# Formability limits, damage and fracture mechanisms in AA5182 Al-Mg sheets formed under subzero temperature conditions

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**Abstract.** The applicability of in demand lightweight Al-Mg alloys is constrained by limited formability and surface defects caused by the Portevin-Le Chatelier (PLC) effect, which manifests as serrated plastic flow due to dynamic strain aging. This study investigated the formability limits, damage and fracture mechanisms for commercially available AA5182 sheets subjected to tensile and Erichsen punch forming tests under room (293 K) and cryogenic (77 K) conditions, that latter was achieved using a liquid nitrogen reservoir. The sheet fracture strain and flow strength increased by 47% and 91%, respectively, for the subzero conditions compared to the reference 293 K case, the Considère necking criterion was also globally satisfied and surface wrinkling was fully suppressed. Optical and scanning electron microscopy confirmed that PLC suppression under subzero forming prevented unstable interactions with opposing shear planes, allowing for more even strain distributions and sheet thinning near the fracture zone. The subzero major strains on the forming limit diagram increased by 18%, 43% and 27% for uniaxial, plane strain and equiaxial strain paths, respectively, compared to 293 K. The average surface roughness was also reduced from 1.16 μm to 0.23 μm, representing the difference between Class B and Class A surface finish designations.

**Keywords:** AA5182 sheets; PLC effect; Cryogenic temperatures; Forming limit diagram

## 1 Introduction

Aluminum alloy (AA) sheet materials are critical for vehicle lightweighting, especially to offset the increased battery weight in electric and hybrid vehicles. There is an acute need for high-quality mechanical data and material observations to identify parameters and design manufacturing processes to maximize sheet formability while minimizing the loss of strength and ductility.

Room temperature (cold) forming of AA sheets is cost effective, however, the benefits are often negated by galling, high levels of springback and low ductility [1]. Al-Mg (5000-series) alloy sheets also experience serrated plastic flow due to interactions between dislocations and Mg solute atoms, known as the Portevin-Le Chatelier (PLC) effect [2]. Necking occurs prematurely and alloy ductility is reduced due to PLC band formation, the effect is also visible as blemishes (strain marks) on the post-forming sheet surface [3].

Warm and hot forming processes improve ductility and reduce springback for AA sheets, however, high energy costs and lubricant breakdown are inherent challenges [4]. Furthermore at elevated temperatures, galling intensifies, friction increases, and oxide fibrous structures form above 250 °C, coinciding with aluminium adhesion to the counterface [5]**.** Cryogenic (< 100 K) forming processes have recently emerged as low-energy alternative that can improve the formability of AA sheets [6] and suppress PLC banding [7] for defect-free surface finishes.

This study investigated the formability and fracture of AA5182 sheets under room (RT) and cryogenic temperature (CT) conditions. Erichsen punch testing was used to generate new data on the formability of AA sheets in the cryogenic regime. Microstructural observations provided qualitative explanations for the dramatically improved formability and surface finish under CT conditions compared to RT, including PLC band suppression and increased grain elongation near the fractured edge.

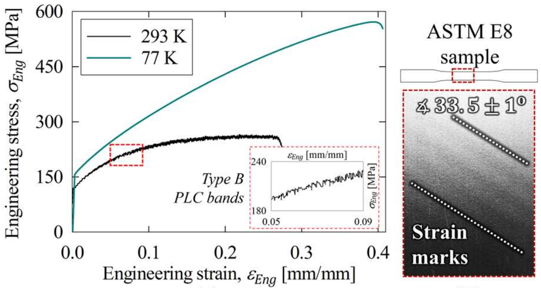
## 2 Results

### 2.1 Materials and methods

AA5182 sheets of 0.5 mm thickness were annealed at 530 °C for two hours, followed by gradual cooling to produce a microstructure with equiaxed grains. Sample sheets were prepared with dimensions for strain paths ranging from uniaxial drawing to equiaxial tension to obtain the forming limit diagrams (FLDs). Room (293 K) and cryogenic (77 K) temperature testing was completed. The latter was achieved using modified tension and Erichsen cupping test apparatuses fitted with liquid nitrogen reservoirs and insulated barriers.

### 2.2 Uniaxial tension testing

Representative tensile stress/strain curves are provided for the AA518 sheet material in Fig. 1(a). The serrations in the RT response are consistent with fine Type B PLC band formation, which also manifested as strain marks on the plastically deformed surface (Fig. 1(b)). The CT conditions greatly improved the strength and ductility of the AA5182 sheets by reducing the diffusion rate within the material, inhibiting solute atom motion associated with dynamic strain aging and suppressing the PLC effect. The surface strain marks were correspondingly absent from the samples tested at 77 K.



(a) (b)

**Fig. 1.** (a) Stress/strain curves for the AA5182 sheets tested under RT (293 K) and CT (77 K) conditions, and (b) strain marks from PLC banding visible on the sample tested at RT.

### 2.3 Erichsen punch forming tests

The forming tests used a 20 mm-radius hemispherical Erichsen punch translating at 5 mm/min. The FLDs obtained from RT and CT forming tests are plotted together in Fig. 2. The minima in the FLDs occur at slightly positive minor strains since the tool contact pressure counteract tensile stress from sheet extension. The major strain limit increased by a near-equal magnitude across the FLD for the CT test conditions.

The AA5182 sheets to experienced shifting strain paths between test conditions. For example, the sheets intended for plane strain experienced this strain path when formed at 293 K but transitioned to biaxial tension at 77 K. More uniform dislocation motion and a higher work hardening rate at 77 K (visible in Fig. 1) allows the plastic deformation to distribute more evenly across the AA5182 sheets under CT forming conditions

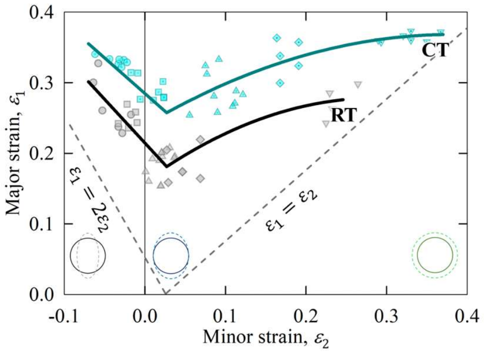


**Fig. 2.** Forming limit diagrams for AA5182 sheets deformed via Erichsen punch at RT (293 K) and CT (77 K).

### 2.4 Through-thickness sheet microstructure

The post-fracture through-thickness AA5182 sheet microstructure (RT) is shown in Fig. 3(a). The fractured edge displays rough protrusions, caused by interactions between PLC bands and opposing shear bands during localized necking. No PLC bands were visible on the complementary sample from CT testing (Fig. 3(b)) and more uniformly distributed sheet thinning was observed leading into the fractured edge. Shear-induced grain rotations were more pronounced since the premature onset of localized necking was prevented.

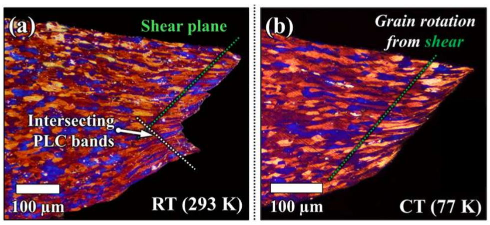


**Fig. 3.** Microstructures observed near the fractured edge in unidirectionally drawn (i.e., $\boldsymbol{\varepsilon_1 \approx 2\varepsilon_2}$) samples after Erichsen punch forming at (a) 293 K, and (b) 77 K.

## 3 Conclusions

This study investigated the formability of AA5182 Al-Mg sheets deformed under room (293 K) and cryogenic (77 K) temperature conditions through uniaxial tension and Erichson punch testing. The CT (77 K) ambient conditions transformed the plastic flow behaviour of the AA5182 sheets compared to RT (293 K) by suppressing PLC banding, with 47% and 91% increases in the yield strength and fracture strain, respectively.

Erichsen punch testing revealed improved sheet formability for every strain path for CT conditions, with the most significant increases noted for the sheet samples intended for plane strain (43%) and biaxial tension (27%). The difference in flow behaviour and more even plastic strain distribution due to improved dislocation flexibility promoted shifts to more biaxial strain paths under cryogenic forming.

The major strain limit under plane strain increased by 43% for CT forming conditions compared to RT. Interactions between opposing PLC and shear bands under RT forming caused intense strain localization and uneven sheeting thinning, compared to CT conditions which experienced more uniform thinning. The CT surface roughness also improved by a factor of 5 due to PLC band suppression, consistent with a Class A finish.

## References

1. C. I. Pruncu, T. T. Pham, A. Dubois, M. Dubar, L. Dubar, Tribol. Trans. **61**, 632 (2018)
2. H. Halim, D. Wilkinson, M. Niewczas, Acta Materialia **55**, 4151 (2007)
3. R. Shabadi, S. Suwas, S. Kumar, H. J. Roven, E. S. Dwarkadasa, Mater. Sci. Eng. A **558**, 439 (2012)
4. J. Noder, R. George, C. Butcher, M. J. Worswick, J. Mater. Process. Technol. **293**, 117066 (2021)
5. O. Gali, A. Riahi, A. Alpas, Wear **302**, 1257 (2013)
6. C. Wang, Y. Yi, H. Wang, J. Dang, Q. An, F. Dong, S. Huang, H. He, M. Chen, J. Mater. Process. Technol. **319**, 118041 (2023)
7. C. Reichl, R. Schneider, W. Hohenauer, F. Grabner, R. J. Grant, Appl. Therm. Eng. **113**, 1228 (2017)