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TENSILE PROPERTIES OF THREE PREFORM-ANNEALED MAGNESIUM ALLOY SHEETS

Junying Min[1], Jon T. Carter[2], Ravi Verma[2]

[1]Tongji University, Mechanical Engineering, 1239 Siping Road, Shanghai, China
[2]General Motors R&D, 30500 Mound Road, Warren, MI, 48090, USA

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Abstract

Magnesium alloy sheet metal is potentially attractive for use in automotive structural applications due to its high strength-to-weight ratio. However, application has been hindered by the low room-temperature formability of typical sheet alloys. One approach to effectively increase formability is to change the forming process from one which involves a single stamping hit to one which utilizes two hits plus an intemediate anneal (i.e., "preform anneal process"). The purpose of the intermediate anneal is to restore some of the softness and ductility which were reduced by deformation during the first hit.

In this report, the preform annealing behavior of three rolled magnesium alloy sheets was studied using uniaxial tensile tests. The sheets studied were: conventionally rolled (CR) AZ31B, CR ZEK100, and specially rolled (SPR) AZ31B. The preform annealing process was found to increase the total elongation of all three sheets compared to the elongation in the annealed O-temper. The CR ZEK100 with a thickness of 1.5 mm showed more attractive tensile properties than the 1.6 mm CR AZ31B. Although the SPR AZ31B has a thickness of only 0.7 mm, it still has elongation comparable to the 1.6 mm CR AZ31B.

Introduction

Magnesium is lightest (lowest density) of the common structural metals and therefore is potentially attractive for use in structural automotive applications to achieve mass reduction and the associated improvements in fuel efficiency and handling. Currently, automotive usage of magnesium is primarily in the form of die castings, and includes steering wheels, transmission housings, sunroof frames [1], and inner panels for doors and liftgates [2,3]. Numerous potential automotive applications of wrought magnesium alloys have been prototyped [4-7], but production implementation has been extremely limited [8]. The issues which preclude greater implementation of the wrought alloys include the high cost of sheet, limited formability at room temperature, difficulty joining to other materials, and corrosion. Potential solutions to all of these issues are being studied by various groups around the world.

Mg sheet is formable at hot temperatures [9,10] and warm temperatures [11,12]. Ultimately, however, sheet formers would prefer to stamp magnesium alloy sheet at room temperature, similar to what is done with steel. This would reduce the costs associated with heaters, hot tools, and high-temperature-capacity forming lubricants, and might enable beneficial strain hardening of the part being formed. Such stamping might be done using blanks which benefit from having either a different chemical composition of the alloy, or which may have been thermomechanically processed differently so as to enhance formability, or by changing the forming process. All three of these options are described briefly below.

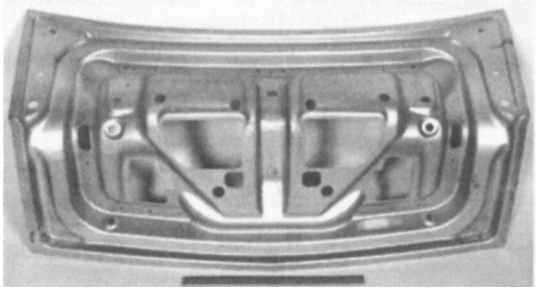

Figure 1. Photograph of experimental decklid inner panel which was formed by hot gas blow forming process, then trimmed/punched.

Wrought magnesium alloys containing rare earth (RE) additions such as Gd, Ce, Nd, and Er, have been found to exhibit greater ductility than their RE-free counterparts. This increase is typically attributed to the the weaker crystallographic texture present in the rolled or extruded forms of RE-bearing alloys upon which forming tests are conducted, especially after recrystallization annealing [13-18].

Alternatively, the texture and/or ductility of rolled magnesium alloy sheet may be reduced by altering the rolling process. For example, beneficial effects have been reported for increasing the rolling temperature [19], increasing the rolling speed [20], and increasing the asymmetry of rolling [21].

Finally, the forming process itself may be altered to effectively increase the formability of metal sheets. Specifically, rather than completely forming a panel with a single press stroke and getting splits, the panel may be partially formed in a first press stroke, annealed to restore ductility to strained areas, cooled back to near room temperature, then formed to completion without splitting in a second press stroke [22]. This process is called "preform annealing". In this process it is beneficial to introduce a large amount of strain during the first press stroke, but less than that at which strain localization, necking, or fracture begin. Components with complex contours, which cannot be manufactured by the conventional stamping process, can be formed successfully by the preform annealing process. Both an aluminum rear door inner panel [23] and an aluminum lift gate inner panel [24] were perfectly produced by using preform annealing process. The latter used localized induction heating in order to reduce cycle time and conserve energy. Some of the more scientific fundamentals of the preform annealing process have been studied both via simulation [25] and experiments [26].

The purpose of the work reported herein was to compare the tensile properties and microstructure of conventionally-rolled AZ31B magnesium alloy sheet with two alternative magnesium alloy sheet products, in both the annealed condition and the preform annealed condition.

Experimental Method

Rolled sheets were obtained from two manufacturers in different thicknesses and tempers. Specifically, the conventionally rolled (CR) AZ31B sheets were 1.6 mm thick, and in the H24 temper ("strain hardened and partially annealed"). The CR ZEK100 sheets were 1.5 mm thick, and in the F temper ("as-fabricated"). The specially rolled (SPR) AZ31B sheets were 0.7 mm thick, and in an unspecified temper.

Tensile bars were waterjet cut at 0°, 45°, and 90° to the rolling direction (RD). The dimensions of the reduced section are 50 mm x 6 mm x sheet thickness. Annealing was done for 15 min in an electric furnace which was filled with argon gas to protect the tensile bars from oxidization. The AZ31B bars were annealed at 350 °C, and the ZEK100 bars were annealed at 500°C. These temperatures were chosen based on unpublished annealing studies in which we observed that AZ31B-H24 rolled sheet softened much at 350 °C, but that the ZEK100-F rolled sheet required 450-500 °C to soften. These treatments were applied to all of the bars regardless of in-coming temper, and are considered to result in O-temper.

Rockwell F hardness (HRF) was measured on the sheet surface with a 1/16" diameter indenter and 60 kg major load. Because the SPR AZ31B sheet is relatively thin and soft, its hardness was measured on the HR15T superficial scale, then converted to Rockwell F. Five measurements were repeated for each datum.

An Instron tensile machine and an extensometer with a gauge length of 25mm were employed. The crosshead speed was set at 10 mm/min for all tests. When performing tests for each type of sheet material and bar orientation relative to the sheet rolling direction (RD), three O-tempered bars were pulled to fracture. From these tests, the average engineering strain at which maximum load occurred was determined for each orientation. This is referred to as the uniform strain (US). Next, for the preform anneal study, four O-tempered bars in each orientation were pulled to 90% of US, re-annealed, then returned to the tensile machine and pulled to fracture. Finally, in order to determine the normal plastic anisotropy ratio (r value), additional bars were marked with ink at five locations within the gauge length, then pulled to 10%, 15% and 20% strain, removed from the tensile machine, then measured with vernier calipers to determine width and thickness at the five axial locations.

For microstructure observation, samples were cold mounted, ground, polished, and etched. The picric etchant which revealed the grains and grain boundaries was mixed fresh with 4.2 gram picric acid, 10 ml acetic acid, 70 ml ethanol, and 10 ml distilled water. Samples were immersed in the etchant for about 1 second, then immediately washed with soap water and distilled water, rinsed with ethanol, and dried with warm flowing air. Metallographic observations were made using a Leica microscope. The grain sizes were measured in different directions using several micrographs from horizontal and vertical sections and a computer aided linear intercept measurement.

Results and Discussion

Compositions
Elemental compositions of the sheet materials are as follows: CR AZ31B contains 3.0 %Al, 1.1 %Zn and 0.48 %Mn. SPR AZ31B contains 2.9 %Al, 1.1 %Zn and 0.44 %Mn. CR ZEK100 contains 1.3 %Zn, 0.2 %Nd, 0.25 %Zr and 0.01 %Mn. Al and Zn are added for strength, and Zn and Mn are added for corrosion resistance. Nd is for reduced crystallographic texture, and Zr is for grain refinement.

Hardness
Hardness data for the three Mg alloy sheets are shown in Figure 2. For all three materials the pattern is similar. First, the hardness in the PA condition is the same as that in the O-temper if the amount of pre-deformation (between anneals) is zero. This is shown by the black and white bars. If, however, deformations of 90% of US are introduced between the two anneals, then the hardness measured after the second anneal is less than that measured after the first. Compare the black and dashed bars. If there is no second anneal, the hardness increases due to work hardening, as shown by the black and gray bars. Since both the strength and grain size influence the hardness, the hardness results will be discussed more in later sections.

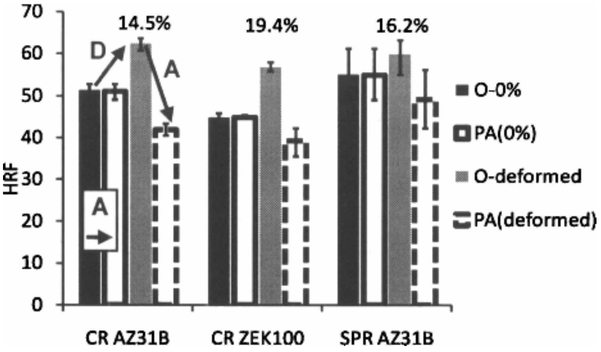

Figure 2. Chart showing hardness data, Rockwell F scale, of CR AZ31B, CR ZEK100, and SPR AZ31B sheets in different conditions. O-0% means O-tempered material with no deformation; PA(0%) means the deformation before 2nd anneal is 0%, namely, just annealed two times; O-deformed means O-tempered material with deformation and the deformation levels are marked above the column; PA(deformed) means the material has deformation before 2nd anneal and the deformation levels are the same as marked above the column. The arrows indicate the changes due to either "A" annealing processes or "D" deformation processes. Samples were pulled in the 90° orientation

Tensile Data
These data are summarized in Figures 3-6, and discussed below.

Effect of alloy and processing: The two AZ31 sheets have strengths which are comparable, and both are stronger than the ZEK100. This is attributed to the higher alloy content and smaller grain sizes in the AZ31 sheets. In contrast, the ductility of the

SPR AZ31 is less than that of the CR AZ31, and both of those are less than the ductility of the ZEK100. The ZEK100 shows the greatest in-plane anisotropy of n, k, YS, and %el, but CR AZ31B shows the greatest in-plane anisotropy of r value, especially in O temper.

Effect of temper: The preform annealing process can be studied in its entirety, or broken into component parts. Because the ultimate goal is to enable the forming of more complex sheet metal parts at room temperature, we'll first look at the overall effect of the process on ductility. Figures 3c, 4c, and 5c show the uniform elongation and elongation-at-fracture for the three alloys, in both the O temper and the PA condition (i.e., annealed, then pulled to 90% of US, then annealed). In addition, they show a "total elongation", which includes both the prestrain (90% of US) and the elongation-at-fracture measured in the PA condition. Large values of total elongation would suggest that the material might be more easily formed in a multi-strike operation. The levels of total elongation achieved are on the order of 35% for CR AZ31B, 44% for CR ZEK100, and 30% for SPR AZ31B. These are all significantly greater than the measured elongations-at-fracture for the O-temper materials of approximately 23%, 25%, and 18%, respectively. Therefore, it appears that the preform anneal process would be beneficial in increasing the effective formability of these sheets.

The preform annealing process can also be analyzed by comparing the tensile test results of each material in both the O temper and the PA condition. For example, as shown in Figures 3a, 4a, and 5a, the preform annealing process very slightly reduces the UTS of all three materials. It also has little effect on YS, except in the case of the 90° bars of ZEK100, for which preform annealing reduces the YS from 125 MPa in O temper to 80 MPa in the PA condition.

The effect of preform annealing on n value and k value (from the strain-hardening equation $\sigma = k\varepsilon^n$) vary greatly with alloy and orientation, as shown in Figures 3b, 4b, and 5b. For the CR AZ31B sheet there is no effect. For SPR AZ31B, there are decreases of approximately 20% for n and 10% for k. For CR ZEK100 the decreases in n and k vary from 0-55% and 0-35%, depending on orientation.

The stated goal of the preform anneal is to "restore the ductility" of the strained material in the partially formed part. As shown in Figures 3c, 4c, and 5c, the effectiveness of the anneals varied with alloy and orientation. They were about 75% effective for CR AZ31B, 70-100% effective for ZEK100, and 65-85% effective for SPR AZ31B.

Effect of orientation: The effects on tensile properties of bar orientation relative to the sheet rolling direction are shown in Figures 3-6. There are some small effects, such as the increase of YS with orientation angle for CR AZ31B-O shown in Figure 3a, and some large ones, such as the effect on n value of CR ZEK100-O, shown in Figure 4b. The former is typically attributed to the typical crystallographic texture of rolled magnesium sheet, in which the hexagonal unit cell basal planes are largely parallel to the sheet surface, but tilted a few degrees toward the RD. This tilting facilitates basal slip and extension twinning when pulling is in the RD. The root cause of the strong orientation dependence of n and k, shown in Figure 4b, is not immediately clear. It is fascinating that preform annealing largely eliminates the dependence on orientation. The CR ZEK100-O also shows in-plane anisotropy of elongation (Figure 4c), which again is largely eliminated by preform annealing. In contrast to this, the orientation dependence of elongation of SPR AZ31B-O gets increased slightly by the preform annealing.

Considering the r values (the ratios of width true strain to thickness true strain measured at 10% elongation) shown in Figure 6, it is clear that the CR AZ31B shows greater orientation dependence than do the other alloys, especially in the O temper. Preform annealing significantly reduces this anisotropy, and reduces the r values at 45° and 90° to approximately 3. R values for the SPR AZ31B are insensitive to orientation, and increase from 1.3 to 1.7 during preform annealing. R values for the ZEK100-O sheet are about 1 at 0° and 45°, and drop to about 0.7 at 90°, opposite the trend seen in CR AZ31B. Those values increase slightly during preform annealing.

Generally speaking, the three alloy sheets exhibit different values of various tensile properties, different in-plane anisotropies of those values, and different responses to the preform annealing process. Judging from the relatively high values of elongation (29-44%) achieved when this process is applied to uniaxial tensile testing, it may be anticipated that these sheets would form well if the process were to be applied to a stamping operation.

Microstructures of the three alloys in four conditions are show in in Figure 7. (Each micrograph also includes grain size data which will be discussed below.) The top row of micrographs shows the as-annealed structures, which have nearly twin-free grains which are equiaxed. The second row corresponds to samples which received a second annealing treatment, with no intermediate deformation, and shows no great change from the once-annealed microstructures. The samples shown in the third row were annealed once, then pulled to 90% of the uniform strain measured for the annealed sheets. These show twins which are attributed to the tensile deformation, and which are most evident in the ZEK100 material, perhaps due to its large grain size. Subsequent annealing of the pulled samples leads to the microstructures shown in the fourth row. Here the twins are largely gone in the two AZ31 sheets, but less so in the ZEK100 sheet. Grain sizes changed during the post-deformation anneal, as discussed below.

Approximate grain size measurements, in microns, are shown numerically in the bottom right corner of each micrograph in Figure 7. The first number is the intercept length in the sheet normal direction, and the second is that in the sheet transverse direction. These bars were pulled in the transverse direction. The intercept length of grains of CR ZEK100 in O-tempered condition is the largest, about 18um, while the O-tempered SPR AZ31B has the finest grains with the size of ~5.5um. The second annealing (with no intermediate deformation) has little influence on the grain size of CR ZEK100 and SPR AZ31B, but for the CR AZ31B, the grain size increases from ~8um to ~10um. In the case of preform annealing shown in the fourth row of micrographs, it has totally different effects on the grain size of the three materials. For both AZ31B Mg sheets, the grain size increases during the second annealing process, compared to the pre-deformed grain size. This is attributed to recrystallization, which is influenced by the stored energy of preforming. The grain size of the SPR AZ31B increases from ~5.5um in O temper to 6.5um in the preform annealed state. In contrast, the grain size of the CR AZ31B doubles from 9 to 19um ! Things are different for CR

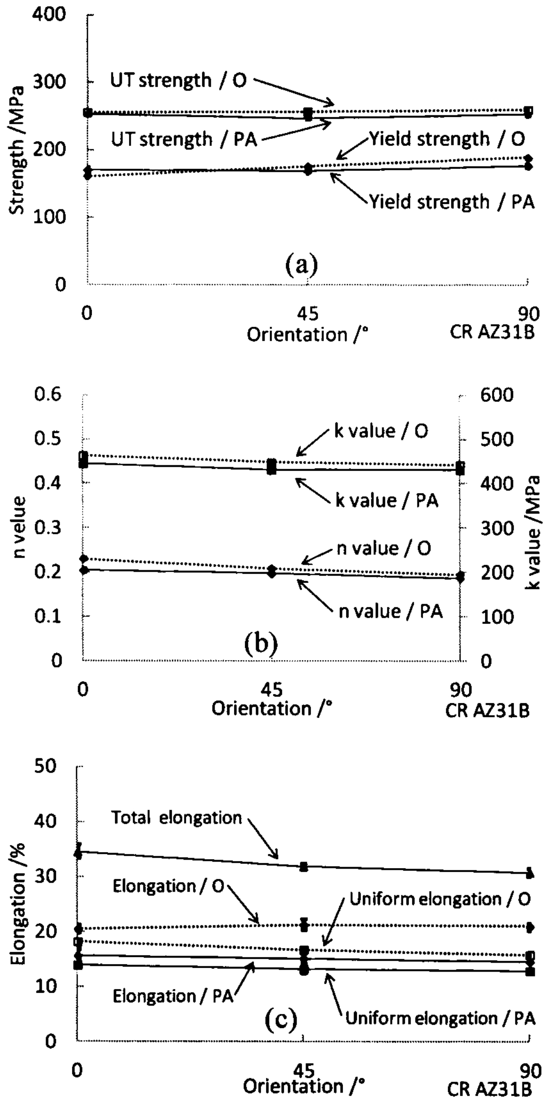

Figure 3. Effect of orientation on tensile properties of CR AZ31B rolled sheet in O-tempered and PA conditions.

ZEK100. Those grains are 18um and equiaxed after first anneal, elongated by pulling, then 17um after the preform anneal. We hypothesize that the apparent stability of grain size of the ZEK100 is due to either the Zr addition or the relatively large initial grain size. The cause of the large difference in change of grain sizes between the two AZ31 materials is not currently known.

Conclusions

1. The preform anneal process increases the overall ductility (%el at fracture in uniaxial tension) of three rolled magnesium sheets by 30-70%. The increase varies with alloy and orientation within the sheet. The greatest ductility observed was 44% elongation, and that was with the CR ZEK100 sheet pulled at 45° or 90°.

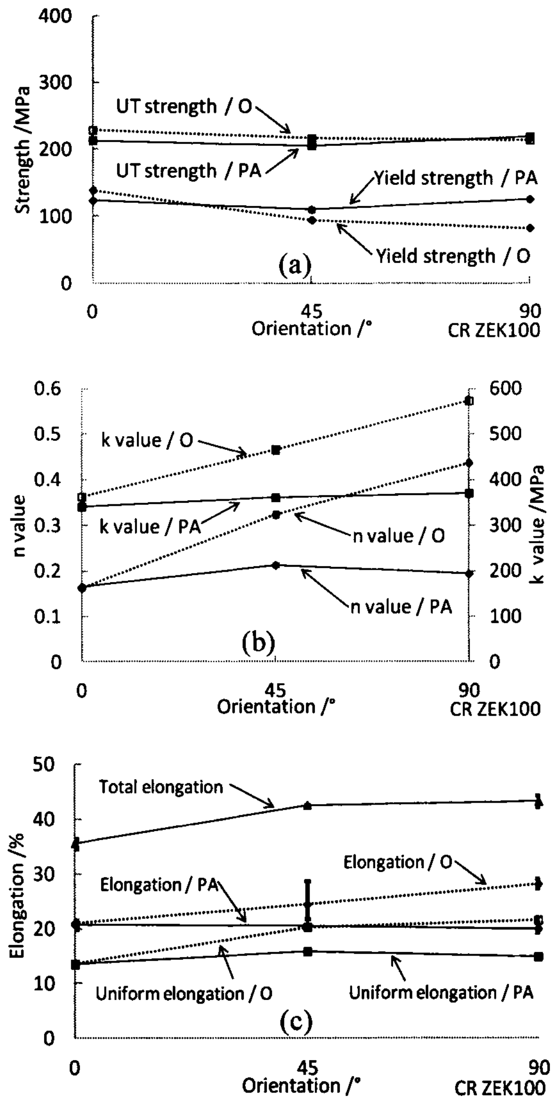

Figure 4. Effect of orientation on tensile properties of CR ZEK100 rolled sheet in O-tempered and PA conditions.

2. Generally, the preform annealing process reduces the hardness and has a little influence on the strength compared with the material in O-tempered condition

3. It reduces the in-plane anisotropy of certain tensile properties, such as the r value of CR AZ31B; and the n, k, YS, and % elong. of CR ZEK100.

4. It does not fully restore the ductility to that of the O-temper material, but typically restores at least 70% of that.

5. The effect of preform annealing on grain size also differs from material to material. The grain size of CR ZEK100 dropped slightly from 18 to 17 microns, that of SPR AZ31B increased slightly from 5.5 to 6.5 microns, and that of CR AZ31B doubled from 9 to 19 microns.

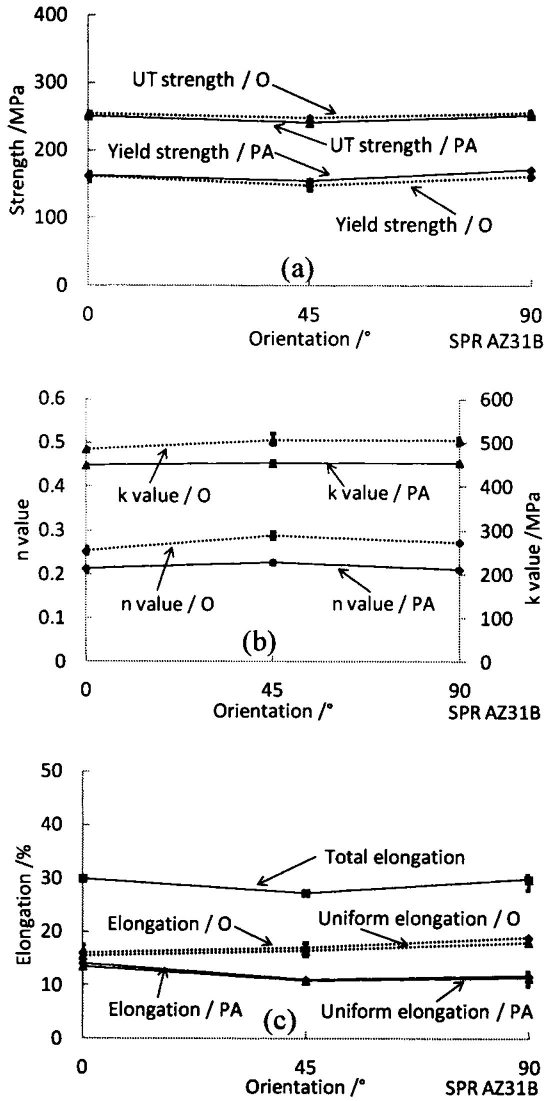

Figure 5. Effect of orientation on tensile properties of SPR AZ31B rolled sheet in O-tempered and PA conditions.

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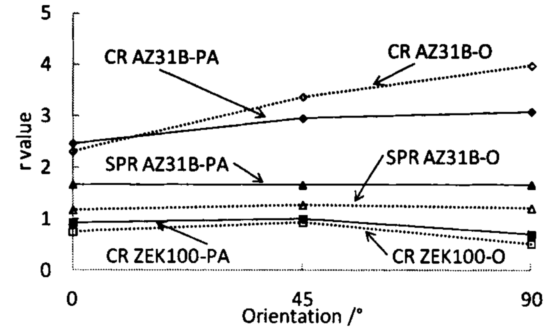

Figure 6. Comparison of r value in each orientation of three rolled magnesium alloy sheets in O-tempered and PA conditions.

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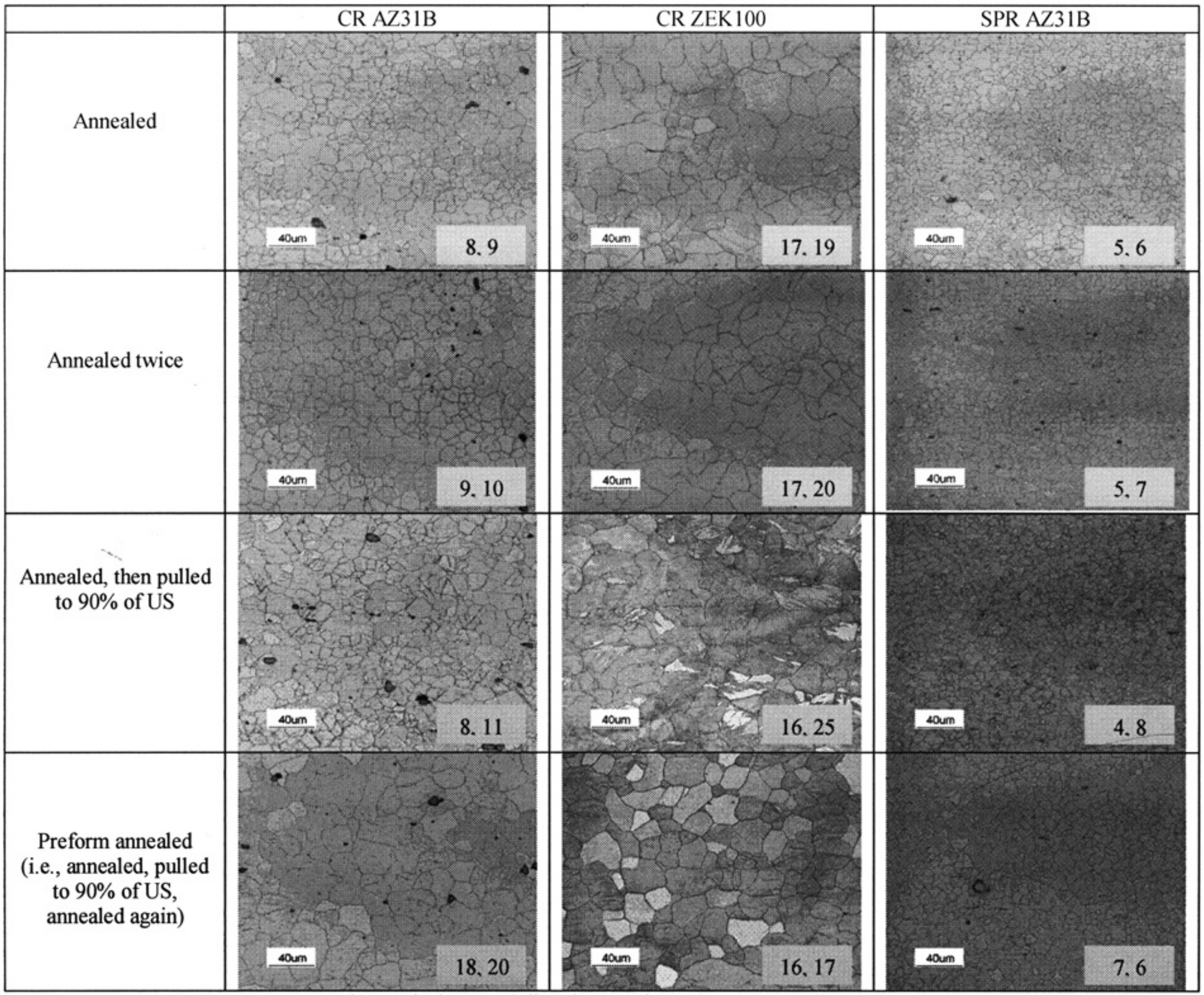

(b) Vertical: normal direction; Horizontal: transverse direction. .

Figure 7. Photomicrographs of tensile bars of three magnesium alloy sheets in four different stages of processing. In each image, the sheet ND is vertical and the sheet TD is horizontal. Approximate grain sizes, in microns, are shown for measurements made in the ND and TD.