FORMABILITY OF TWIN ROLL CAST AA 5XXX ALLOY SHEET FOR AUTOMOTIVE APPLICATIONS

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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 AA5XXX alloys. Twin-roll casting has recently been used to produce low-cost/high-quality AA5XXX aluminum sheet for such applications. Inıtial results are encouraging and the strip-cast AA5052 and AA5182 alloys are shown to have equivalent or superior mechanical properties and better corrosion resistance with respect to their DC-Cast and Hot Rolled counterparts. 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 AA5XXX alloy sheets further by employing forming limit diagrams and other standard formability assessment tests.

Introduction

Aluminum alloys with %2-5 Mg are extensively used in automotive applications requiring high strength, good formability and corrosion resistance. The material of choice for inner supporting panels has been the 5XXX series alloys, since they offer a very attractive combination of in-service strength and formability. The good formability performance of these alloys is attributed to the Mg in solid solution, which by segregating to dislocations, hinders their mobility and leads to a retention of a high work hardening rate at large strains and thus favors diffuse necking. For inner panel applications the strength is secondary to stiffness. Downgauging, while maintaining stiffness implies a more complicated structure and deeper ribs, in particular. Therefore, material selection for such applications is dominated by gauge and formability.

The results of the earlier work on the microstructural and mechanical characterisation of the Twin-Roll Cast (TRC) 5XXX alloys by the authors were encouraging and the strip-cast AA5052 and AA5182 alloys were shown to have equivalent or superior mechanical properties and better corrosion resistance with respect to their DC-Cast and Hot Rolled counterparts [1]. This work, however, was limited to the uniaxial tensile test results. The prediction of "formability" in modes other than uniaxial stretching from parameters calculated from uniaxial tension test results often referred to as "forming indices", has often been attempted in the sheet metal forming industry. However, the uniaxial tension test should not be considered a formability test. Although, the results correlate with field failures in the uniaxial stretching mode, few forming operations result in failures that occur in the uniaxial mode. Therefore, response of TRC 5052, 5754 and 5182 alloy sheets under more complex strain states, as encountered in industrial press forming operations was determined with the concept of Forming Limit Diagrams (FLD) in the present study. Identical tests were also conducted for their Direct-Chill Cast (DCC) and hot/cold rolled counter parts.

Experimental

The TRC 5XXX alloys used in the present study were cast at ASSAN Aluminum with a 1725 mm wide *SpeedCaster®* at width and gauge ranges of 1400-1700 mm and 5-6 mm, respectively. All materials, including those produced with the DC casting route were 1 mm thick, except for the DCC 5754 sheet with a thickness of 1,15 mm.

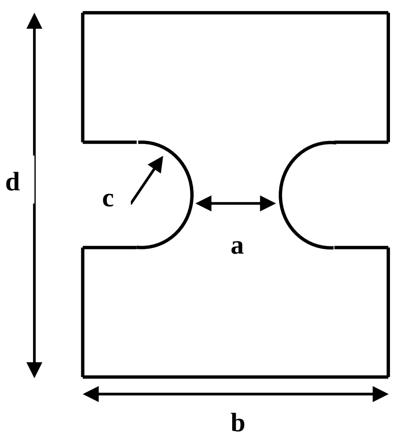
Uniaxial tensile tests were conducted along the rolling direction, and at 45 and 90 degrees to the rolling direction, to determine the tensile properties as well as the strain hardening exponent, n, and the plastic anisotropy ratio, r. FLD experiments were carried out with a standard hydraulic bulge test unit based on an original design proposed by Duncan [2], 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 hyrostatic 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 gridded using a grid pattern consisting of 2,54 mm diameter interlocking circles before testing (Figure 1).

Figure 1. Electrochemically etched interlocking grid patterns on the surface of the specimens.

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 minor and major 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 six or seven circles or ellipses were found to meet this requirement in any single test. Left-side of the FLD, where $\varepsilon_2<0$, was constructed with the notched tensile specimens having 4 different geometries, adopted from those given by Melander [3]. Specimen geometry and dimensions are given in Figure 2. 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 2. Geometry and dimensions of the samples used for constructing the left-hand side of the FLD.

Table 1. Mechanical properties of the TRC 5XXX and DCC 5XXX alloy sheets used in the present investigations.

Alloy	Sample orientation	$\sigma_{p0.2}$ MPa	σ_{max}, MPa	Elongation, %		n	r
				Total	Uniform		
TRC5052	0^0	101	207	22,5	19,3	0,26	0,63
	45^0	102	205	27,2	25,1	0,27	0,62
	90^0	104	206	24,6	21,8	0,26	0,68
DCC5052	0^0	131	216	17,5	14,2	0,19	0,60
	45^0	124	204	20,9	15,9	0,19	0,61
	90^0	126	209	21,3	17,3	0,18	0,87
TRC5754	0^0	131	265	22,8	19,2	0,27	0,65
	45^0	127	253	22,9	20,4	0,28	0,81
	90^0	129	255	18,5	20,6	0,27	0,64
DCC5754	0^0	127	232	21,4	19,1	0,26	0,64
	45^0	119	222	26,2	24,1	0,27	0,84
	90^0	123	224	26,1	24,2	0,26	0,75
TRC5182	0^0	157	294	22,5	18,8	0,26	0,62
	45^0	151	286	26,7	22,3	0,26	1,11
	90^0	156	290	21,2	19,2	0,26	0,77
DCC5182	0^0	139	284	26,9	23,1	0,32	0,71
	45^0	137	272	30,4	25,5	0,32	0,76
	90^0	142	282	28,6	23,3	0,32	0,74

Results and Discussion

The macro and microstructures of the TRC and DCC 5182, 5052 and 5754 alloy sheets are illustrated in Figure 3 and 4, respectively and the uniaxial tensile test results are given in Table 1. Both TRC and DCC 5052 and 5754 sheets appear to show highest tensile elongation values at 45

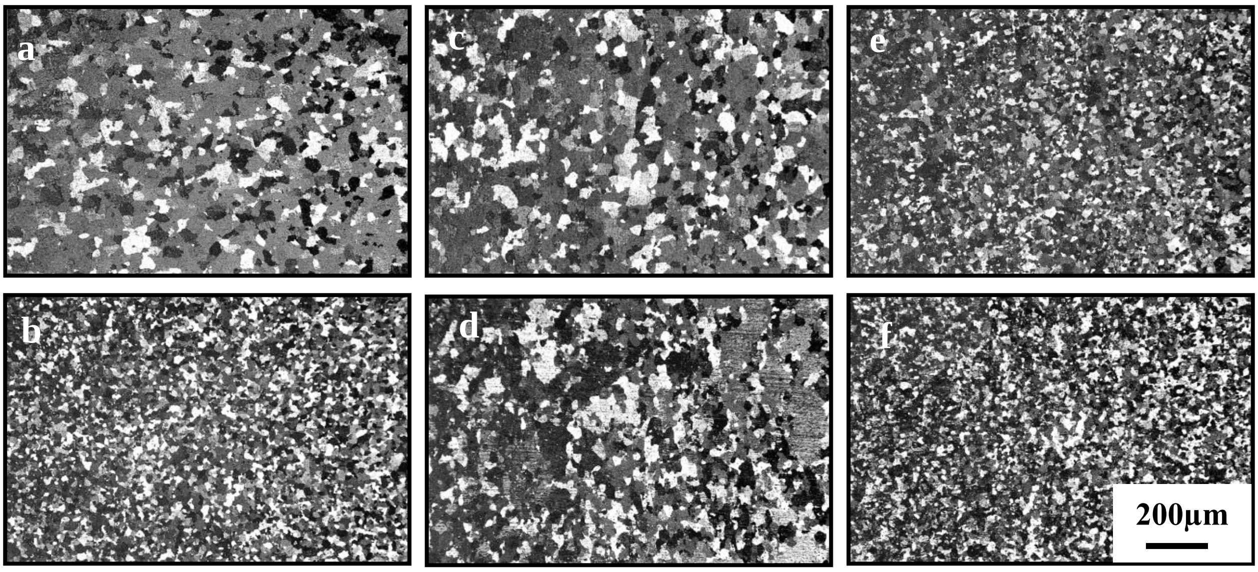


Figure 3. The grain structures of the (a) TRC and (b) DCC 5182, (c) TRC and (d) DCC 5052 and (e) TRC and (f) DCC 5754 alloy sheets.

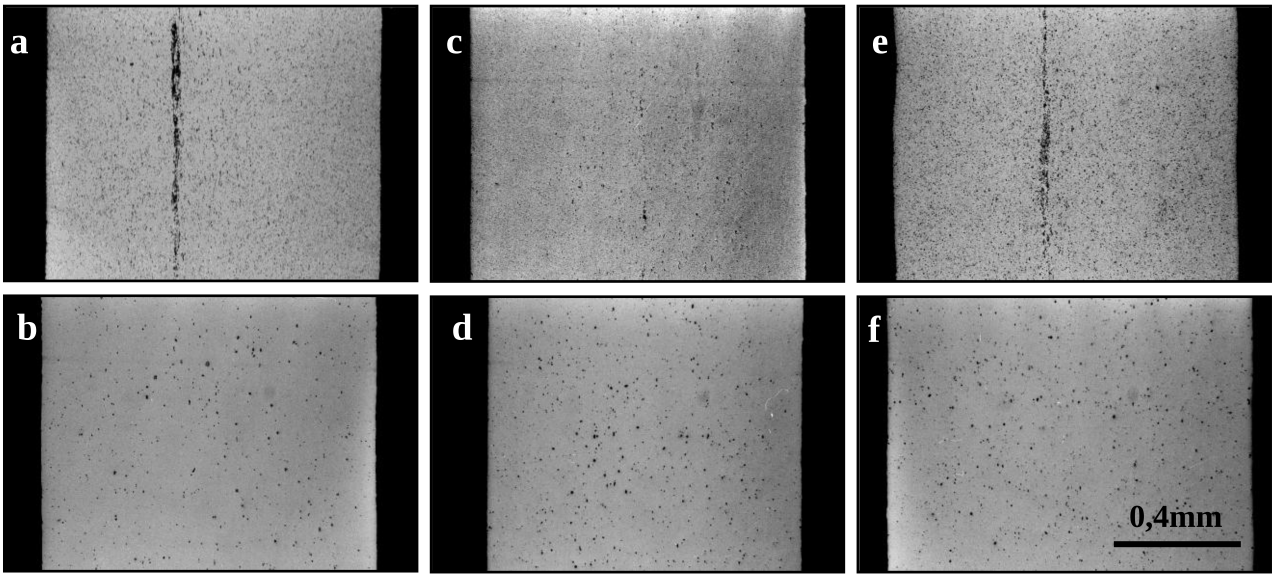
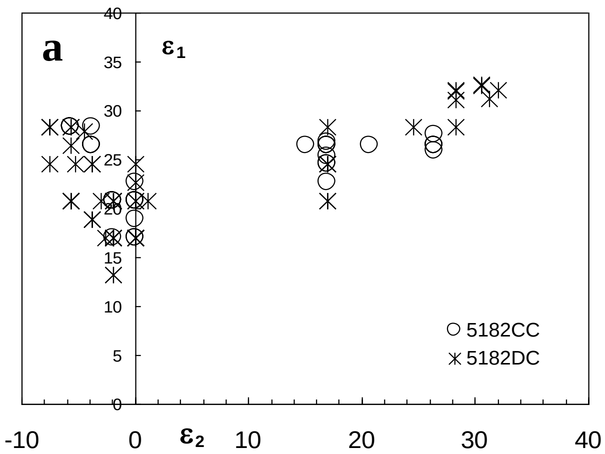
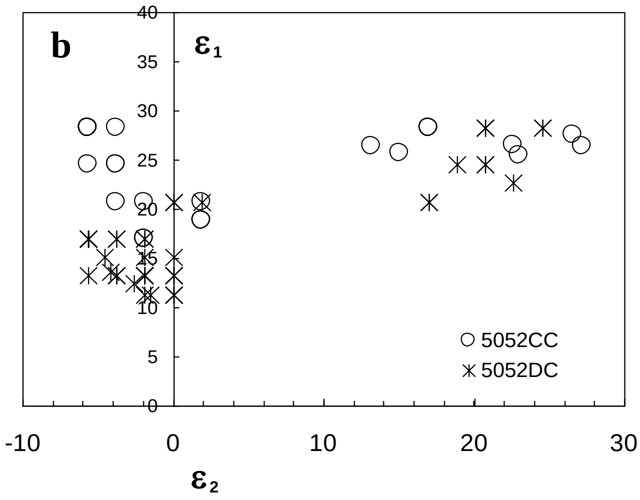


Figure 4. The microstructures of the (a) TRC and (b) DCC 5182, (c) TRC and (d) DCC 5052 and (e) TRC and (f) DCC 5754 alloy sheets.

degrees to the rolling direction. These results aggree with those reported for similar materials in 0 temper [4] and are attributed to the crystallographic texture developed during processing. All 5XXX sheets, regardless of the production technique used and with the Mg levels tested in this investigation, deform inhomogenously at the start of plastic deformation, displaying a Luders elongation at the initial yield, and serrated flow at higher strains. The strain hardening exponent values of the TRC 5052 are higher than the DCC 5052 values whereas those of the TRC and DCC





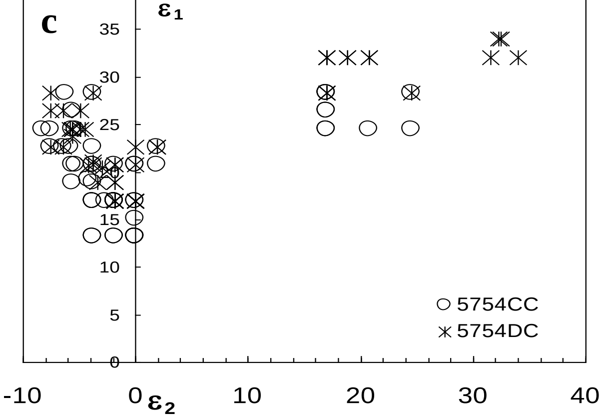


Figure 5. FLDs of the DCC and TRC
(a) 5182 (b) 5052 and (c) 5754 alloy sheets.

5754 sheets are similar. DCC sheet has better tensile elongation and n values than its TRC counterpart in the case of 5182 alloy. The former reveals a very fine grain structure and a coarse but very uniform particle dispersion, both of which are believed to have contributed to the formability performance of this alloy. This is clearly seen in the FLD of this material, especially under balanced biaxial deformation mode (Fig. 5a). The n value is a measure of the material's ability to distribute strains uniformly during press forming. The material with a higher n value will resist localized deformation, leading to a more uniform strain distribution, with a reduced tendency for cracking. The formability of the Al-Mg alloy is controlled by the strain that can be achieved without localization. This is the uniform strain contribution due to neck growth. The uniform elongation is controlled by the relative strain hardening rates up to the maximum load while the extent of post-uniform elongation depends on both strain hardening and strain rate sensitivity. A substantial portion of the total elongation originated from uniform elongation in the case of the TRC 5XXX sheets.

The TRC 5052 sheet exhibits a marked difference on the left-hand side of the FLD when compared to the DCC 5052 (Fig. 5b). The performance of the TRC 5052 under balanced biaxial stretching is also remarkable. Uniaxial tensile test results, n values in particular, of these materials serve as a clue to these results. For the balanced biaxial stretching test, i.e., aspect ratio of the mask is equal to 1, the direction of crack formation and its propagation is perpendicular to the rolling direction in DCC 5052, whereas it is parallel to the rolling direction in TRC 5052. It is also worth noting that DCC 5052 developes "orange peel" on the surface after all testing modes of $\varepsilon_2>0$.

The r and n values of the TRC and DCC 5754 measured in uniaxial tensile tests are not significantly different. However, strain measurements, carried out for determining the right-hand side of the FLD on both samples show that DCC 5754 has relatively higher forming limit strains than that of TRC 5754. This is more pronounced for the samples tested under loading conditions imposed by the circular die. Better limit strains of DCC 5754 are thought to be the consequence of the difference in material thickness. The very small grain size of this material could also be responsible. As in the case of TRC 5052, direction of crack formation and propagation is parallel to the rolling direction of the sheet in all loading conditions where $\varepsilon_2>0$, and located at the top of the dome (Fig. 6). The influence of material thickness on formability performance, specifically under biaxial stretching of ductile materials, has been clearly established in several studies [5-9]. Thus, lower limit strains achieved under balanced biaxial stretch mode of TRC 5754 can be accounted for, at least in part, by the material thickness.

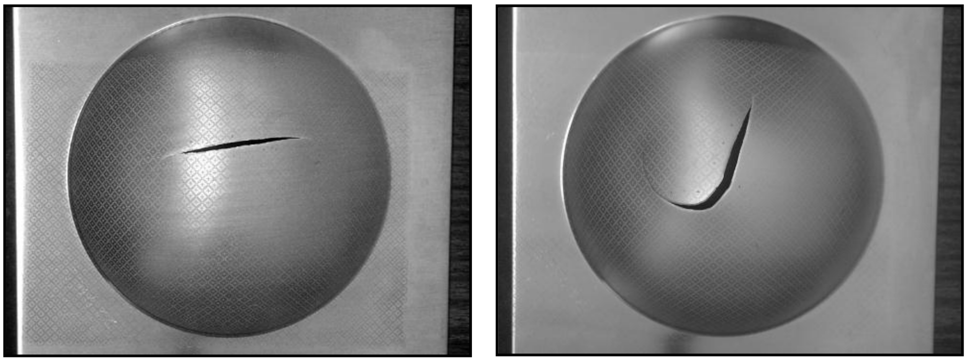


Figure 6. Typical crack propagation in samples of TRC5754 (a) and DCC5754 (b) deformed under balanced biaxial stretching mode.

The most general sources of plastic inhomogenity on the microstructural scale are anisotropy of the individual grains and second-phase particles. Those particles which are brittle and/or poorly bonded to the matrix, give rise to internal cavities at an early stage of strecthing, and are thus the most damaging. All the samples of TRC sheets produced in the soft temper at the final gauge of 1 mm revealed very fine intermetallic particles uniformly dispersed in an aluminum matrix except at or near the center plane (Fig. 4).

Channel segregates, typical of TRC materials, can be identified on the fracture surface of the biaxially strecthed samples of the TRC sheets (Fig. 7). These segregates, however, cannot be held responsible for the local instabilities and associated localized necking, in view of the magnitude of the differences in the limit strains of DCC 5754 and TRC 5754. The difference in sheet thickness of the TRC and DCC 5754 should be taken into consideration in strain limits and fracture behavior of these samples.

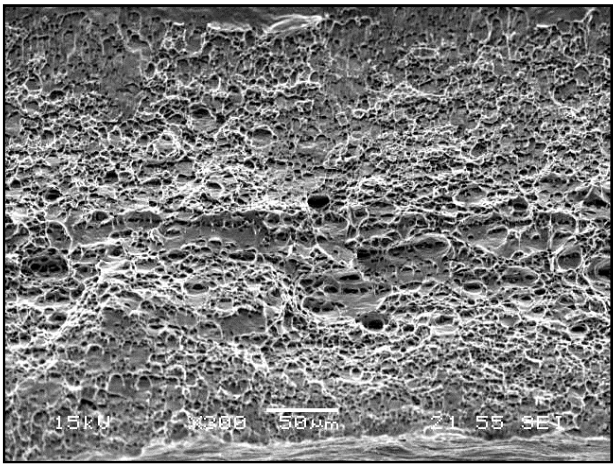


Figure 7. Fracture surface of the TRC5754 after deforming in balanced biaxial deformation mode.

Forming limit strain of DCC 5182 is slightly better than that of the TRC 5182. Directionality in strain hardening exponent, obtained through uniaxial tensile test results, was not observed in either of these sheets. TRC 5182 has the highest r value at 45^0 to the rolling direction while the DCC 5182 exhibits similar r values in all testing directions. Significantly higher n value of DCC 5182 can be correlated with the suppression of local necking that extends the forming limit strains under biaxial stretching. Although the maximum strain may be determined by fracture criterion, material with a high strain hardening capacity will distribute the strains over a larger area than one with a low strain hardening capacity.

For Al-alloys the r values is always smaller than 1 suggesting that the direct impact of r is limited. However, there is an indirect impact such that if the material shows no anisotropy (r identical for all directions) there will be no localized thinning in any particular direction leading to a more homogeneous thickness-strain distribution avoiding premature cracking [10-11]. Similar r values of 5182 measured through uniaxial tensile test in three different direction are consistent with the superior forming limits of this material. However, the TRC 5182 exhibits rather high anisotropy in tested directions. Relatively high n and elongation of DCC 5182 are clear evidences of better formability performance. Comparing the DCC 5182 with the TRC 5052, better forming properties of the TRC 5052 originate from the same type of material characteristics which dictate the operating deformation mechanism during forming.

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