Proceedings of the 9th International Conference on Aluminium Alloys (2004)
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

Formability of a Twin- Roll Cast AA 6016 Sheet for Automotive Applications

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Keywords: Automotive sheet, formability, AA6xxx, Forming limit diagrams.

Abstract

Properties required of aluminum sheet for automotive applications are high strength, good formability, weldability and corrosion resistance and are met largely by a number of AA6XXX alloys. Twin-roll casting has recently been used to produce low-cost/high-quality AA6XXX aluminum sheet for such applications. Inıtial results are encouraging. While the use of aluminum sheet in automotive structural applications is increasing, better formability to overcome the problems encountered in sheet forming operations has become a critical issue. An attempt was made, in the present work, to characterize the formability of the twin-roll cast AA6016 alloy sheets further by employing forming limit diagrams and other standard formability assessment tests.

1. Introduction

The need to lower vehicle weight has led to a growing interest in aluminum sheet for skin panel applications [1-3]. The material of choice has been the Al-Mg-Si alloys as they offer a very attractive combination of high formability when shipped while providing adequate in-service strength after the paint-bake cycle [4-6]. Those with little or no Cu (AA6016) are preferred in Europe as they exhibit better corrosion properties. High cost, however, has been a major barrier to the widespread use of aluminum sheet in high-volume applications [7]. Hence, strip casting has recently attracted a great deal of attention as a method to produce low-cost aluminum sheet for body panel applications [8,9].

AA6XXX auto body panel is required to have a low yield strength for low spring back and high formability for stamping of complex shapes with high accuracy [10-12]. A T4 yield strength less than 130MPa and an elongation of at least %24 are often considered adequate [13] while a T8X yield strength exceeding 200MPa is desired for the dent-resistance reqired in service. The Twin Roll Cast (TRC) AA 6016 sheet was shown recently, to meet these conflicting demands with a much shorter process cycle with respect to the DC casting and hot mill route [14].

Prediction of “formability” in modes other than uniaxial stretching from parameters calculated from uniaxial tension test results is thus of great value. The present work was undertaken to investigate the formability of TRC 6016 alloy sheets, processed with and without pre-aging treatments, under more complex strain states, as encountered in industrial stamping operations, with the concept of Forming Limit Diagrams (FLD).

2. Experimental

The AA 6016 strip used in the present investigation was strip-cast at ASSAN Aluminum at a gauge and width of 5.8mm and 1800mm, respectively. The chemical composition of this alloy is given in Table 1.

Table 1: The chemical composition of the Al-Mg-Si alloy used in the present investigation (%wt).

Si	Fe	Mg	Mn	Cu	Cr	Ti	Al
1.002	0.189	0.429	0.073	0.003	0.001	0.028	98.25

Twin-roll cast 6016 strip samples were cold rolled to 1mm in several passes on an industrial scale and subsequently solutionized in a laboratory furnace at 550°C for 30 minutes. The solutionized samples were cooled in circulating air and were then pre-aged (T4P) before they were finally given a paint bake cycle. The pre-aged sheet samples were held at room temperature for one week before they were given the paint-bake treatment as the body panel sheet is often stored for quite some time before finally stamped at the automobile plant. A paint bake cycle in the present work refers to a combination of treatments where the pre-aged sheet samples are first stretched 2% in tension and held at room temperature for 24 hours before they are finally aged at 180°C for 30 minutes (T8X treatment). Several sheet samples were processed without pre-aging and analyized for their forming behavior to identify the effect of pre-aging on the formability of 6016 sheet.

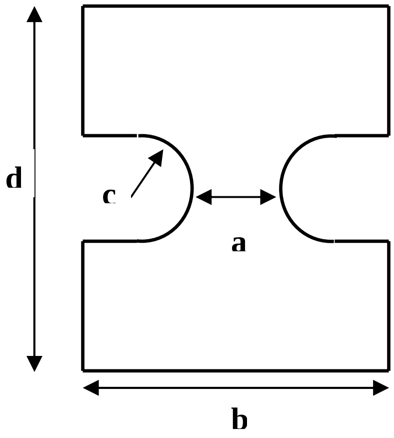
Uniaxial tensile tests were performed on sheet samples processed with and without pre-aging, with a Zwick Z050/TN2A model tensile testing machine, on 50mm gauge length samples taken in the rolling direction, and at 45 and 90 degrees to the rolling direction, to determine the tensile properties as well as the strain hardening exponent, n, and the plastic anisotropy ratio, r. Tests were conducted both before and after the paint bake cycle. FLD experiments were carried out with a standard hydraulic bulge test unit based on an original design proposed by Duncan [15], but with the additional provison of elliptical forming masks, or dies, having two different aspect ratios, namely 50:100, 70:100. Through the use of these masks, the hydrostatic bulging of sheet samples was possible for various ratios of the forming limit strains. For the right side of the FLD, circular blanks approximately 300 mm diameter were electrochemically etched using a grid pattern consisting of 2,54 mm diameter interlocking circles before testing.

The rolling direction of the sheet was parallel to the minor axis of each elliptical die and the orthogonal forming limit strains ε_1 and ε_2 were measured along directions corresponding to the major and minor axes of the die, respectively. With the circular dies, the forming limit strains were always measured along the same directions in the plane of the sheet as were used in the corresponding elliptical die tests. Strain measurement criterion involved the determination of major and minor strains on the deformed circles or ellipses adjacent to the fractured edge with the help of the following equations:

$$\varepsilon_1 = \ln (d_{maj} / d_i) \quad (1) \qquad \varepsilon_2 = \ln(d_{min} / d_i) \quad (2)$$

where d_{maj} and d_{min} are the major and minor diameters at the end of the test and d_i is the initial diameter of the circles. Typically ten or twelve circles or ellipses were found to meet this requirement in any single test. Left-side of the FLD, where ε_2<0, was constructed with the notched tensile specimens having 4 different geometries, adopted from those given by Melander [16]. Specimen geometry and dimensions are given in Figure 1.

Strain measurements were carried out on the deformed circles that were previously etched on the specimen surface, as performed for the left side of FLD. Tensile direction of the samples was parallel to the rolling direction.



sample	a	b	c	d
1	34	100	5	150
2	34	100	10	150
3	34	100	15	150
4	34	100	30	150

Figure 1: Geometry and dimensions of the samples used for constructing the left-hand side of the FLD.

Better understanding of formability performance of a cold rolled material necessitates elucidation of dominant crystallographic texture that develop during the processing route. Coupling of mechanical behavior with the crystallographic texture data provide complementary information about a material. Therefore, test results of the present study was enhanced with pole figures. By using Shultz reflection method, {111} pole figures were determined on the specimens. Rigaku RINT 2200 diffractometer equipped with a texture goniometer were employed.

3. Results and Discussion

The macro and microstructures of the TRC 6016 sheet processed with a pre-aging treatment are illustrated in Figure 2. Features of the samples processed without a pre-aging treatment are very similar to those of the pre-aged samples at this resolution.

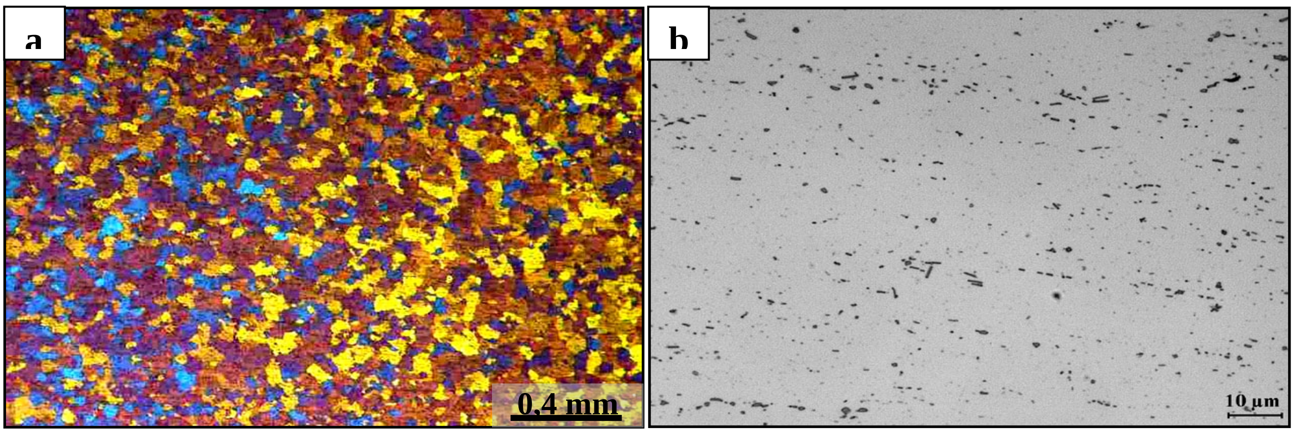


Figure 2: The grain structure (a) and the microstructure (b) of the TRC 6016 alloy sheet.

Table 2: Mechanical properties of the TRC 6016 alloy sheet used in the present investigations.

process	temper	Sample orientation	$R_{p0.2}$ MPa	R_{max}, MPa	A50 %	n	r
w/o pre-aging	T4	0	119.2	236.5	27.8	0.28	0.70
		45	116.3	231.0	26.5	0.28	0.63
		90	113.5	230.7	30.6	0.28	0.71
	T8X	0	145.2	236.7	27.2	0.24	0.71
		45	144.3	233.1	25.1	0.24	0.61
		90	141.3	231.5	23.6	0.24	0.70
w/ pre-aging	T4P	0	104.3	220.5	27.2	0.29	0.73
		45	100.7	213.8	27.9	0.29	0.62
		90	102.2	216.1	27.3	0.29	0.70
	T8X	0	217.1	281.2	18.5	0.16	0.71
		45	214.9	278.1	18.6	0.16	0.62
		90	217.5	281.7	20.2	0.16	0.70

The uniaxial tensile test results are given in Table 2. It is clear from a simple comparison of the T4 and T4P tensile data show that a pre-aging treatment at 180°C for 5 minutes performed soon after air cooling from the solution heat treatment does a number of very nice things. Pre-aging under these conditions not only improves the bake hardening response of the TRC 6016 sheet (higher T8X strength values) but also gives a lower T4P yield strength and a higher T4P elongation. Such a pre-aging treatment could offer a significant advantage from the formability standpoint. Relatively higher strain hardening exponent values and similar and balanced elongation values in all orientations of pre-aged samples are encouraging. A large n value means that the material will resist localized deformation or necking. This results in a more homogenous strain distribution and thus less tendency to premature failure. r values in the rolling direction and perpendicular to it are very close while they are smaller at 45 degrees to the rolling direction.

Mechanical performance of both materials were assessed in detail with their forming limit diagrams. Limit line designating the safely workable strain combinations of major (RD) and minor (TD) directions on the right-side of FLD are almost the same for both samples (Figure 3).

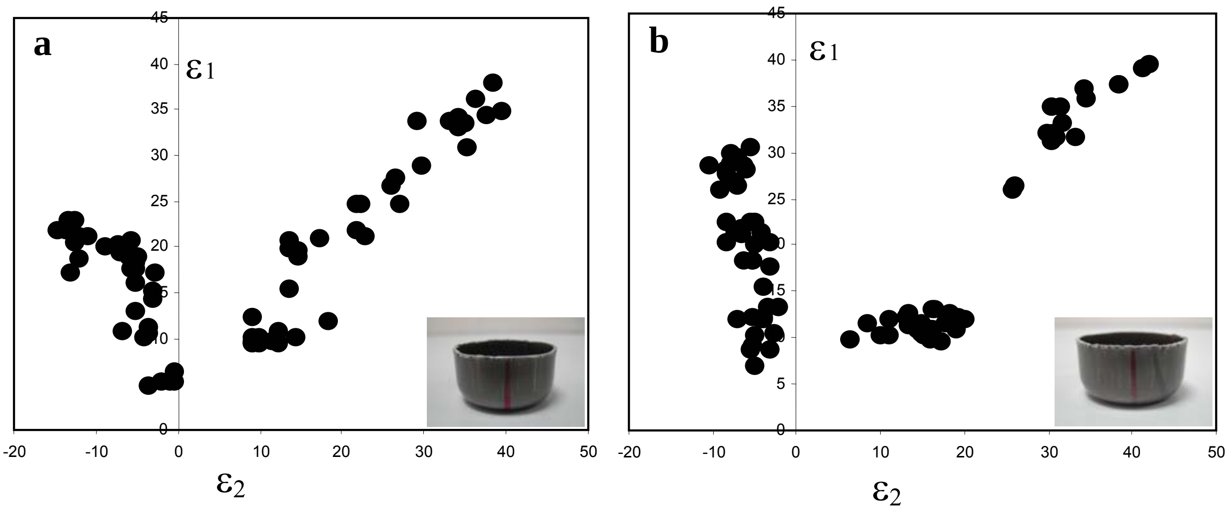


Figure 3: FLD of both materials, without (a) and with (b) pre-aging treatment.

Forming limit strains of both material exhibit very close values in biaxial stretching mode, $\varepsilon_2/\varepsilon_1=1$. At the strain state, $\varepsilon_2<0$, where the results provide clear indications related to the deep drawing capability of the material, slightly higher limiting values were obtained for the major strain (ε_1) of pre-aged samples. Flat-bottomed cup test was also employed to show the tendency of materials to form ears during drawing. Photographs embedded in the respective FLD's exhibit very similar earing behavior of the samples. These results are in accord with the material indices n and r in three directions.

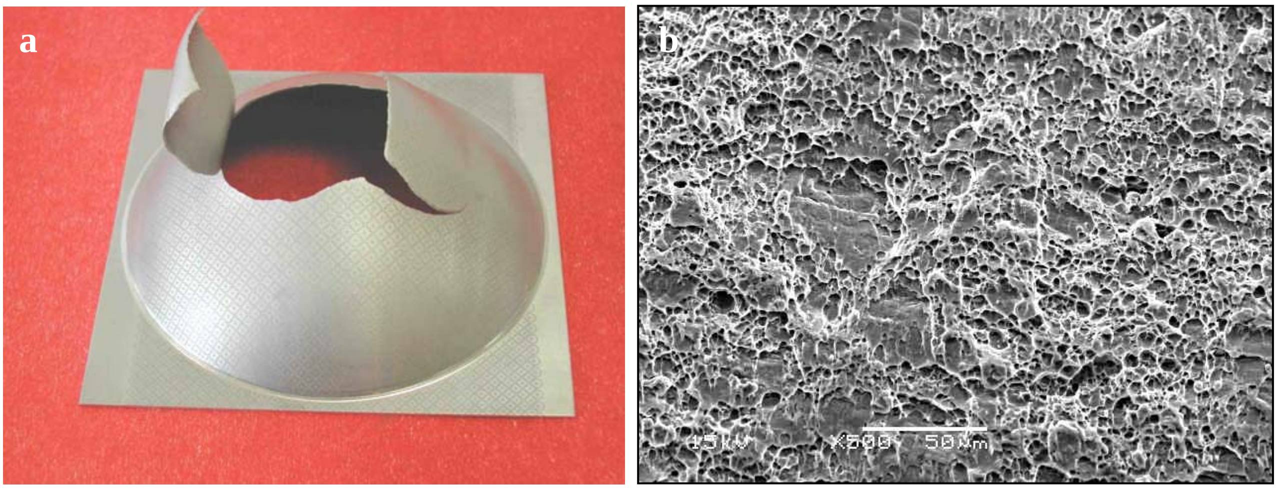


Figure 4: Typical macroscopic failure mode (a) and fracture surface (b) of the TRC 6016 sheet samples.

Position of the crack that initially appeared and resulted in failure of the samples of biaxial stretching mode, was always at the top of the dome. Regardless of the processing route, whether pre-aged or not, all the samples tested at biaxial deformation mode revealed very similar macroscopic failure mode shown in Figure 4. Initial crack first appears parallel to the rolling direction at the highly strained area, i.e. top of the dome, then propagates perpendicular to the rolling direction by splitting the dome into two distinctive pieces. Nature of dimples on the fractured surface of the biaxially stretched samples are also illustrated in Figure 4. Fracture mode of both samples were observed to be very similar.

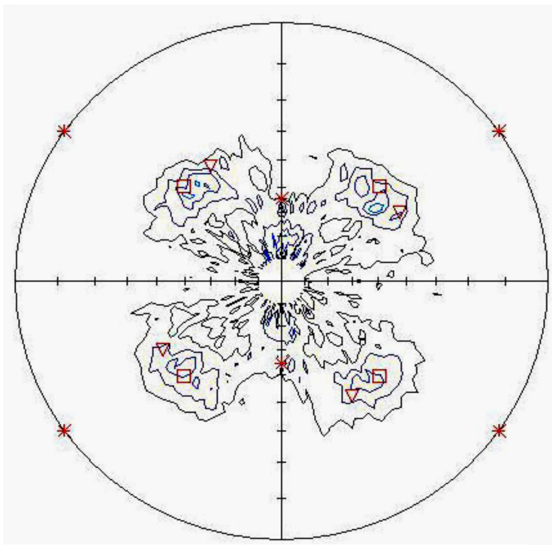


Figure 5: {111} pole figure of pre-aged sample.

The samples that were subjected to the pre-aging treatment contain recrystallisation texture {001}<100>, and deformation component of {011}<100> at T4 temper (Figure 5). One way that the texture is manifested in the measured mechanical properties is through the plastic strain ratio (r-value) and accordingly Δr value. A positive Δr indicates that the recrystallization components begin to dominate and a negative Δr stands for the dominating deformation textures. Δr values of samples with and without preaging treatment were calculated to be 0,095 and 0,075, respectively.

One important consideration for the alloys that are subjected to press forming for outer panel applications is the surface appearance of the final part. Evolution of surface roughness, specifically called ridging or roping, is reported as an important problem due to aesthetic impairment of finished surfaces [17]. This phenomenon has been linked to the presence of bands of similar orientation in the sheets [18]. Bands of similar orientation will deform collectively and thus tend to form elevated or depressed band-like regions. Because of the typically strong cube recrystallisation texture of material that reveals ridging, the occurrence of ridging has been attributed to the existence of cube bands in the recrystallised state. Eventhough all the samples, for the right side of FLD, were tested until failure, no roping or ridging was observed at the vicinity of the crack.

Non-uniform grain size distribution through the thickness and variation in second-phase particle size are the most general sources of plastic inhomogeneity, especially for thin gauge materials deformed under severe forming operations [19]. Twin roll casting produces a very fine and uniform dispersion of intermetallic particles owing to very high solidification rates involved. It thus offers unique as-cast microstructural features in this respect compared to its DC cast counterparts, which reveal much coarser intermetallic particles with higher aspect ratios. Such particles are broken into two or more pieces in the course of rolling and intrinsically create voids or cavities that can readily lead to premature crack initiation in early stages of stretching and are usually the most damaging. However, the TRC 6016 sheet samples, enjoy a fine dispersion of intermetallic particles maintained throughout processing all the way to the final gauge and temper. This feature is believed to play a critical role in superior formability performance of TRC AA6016 alloy.

Acknowledgements

It is a pleasure to thank Osman Cakır and Fahri Alageyik of Marmara Research Center and Husnu Ozturk and Cemal Celebi of ASSAN Aluminium for their help in the experimental part of this work. The financial support of TIDEB-TUBITAK is gratefully acknowledged.

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