывки, нанесения покрытий, а также при правке, гибке и глубокой вытяжке. Исследованы механические свойства, микроструктура и текстура листов из магниевого сплава AZ31, технически чистого алюминия и низкоуглеродистой стали после циклической гибки на трехроликовом гибочном устройстве и 11-роликовой правильной машине. Установлено значительное влияние этого вида деформации на свойства листов, особенно из материала с гексогональной плотноупакованной кристаллической решеткой. Для этого материала (AZ31) наблюдается большая анизотропия свойств, которая объясняется, эффектом текстурного разупрочнения в направлении гибки, активизируемого значительным влиянием механизма двойникования. Улучшения свойств этого листа можно добиться путем выбора оптимального обжатия в последних проходах при прокатке, режима правки и термической обработки.