

FORMING ASPECTS OF HIGH-STRENGTH Al-Mg ALLOY SHEET

OBLIKOVALNE ZNAČILNOSTI VISOKO TRDNIH AlMg PLOČEVIN

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Room-temperature formability testing was carried out on an AlMg6.8-type alloy sheet after different working conditions. The comparison of the measured limiting dome heights (LDH) and forming limit curves (FLC) with some high-strength formable alloys has shown that the tested alloy in the recrystallized condition (YS=175 MPa) exhibited a better stretch formability (at the same or even higher YS level), while in the partially annealed condition (YS=280 MPa) it had a ~40% lower formability, limiting its application to some moderate forming requirements for very high-strength parts. The Lüders elongation was eliminated by applying partial annealing or by annealing to coarser grain sizes, avoiding the appearance of the undesirable "A" type surface markings. The "B" type markings associated with the higher strain regime, (caused by the Portevin-LeChatelier effect) were found to disappear when the biaxiality of straining was increased.

Keywords: Formability, Al-Mg alloy, annealing conditions

Preizkusi oblikovalnosti so bili izvršeni po različni predpripravi pločevine iz zlitine AlMg6.8. Primerjava limitne višine izbokline (LDH) in krivulj končne oblikovalnosti (FLC) pri nekaterih visoko trdnih oblikovalnih zlitinah je pokazala, da ima rekristalizirana zlitina (YS=175 MPa) boljšo vlečno oblikovalnost (pri enakem ali višjem YS-nivoju). Zlitina v delno žarjenem stanju (YS=280 MPa) ima 40 % nižjo oblikovalnost. To omejuje njeno uporabo na zmerne pogoje oblikovanja za dele velike trdnosti. Lüders-podaljšanje je bilo odpravljeno z delnim žarjenjem ali z žarjenjem na večja zrna, s čimer se je preprečilo nastanek neželenih A-tip površinskih oblik. Oblike vrste B, ki so značilne za stanje večje deformacije, ki so posledica Portevin-LeChatelierjevega efekta, so se pojavljale v manjšem obsegu pri naraščujoči dvoosialnosti deformacije.

Ključne besede: zlitina Al-Mg, oblikovalnost, pogoji žarjenja

1 INTRODUCTION

A number of aluminium alloys have been under investigation with the aim of replacing steel in the manufacturing of autobodies¹⁻³ because of the significant weight saving. Research involves the optimization of known and the development of new alloys with the requirement that they achieve high strength and good formability. Aluminium alloys should also have some other advantages such as high corrosion resistance^{1,7} and good weldability¹. The alloy compositions and thermo-mechanical treatments under investigation mostly based on the strengthening effect of magnesium - assigned as a 5000 series (non heat-treatable alloys), or Al-Cu, Al-Mg-Si-Cu and Al-Mg-Si alloys - assigned as 2000 and 6000 series, which strengthen by precipitation (heat-treatable alloys).

The non heat-treatable Al-Mg alloys seem to be useful in complex forming operations, as the excellent formability can be regained by inter-annealing (without quenching which is detrimental for the consistency of tolerances). Since the important properties of ductility and strength can be kept in good balance efforts are focused on increasing the Mg content even further^{8,9}. Besides the strengthening effect of magnesium, the annealing condition (recovery degrees) can also be

exploited to make partially hardened tempers¹⁰. The detrimental effect of higher Mg content (> 3%) on the inter-crystalline corrosion resistance seems to be improved considerably by heat treatment¹¹⁻¹³. The dynamic strain aging (DSA) of AlMg alloys is followed by the appearance of very harmful "A" type surface markings, formed in the region of Lüders elongation. This problem reduces the applicability of this material to the production of inner panels in car bodies.

The present paper will present some results concerning deformation behaviour and formability analysis of an Al-Mg6.8-type alloy with a fully recrystallized structure. In addition, a formability assessment is presented for the partially annealed condition, i.e. with partly retained work-hardened strength, revealing a formability change relevant to such broad limits of the achieved strength levels.

2 EXPERIMENTAL

Material. The as-received Al-Mg sheet was 3.0mm thick, in the annealed condition, and with the chemical composition shown in **Table 1**. It was subsequently 70% cold rolled (to 0.9 mm) and annealed at 320 °C for 3h in an inert gas atmosphere which resulted in the material being in a recrystallized condition (assigned as series A).

An additional group of samples was cold rolled between 5% and 70% and annealed under the same conditions. Some samples were partially annealed at 260 °C for 3h, (close to H26 temper, assigned as series B) and retained the pancake structure.

Tensile test. The tensile test was made using ASTM sheet specimens with a gauge length of 25mm and a width of 6.25mm, oriented at 0, 45, and 90° to the rolling direction.

Forming limits. Gridded rectangular blanks of various widths (from 150 mm to 20 mm) were firmly clamped in the longer direction, and stretched in an Erichsen sheet-metal testing machine over a 75 mm diameter, unlubricated, hemispherical punch as proposed by A. K. Ghosh¹⁴. For every specimen, the dome height at maximum load and the minor strain (e_2) in the necked region were measured. Limiting dome height (LDH) values were normalized with respect to the punch radius, and plotted against the respective values of minor strain (e_2). Forming limit curves (FLC) were evaluated by plotting the combination of major and minor strains obtained from the same specimens. The grid circles selected for measuring the strain are those situated in the regions of fracture, localized necking and uniform deformation. Additional stretching is made on full-sized samples using a combination of polyethylene sheet and mineral oil as a lubricant in order to extend the equibiaxial part of the FLC. Finally, the FLC was drawn following the procedure proposed by Hecker¹⁵, taking the necking values as the forming limit.

3 RESULTS

Tensile properties. **Figure 1** shows that the yield point or Lüders elongation is suppressed after applying rolling reductions of less than 15% to 20%. The applied reductions and appropriate grain sizes are shown in

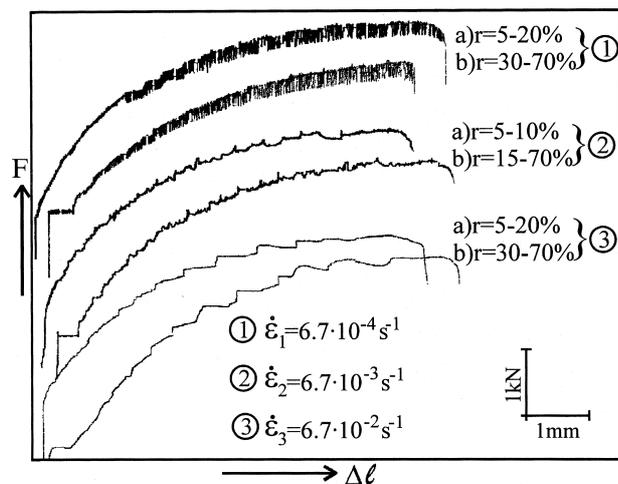


Figure 1: Load vs. extension curves at different strain rates and after different working conditions

Slika 1: Krivulje - sila raztezanja pri različnih hitrostih deformacije in po različni predpripravi zlitin

Table 2. The average grain diameter of the as-received material (~30 μm) was increased to 40.5 μm after a 15% reduction and annealing. For higher reductions (20% to 70%) the grain sizes were reduced to 16 μm, indicating the critical deformation for recrystallization was around 15%. For the A and B materials the Lüdering was eliminated in the case of the partially annealed B material, while it was ranged to ~1% for the case of samples A with a fully recrystallized structure.

The mechanical properties of the A and B materials, shown in **Table 3**, differ significantly. The partially annealed samples (B) have a considerably higher strength (YS increases by about 38% and UTS by about 18%) and lower ductility compared to the recrystallized samples (e_t was lowered by about 40%). The terminal n values (**Table 2**), reveal a superior hardening ability of the recrystallized material A.

Forming Limits. Normalized limiting dome height (LDH/R) versus critical minor strain (e_2) curves in **Figure 2**, show a considerably higher ductility of the recrystallized material over the entire range of tested strain states. The maximum difference of 42% in LDH appeared for $e_2=0$. Similar results were found using the FLC criterion (maximum difference of 35% in radial peak strain (e_1) was also ranged to around $e_2=0$, **Figure 3**). The major strain (e_1) distribution, after stretching A and B sheet specimens, (blank sizes were 150x95mm), simulating the plain strain state is shown in **Figure 4**. The failure site is shifted further away from the pole in

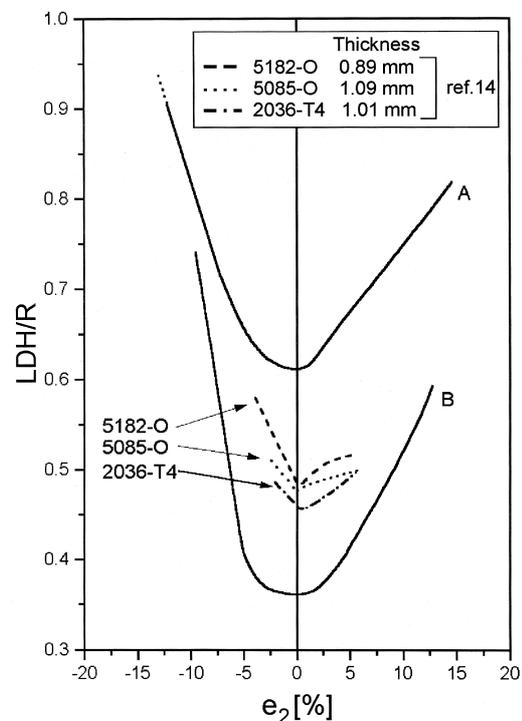


Figure 2: LDH/R- e_2 curves for the A and B conditions of the tested AlMg6.8 alloy sheet compared to some for Al alloys from literature

Slika 2: LDH/R-vrednosti za nekatere Al-zlitine iz literature v primerjavi s podatki s slike 2

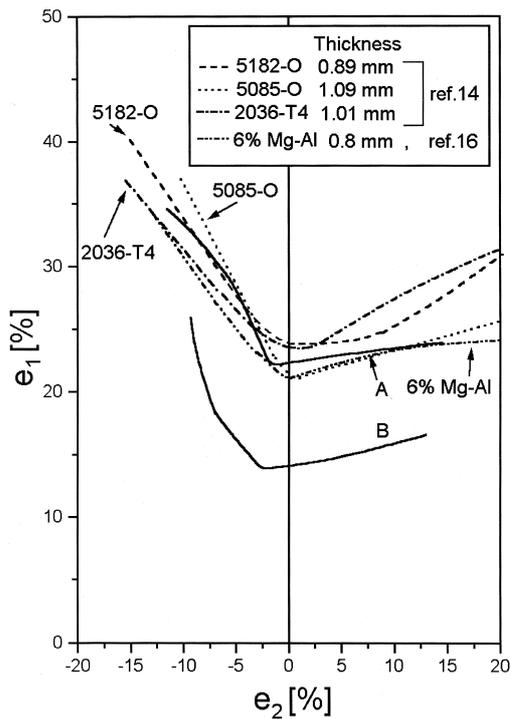


Figure 3: FLCs for the A and B conditions of the tested AlMg6.8 alloy sheet compared to some for Al alloys from literature
Slika 3: FLC za pogoja A in B pločevine iz zlitine AlMg6.8 v primerjavi s podatki o Al-zlitinah iz literature

the case of sample A, attaining higher critical-peak strains. The strain distribution is also more uniform for sample A and the area under the distribution curve is larger.

A comparison is made with some formable high-strength aluminium alloys, taking the available

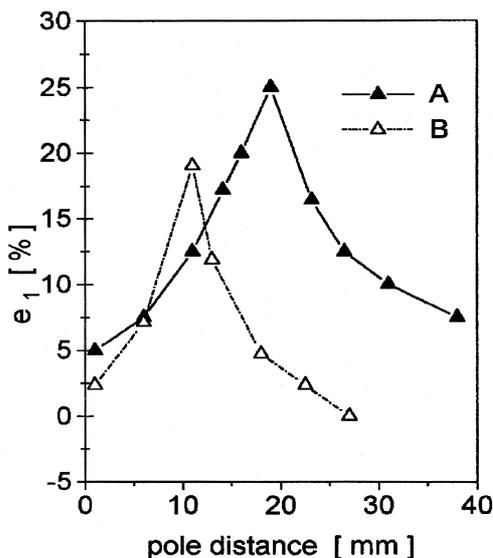


Figure 4: Major strain (ϵ_1) distribution for plain-strain state ($\epsilon_2=0$)
Slika 4: Razdelitev glavne deformacije (ϵ_1) za čisto deformacijsko stanje ($\epsilon_2=0$)

Table 1: Chemical composition (mass %)

Tabela 1: Kemijska sestava (mas.%)

Mg	Mn	Si	Fe	Zn	Ti	Cu	Pb	Cr	Ni	Al
6.8	0.5	0.1	0.2	0.03	0.054	0.001	0.002	0.001	0.005	rest

Table 2: Average grain diameters after different working conditions

Tabela 2: Poprečna velikost zrn za različne pogoje predelave

r (%)	d _{av} (µm)	r (%)	d _{av} (µm)
0	30.9	30	30.4
5	35.1	40	23.2
10	38.4	50	21.8
15	40.5	60	20.6
20	35.4	70	16.1

Table 3: Tensile properties

Tabela 3: Natezne lastnosti

Material	YS (MPa)	UTS (MPa)	e _t (%)	n
A	175.4	344.5	24.6	0.227
B	283.0	423.2	13.7	0.125

The properties averaged as: $X_{AV}=(X_0+2X_{45}+X_{90})/4$; n-terminal values ($n=n_{max.load}$).

Table 4: Mechanical properties

Tabela 4: Mehanske lastnosti

Alloy	YS (MPa)	UTS (MPa)	e _t (%)	n	ref.
5085-O	139.5	320.3	27.6	0.266	14
5182-O	142.4	335.3	25.3	0.240	-
2036-T4	189.8	358.5	23.0	0.166	-
AlMg6-H111	163.0	311.9	34.2	0.285	16

n-terminal value; test specimen gauge length 50.8mm and 12.5mm width.

limiting dome heights (**Figure 2**) and FLCs (**Figure 3**) from the literature^{14,16}. The mechanical properties of these alloys are shown in **Table 4**. It should be noted that the tensile strength of Mg-based non heat-treatable alloys (5085-O, 5182-O and AlMg6) is lower than for the tested AlMg6.8 alloy, even for the A condition with a recrystallized structure, while in the case of the partially annealed material (series B) this difference is further increased (the YS is twice that of the Mg alloys in **Table 4**).

The LDH/R values for the alloys chosen from the literature fall between the two conditions of the tested AlMg6.8 alloy, while their FLC's are rather leveled as for the A condition (**Figure 3**).

Surface appearance. The common types of "A" and "B" surface markings appeared during uniaxial straining of the sheets as schematically shown in **Figure 5a**. While stretching blanks of different widths across the hemispherical punch in a hydraulic press a net of parallel bands can be seen at the surface of the nearly uniaxially stretched samples which are "B" type (**Figure 5b**) without any traces of "A" type. In the plain-strain condition, the banding out of the punch contact is also of

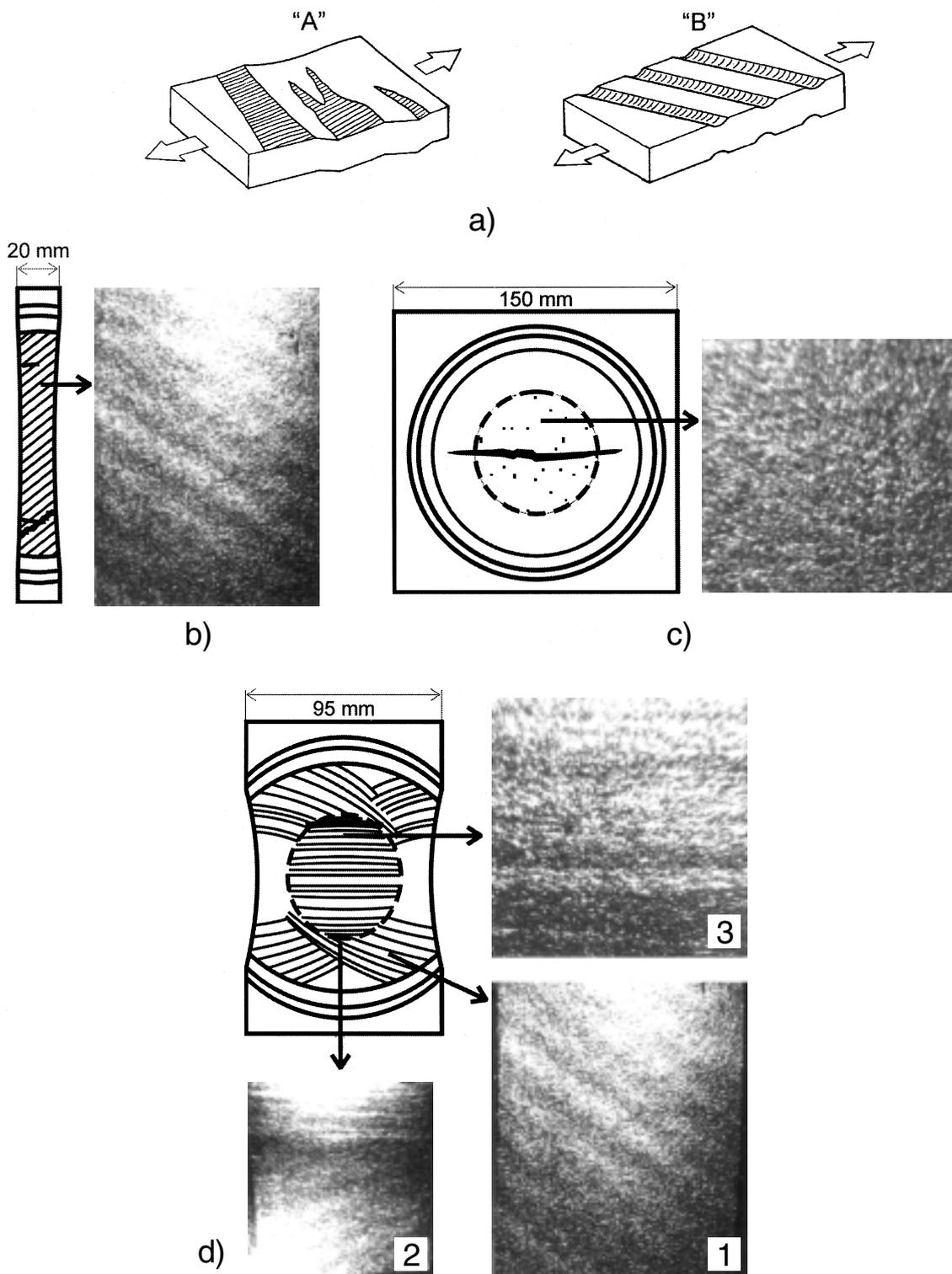


Figure 5: Sketches of the "A" and "B" type surface markings (a); macrophotographs and appropriate sketches for the samples stretched over a hemispherical punch in near uniaxial tension (b), plain-strain condition (c), and equibiaxial tension (d)

Slika 5: Skice A in B površinskih oblik (a); makrografije in ustrezne skice za preizkušance, vlečene preko polkroglastega zrna v približno enoosni napetosti (b), s čisto deformacijo (c) in dvoosnim nategom (d)

the same nature, but in the area of contact the band configuration appeared to be parallel to the shorter side of the blank (**Figure 5c**). The transition of $\sim 60^\circ$ aligned bands to the parallel net in the area of contact is shown in macrophotograph 2. The surface banding completely disappeared in the case of the biaxially stretched sample (**Figure 5d**). It is important to note that in the samples even nearly uniaxially stretched over the punch, the very harmful "A" type ("flamboyant" type) surface markings could not be observed.

4 DISCUSSION

The suppressed effect of Lüdering found in samples deformed with low reductions before the final annealing (**Figure 1**) is in agreement with previous reports¹⁷, that the Lüders elongation is suppressed in the AA5754-O alloy (Mg - 2.6 to 3.6%), keeping the grain sizes above 35 to 40 μm , matching that of the grain sizes for the discussed materials (**Table 2**).

The two conditions of the tested alloy differ significantly in terms of the achieved strength level, as well as in formability. Using partial annealing a remarkably higher strength (YS increase from 175.5 MPa to 283.0 MPa) is followed by serious formability loss, which assessed by the LDH change seems to be maximized around the plain-strain state (**Figure 2**). This effect is similar in the FLC presentation (although the two FLCs are rather parallel, **Figure 3**). The applied partial annealing allowed for the retention of a partly work-hardened strength. So, the reduced hardening ability (n) and hence the tensile elongation (**Table 3**), during the straining of the B material, in comparison to the recrystallized A material, can be understood by taking into account the higher dislocation density retained after partial annealing.

The strain states at failure in most stamped parts are usually very close to the plain-strain condition ($e_2=0$) and it was estimated that as much as 85% of ductile failures are in the region $0 < e_2 < 5$ ¹⁸. Consequently, any stretch formability analysis should concentrate on the plain-strain region and the 42% decrease of the dome height at around $e_2=0$ seems to be the relevant assessment of stretchability loss after partial annealing of the tested AlMg6.8 alloy. Although the LDH was suggested as the most suitable stretchability rating mode (because it includes both the limit strain and the strain distribution¹⁴), in the FLC presentation the plain-strain stretchability also appeared to be lowered by 35%. This similarity in stretch-formability assessment is due to a big difference in the general strain-hardening ability.

Comparing the data in **Tables 3 and 4** it is apparent that the tested alloy with the recrystallized structure (A) achieved an YS higher than the listed values for the Mg-based formable alloys in Table 4. It is difficult to compare the uniaxial ductility (e_u) as the tensile test specimens were of different sizes. The normalized

limiting dome heights of the 5182-O, 5085-O and 2036-T4 alloys are higher than for the B condition but also lower than the values attained in the A condition (**Figure 2**).

The peak strain criterion (FLC) did not reveal such a difference and the data taken from the literature is close to the FLC for the tested alloy with the recrystallized structure (**Figure 3**).

The general point, after testing this alloy and recognizing the formability change for the wide limits of strength, achieved by full recrystallization and partial recovery, allow to produce different conditions between the two materials tested. This seems to be very attractive in satisfying different forming-severity requirements in producing lightweight high-strength parts.

In terms of the surface quality, the Lüders elongation of about 1% in material A results in the appearance of the well-known "A" type sheet surface markings, which are often very undesirable in a forming application^{19,20}. These markings were eliminated by applying specific working conditions (partial annealing or annealing to grain sizes $> 35 \mu\text{m} - 40 \mu\text{m}$). The absence of "B" type markings at the surface of the equibiaxially stretched samples (**Figure 5d**), which cannot be eliminated during uniaxial tension, could not be ruled out in this work.

5 SUMMARY

Stretch formability and deformation behaviour analyses were performed using 0.9 mm thick AlMg6.8 alloy sheet after different working conditions. The formability analysis is made using both the normalized limiting dome heights (LDH/R) and the forming limit criterion (FLC).

The fully recrystallized condition (an average grain diameter of 18 μm) of the tested AlMg6.8 alloy sheet has the same or even better formability (at a similar strength level) to the high-strength formable alloys 5182-O and 5085-O or the heat-treatable 2036-T4 alloy. The partially annealed condition considered in this work could satisfy the moderate forming requirements for the production of very-high-strength parts, but generally, the tested alloy can be worked out to different strength-formability levels between the two tested conditions leading to attractive application possibilities.

The Lüders elongation which is followed by the very harmful "A" type sheet surface markings was eliminated by applying specific working conditions (partial annealing or annealing to the grain sizes $> 35 \mu\text{m} - 40 \mu\text{m}$). The "B" type markings associated with the higher strain regime, (caused by the Portevin-LeChatelier effect) were found to disappear by increasing the biaxiality of the straining. At the surface of equibiaxially stretched samples these bands were completely suppressed.

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