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Large deformation of magnesium sheet at room temperature by preform annealing part I: Uniaxial tension

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ABSTRACT

Magnesium alloys do not generally show large formability at room temperature. This paper is part I of a study to utilize multi-step uniaxial stretching and annealing (MUSA) method to deform AZ31 magnesium alloy to large strains at room temperature. Mechanical properties of MUSA materials have been correlated to microstructural observations. Microstructure parameters such as grain size, twin fraction and textural changes arising from the different variants of MUSA process and their effect on work hardening behavior and cumulated room temperature elongation of AZ31 sheet are studied. Depending on the annealing conditions and pre-strains in different steps of the MUSA process, grain refinement or grain coarsening as well texture spreading was observed. The results indicate that a MUSA process can yield equivalent elongations in AZ31 sheet at room temperature to those attained at higher temperatures.

1. Introduction

There has been considerable interest in the use of Mg sheet for automotive applications due to its lighter weight resulting in increased fuel economy and lesser environmental footprint. The adaptation of Mg alloys in automotive body applications, however, have been limited by their poor formability at room temperature due to its hexagonal close-packed (hcp) structure and limited slip systems. There is evidence that weakening and spreading the texture could improve the ductility of AZ31 at room temperature [1]. Refining the grain size also enhances the ductility by easing dislocation glide and transition in fracture mode [2]. Grain coarsening has been also reported effective in ductility improvement by facilitating the formation of tension twins [3]. The microstructural and textural modification may improve Mg performance during crash, but not enough for attaining room temperature formability levels similar to other conventional automotive aluminum alloys and steel. Therefore, Mg parts continue to be formed at elevated temperature where non-basal slip systems are activated. However, the process costs and part quality still remain issues at high temperature. Therefore, for improving the formability of magnesium sheet, a promising alternative option could be multi-step forming at room temperature by pre-forming the material at room temperature and intermediate annealing it to remove the cold work. Repeating this for several times during the process could yield the desired forming level and the process can be finished by forming to the final shape. This has been demonstrated as a feasible process for AA5182 aluminum alloy under different strain paths, pre-strain levels and annealing conditions [4]. It has also been used to modify the microstructure of AZ31 and enhance its stretch formability [5]. However, no effort to the author's knowledge has been made to deform Mg sheet to large strains by a multi-step forming process. The present paper aims to fill this gap by focusing on formability improvement by multi-step uniaxial stretching and annealing (MUSA). The topic is further explored in a companion paper by studying the feasibility of multi-step bending and annealing (MBA) to improve the cumulative bendability of AZ31 magnesium sheet. These two papers also try to build an understanding of the governing mechanisms and limitations of the more general process of multi-step forming and annealing (MFA).

2. Experimental procedure

AZ31 magnesium sheet of 1.5 mm thickness in the H24 temper condition was annealed at 400 °C for 2 h and machined along the rolling direction (RD) to 10 mm wide and 100 mm long tensile specimens to obtain true stress–true strain curves at an initial strain rate of 0.01 s^{-1}. The samples were deformed by MUSA, as schematically illustrated in Fig. 1. The first sample was pulled to

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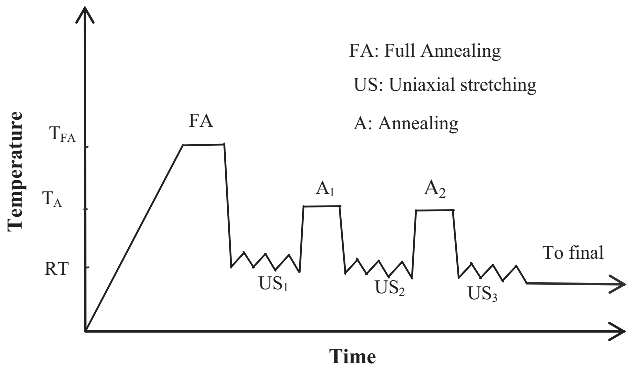

Fig. 1. A schematic illustration of MUSA process.

fracture. The second sample was pulled to 85–90% of the first elongation to fracture and followed by 3 different annealing conditions: (i) 200 °C for 1 min (MUSA-I), (ii) 200 °C for 60 min (MUSA-II) and (iii) 400 °C for 1 min (MUSA-III). The samples were then pulled to fracture at room temperature. The pre-straining and annealing steps for each of the above pre-straining and annealing conditions were repeated several times while subjecting the sample to 85–90% of the previous elongation to fracture to assess the cumulated strain (formability). High temperature tensile tests were also conducted at the above temperatures of annealing, 200 °C and 400 °C as well as at room temperature. The MUSA parameters, pre-straining and annealing conditions, were chosen from a broader study which will be reported separately. The sequence of events during deformation was also studied by uniaxial test using a manual miniature test jig and an optical microscope. Specimens for the optical microscopy study were prepared by sectioning, polishing and etching. The polishing was done progressively by 9 μm, 3 μm, and 1 μm diamond solutions, followed by 50 nm colloidal silica slurry. The polished samples were etched with picric–acetic acid solution (1 ml acetic acid, 1 ml water, 420 mg picric acid and 7 ml ethanol) for 3 s to reveal the grain structure. The macro- and micro-texture were studied by X-ray diffraction (XRD) and electron backscatter diffraction (EBSD) respectively. The samples for the EBSB-based texture studies were prepared by polishing as noted earlier and a quick final etching step (5–10 s) with a solution of 60% ethanol, 20% water, 15% acetic acid and 5% nitric acid. These experiments were conducted using a LEO VP SEM equipped with TSL data acquisition software at an acceleration voltage of 20 keV, with a working distance of 18 mm and a tilt angle of 70°.

The true stress–true strain data from the various steps of pre-stretching for each of the three MUSA processes were fitted to the Hollomon equation ($\sigma = K\varepsilon^n$) and the n-value at each step was obtained as a measure of changes in the work hardening behavior from step to step. The twin fraction was also quantified in a similar manner from the optical micrographs at different steps, as a function of engineering strain, where optical micrographs at a magnification of 100× and a point counting technique based on ASTM E562-02 standard was used [6]. The error in these optical measurements was estimated to be ±10% error primarily arising from uncertainty in the recognition of matrix and twin boundaries in some cases. The compressive twins were also rather difficult to detect due to their narrow widths.

Fractured tensile specimens were also mounted along the LT plane for the three MUSA processes to observe with an optical microscope their necking and fracture profiles to investigate the nature of the final failure.

Vickers micro-hardness on 17% pre-strained materials was measured using 100 gf indenting load for a 15 s dwell time after annealing. The annealing was done at 200 °C and 400 °C for the annealing times of 5 s, 15 s, 30 s, 60 s, 90 s, 300 s, 600 s, 900 s, and 1200 s. The tests were repeated three times and the average values were calculated.

3. Results

The uniaxial tensile properties of AZ31 from MUSA process and constant temperature continuous tensile tests are given in Fig. 2(a–d). In Fig. 2(a–c), the first deformation step consisted of a uniform region of work hardening. The uniformity of flow behavior during the subsequent steps, however, was observed to vary with the amount of pre-strain and degree of subsequent annealing. For MUSA-I process (Fig. 2(a)), the stress level upon reloading of the specimen rapidly reached that of the specimen at the end of the previous deformation step. For MUSA-II process (Fig. 2(b)), however, the stress in the pre-strained steps increased more slowly compared to MUSA-I. This was especially evident for MUSA-III (Fig. 2(c)) where not only stress in the pre-strain step rose even more slowly but the saturation stress values were also reduced as the pre-strain steps were added. Lastly, Fig. 2(d) for continuous tensile tests to fracture at three constant temperatures, with 2 different crosshead speeds at 400 °C, are typical of magnesium sheet materials. Significant work hardening to saturation

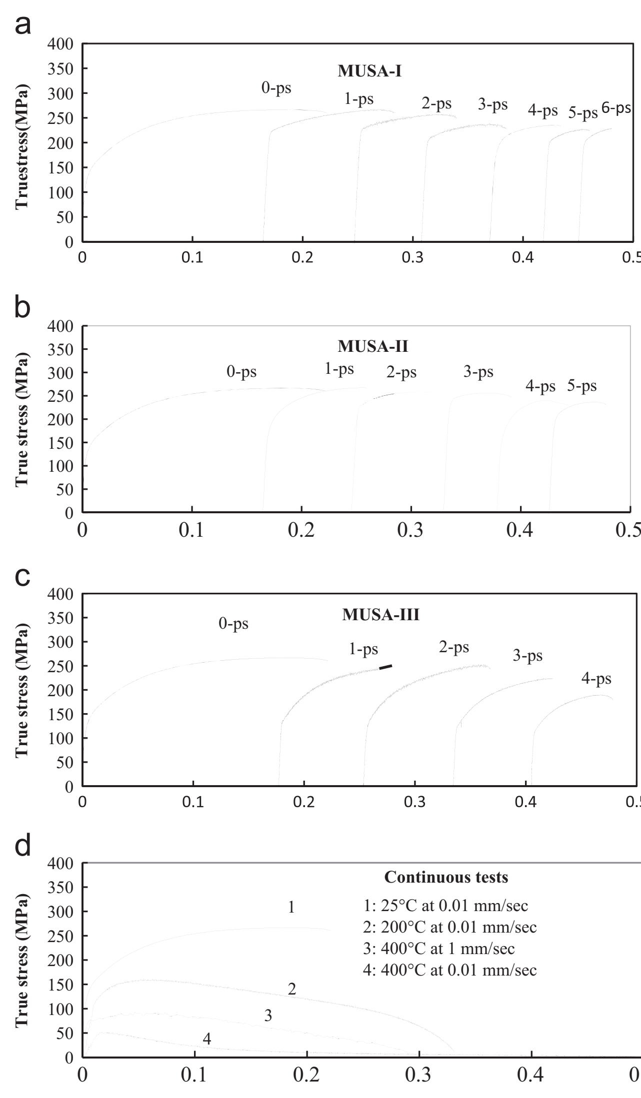

Fig. 2. Stress–strain curves of AZ31 deformed by (a) MUSA-I, (b) MUSA-II, (c) MUSA-III and (d) continuous tests to fracture.