Temperature Dependent Fracture Loci Of AZ31 Magnesium Alloy Sheets

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Abstract

Magnesium alloys have been used in the automotive and aereospace industry for several years, thanks to their high strength-to-density ratio. Their mechanical characteristics at room and even at elevated temperature have been well-studied, whereas, when it comes to temperatures lower than the room one, only a few studies are available in literature. To this aim, the present paper investigates the mechanical behaviour of AZ31 magnesium alloy sheets deformed at different temperature regimes. Tensile tests till fracture were carried out at room temperature, -100 °C, -50°C, 100°C and 300°C using different specimen geometries in order to vary the stress triaxiality. The fracture strain values were identified making use of a combined numerical-experimental approach, whereas the fracture surfaces were qualitatively characterized by means of stereoscopy and scanning electron microscopy. Finally, the AZ31 fracture locus as a function of the stress state and temperature was constructed.

Keywords: Magnesium alloys; Cryogenic; Fracture locus; Fracture surface

1. Introduction

Magnesium alloys can be used in many structural and non-structural applications thanks to their high specific strength, high specific stiffness, and good damping capacity [1]. Nevertheless, the major limit to their widespread application is represented by the poor formability characteristics of their Hexagonal Close Packed (HPC) crystalline structure. In fact, in magnesium alloys, non-basal slips planes are hardly operative at room temperature since their Critical Resolved Shear Stress (CRSS) are much higher compared to the one of the basal planes [2]. In addition, in case of sheets, the rolling process generally introduces a strong basal texture, aligning the hexagonal structure mostly normal to the rolling plane [3]. This confers a high anisotropy to the sheet and increases the difficulty in deformation accompanied with thickness reduction, and consequently leads to a very limited formability at room temperature. [4] For these reasons, magnesium alloy sheets are generally formed within the warm/hot temperature regime and a lot of research works are available on this topic [5].

Magnesium alloys can be exposed to very low temperatures, when used for aerospace, satellite parts or tanks for liquefied gases. Some studies are available in literature addressing their mechanical behavior at cryogenic temperatures, which may also useful to evaluate if an increase of ductility can be obtained at those temperature, with the aim of proving the feasibility of cryogenic forming.

Bussiba et al. [6] studied the uniaxial mechanical response of round specimens made of ZK60 and AZ31 magnesium alloys at temperatures of 123 K and 296 K. A completely different behavior was found for the two materials, namely ductile in the case of ZK60 and semi-brittle for the AZ31. This was attributed to the presence of different second phases, which were found to be responsible of controlling both the non-basal and basal plane slip activities. Jiang et al. [7] evaluated the strategy of applying a Cryogenic Treatment (CT), namely cooling the material to 77 K at a rate of 2 K per minute, as a strategy to increase both the tensile strength and ductility of the AZ31 magnesium alloy. Different soaking times were applied. The obtained results showed that the highest increase in mechanical performance (+42%) was found for the sample soaked for 2 h. The contribute of CT was identified on two levels: i) the formation of a frame-like twinning due to the movement of grains as a consequence of thermal contraction at low temperatures, and ii) the development of a compressive residual stress state. Different conclusions were achieved by Wang et al. [8], who studied the tensile deformation behavior of the Mg-3Al-1Zn alloy at low temperatures ranging from 300 K to 77 K at different strain rates. By reducing the temperature, the yield stress and ultimate tensile stress increased while the strain to failure were found to decrease. It was argued that the dislocation motion changed with temperature. Specifically, above 173 K the interaction between dislocations and forest dislocations was dominant, whereas at temperature below 173 K the dislocation motion was governed by the interaction with local lattice friction.

It is worth noting that in all these studies the mechanical performances of magnesium alloys were evaluated in a wide range of temperatures, including that below room temperature, but solely under uniaxial loading conditions, without

considering different stress states. In this framework, the present paper investigates the mechanical behavior of the AZ31 magnesium alloy at different temperatures and stress triaxiality conditions. For each experimental condition, the strain at fracture was identified by means of a combined experimental-numerical approach, whereas the fractured surfaces were inspected using a Scanning Electron Microscope (SEM) at different magnifications.

2. Experimental

2.1 Material

The material under investigation is the AZ31 magnesium alloy provided in form of 1 mm thick sheets. The chemical composition of the alloy in the as-delivered condition is reported in Table 1, whereas its microstructure is shown in Fig. 1. The latter was obtained by cutting the sheet along its thickness, then polishing, etching and inspecting the sample through a Leica DMRE^{TM} optical microscope equipped with a high definition digital camera. The microstructural analysis revealed that the as-delivered material was characterized by a dual grain size distribution, possible consequence of the dynamic recrystallization phenomenon during hot rolling. The resulted average grain size was calculated to be equal to 9 ± 4.8 µm. The AZ31 sheets were laser-cut along the rolling direction to provide specimens for the mechanical tests. Afterwards, a finishing milling step was carried out to avoid any influence of the laser heat-affected zone on the experimental results.

Table 1. Chemical composition (% mass) of the AZ31 magnesium alloy sheets

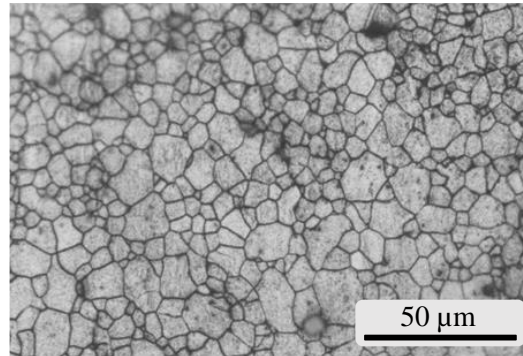| Element	Aluminum	Zinc	Manganese	Magnesium
Content	3	1	0.2	Bal.

Fig. 1. Microstructure of the AZ31 magnesium alloy sheets in the as-delivered condition.

2.2 Mechanical testing

Tensile tests were carried out on the MTS™-322 hydraulic wedge shown in Fig. 2 a), equipped with an environmental chamber that allowed setting the testing temperature in a range from –130 (±2) °C to 315 (±2) °C. To control the temperature during testing, a k-thermocouple was spot-welded on each specimen, as can be seen in Fig. 2 b). Each test was carried out at a fixed strain rate of 0.1 s^{-1} and repeated three times to assure reproducibility of the results.

The effect of the testing temperature and stress triaxiality was investigated. To this aim, five different temperatures, namely -100°C, -50°C, 25°C, 200°C, and 300°C, as well as four different stress triaxiality states were adopted. The latter were achieved by changing the specimen geometry: besides the classical dog bone sample, a 5 mm notched sample, a shear sample, and a special one, which accounts for a shear-tension state according to [9], were selected. The nominal stress triaxiality values are 0.1, 0.17, 0.33 and 0.47 for shear, special, smooth and notched, respectively [10]. Fig. 2 c) shows the specimen geometries considered in this paper and highlights their main geometrical features.
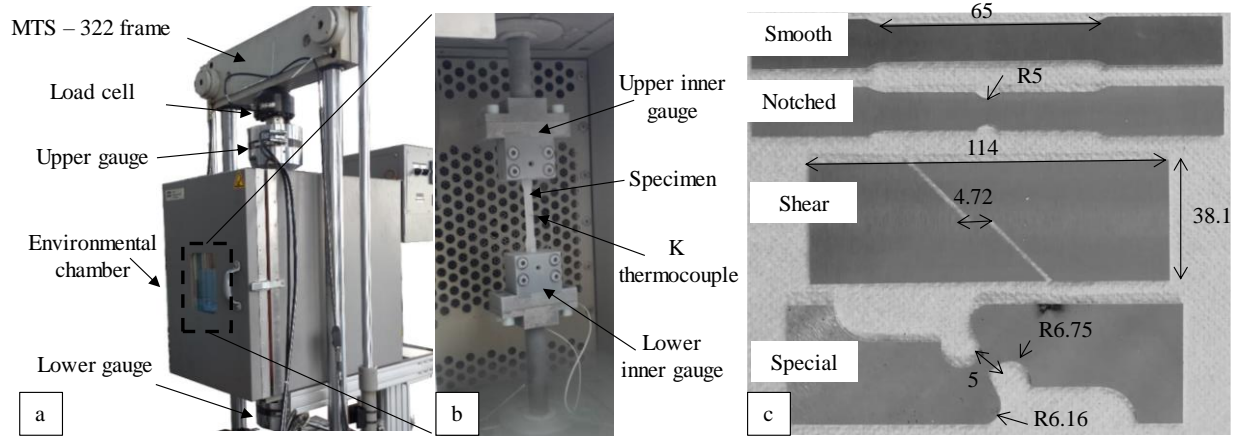
Fig. 2. a) MTS™-322 hydraulic wedge equipment, b) experimental setup configuration for testing smooth specimens, and c) geometry of samples used in this study (measures are given in mm).

2.3 Procedure to identify the fracture strain

The determination of the fracture strain is always a challenging issue in mechanical testing. It is generally recognized that its evaluation by measuring the specimen cross-section area through a microscope leads to some uncertainties due to the high level of strain attainable especially in hot conditions [11]. Nevertheless, the presence of the environmental chamber makes impossible the use of any kind of optical techniques for its direct measure. For these reasons, in the present study, a hybrid experimental–numerical method was used to assess the strain at fracture.

The numerical simulations were performed as implicit analysis using the Ls_Dyna™ code version R9.1.0 (Ls_Prepost V4.7) with shell elements. The results of the tensile tests in terms of flow stress as a function of the temperature were used to calibrate the hardening law. The developed FEM model was validated using experimental data other than the ones used for its calibration.

Fig. 3 illustrates the procedure used in this paper in the case of a shear specimen tested at -100°C, as reference example. The experimental and simulated force vs stroke curves are represented in the same figure, as well as the equivalent plastic strain vs stroke curve. It can be observed that the simulated force-stroke curve agrees with the experimental one with a good level of accuracy. The strain at fracture was assumed to be the maximum equivalent plastic strain at the experimental fracture stroke.
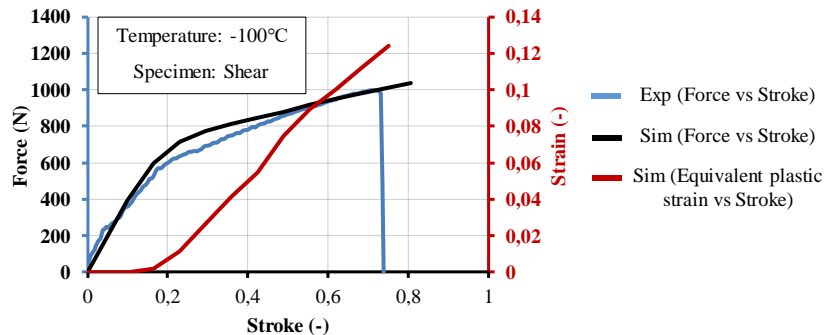

Fig. 3. Calculation of the equivalent plastic strain at fracture using the hybrid experimental-numerical method (case of a shear specimen deformed at -100°C).

2.4 Characterization after mechanical testing

After mechanical testing, the specimen fracture surfaces were analyzed using the FEI™ QUANTA 450 Scanning Electron Microscope (SEM) equipped with the Everhart-Thornley Detector (ETD). Images at 2000X and 5000X magnifications were acquired in different zones of the samples for each testing condition.

3. Results and discussion

3.1 Mechanical behaviour

The force vs. stroke curves for the investigated experimental conditions are reported in Fig. 4. Both the temperature and specimen configuration played a significant role in affecting the alloy mechanical behavior.

For a given stress triaxiality, the force increased as the testing temperature was reduced. On the contrary, the stroke at fracture diminished by deforming the specimen at temperatures lower than the room one compared to tests conducted at higher temperatures. It is worth noting that for the special and shear samples no sensible differences were seen between tests performed at 25°C, -50 °C and -100°C. The smooth specimen was characterized by the highest recorded forces, whereas the shear specimen by the lowest ones. Similarly, the stroke at fracture gradually decreased from smooth, notched, special to shear specimens.

Similar results in terms of force sensitivity to temperature can be found in Jiao et al. [12], where the AZ31B magnesium alloy was tested at -230°C, -196°C, -73°C, and 27°C, but under uniaxial testing conditions. The specimen deformed at the lowest temperature showed an increase in the ultimate tensile strength and yield strength over 60% compared to the one deformed at room temperature. This was attributed to the reduced solubility of aluminum and zinc atoms at low temperatures, which are the main strengthening elements of the AZ31 alloy, inducing the formation of a fine distributed second phase in the matrix, which reinforced the alloy.
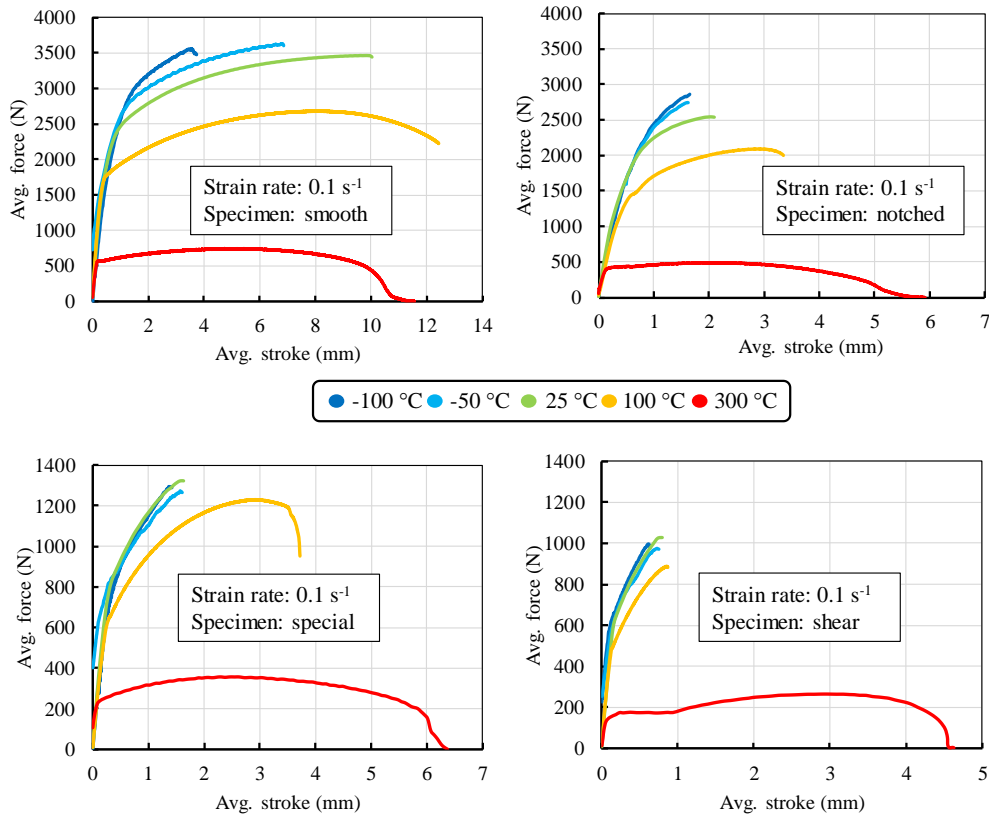

Fig. 4. Force vs. stroke curves at varying testing temperature and stress triaxiality.

The AZ31 fracture loci as a function of the temperature and stress triaxiality are reported in Fig. 5. As an example, in case of smooth specimens, the maximum fracture strain value (identified on the basis of the procedure described in § 2.3) was exhibited by the specimen deformed at the highest testing temperature, with an increase up to 1000% compared to the specimen deformed at the lowest temperature. This indicates the activation of additional deformation mechanisms above 200°C. The fracture strain gradually decreases from 300°C, 100°C, 25°C to -50°C. However, the fracture strain at -50°C nearly overlapped the one at -100°C, regardless of the stress triaxiality indicating the presence of a threshold temperature value below which the alloy ductility is no more sensitive to the testing temperature.

It is worth noting that the fracture strains of the shear and special specimens tested at room temperature are 50% and 81% higher compared to the ones obtained at low temperature, even if the same maximum load was reached during mechanical testing.
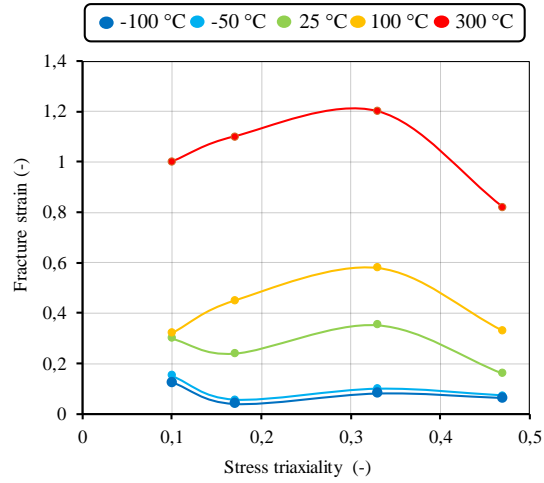
Fig. 5. AZ31 fracture loci at varying testing temperature and stress triaxiality.

3.2 Fracture surfaces

Figs. 6 and 7 show the SEM images of the AZ31 specimens fractured at 300°C, 25°C and -100°C at magnifications of 2000X and 5000X, respectively. In Fig. 6 (i-l), wide and deep dimples structures, indicative of a ductile fracture mode, can be seen in the specimens deformed at 300°C. On the contrary, at the lowest testing temperature, no ductile fracture features can be seen, since the dimples disappeared in favor of elongated fluted that are known to be symptomatic of a brittle fracture [10] (see Fig. 6 (a-d)). In addition, on the fracture surfaces of Fig. 6 (c-d), cracks along the grain boundaries can be observed, which is another typical brittle fracture structure. The fracture surfaces of the specimens deformed at room temperature have features in the middle, being a mixture of ductile and brittle type of fracture. Even if not here reported, the fracture surfaces of the specimens deformed at -50 °C are similar to those obtained at -100°C, thereby confirming a fragile rupture when testing below the room temperature.
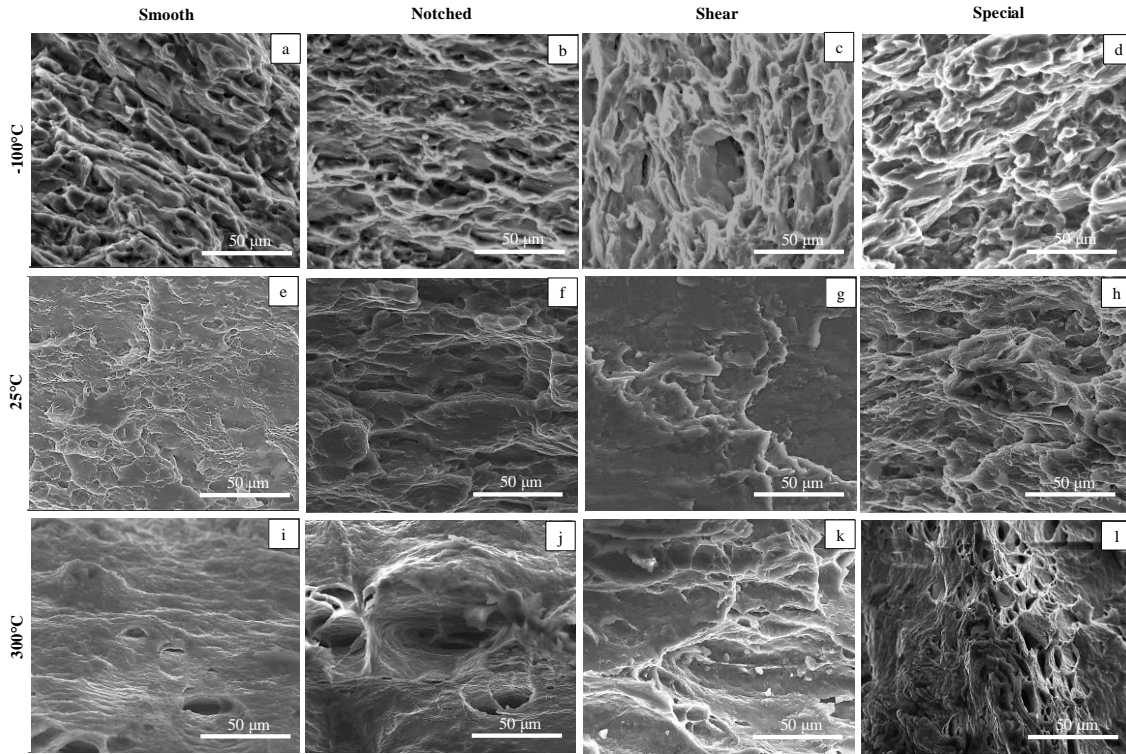

Fig. 6. 2000X SEM magnification of the AZ31 fractured surfaces as a function of the temperature and stress triaxiality.

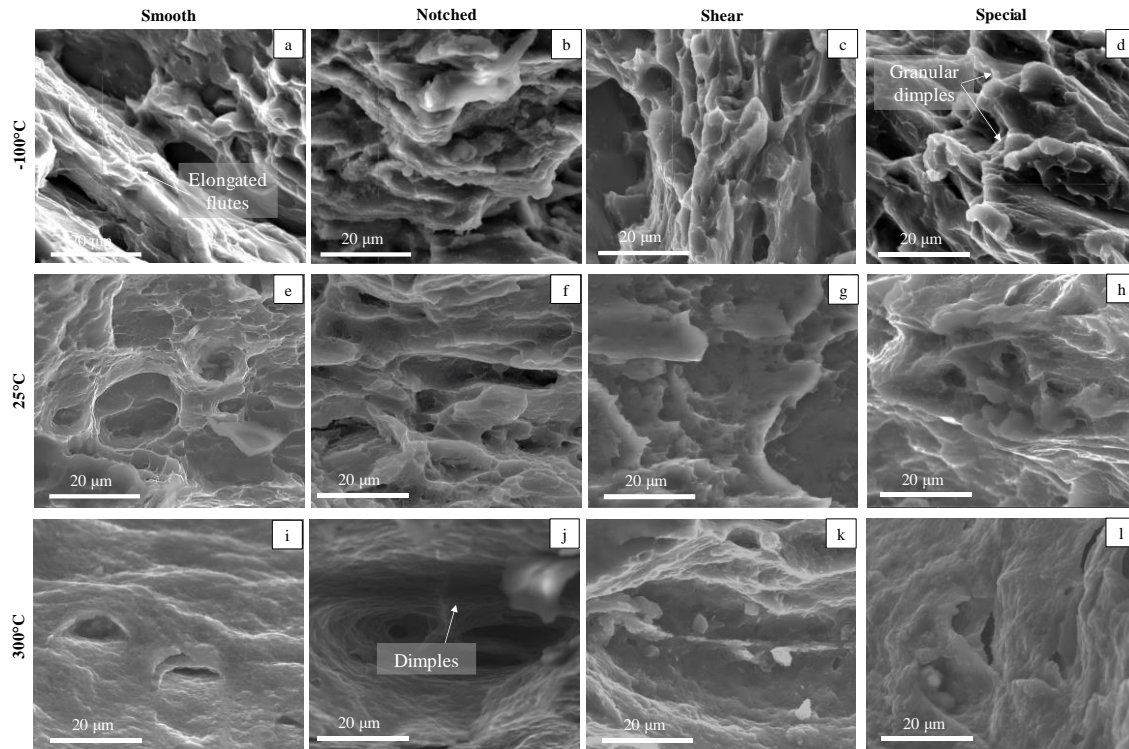|	Smooth	Notched	Shear	Special

Fig. 7. 5000X SEM magnification of the AZ31 fractured surfaces as a function of the temperature and stress triaxiality.

4 Conclusions

In this work, tensile tests till fracture and SEM observations of the fracture surfaces were employed to characterize the mechanical properties and fracture morphology of the AZ31 magnesium alloy deformed in a wide range of temperature and stress triaxiality.

The main conclusions can be summarized as follows:

- The force increased monotonically by decreasing the temperature for the smooth and 5-mm notched samples. In the case of shear and special samples, at temperatures below than the room one the force was no longer sensitive to the testing temperature.
- Higher fracture strains were obtained at elevated temperatures, whereas no sensible differences were shown between tests carried out at -50°C and -100°C.
- The reduction of temperature favored a brittle mode of fracture. The fractured surfaces of the specimens deformed at -50°C and -100°C were in fact characterized by the presence of elongated flutes and intergranular cracks.

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