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Effects of weld line position and geometry on the formability of laser welded high strength low alloy and dual-phase steel blanks

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ABSTRACT

Formability of laser welded blanks (LWBs) was measured in the biaxial stretch forming mode using the limiting dome height (LDH) test. High strength low alloy steel and two dual-phase (DP600 and DP980) steels were used for fabricating LWBs. The failure location and the LDH values of the formed blanks were correlated to the hardness across the welds. The effects of weld line position and geometry on the formality was evaluated by investigating LWBs with three different weld line positions (0, 15 and 30 mm offsets from the blank center) for both linear and curvilinear geometry. The formability was found to be dependent on the weld line position and increased when the weld was located farther from the blank center due to more uniform strain developed during LDH tests. Interestingly, weld line geometry was observed to have a stronger influence on the formability DP600 steel. In addition to weld line position and geometry, heat affected zone softening was observed to be the dominant factor in controlling the formability of all the DP980 LWBs and the curvilinear welds of DP600 with failure consistently occurring in the region with more severe softening.

1. Introduction

The continuous growth in environmental and economic concerns has pushed automotive manufacturers to implement innovations to reduce vehicle emission, improve fuel economy without compromising the safety, structural integrity and crash performance of the vehicle. One of the ways the auto makers have been trying to resolve above mentioned issues is by increasing the use of laser welded blanks (LWBs) in car body structure. LWBs are composed of two or more sheets of similar or dissimilar materials, thicknesses and/or coating types welded together. These composite blanks are then stamped to form the required three dimensional automotive body parts [1]. The advantages of LWBs include weight reduction, cost minimization, and scrap reduction with improved steel utilization. Typically, LWBs are made with low or ultralow carbon steels; however, their weight reduction ability can further be increased by employing high strength steels like high strength low alloy (HSLA) steel and even more so by advanced high strength steels (AHSS) which also improves the crash performance of the blanks [1–4].

AHSS family includes wide variety of steels such as dual-phase (DP) steel, transformation induced plasticity (TRIP) steel, complex phase steel, martensitic steel and twinning induced plasticity (TWIP) steel, which are categorized based on the microstructure and processing history. AHSS has superior ultimate tensile strength and excellent formability compared to HSLA and is able to form complex shapes due to its high strain hardening behavior [5]. These characteristics make AHSS a potential candidate for manufacturing energy absorbing components for vehicles [5,6]. Amongst all AHSS, DP steel is of particular interest due to the optimum combination of strength and formability, which is attributed by its unique microstructure consisting of a continuous soft/ductile ferrite matrix embedded with hard martensitic phase. Although DP steels have several advantages, they exhibit heat affected zone (HAZ) softening when welded, which occurs at the sub-critical region of the HAZ due to tempering of martensite in the base metal (BM). The HAZ softening phenomenon has been known to result in reduction of the local hardness below that of the BM [7–9], which is more significant in the higher grades (UTS $\geqslant$ 800 MPa) of DP steels [10,11]. HAZ softening has been reported to degrade the performance of the DP steel welds [12–17]. For example, the tensile strength and ductility of the DP steel LWBs decreases because of HAZ softening [12,13], with increase in softening and width of the soft zone reduces the strength and ductility further as reported by Panda et al. [14]. Lap-shear tensile strength of the DP steel spot welds have also been observed to reduce with increase in softening due to premature failure in the soft zone, as reported by Okita et al.

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[10] and Ghosh et al. [15]. Furthermore, recently Xu et al. [16] and Parkes et al. [17] have reported that the HAZ softening reduces the fatigue resistance of the DP980 steel with a decrease in softening improved the fatigue performance [18].

The formability of the LWBs have been an important subject for the researchers as can be observed from the studies reported so far; such as clarifying fundamental formability characteristics of LWB [3], methods of evaluating formability of the LWBs in punch stretching, stretch flanging and deep drawing [4]. There are also reports on the effect of the weld design on the formability of LWBs for different material combinations such as dissimilar thickness or strength ratios [19–22] and weld line movement in dissimilar materials combination [23]. For instance, Chan et al. [19] observed that increasing the strength ratio of the LWBs resulted in decrease in the formability and forming limit curve. Like the tensile and fatigue properties, HAZ softening reduces the formability of laser welded DP steels because of the strain localization in this region leading to premature failure in the forming process [20–24]. It has also been reported that the detrimental effect of HAZ softening can be reduced by increasing the welding speed (i.e. lowering the heat input), which decreases the softened zone width as a result of less severe martensite tempering, hence improving the mechanical properties [14,18] and formability of the DP steel LWB [21,26,27–29]. For example, tensile strength close to the BM was observed when higher welding speed was used [18], the soft zone width was found to increase with increasing welding speed resulting in improved strength and ductility [14]. Sreenivasan et al. [21] concluded that higher welding speed in Nd:YAG laser resulted in an improved formability compared to lower speed used in diode laser. Friction stir welding has been reported to result in 20% higher formability compared to CO_2 laser welding in DP590 steel [29]. In another study, Padmanabhan et al. [30] have reported the effects of anisotropy on the forming behavior of mild steel-DP steel welded blanks and they concluded that by controlling the anisotropy, formability can be improved. However, the effect of anisotropy was not beneficial when applied to DP steel welded blanks, where the HAZ softening dominates formability [30]. Another successful attempt to improve formability of DP steel was by fabricating dissimilar LWBs with HSLA steel [23]. Additionally, there were also attempts on varying the weld line positions in dissimilar welded blanks; wherein it was observed that the formability increases due to improved uniform strain distribution on the deformed blank when the weld line is placed farther from the center of the blank [22,30,32,33].

Recently, the effects of seam radius (i.e. radius of curvature of the weld) and thickness ratio [34,35]; and the influence of blank size [35] on the forming behavior of curve seam welded blanks on formability have been reported. However, there is lack of reports on the comparison of the effects of curved and linear weld line positions on forming behavior of LWBs. Thus, the present study aimed to investigate the effects of weld line position and geometry on the formability of laser welded HSLA and DP steel blanks considering this will facilitate the understanding of the influence of weld design on the forming behavior of LWB involving these automotive steels.

2. Experimental details

In the present study, three steel sheets were chosen to manufacture LWBs: HSLA (high-strength low-alloy) steel, DP600 and DP980 dual-phase steels (both are AHSS) with nominal thickness of 1.14 mm, 1.2 mm and 1.2 mm, respectively. The BM microstructure of HSLA steel contains a ferrite matrix decorated with fine alloy carbides, whereas DP steels consist a mixed microstructure containing continuous ferrite matrix and martensite islands (26% in DP600 and 54% in DP980) as shown in Fig. 1 [32]. The mechanical properties of the steels are given in Table 1. These materials were chosen because of their applications in the automotive industry as structural materials, and in rails and pillar components to enhance crash performance [4,5].

To fabricate LWBs the steel sheets were sheared in to 200 mm × 200 mm coupons. The steel coupons were clamped tightly with a specially designed fixture alignment intact and to minimize distortion during welding. This custom fixture had a widened back shielding gap to accommodate the weld curvature and an inlet for the back shielding gas to enter. A Nuvonyx ISL-4000L High Power Diode Laser head mounted on a Panasonic VR-16 robotic arm was used for welding. The laser beam was aligned with the guide lines drawn on the blanks prior to welding. The laser beam had a rectangular spot (12 mm × 0.9 mm) and a focal length of 80 mm. Welding was carried out using 4 kW power and a welding speed of 0.85 mm/min in the bead-on-plate orientation. All the welds were made perpendicular to the rolling direction with the weld line located at 0 mm, 15 mm and 30 mm from the center of the blank. In case of curvilinear weld geometries, welds were made with a curvature of 220 mm as illustrated in Fig. 2; showing the naming convention of the blank. The left side of the

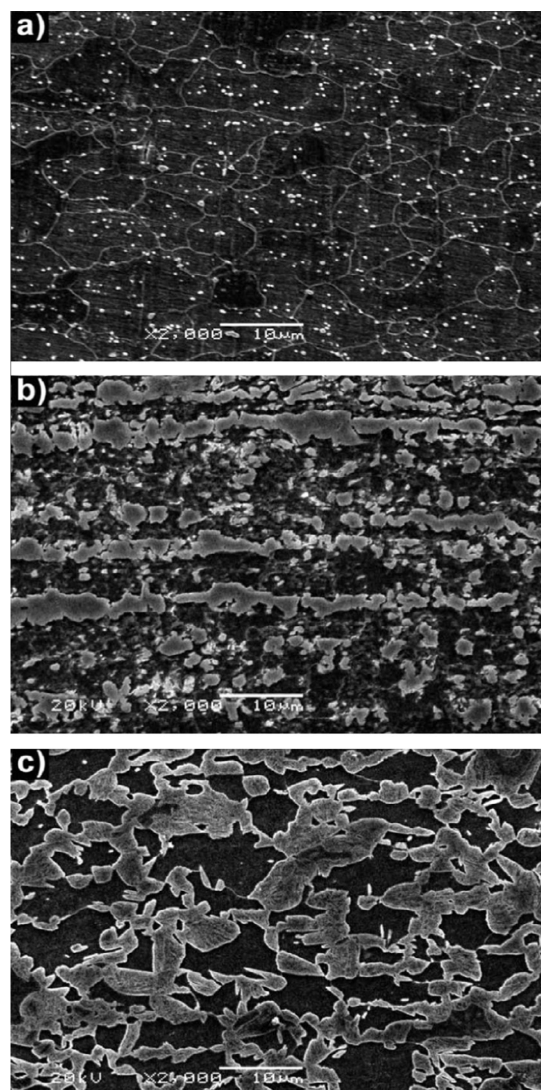

Fig. 1. Base metal microstructure of the steels used in the study: (a) HSLA, (b) DP600, and (c) DP980, taken from [32].

Table 1
Mechanical properties of the steels used.

Steel grade	HSLA	DP600	DP980
Yield strength, MPa	421	365	672
Ultimate tensile strength, MPa	511	631	1058
Uniform elongation,%	13.5	16.0	6.9
Total elongation,%	25.6	25.6	12.1

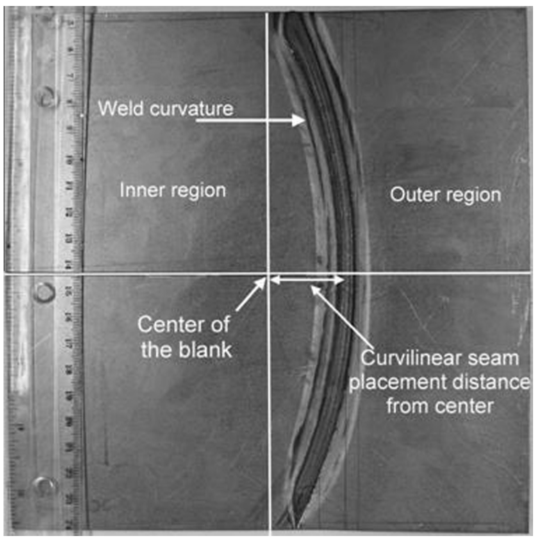

Fig. 2. An example of curvilinear welded blank with weld curve placed at a distance from the center of the blank.

curvilinear welded blanks is referred as the inner region and the right side as the outer region (Fig. 2). The center of the blank has been labeled to show the weld line offset distance.

The cross-sections of the curved welds were cold mounted, mechanically ground and polished to 0.5 μm. After polishing, the specimens were etched with 2% Nital solution to reveal the microstructures of the weld cross-sections. Vickers microhardness was conducted on the etched specimens with a load and dwelling time of 300 g and 15 s, respectively. In order to get better resolution, microhardness measurements were carried out in three rows across the weld cross sections. Sufficient distance (200 μm) was maintained between the horizontal and vertical indentations to avoid the interference from neighboring indentations.

To evaluate the formability of the LWBs, Hecker's LDH tests [36] were conducted using a hemispherical punch of diameter 101.6 mm mounted on a double action MTS 866 hydraulic press, the schematic diagram with details can be found elsewhere [21]. An optimum blank holding force was applied to deform the blank only within the die opening. All blanks were lubricated with a Teflon sheet placed in between the blank and the punch to induce biaxial stretch forming. Domes were pushed with a punch speed of 12 mm/min. The LDH of each specimen was captured using the Labview data acquisition software. All the tests were stopped when necking or fracture was observed on the specimens, when the punch load dropped and the LDH was the punch height that corresponded to the maximum load of the LWB. To facilitate the measurement of the major and minor strains, 2.5 mm diameter circular grids were electro-etched on the blanks prior to forming. After forming, the engineering strains were measured using grid analyzer, GridMouse. This program determines the difference between the deformed grids with the original calibrated grids. The biaxial strain state during forming was confirmed from the strain distribution profiles of the parent steel sheets illustrated in Fig. 3.

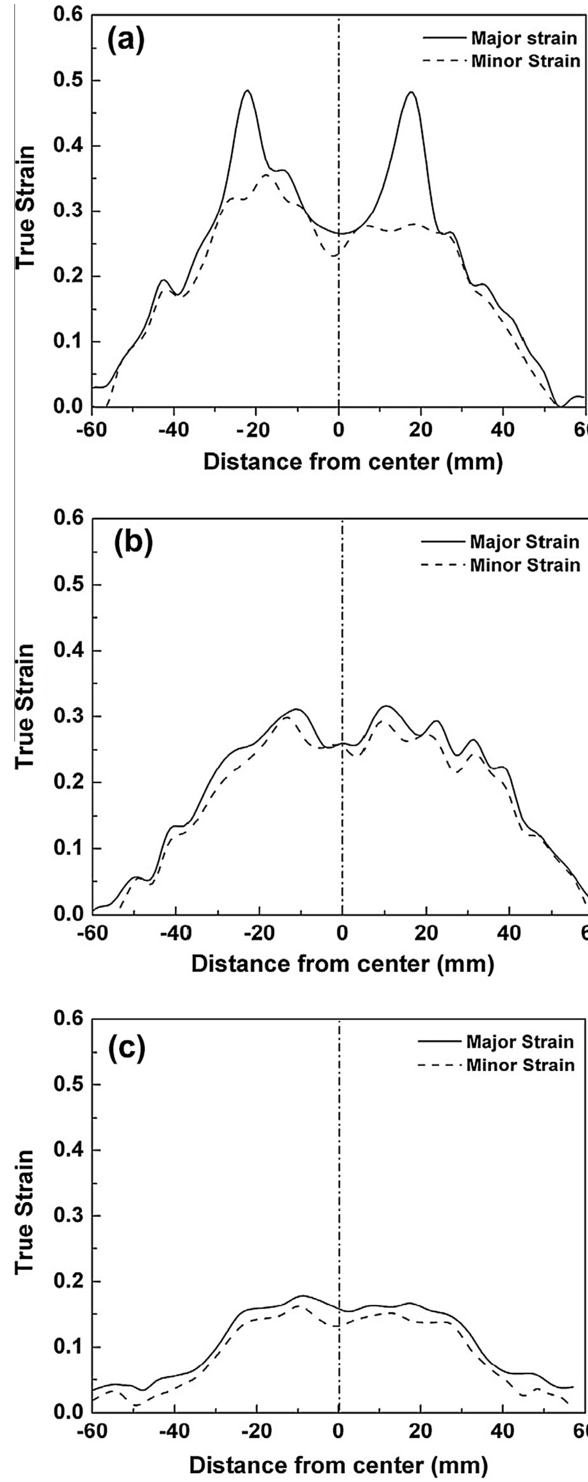

Fig. 3. Major and minor strain distribution on biaxial stretch formed parent steel sheets: (a) HSLA, (b) DP600, and (c) DP980, taken from [32].

3. Results and discussion

3.1. Hardness profiles of the LWBs

Hardness profiles obtained from the average of three rows of indentations made across the cross sections of the curvilinear welds of HSLA, DP600, and DP980 steels are shown in Fig. 4a–c, respectively. For easy reference, different regions of the weldment

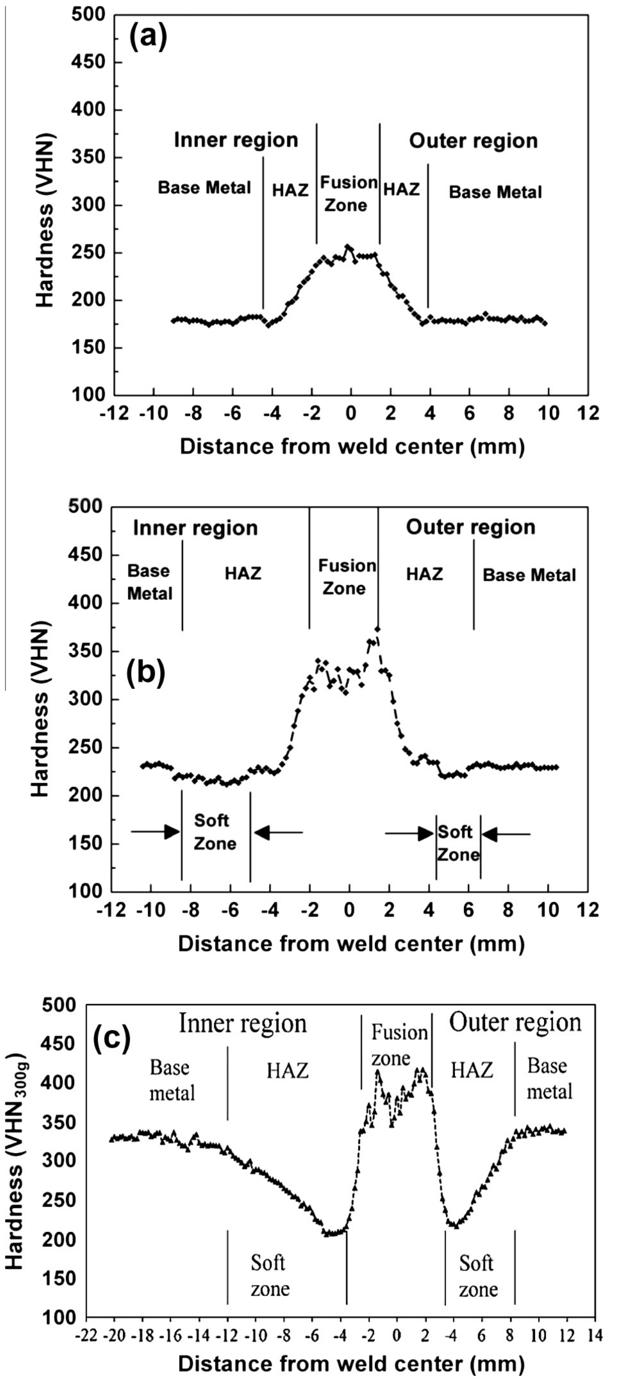

Fig. 4. Hardness profiles obtained from the curvilinear welds of (a) HSLA, (b) DP600, and (c) DP980 steel.

such as fusion zone (FZ), HAZ and BM have been indicated in the hardness profiles. The left side of the FZ in the plots corresponds to the inner region of the curvilinear weld whereas the right side is the outer region as illustrated in Fig. 2. It may be noted that the specimens for hardness profiling were sectioned normal to the local weld path near the horizontal arrow shown in Fig. 2.

The average FZ hardness was measured to be 246 ± 5 HV in the HSLA weld (Fig. 4a). The HAZ was also characterized by high hardness (∼245 HV), but lower than the FZ hardness, close to the fusion zone line followed by continuous drop before merging into the BM hardness (179 ± 2 HV). The continuous drop in the HAZ hardness is attributed to the decrease in the fraction of the martensite, with increased distance from the fusion line, formed by solid-state phase transformation of austenite during fast cooling that occurs in laser welding. Interestingly, the HAZ in the inner region (3.2 mm) was observed to be 14% wider than the outer region (2.8 mm). Additionally, HAZ softening was not observed from the hardness profile. This was expected as the BM microstructure of HSLA steel does not contain martensite (Fig. 1a).

The DP600 steel weld showed a higher average FZ hardness of 330 ± 7 HV (Fig. 4b) compared to HSLA (246 ± 5 HV, Fig. 4a). Similar to HSLA, the HAZ of DP600 weld was characterized by high hardness values (∼320 HV) close to the fusion line and by a decreasing hardness along the HAZ towards the BM. However, a slight reduction in hardness (marked as soft zone in Fig. 4b) with respect to the BM (200 ± 8 HV) was found at the HAZ close to the BM (Fig. 4b). The width of the soft zone at the inner region (∼3 mm) was observed to be 50% wider than at the outer region (∼2 mm). The wider HAZ at the inner region is consistent with the HSLA hardness profile shown in Fig. 4a. However, there was no significant difference in the softening between the inner region (∼189 HV) and the outer region (∼193 HV).

Fig. 4c shows that the average FZ hardness (400 ± 11 HV) and the BM hardness (340 ± 13 HV) in the DP980 steel was higher than both DP600 and HSLA steels. In addition, there was a significant drop in hardness in the soft zone suggesting severe softening in the HAZ of DP980 steel. Again, this was not observed in HSLA steel (Fig. 4a) and was insignificant in DP600 steel (Fig. 4b). Similar to the DP600 steel, the extension of the softened region at the inner region was ∼8 mm, which was 60% higher than the soft zone width at the outer region (∼5 mm). However, the softening was slightly higher in the inner region (∼208 HV) than in the outer region (∼215 HV) of the DP980 weld.

Based on the results of hardness profile (Fig. 4a–c) it was concluded that the curvilinear weld formed an nonuniform extension of the HAZ on its either sides regardless of the steel type and grade. For example, the soft zone width observed in the DP steel welds was always higher at the inner region compared to outer region. In addition, the soft zone width was also seen to increase with the grade of the steel i.e. DP980 steel (Fig. 4c) formed wider soft zone compared to DP600 (Fig. 4b). Although softening was not observed in the HSLA steel, the extent of the HAZ in the inner region was still found to be longer than the outer region. The severity of softening in DP steels can be represented by the hardness difference (ΔH) between the BM and the lowest hardness in the soft zone. From this, it can be found that the more severe softening was observed at the inner region of the curvilinear welds in both DP600 (ΔH = 11 HV) and DP980 (ΔH = 132 HV) steels. It has been reported that the above-mentioned factors (HAZ width and severity of softening) are directly related to the heat input/thermal cycle in welding for a given martensite fraction in the BM [7–12,14,18,25] i.e. higher heat input results in wider soft zone/HAZ with more severe softening (higher ΔH). In the present case the soft zone width and severity of the softening was affected by the nonuniform heat distribution due to the weld line geometry; the curvature of the weld caused the heat to concentrate more in the inner region whereas in the outer curvature region there is a larger area for the heat to dissipate because the heat transfers in the radial direction for curved geometry [37]. This caused the wider soft zone and HAZ at the inner region than outer region of the curvilinear welds (Fig. 4). On the other hand, for a given heat input the severity of softening is related to the volume fraction of martensite in the BM [7,10]; higher fraction of martensite results in more severe softening (higher ΔH). Accordingly, the DP600 steel used in the present study contains lower fraction of martensite (26%), which resulted in a less severe softening when compared to DP980 steel with higher martensite content (54%) leading to more severe softening (Fig. 4).

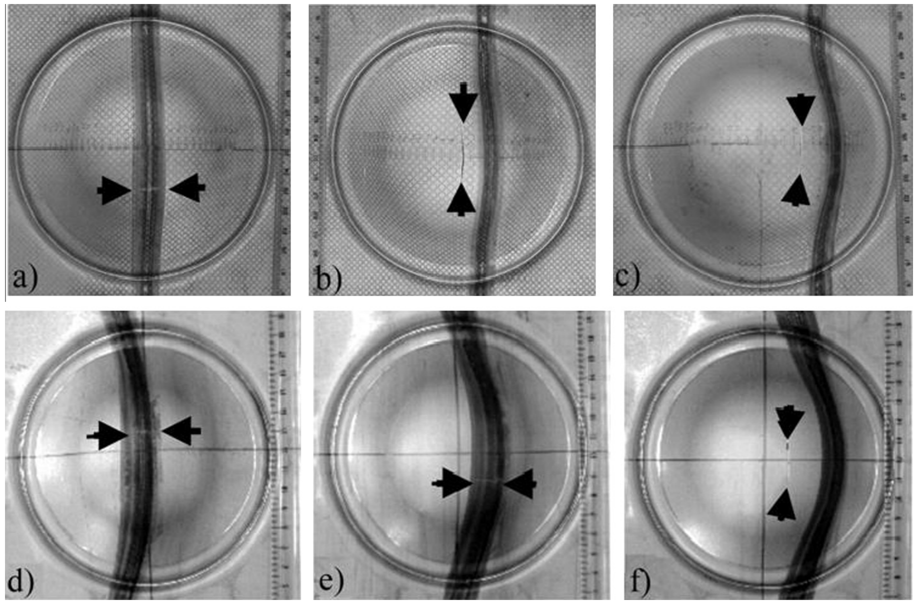

Fig. 5. Failure locations in formed (a–c) linear and (d–f) curvilinear HSLA welded blanks with weld line positions of 0 mm, 15 mm, and 30 mm from center.

3.2. Failure location

The biaxial strain stretch formed blanks of HSLA with linear and curvilinear welds at different positions are compared in Fig. 5. For the ease of observation, the failure locations are marked by arrows in the images of all the formed blanks. A mix mode failure was observed in the HSLA welded blanks i.e. across the weld (Fig. 5a, d, and e) or parallel to the weld in the BM with the fracture occurred consistently 10–20 mm away from the weld line (Fig. 5b, c, and f). This is supported by the results of Xia et al. [25,31] indicating that the fracture consistently follows a curved path with the maximum radial distance of the fracture 30 mm away from the blank center in both monolithic and linear (weld line at center i.e. 0 mm offset) welded blanks of HSLA steel. They also reported that the welded blanks consistently failed across the weld regardless of the orientation between weld line and rolling direction [25] supporting the failure locations in the present study for weld line position at 0 mm offset (Fig. 5a and d). However, the blanks, where the weld line was offset by 15 mm and 30 mm, failed in the base metal. This is due to the fact that maximum deformation occurs at the center and the vicinity of the punch pole. So, failure occurs in the region where the local strain first crosses the strain limit of the material. Thus, the present results agree with literature, which indicate that failure in the HSLA welded blanks was located 10–20 mm away from the blank center with insignificant effects of weld line position and geometry. The discussion on the strain distribution will follow later in the article.

Like HSLA, inconsistency in the failure location was observed in the DP600 linear welded blanks (Fig. 6a–c); however, the failure in the DP600 curvilinear welded blanks was consistently in the HAZ i.e. 3–5 mm away from the weld center (Fig. 6d–f). These failure locations correspond to the soft zone, which was observed in the inner region of the weld where slightly higher softening was measured than the outer region (Fig. 4b). This indicates there is a strong relation between the HAZ softening and the failure location in DP600 curvilinear welds whereas no such correlation was observed for linear welded blanks where the HAZ softening was symmetrical on both sides of the weld line suggesting that failure occurred in the region where local strain reaches the maximum limit of the material. The failure at the soft zone is related to non-uniform straining of the blank which will be discussed in the later section.

The DP980 welded blanks failed consistently in the HAZ and fracture was located ~3–5 mm away from the weld center, irrespective of the weld line position and geometry, as shown in Fig. 7. Similar to the DP600 steel, the failure location in the DP980 curvilinear welds was found to occur on the inner region of the weld line corresponding to the location of minimum hardness in the soft zone as observed in the hardness profiles (Fig. 4c). The soft zone is the weakest part of the blank, and during the LDH testing strain is localized in this area leading to premature failure of the specimen. Failure location at the soft zone in the DP980 LWBs was corroborated well by the literatures [20,21,23,25]. It may be noted that in monolithic DP980 sheets the failure always followed a straight path and occurred at a radial distance of 17 mm from the center of the blanks [21,25,31].

Based on the failure location observations, a strong correlation was found between the HAZ softening and failure location in DP980 steel where fracture occurred consistently in the maximum softened zone regardless of the weld line position and geometry. Additionally, in the curvilinear welded blanks, prediction of the failure location was found to be easier for DP steels as fracture was observed to take place consistently in the soft zone in the inner region of the weld line, which was absent in the HSLA LWBs.

3.3. Limiting dome height

The comparison of LDH values obtained in biaxial stretch forming experiments of the linear and curvilinear welded blanks with different weld line positions is shown in Fig. 8. It was clearly observed that for all the steels welding (with the exception of HSLA with weld line position of 30 mm) lowers the LDH compared to the parent materials suggesting reduction in formability. The lowered formability are generally attributed to the presence of weld zones and the heterogeneity in the properties at the region of the maximum strain, which leads to non-uniform deformation.

In the HSLA specimens, the LDH increases as the weld line position becomes farther from the blank center and eventually comes close to the parent monolithic sheet, this trend occurred in both the linear and curvilinear welds. This can be attributed to the in-

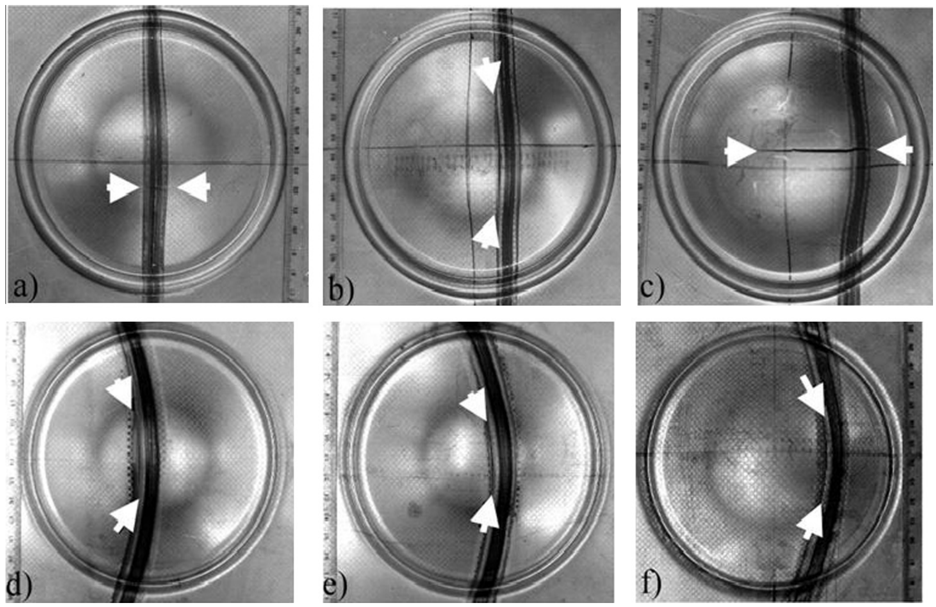

Fig. 6. Failure locations in formed DP600 LWBs with different weld line positions of linear welds: (a) 0 mm, (b) 15 mm, (c) 30 mm from center; and curvilinear welds: (d) 0 mm, (e) 15 mm, and (f) 30 mm from center.

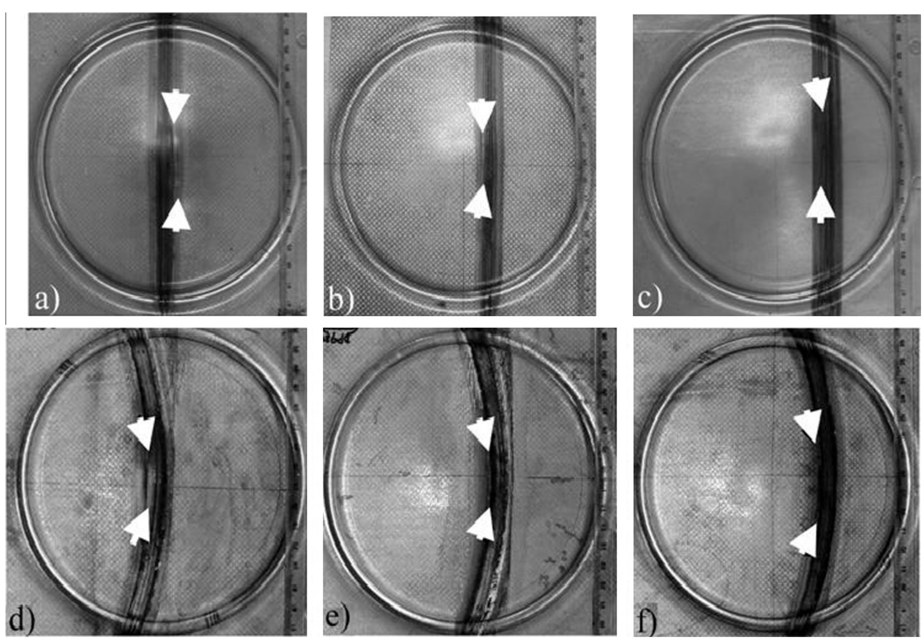

Fig. 7. Failure locations in formed DP980 LWBs with different weld locations of linear welds: (a) 0 mm, (b) 15 mm, (c) 30 mm from center; and curvilinear welds: (d) 0 mm, (e) 15 mm, and (f) 30 mm from center.

crease in the amount of HSLA BM available for deformation during stretching leading to an increased formability, which becomes similar to BM when weld line is placed at 30 mm offset when most of the deformation occurred in the BM present on the left side (linear welds) or inner part (curvilinear welds) of the weld line. It may be noted that there was a less than 5% difference in the LDH observed between the linear and the curvilinear welded blanks when compared for a specific weld line position. However, for the weld line position of 0 mm offset the LDH decreased by 20% when compared to the monolithic sheet, which is attributed to formation of the harder FZ and HAZ (Fig. 4a), limiting the deformation and leading to fracture across the weld line (Fig. 5). Thus, it was observed that although the weld line geometry has no significant effects on formability of HSLA LWBs, it can be increased by placing the weld line farther from the blank center.

DP600 showed a significant reduction (∼35%) in the LDH compared to the BM when weld line was placed at the 0 mm offset (Fig. 8). This was attributed to the formation of the soft zone where strain localization occurs during stretch forming, which reduced the formability and led to premature failure. The reduction in LDH was seen to be less severe as weld line was moved away from the blank center with the linear weld showing a lower (9%) reduction than the curvilinear weld (29%). The higher reduction in LDH of the curvilinear welded blanks is associated to the non-uniform extension of the soft zone on each side of the weld line. This is in contrast to the linear welded blanks, which have uniform soft

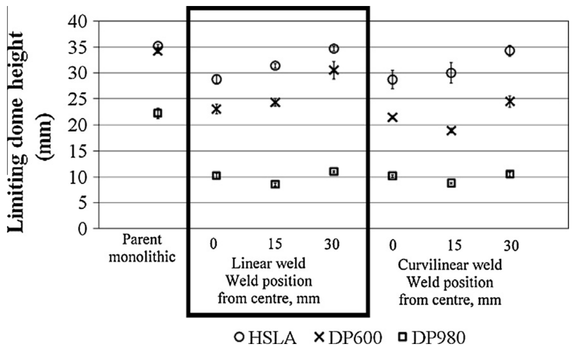

Fig. 8. Comparison of LDH of the parent monolithic sheets and the LWBs with different weld line position and geometry.

zones on both sides of the weld (Fig. 4). Overall, the LDH of the curvilinear welds was found to be 20% lower than the linear welds mainly when the weld line was placed at 15 mm and 30 mm off the center of the blank. This indicated that use of curvilinear weld geometry leads to reduction (about 20%) in formability in DP600 steel, unlike HSLA. Therefore, the effect of weld line geometry was concluded to have significant effect on formability of DP600 steel welds. However, an increase in the LDH values was observed when the weld line was shifted away from the center similar to the observation in HSLA (Fig. 8) the reason being similar as well i.e. availability of increasing amount of BM for deformation with moving the weld line away from the center. Interestingly, placement of the weld line at 15 mm off the center resulted in the lowest LDH in DP600, this agreed with the earlier report where the weld line was placed 15 mm from the blank center, which resulted in lowest LDH in a DP600-HSLA welded blank [32]. Thus, it was concluded that formability of the DP600 welded blanks can be increased by placing the weld away from the blank center using a linear weld, which shows higher LDH compared to curvilinear welds.

The DP980 welded blanks showed the highest reduction in the LDH (Fig. 8) compared to the parent material and all the other welded blanks (HSLA and DP600 steels). This was attributed to the more severe softening (Fig. 4), which limited deformation

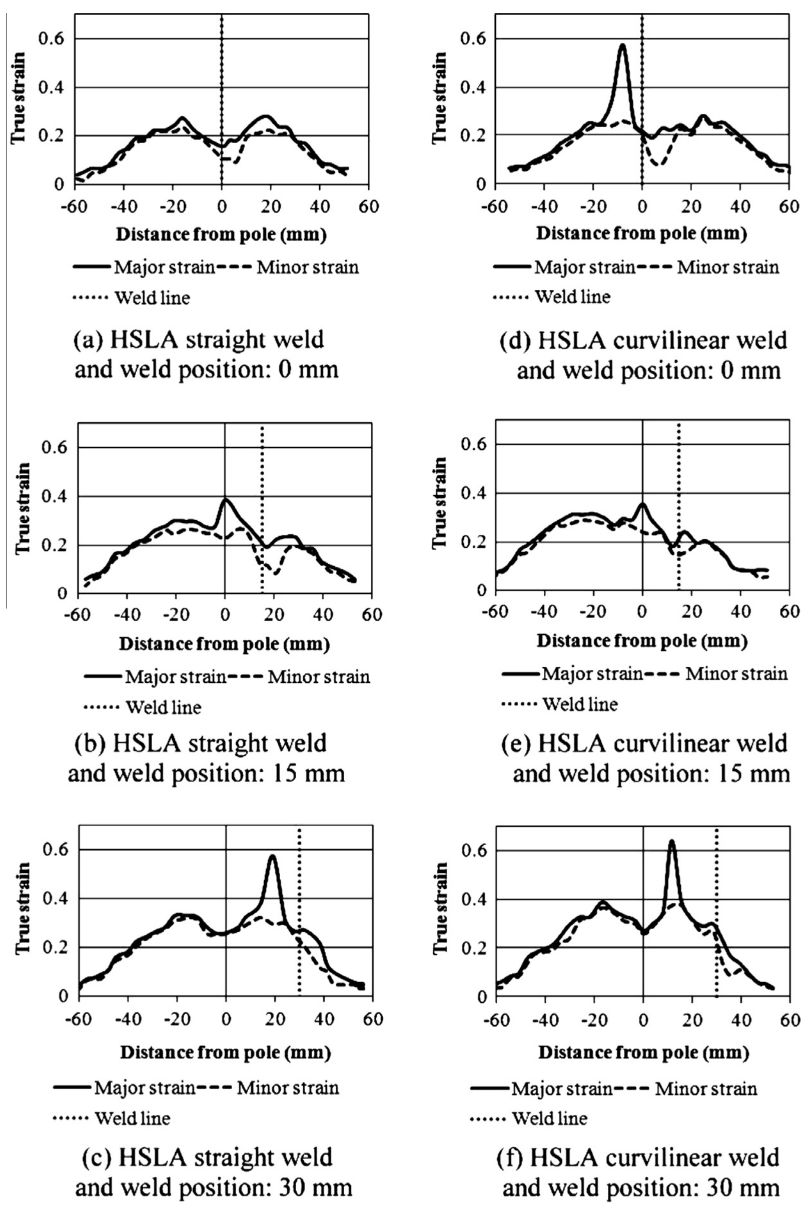

Fig. 9. Strain distribution profiles in HSLA as a function of weld line position and geometry.

due to early failure in the soft zone (Fig. 7). Interestingly, similar LDH values were found for both linear and curvilinear welded blanks, but both were well below that of the BM. In addition, the non-uniformity in the soft zone extension in curvilinear welds was not observed to affect the formability. Thus, it was concluded that HAZ softening played an important role in determining the formability of DP980 welded blanks as reported in earlier work [21–23,25,28,31]. However, weld line position and geometry was not seen to affect the formability.

3.4. Strain distribution

The strain distribution profiles indicate the forming behavior across the deformed blanks. In all the strain profiles of the HSLA steel blanks in Fig. 9, the major and minor strains were found to be very close, indicating biaxial stretch forming condition. Also, the strain level was similar to that developed in the parent monolithic HSLA sheet (Fig. 3a). The strain profiles of the linear welds were observed to be close to the curvilinear welds in terms of the strain distribution, amount of strain at the pole, and peak strain locations. This explains the similar change in the LDH with respect to weld line geometry for a given weld line position as observed (Fig. 8). The peak strains in the HSLA steels were located approximately 15–20 mm away from the weld. Furthermore, the similarity between the strain profiles at the respective weld line positions confirmed that the weld line geometry in the HSLA LWBs did not significantly influence the formability.

Another aspect of HSLA LWBs was the change in the amount of strain with respect to the weld line position. The strain profiles were well developed (i.e. higher strain concentration) when the weld was placed farther from the blank center. The strain distributions at weld line positions of 0 mm and 30 mm offset, regardless of the weld line geometry, also showed twin peaks similar to the parent HSLA steel (Fig. 3) at similar locations. The strain profile was observed to be very much close to the parent monolithic sheet when the weld line was placed 30 mm from the pole confirming the similarity in the formability of them.

The strain distribution profiles of DP600 linear welded blanks are shown in Fig. 10a–c. The major and minor strains were well-developed and uniform, indicating strain path more towards biax-

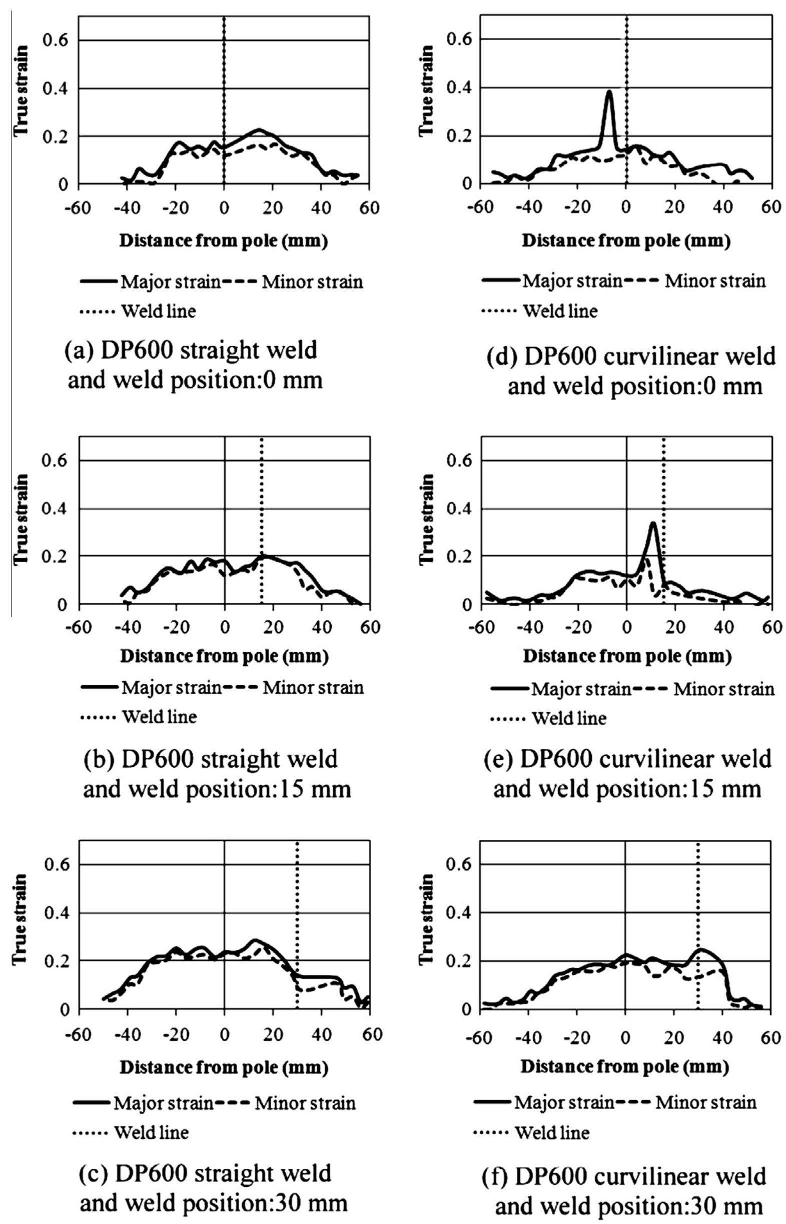

Fig. 10. Strain distribution profiles in DP600 linear and curvilinear welded blanks with different weld positions.

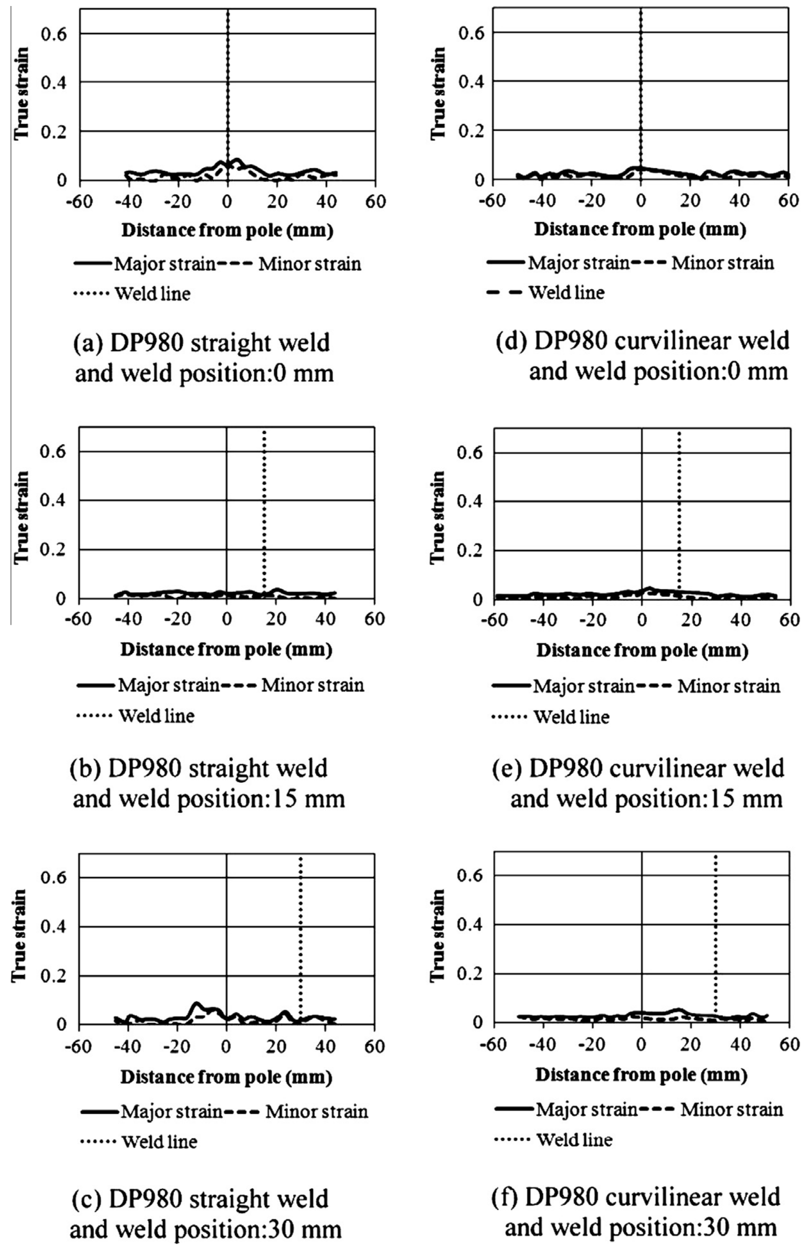

Fig. 11. Strain distribution profiles in DP980 linear and curvilinear welded blanks with different weld line positions.

ial during stretch forming. Strain development appeared on both sides of the weld. The overall strain increased as the weld line position shifted away from the center of the blank. While in the curvilinear welded blanks, Fig. 10d and e shows non-uniform major strain distribution for weld line position at 0 and 15 mm offset. The strain profile of the 0 mm offset curvilinear blank showed that the strain on the outer region was developed, but the strain concentrated mostly in the inner region, i.e. around 5 mm away from the weld centerline, prior to further development of the strain in the rest of the inner region. This caused non-uniform and underdeveloped strain profiles in curvilinear welds in comparison to the linear welds. Similarly, the strain profile for the curvilinear welded blank with the weld line at the 15 mm offset (Fig. 10e) showed that the strain pattern was underdeveloped compared to the linear weld. So, the failure location at the inner region soften zone was attributed to concentration of the strain at this location causing premature failure, which limits further deformation of the outer region of the blank. In addition, the underdeveloped strain in the inner region and negligible strain in the outer region resulted in the significantly lower LDH of the curvilinear welded DP600 blanks. Therefore, the weld line geometry is an important factor in designing LWBs especially of specific materials such as DP600 steel, which forms non-uniform extension of HAZ on both side of the weld line.

Fig. 11 shows the strain profiles of the welded DP980 steel blanks. These profiles show that the amount of strain present in the DP980 steel welds was low irrespective of the weld geometry, with the smallest strain magnitudes at the 15 mm location. The strain development was observed to be low in the DP980 steel welds, which was corroborated by earlier work on DP980-HSLA welded blanks [32]. Comparison of the DP980 steel strain profiles to the HSLA steel (Fig. 9) and DP600 (Fig. 10) indicated that DP980 steel showed the least formability and the cause of this was attributed to the effect of the severe softening seen in the hardness profile (Fig. 4c). Based on the strain distribution profiles observation, only DP600 steels showed a significant effect of weld line geometry on the formability; whereas both HSLA and DP980 steels showed comparable strain profiles in the straight-line welded blanks as compared to the curvilinear welded blanks. In HSLA steel, weld line geometry did not affect formability [2]; while HAZ softening in DP980 steel was dominant factor in reduction in the formability compared to weld line geometry as corroborated by earlier reports [14,22,28].

4. Conclusions

The effects of weld line position and geometry i.e. linear and curvilinear welds on the formability of HSLA, DP600, and DP980 steel LWBs were investigated. The following conclusions were drawn from the present study.

(1) Hardness profiles indicated that the curvilinear welds formed an inconsistent extension of the HAZ on either sides of the weld line. Also, more severe HAZ softening, in both DP600 (ΔH = 11 HV) and DP980 (ΔH = 132 HV) steels, was observed at the inner region of the curvilinear welded blanks.
(2) A strong correlation between HAZ softening and failure location in DP980 was observed with fracture consistently occurring in the soft zone located at 3–5 mm away from the weld centerline. In general, prediction of the failure location in the curvilinear welded DP steels was easier compared to HSLA as fracture always occurred in the soft zone at the inner region of the curve.
(3) For DP980 and HSLA steels the effect of weld line geometry on formability was insignificant because the effect of HAZ softening dominated in DP980 steel and welding did not alter HSLA steel. Interestingly, the effect of weld line geometry was most significant for the DP600 steel, especially for the weld line position at 15 mm offset from the center.
(4) Weld line geometry was observed to have a stronger influence on the formability for lower grade of DP steel. For example, changing the weld line geometry to curvilinear in DP600 LWBs increased the HAZ softening effects in the inner region of the weld, which restricted the strain development during forming, which resulted in premature failure.
(5) Strain distribution profiles confirmed that formability of only DP600 LWBs was affected significantly by weld line geometry; whereas both HSLA and DP980 showed comparable strain profiles in the linear and the curvilinear welds.

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