

Effect of Al Addition on the Formability of Uncoated Commercial Dual Phase 1180 Steel Products

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Abstract. This paper presents the results of intentional Aluminum addition on formability of commercial DP1180 steel grades produced at ArcelorMittal. Formability was evaluated using a suite of tests such as bending under tension test, the plane strain forming limit, crack propagation resistance using compact tension test, hole expansion, bendability, etc. Results of these formability tests demonstrated that the local formability, especially the resistance to edge fracture of the product with higher Al addition was improved in comparison with the nominal product. In addition, more detailed microstructural characterization and mechanical behavior of the products was conducted to further the understanding of the effect of Al on the performance of Dual Phase microstructures.

1. Introduction

Dual-phase steels have been utilized in automotive structural applications for over two decades. The combination of high strength and ductility facilitated weight reduction of the Body-in-White (BIW) for improved fuel efficiency and increased energy absorption for enhanced crash worthiness. However, as the strength requirements for the same application increased with time, shear edge failures in stamped components became more notable. Therefore, as newer AHSS were being conceived, superior hole expansion, a characteristic that defines a steel's resistance to thinning, evolved into a critical product attribute. The current investigation was one of many studies that were undertaken at ArcelorMittal to address this need.

2. Experimental procedure

2.1 Materials

Table 1 shows the chemical composition of the two melts. The wt. % of Aluminum is indicated as low and high in the two rows. The steels were melted and finished at an ArcelorMittal USA production facility. The hot rolling, pickling, tandem rolling, annealing and finishing processes for the two steels were similar.

Table 1. Chemical composition of the two heats used to produce finished steel samples for the study.

Steel	wt. % C	wt. % Mn+Si	wt. % Al	Others
Base	0.13	2.75	Low	Nb+Ti
Base + Al addition	0.14	2.76	High	Nb+Ti

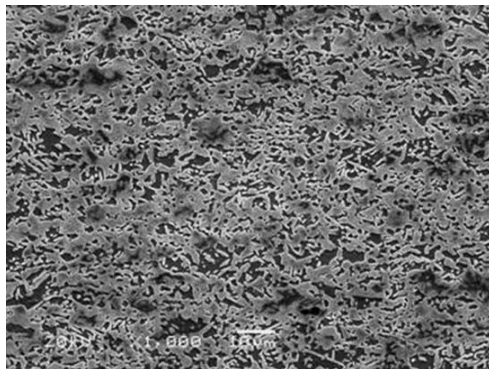


Table 2 shows the mechanical behavior including bendability and hole expansion behavior of select coils used in this study. Tensile testing was conducted using the ASTM standard in the T direction, while the ISO method [1] was used for hole expansion testing and a 90° V-bend test was used to determine the critical R/t ratio prior to fracture. As seen in Table 2, there seems to be no obvious difference in the typical mechanical properties and bendability, however the hole expansion ratio between the two coils is significantly different.

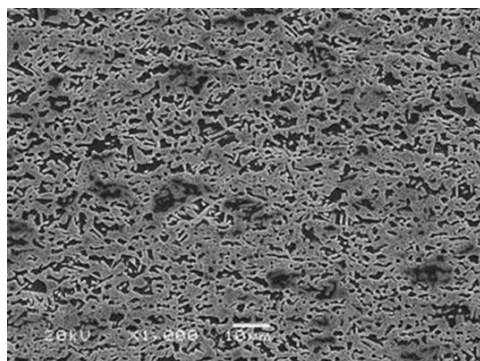
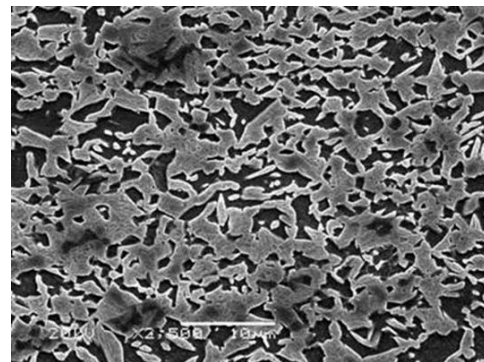
Table 2. Mechanical properties of the steels used in the study including bendability and hole expansion.

Steel	Thickness, (mm)	YS, (MPa)	TS, (MPa)	TE (%)	90° V - Bend, (R/t)	HE, (%)
Base	1.4	870	1300	10.0	2.0	25-27
Base + Al addition	1.2	893	1238	11.7	2.5	48-50

Figure 1 shows the microstructures of samples from the two coils. As seen in the images, the martensite volume fraction of the two samples is very similar ~ 60%. It can also be seen that the morphology of the martensite colonies between the two coils is also similar. Figure 2 shows results from the Electron Probe Micro Analysis (EPMA) instrument for the microstructures shown in Figure 1 focusing on Mn distribution between the two products. As seen in the figure, the coils with the higher Al addition had significantly more uniform distribution of Mn in the product. Apparently, the addition of Al resulted in a more uniform partitioning of Mn between the ferrite and martensite phases.



(a)



(b)

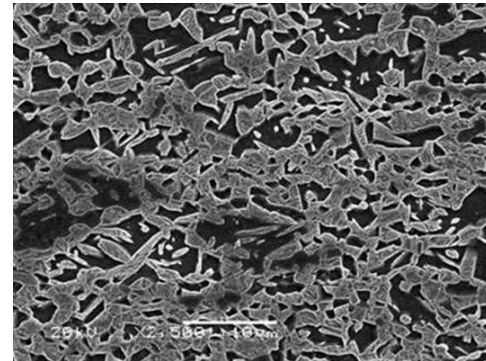


Figure 1. Microstructures of samples of coils from (a) base steel and (b) base steel + Al addition.

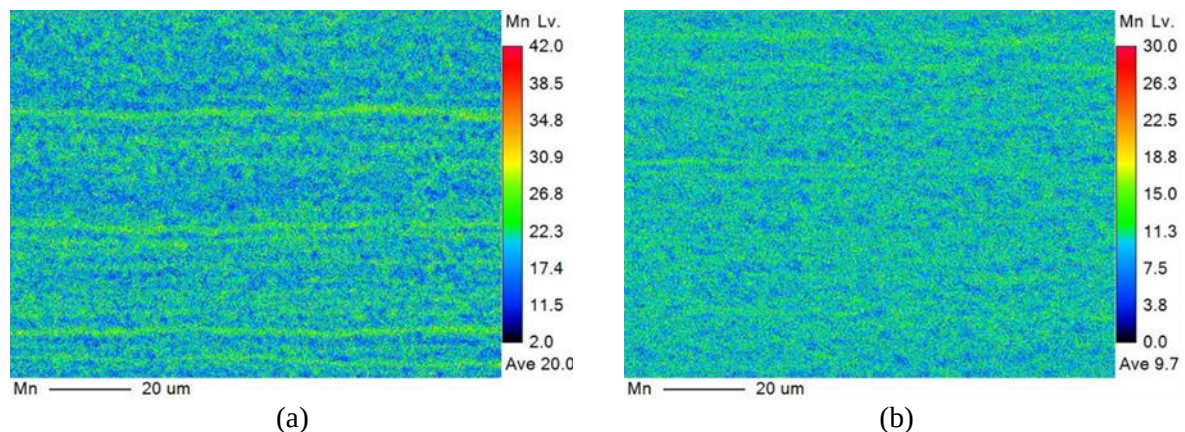


Figure 2. EPMA results of the Mn distribution for (a) base steel and (b) base steel + Al addition.

2.2 Formability Tests

2.2.1 Plane Strain Forming Limit (FLC_0). Figure 3 shows the experimental setup used to determine the FLC_0 . An MTS servo hydraulic testing system was employed to conduct the tests where Nakajima testing method (101.6mm hemispherical punch) was applied. Following some trial and error experimentation to determine the sample width for plane strain, samples of size: 95.25mm X 177.8mm were used for testing. The blanks were prepared with paint speckles on the surface. During the forming process, two cameras oriented at a fixed angle were positioned above the forming equipment, as shown in Figure 3. Images of the specimen and the speckle pattern were recorded simultaneously by the two cameras at speed of 15-20 frames/sec during forming until fracture occurred. After testing, the dedicated Digital Image Correlation (DIC) software, Vic 3D (from Correlated Solutions Inc.), was used to analyze the acquired images to calculate the major and minor strains of every point of the deformed specimens at each imaging moment. The instance of incipient necking was determined using a mixed time and position dependent approach which has been published elsewhere [2].



Figure 3. Experimental setup for determination of FLC_0 using DIC showing samples exhibiting necking and fracture.

2.2.2 Bending Under Tension Tests. Different bending conditions were generated using tooling and loading modes for deforming the samples. Figure 4 shows schematics of the two test methods. The two types of bending tests are described below.

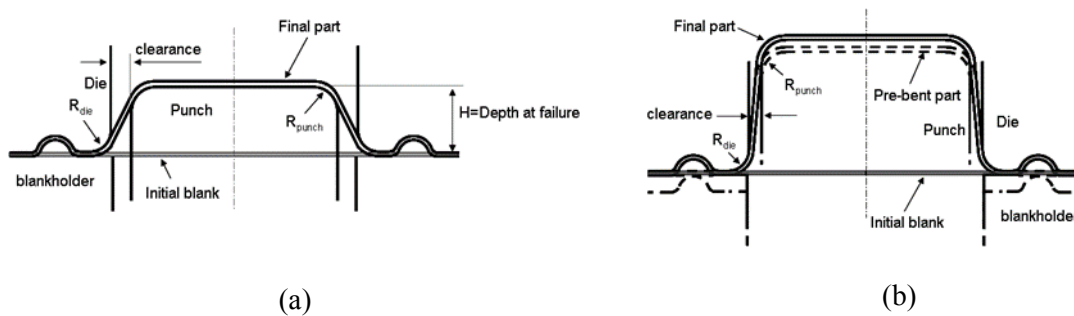


Figure 4. Schematic of the test methods used in the study (a) Stretch Bend test and (b) Draw Stretch test.

Stretch bend tests were conducted on a double action servohydraulic press using a specially designed tooling. The sample is locked using drawbeads and by applying a high blankholder force to prevent movement of the material into the die cavity as shown in Figure 4(a). As the punch moves up, the sample is stretched and bent across the punch radius simultaneously till failure of the material. In this test, the wrap angle is not constant as the metal is being stretched and bent. This test is simulative of conditions in the part, where an embossment is being formed on a main feature. A variation of the stretch bend test was also conducted in which the sample was pre-bent to 90° by movement of the punch to 50.8mm without any restraint applied to the metal. At the end of the pre-bend process, a substantial amount of material is still present in the area between the blankholder and the die. The full binder pressure of the press is then applied and the material beyond the drawbead is locked out. After lockout, the metal is stretched by moving the punch up till failure of the sample. The test is shown schematically in Figure 4(b). Thus, in the draw stretch test, tension is applied after bending. Three replicates were tested for each condition. Before testing, the lubricant, FERROCOTE[®] 61 MAL HCL1, was thoroughly applied to both sides of the samples. In the stretch bend and the draw stretch tests, the upward motion of the punch was stopped and retracted when the force on the punch actuator reduced by 5% with increasing punch travel. Use of the 5% load drop as a stopping point was determined after several exploratory experiments to determine a suitable measure of load drop to stop the forming process to capture the early stages of strain localization or fracture. This method of combining bending and stretching deformation has been used in the past [3]. The stretch bend and draw stretch tests are somewhat like the bending under tension test [4-6] which also evaluates the formability in bending under tension conditions. However, the bending under tension test involves significant metal movement over the roller radius, which is more simulative of conditions at the die entry radius. In contrast, the stretch-bend and draw stretch tests conducted in this work is more simulative of the conditions on the punch with limited movement of the metal over the radius.

2.3 Advanced Mechanical Characterization

In addition to conventional formability testing, advanced mechanical testing was also conducted to understand the difference in behavior between the two materials.

2.3.1 Compact-Tension Testing. Crack propagation resistance was determined using the Compact Tension (CT) test geometry shown in Figure 5a. Over the last few years, there has been considerable evidence correlating the hole expansion behavior to fracture toughness [7-8] of the material. In this study, axial fatigue loading (P_{max} : 600N, $R=0.1$ and 100,000 cycles) was used to create a pre-crack of length 1mm. The specimen was then loaded in tension and the crack displacement was determined using the acquired images. The images from the camera and the displacement signal from the test frame were synchronized to determine the energy dissipated in the specimen as a function of crack length. Figure 5b shows an example of the load-displacement curve obtained from this test. In this case, the displacement of 1.5mm corresponded to a crack growth of 4mm. As shown in the figure, the energy absorbed by the specimen for a given crack opening displacement can be determined by calculating the area under the load-deflection curve.

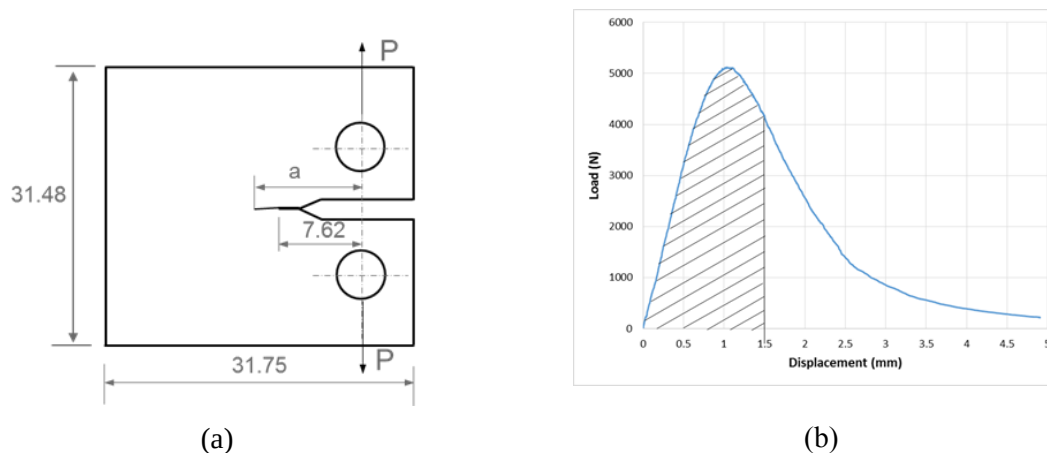


Figure 5. Compact Tension (CT) test used to quantify crack propagation resistance of the materials used in this study showing (a) Geometry of test specimen with dimensions in mm and (b) Load displacement curve with the shaded area showing the energy absorbed for the crack tip displacement of 4mm.

2.3.2 Nano-indentation. Nano-indentation was conducted using the system from Agilent Technologies. Testing was done using a Berkovich indenter. The specimen is mounted and prepared as for traditional metallography. The surface is indented using a prescribed force in a series of indents across the length and width of the examined region resulting in a matrix of nano-hardness results across the examined region. The distance between the indents ranged between 15-25 μm . The samples were then examined to isolate the phases of the indented regions to determine the hardness distribution for the different phases. In this study, the technique was used to examine hardness of the martensite colonies in the two steels.

3. Results

3.1 Formability Testing

Figure 6 shows the FLC_0 of the two materials determined using DIC and the traditional NA method using circle grid analysis and the finger touch method to determine incipient necking. A combined time and position dependent method was used [2] with DIC to determine the point of incipient necking. As seen in Figure 6, the results using DIC and the traditional NA method are comparable for both steels.

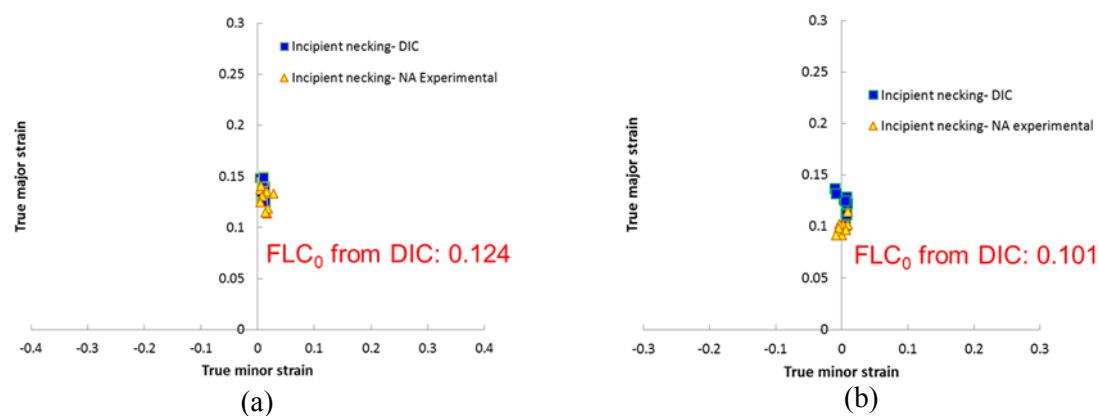


Figure 6. Plane strain forming limit FLC_0 of the (a) Base steel and (b) Base steel + Al addition.

Table 3 shows the comparison of FLC_0 determined using the traditional NA approach and DIC for the two steel grades in this study. Also shown is the prediction of FLC_0 using the Keeler Brazier

equation, which is typically used to assess formability using the terminal n-value and thickness of the product. As seen in Table 3, the terminal n-values between the products being comparable, the difference in the FLC_0 results primarily from the difference in thickness.

Table 3. Comparison of FLC_0 determined using the DIC, traditional NA experimental method and the Keeler-Brazier equation.

Material	Thickness (mm)	Terminal n-value	FLC_0 (True Strain)		
			DIC	NA Experimental	KB equation
Base steel	1.4	0.055	0.124	0.112	0.106
Base steel + Al addition	1.2	0.052	0.101	0.092	0.095

Figure 7 shows the samples from the two variations of the Bending Under Tension test; stretch bend test and draw stretch test as described earlier. As seen in the picture, the stretch bend test results in a much smaller forming depth (similar to forming embossments) when compared to the draw stretch test.

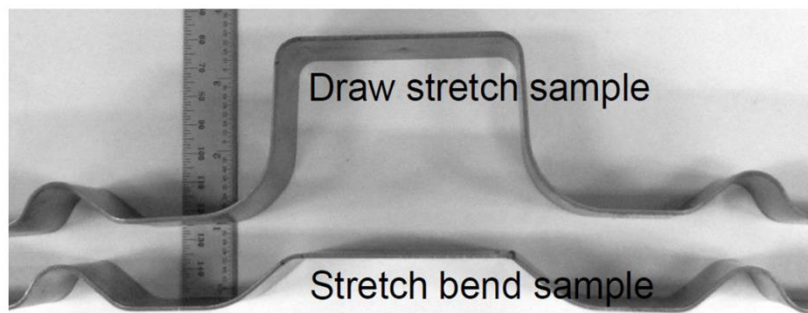


Figure 7. Photograph of bending under tension test specimens showing the stretch bend sample and the draw stretch sample.

Figure 8 shows the results from the bending under tension testing, where formability is expressed as the height to failure as a function of the R/t ratio. It should be noted that in the draw stretch test, the initial pre-bend height of 50.8mm is subtracted from the total actuator displacement. As seen in the figure, especially for the draw stretch test, the formability under very tight bend radii is superior for the base + Al steel in comparison with the base steel. Under more generous bend radii conditions, the formability is somewhat comparable.

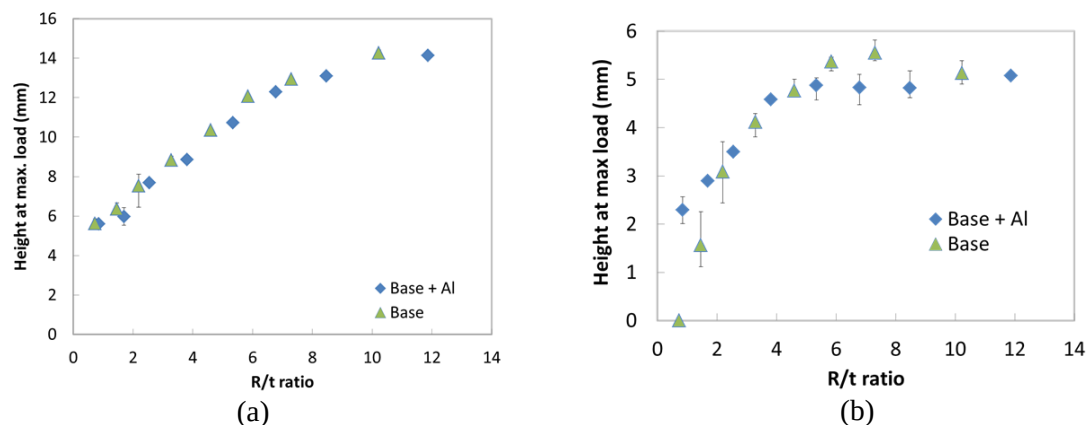


Figure 8. Formability under bending under conditions for the (a) stretch bend test and (b) draw stretch test. For the draw stretch test, the initial pre-bend height of 50.8mm is subtracted.

3.2 Compact Tension Testing

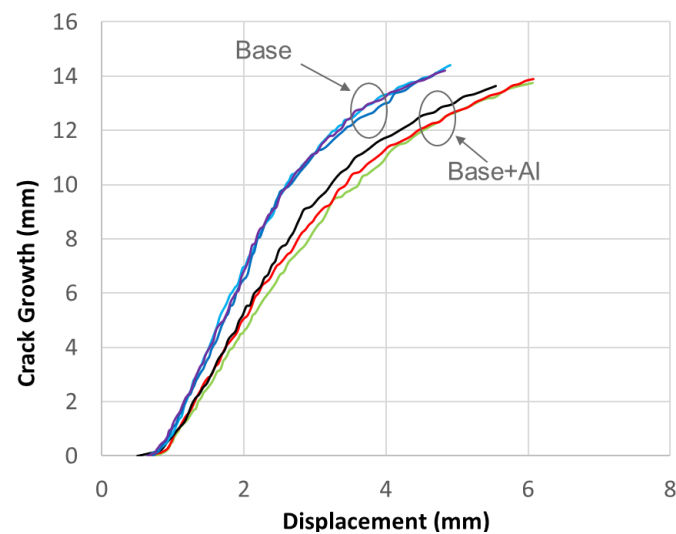


Figure 9. Crack growth rate as a function of actuator displacement for the different steel samples.

Figure 9 shows the comparison of the crack growth rate determined using the C-T test method described earlier expressed as a function of actuator displacement for the steel samples used in the study. As shown in Figure 9, the crack growth rate for the Al containing steel is significantly lower than the base steel. Figure 10 shows a comparison of the crack propagation energy for the two steels as a function of the crack growth where it can be seen that for the same crack length, the energy required to propagate the crack is higher for the Al added steel. The C-T test thus very clearly shows the improvement in local formability shown in the hole expansion results in Table 2 and the bending under tension results shown in Fig. 8 resulting from an increased energy required for crack propagation. On the other hand, from Figure 6, the difference in FLC_0 was not very significant after accounting for the different thicknesses.

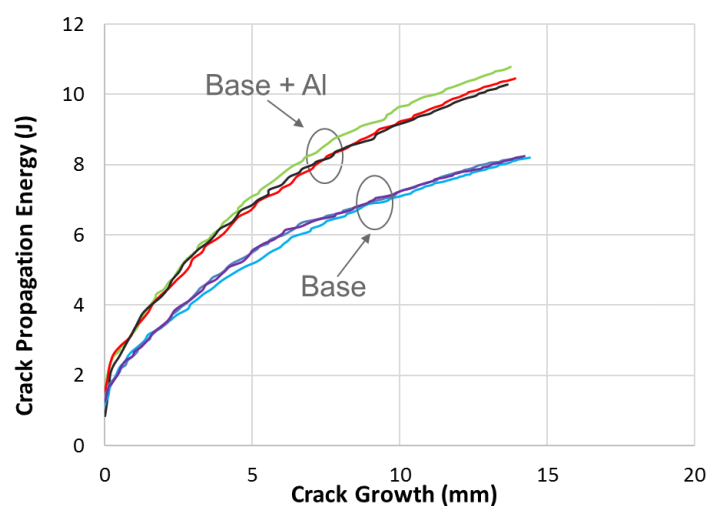


Figure 10. Crack propagation energy as a function of crack growth for the steels in the study.

3.3 Nano-Indentation Results

Figure 11 shows the distribution of the hardness of the martensite for the (a) base steel and (b) base steel + Al as determined by the nano-indentation testing. As seen in the figure, for the base steel, for more than 50% of the martensite colonies indented, the hardness ranged between 8-10 GPa. In contrast for the base + Al added steel, for more than 50% of the indented colonies, the martensite hardness ranged from 4-7 GPa. It seems that the addition of Al somehow influences the hardness distribution and the maximum hardness of the martensite contributing to better local formability as shown previously.

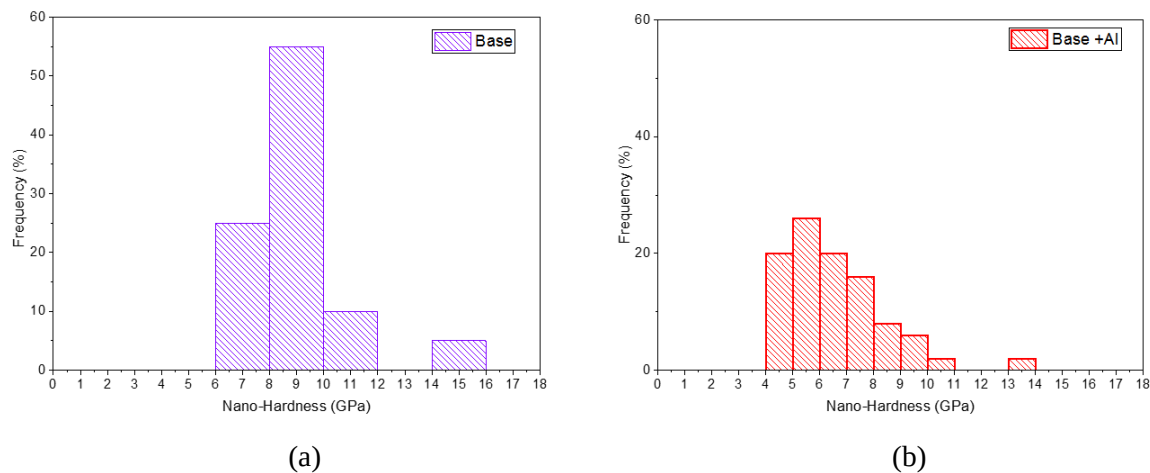


Figure 11. Nano-hardness measurement distribution for the (a) base steel and (b) base steel + Al.

4. Discussion

It can be clearly seen from the results presented in this paper that intentional addition of Al seems to have a strong influence on the hardness of the martensite colonies in the traditional dual phase microstructure which in turn improves the resistance to crack propagation and hence results in improved local formability. On the other hand, under more generous forming conditions, there was no clear advantage with using the higher Al added product. Thus, the study offers some guidelines on the choice of materials for stamping. When the local forming conditions can be challenging especially with respect to edge stretching or bending over a tight radius including tension, products with a more uniform and homogeneous microstructure might perform better. However, when the forming conditions are more generous, strain hardening behavior will probably be dominant.

The effect of Al on the hardness of martensite colonies and subsequent improvement in local formability is clearly interesting. From Figure 2, in the EPMA results of the Mn distribution, there is some clear evidence of differences in chemical homogeneity in the martensite colonies. This effect needs to be studied further, however there is some recent evidence [9] of the effect of Al on chemical segregation of Mn in the different phases during upstream steel processing. Interestingly, from Table 2, it can be seen that for the 90° bendability the critical R/t ratios for the two steels are similar. This could be explained by the fact that for the assessment of bendability, the presence of a visible crack on the surface is used as a criterion for failure. The strong advantage of Al addition is evidenced by the resistance to crack propagation as seen in Figure 10 and is also reflected in the difference in hole expansion ratio shown in Table 2. This positive effect of Al on local formability can be exploited effectively for good combination of local and global formability.

5. Conclusions

The following are the conclusions from this study

- Two versions of DP1180 steel were industrially processed to produce similar tensile properties in the as annealed state. Both steels exhibited similar dual phase microstructures; however, the base steel exhibited a higher degree of Mn banding.
- Of the two steels, the base + Al steel showed a significantly higher hole expansion than the base steel
- Fracture toughness data suggests that the higher resistance to crack growth / higher crack propagation energy may contribute to the higher hole expansion in the base + Al steel
- Traditional forming limits (FLC₀) for both steels are similar and compare well with the Keeler-Brazier equation
- Both steels behaved similarly in stretch bend testing. Under draw stretch conditions, the base + Al steel performed better than the base steel under tight bend conditions. At larger R/t ratios, the behavior of both steels was similar
- Overall, the addition of Al to the base version of the DP1180 steel enhances local formability as evidenced by higher hole expansion capability and tighter R/t stretch drawability.

Acknowledgments

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