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Research Article

Investigation of Forming Behaviour of Metal-Polymer Sandwich Composite through Limit Dome Height Test Simulations

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Metal-polymer-metal (MPM) sandwich composites are in the class of proficient engineering materials which give outstanding strength-to-weight ratios because of their comparatively low density. These materials are vital constituents within the automobile, aerospace, marine, and civil construction industries as substitutes for sheet metals that considerably reduce weight while not compromising functionality. Moreover, these materials have supplementary qualities like sound dampening and thermal insulation capabilities. For these materials to be utilized within the aforesaid industries, they need to bear numerous forming processes that are essential in product manufacturing. This paper investigated formability analysis of metal-polymer sandwich composites made of "AW 6082-PVC-AW 6082 (APA)" and "galvanized steel-PVC-galvanized steel (GPG)" sandwich sheets, considering epoxy structural adhesives as the binding agent, via FEA simulation. All the FEA simulations were performed using Altair HyperWorks software. For evaluating the formability, the actual limit dome height (LDH)—biaxial strain path—tests were simulated using FEM software. The results analyzed are forming limit diagram (FLD), punch force distribution, and a dome height at diverse conditions of punch velocity and friction. A comparison is made to represent the best combinations for formability of the sandwich composites. Maximum formability and dome height are attained at low friction conditions and forming speed. It has also been observed that LDH simulations are very sensitive to friction, and it has a substantial impact on the test outputs. Maximum thinning (or fracture) generally moves away from the apex of the dome towards the die corner radius as the friction increases from zero upwards.

1. Introduction

In manufacturing engineering, it is common to specify and select suitable and reliable materials that can fulfil a product's requirements. Now and then, the existing materials are also able to accomplish these demands with or without necessary modifications. Otherwise, new materials are designed and manufactured according to necessities of the product being manufactured. The need for contemporary materials, hence, arises to deal with the requirements of recent and economical engineering innovations. Handiness of engineering materials that meet design necessities is the major issue that influences engineering design flexibility.

Composite materials play an important role in achieving the aforesaid development. One of the ways to develop composite materials is by formation of metal-polymer-metal (MPM) sandwiches joined together to fabricate composite sheets. It consists of two metal skin sheets and a low-density polymeric core material as shown in Figure 1. The polymeric core material offers benefits for weight reduction, lower

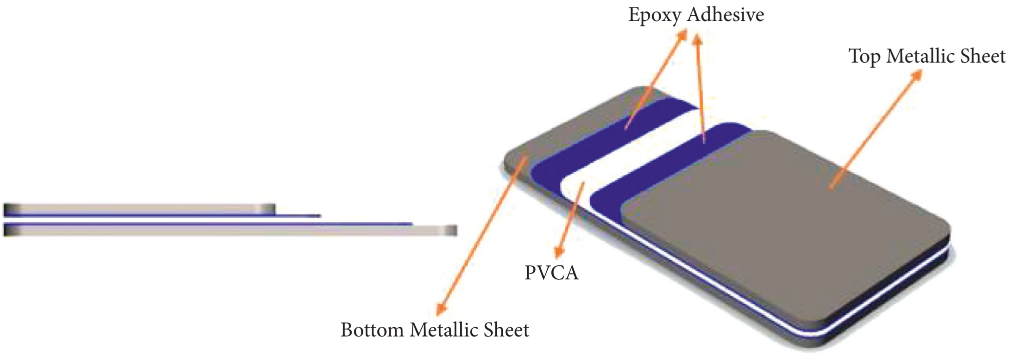


Figure 1: Schematic of MPM sandwich composite.

density, higher sound, and vibration damping characteristics and improved specific mechanical properties compared to monolithic metallic sheets [1].

Nowadays, MPM sandwich composite materials pulled in noteworthy attention for their widespread properties which include not having any of the layers alone. Metallic sandwich sheets have better strength-to-weight proportion, vibrational damping, and sound-stifling properties than monometallic layers [1, 2]. Subsequently, sandwich composites are broadly used in the automotive and aviation industries [3, 4]. Sandwich structures were made out of a high-strength metallic sheet as the skin layer and thermoplastic or thermosetting polymers as the middle layer. These MPM laminates were developed by various cycles like roll bonding, layup technique, and hot pressing [5, 6].

Because of the inhomogeneous behavior of the complex sandwich materials over their thickness, a few exploration needs have been in concern regarding their forming behavior. Underlying elements, for example, face-to-core sheet thickness proportion, physical and mechanical properties of the face and core materials, and bonding between the layers and the interfacial properties are the principal boundaries influencing the physical (for example, sound and vibration damping) and mechanical (for example, strength and formability) properties of the sandwich sheets [7].

Numerous sorts of aluminum-plastic sandwich sheets had been produced with various aluminum alloys as skin sheets and distinctive plastics as the core layer, for example, the AA5182-polypropylene-AA5182 sandwich sheet, AA5005-polypropylene-AA5005 sandwich sheet, and AA3105-polypropylene-AA3105 sandwich sheets. Among these sandwich sheets, the AA5182-polypropylene-A5182 sandwich sheet was preferred for the car body boards in future superior automobiles with a critical weight decrease [8].

Albeit the metal-plastic sandwich sheets have numerous benefits, in any case, the forming of these materials is exceptionally complicated because of the very huge distinction in mechanical properties and in the measures of polymer core and the metal skins. The practices of sandwich sheets are not the same as those of homogeneous metallic sheets during forming measures. Forming processes of parts in MPM sandwich sheets typically include issues, for example, wrinkling, delamination, and shearing, identified with the deficient interlayer metal-polymer bondage. The adhesive strength at the metal-polymer interface is a critical factor for MPM sandwich composites since the interfacial collaboration produces a framework that can emphatically influence the sheets to either act autonomously or feebly or as unequivocally coupled. A frail polymer core can go about as an oil between the metal skins; such behavior can cause the event of debonding at interfaces between sheet and plastic centers, prompting sliding of metal skins and an untimely failure during forming activities. Then again, a highly solid attachment power between a polymer core and a metal sheet adversely influenced formability since the ceaseless smooth sliding between the layers was prevented [4, 9].

As reported by Kim and Yu [10], the bonding between dissimilar materials to obtain a multilayered component generates inhomogeneities leading to discontinuities in stress distributions across the sheet thickness. A further drawback taking place during forming processes of sandwich composites is the higher tendency to wrinkle with respect to monolithic metal sheets. This is due to the weak interlayer adhesion that, allowing the two metal sheets to act independently, make them be more susceptible to wrinkling than a single thicker sheet. Also, delamination can occur during forming operations due to different lengths of metal skins, as they are deformed around the die, which can cause the occurrence of high shear forces in the polymer core [11]. Harhash et al. analyzed the effect of the polymer core thickness on spring back of steel-polymer-steel sandwich composites; they showed a reduction in the spring back with decreasing core thickness even though, with thicker polymer films, crack probability rises due to the increase in tensile stresses on the outer metal skin [7]. Furthermore, as shown by Carrado et al., the presence of cavities in the polymer core, caused by air bubbles trapped during the manufacturing process of sandwich laminates, can accelerate cracking. Factors such as the inhomogeneous cross-section structure of multilayered sandwiches, composition and characteristics of different constituents, bonding method used to hold together the single layers, shape complexity of the final component, forming techniques, and loading conditions can strongly affect the success of forming processes of multilayered materials and, consequently, the final performances of the formed parts [12].

The FLD of the sandwich sheets with aluminum as the skin layer and glass fiber-reinforced polymer as a core was predicted numerically and experimentally by Jalali Aghchai and Khatami [13]. They utilized the M-K model to predict the FLD numerically. The study on the effect of the variation in thickness of the core and skin layers revealed that the increase in the thickness of both skin and core layers improves the FLD of the sandwich sheet, but variation in the thickness of the skin layers has a greater effect on the formability. Also, Keipour and Gerdooei studied the spring back behavior of the aluminum-reinforced polymer sandwich composites [14]. The results show that for thicker cores, a reduced spring back could be stated.

A fracture forming limit diagram (FFLD), which was first proposed by Embury and LeRoy, is a graphical representation of the fracture limit in the principal strain space [1]. For metal-polymer sandwich composites, however, the material's failure is not restricted to fracture. Instead, the composite can lose its functionality even prior to necking. Hence, the forming limit diagram (FLD) is a better determinant of these materials' behavior since it clearly indicates the safe zone of deformation.

Overlaid metal-polymer materials show a satisfactory or even great formability. For example, Hylite, an Al/PP/Al sandwich showed a decent forming behavior under profound drawing or bending conditions [12].

Although many research studies had been conducted in the characterization of MPM sandwich composites, a very few combine the effects of process parameters in addition to material properties in the analysis of their formability. This paper worked on the effects of process parameters—lubrication condition and forming speed—in amalgamation with the composites' mechanical properties and studied the forming behavior by LDH simulation. In this investigation, the metallic components of the sandwich composites are aluminum (AW 6082) and galvanized steel sheets. The polymeric core, for both, is poly vinyl chloride (PVC) acetate.

LDH simulation results, attempted by means of Altair HyperWorks software, are examined thoroughly. The obtained information is utilized in forming analysis of "AW 6082-PVC-AW 6082 (APA)" and "galvanized steel-PVC-galvanized steel (GPG)" sandwich plates, and henceforth, its forming capability is resolved.

2. Methodology

The strategy followed for the prediction of the formability of the APA and GPG sandwich plates started with the characterization of the skin sheet layers and core (PVC) material properties. Poly vinyl chloride (PVC) is a polymer of vinyl chloride monomers (VCM) which are polymerized to form PVC resin, to which appropriate additives are incorporated to make a customized PVC compound [15]. It has a high strength-to-weight ratio and is a good electrical and thermal insulator. PVC is also self-extinguishing as per UL flammability tests. PVC is used at temperatures of 140°F (60°C) and is readily available in sheets, rods, and tubing.

A two-component structural epoxy adhesive, which cures at room temperature, was utilized in preparation of samples for experiments undertaken in this paper. The polymers, metallic skin sheets, galvanized steel sheet (GSS) and aluminium sheet (AS), and MPM sandwich composites were made from these substrates had undergone various testing procedures—tensile test, single-lap adhesive test, and density evaluation—in order to obtain their mechanical properties as tabularized in Table 1. Their density is evaluated by converting each constituent component's percentile contribution to the sandwich to a decimal number (a number between 0 and 1) by dividing by 100 and then multiplying each decimal by the density of its corresponding constituent component.

Lankford's coefficient (R) is a measure of the ability of a sheet metal to resist thinning or thickening when subjected to a tensile or compressive force. To determine this ratio, assuming constant volume, both axial and transverse strains need to be obtained during a uniaxial tensile test. It is given by

$$R = \frac{\ln\left(W_0/W_f\right)}{\ln\left(L_f W_f/L_0 W_0\right)}, \tag{1}$$

where w_f = final width; w_0 = original width; L_f = final length; and L_0 = original length.

2.1. FEA Simulation. The considered APA and GPG sandwich composite materials for the examination comprise three layers each: two layers of metallic sheets and a PVC core, with a structural epoxy adhesive layer at their interfaces. To replicate the composite material's actual behaviour, the empirically tested material properties, tabulated in Table 1, were allotted to the numerical model. The coefficient of friction between the surfaces has been allotted into the model as indicated in Table 2 [16]. The friction coefficient values, under dry and lubricated conditions, at the interfaces have been obtained from an archive coefficient of friction [16], and it is varied from zero up to these points for both materials. The tooling geometric specifications have been replicated from the actual experimentation dimensions [17]. To observe the effect of forming speed on the materials' formability, an extremely large gap between punch velocities has been assigned for different cases. Various combinations of these process parameters have been assessed in order to find out the optimum conditions for both materials.

Radioss incremental solver, which is one of the solvers in Altair HyperWorks software, is used to perform the LDH simulations. The input process parameters and geometrical specifications of the components, punch (dome shaped), binder, blank, and die, are reproduced in FEA software so as to simulate the experimental LDH test, first proposed by Ghosh and Hecker [17] as shown in Figure 2.

Among the four components, the punch, binder, and die are made rigid components (meshed with R-mesh) while the blank (MPM sandwich sheets) are deformable with their mechanical properties fed into the model. For non-deformable bodies (R-meshed), software decides the element size so as to provide the optimum mesh density. The deformable blanks (Q-meshed), however, have a uniform element size of 1 mm.

In the LDH experiment, there is a lock-bead mounted between a die-flange and a binder to hold the blank in place while stretching takes place [17]. This lock-bead is imitated,

Table 1: Mechanical properties of AS, GSS, PVC, APA, and GPG.

Materials	AS	GSS	PVC	APA	GPG	Epoxy adhesive
Thickness (mm)	1	0.45	0.5	2.7	1.6	—
Density (g/cm^3)	2.71	7.874	1.38	2.19	7.3	1.24
Young's modulus, E (GPa)	70	211	3.1	137.9	406.82	1.4
Ultimate tensile strength, UTS (MPa)	308.6	474.56	78.5	333.66	701.57	34
Yield strength, σ (MPa)	260.49	287.7	—	314.43	648.13	—
Strength coefficient, K (MPa)	423	555.1	—	475.1	958.04	—
Hardening exponent, n	0.27	0.22	—	0.25	0.2	—
Lankford's coefficient, R	0.89	1.6	—	1.12	1.65	—

AS: Al sheet; GSS: galvanized steel sheet; APA: AW 6082/PVC/AW 6082; GPG: galvanized steel-PVC-galvanized steel.

Table 2: Input process parameters and geometrical specifications.

	Sandwich plates	
	GPG	APA
Thickness of sandwich plate, t (mm)	1.6	2.7
Die diameter (mm)	105.7	105.7
Punch dome diameter (mm)	101.6	101.6
Die corner radius (mm)	6.35	6.35
Friction coefficient (lubricated, dry)	(0.029, 0.42) [5]	(0.04, 0.47) [5]
Binder, by keeping gap (mm)	1.6	2.7
Punch velocity (mm/min)	5000 and 10000	5000 and 10000

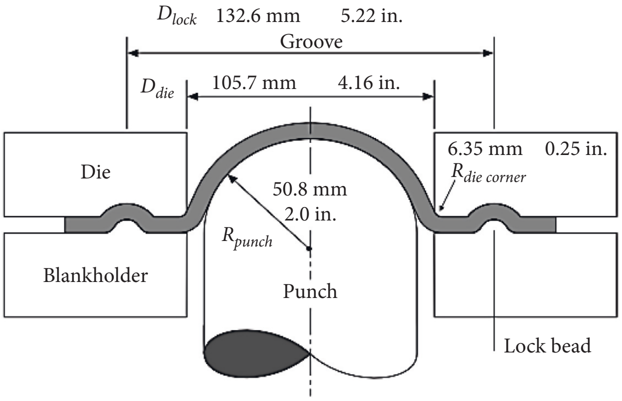


Figure 2: LDH experiment tooling [17].

on the FEA analysis, by a fixed edge constraint applied on the MPM sheet such that it cannot be drawn into the die cavity (pure stretching takes place).

2.2. Modelling for Limit Dome Height (LDH) Simulation. For the geometrical modelling of the components, SolidWorks CAD software was used. The finite element software utilized in the present work is HyperWorks to simulate (limit dome height) test on the biaxial strain path. Blank dimensions are shown in Figure 3. These blanks model the GPG and APA sandwiches' properties with a thickness of 1.6 and 2.7 mm, respectively. The process parameters are indicated in Table 2.

The simulations are allowed to run until failure starts in the blank, and the dome height was taken just before failure. From the data obtained, the forming limit diagram (FLD) and dome height graphs are plotted and analyzed thoroughly.

2.3. Meshing and Process Setup. The LDH simulation components and APA and GPG sandwich composite blanks were meshed using the Hypermesh tool. The four-nodded rigid quadrilateral element (R-mesh) was used for the dome test tools, namely, punch, binder, and die, whereas the eight-nodded linear brick tetrahedron element was used for the blanks. The surface-to-surface explicit contacts were defined by using the penalty function, and the coefficient of friction was assigned between tools and the sample. The adhesive layer's contacts between skin Al, galvanized steel sheets, and PVC core were defined by using ply laminates. The generated mesh model was further utilized for the explicit analysis, which was carried out in two different stages. In the first stage, the sandwich composite blank was pressed over the die by applying force using the blank holder, whereas in the second stage, the pressed blank was further formed by applying force using the dome-shaped punch.

The type of process used in the simulation is Double Action Draw. The setup window is utilized to incorporate the process parameters which are blank thickness and material properties, punch speed, and binding mechanism. The obtained mechanical properties were fed into custom materials before they were assigned for the blanks.

The simulation setup (preprocessing) in the graphics area after meshing is shown in Figure 4.

2.4. Yield Criterion and Flow Stress. When a material is subjected to large plastic deformations, the grain sizes and orientations change in the direction of deformation. As a result, the plastic yield behaviour of the material shows directional dependency. Under such circumstances, the isotropic yield criteria such as the von Mises yield criterion are unable to predict the yield behaviour accurately. Several anisotropic yield criteria have been developed to deal with

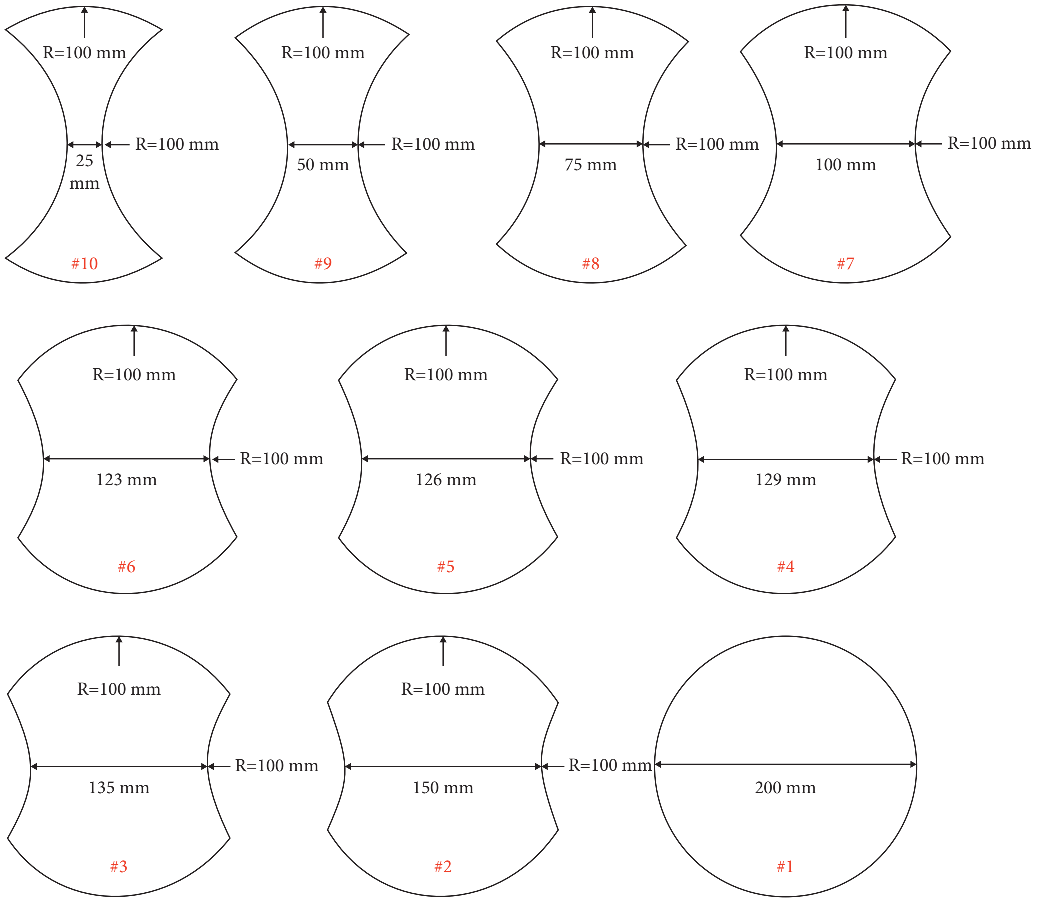


Figure 3: Blank geometry with numbering [17].

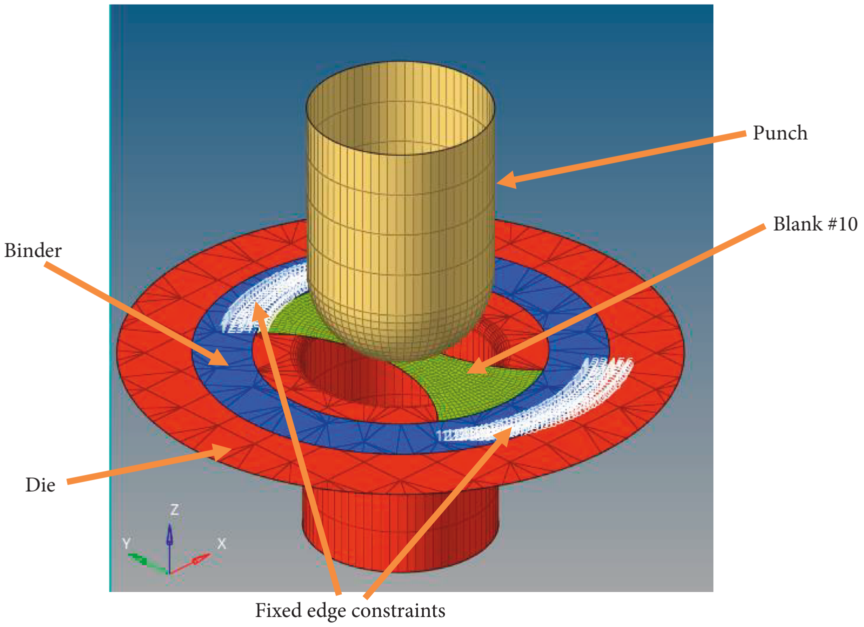


Figure 4: Typical LDH simulation setup.

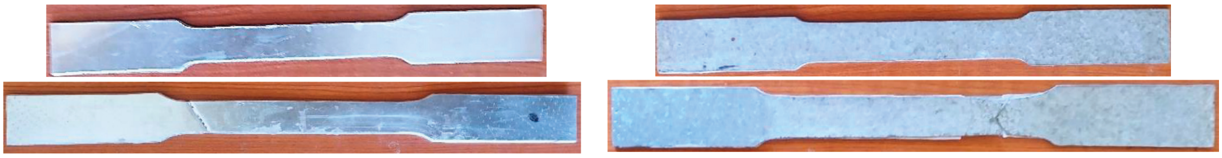

(a) (b)

Figure 5: Tensile specimen deformation of APA (a) and GPG (b).

such situations. For this work, the Hill 1948 yield criterion was applied (while modelling in HyperWorks environment) during LDH simulations in order to account for anisotropic plastic deformations. This yield criterion works for metals, polymers, and composites.

Flow stress is the instantaneous value of stress required to continue deforming a material plastically, to keep it flowing. On a stress-strain curve, the flow stress can be found anywhere within the plastic regime; more explicitly, a flow stress can be found for any value of strain between and including a yield point and an excluding fracture. Hence, from the tensile experimentations performed, the flow stress (σ_{f}) can be calculated using the following formula:

$$\sigma_f = K\varepsilon^n, \tag{2}$$

where K = strength coefficient, ε = strain, and n = strain hardening exponent.

3. Results and Discussion

3.1. Stress and Strain. Figure 5 shows tensile test specimens before and after deformation. From stress-strain plots, shown in Figure 6, yield strength, ultimate tensile strength (UTS), and maximum allowable elongation before necking and before rupture are studied. Further analysis provided the K and n values. All of these results are tabulated in Table 1.

The main objective of this work is to observe the composite sandwich sheets' forming behaviors applying various punch velocities and frictional conditions (process parameters) as specified in Table 2. The blank holding force is fixed to a constant value that prevents the blank from being drawn into the die cavity (pure stretching is required). Simulations with various combinations of geometry and process parameters are performed using HyperWorks software. The properties of the APA and GPG sandwich sheets that have been obtained through empirical testing are replicated with FE models in HyperWorks, and simulations are conducted using the Radioss incremental solver.

Forming limit diagrams (FLDs), which encompass forming limit curves (FLCs), have been generated for each simulation. The FLC is a failure limiting criterion for sheet material formation. The entire diagram is known as FLD, which indicates thinning, wrinkling tendency, insufficient stretch, and safe forming zones in addition to FLC. FLC illustrates the onset of localized necking in linear straining paths in a diagram of major and minor strains (i.e., in-plane minimum and maximum principal strains). The forming limit curve (FLC) for both APA and GPG sandwich sheets is shown in Figure 7. Figure 8 shows the sandwich deformation along with the failure zones and FLC, which shows the preliminary stage of failure zone in the sheets. The colour coding helps to visualise different zones, failure, marginal, safe, compression, loose, and high wrinkle tendency, which exists in both contour plots and corresponding FLDs.

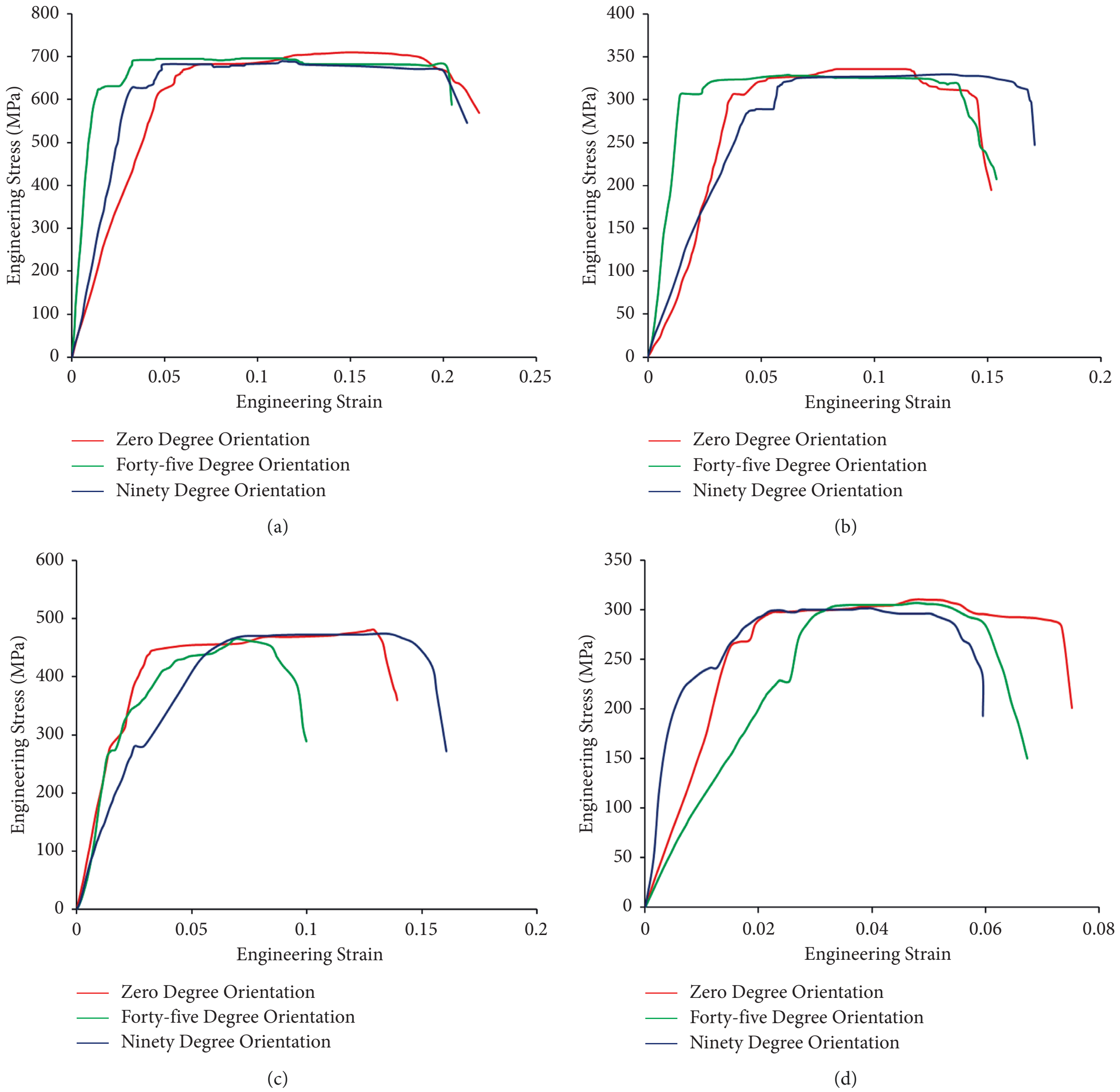
FE simulations for the LDH test indicate that the test is very sensitive to friction and it affects the test measurements. Friction at tool-workpiece interface (in this case, mainly at punch-blank interface) has an effect on formability and thinning distribution. It can be expected that maximum thinning when friction is zero occurs at the apex of the dome. Some simulations have been conducted with zero interface frictional value (between punch and blank), and the failure did in fact occur at the tip of the dome. Figure 9 indicates this condition for APA blank #1. Generally, maximum thinning moves away from the apex of the dome (moves toward the die corner radius) as interface friction increases, and punch force also increases as interface friction increases.

From Figure 8, it clear that failure zones are in the side wall of the sandwich dome, which means more thinning has happened in the side wall of the sandwich sheet along with punch travel. From all the simulations in the biaxial sandwich sheets, almost a similar failure phenomenon is noticed.

Along with the FLD, the graphs of dome height till (just before) failure, also known as LDH, have been extracted from the simulations. From all the simulation conditions, the maximum dome height has been recorded at blank #4 for APA (0.015 friction coefficient) and at blank #2 for GPG (0.005 friction coefficient). This indicates that better formability is achieved when friction is decreased to a minimum possible value. This is because the material can easily flow for smaller frictional restrictions. For illustration, graphs for all blank geometry and process parameters are shown in Figure 10.

Another crucial process parameter being studied is the punch velocity, which has a direct correlation with the forming speed. Two punch velocities (5000 and 10000 mm/min) have been applied, with a considerable gap between the two, to see the effects clearly.

Maximum LDH for both APA and GPG is attained with 5000 mm/min punch velocity. For the larger value of punch velocity, however, poor formability is observed, with the blank material being rapidly drawn into failure. As the forming speed is lowered, the material had enough time to flow and take the shape being imposed with tooling. For instance, blank #8 is formed with 10000 mm/min punch velocity, and it can be observed that small LDH is attained for both blank materials (Figure 10).



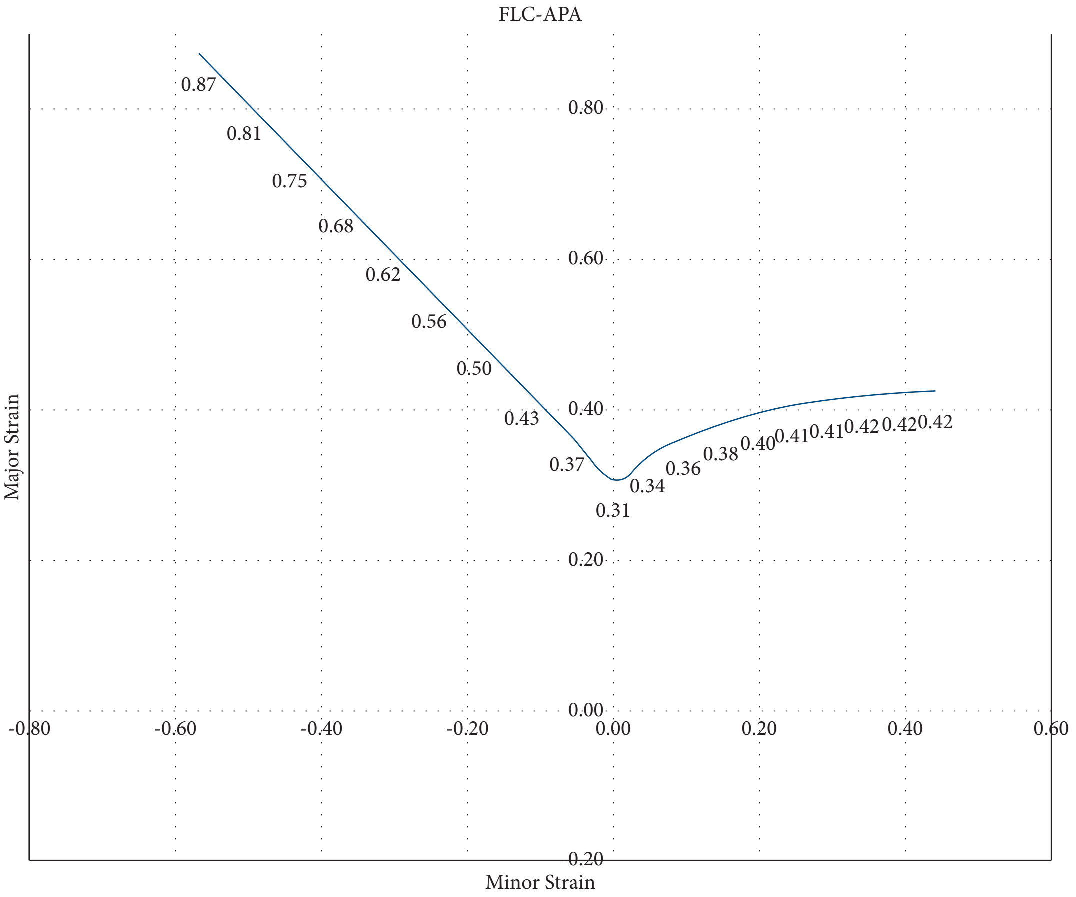
(a)

(b)

(c)

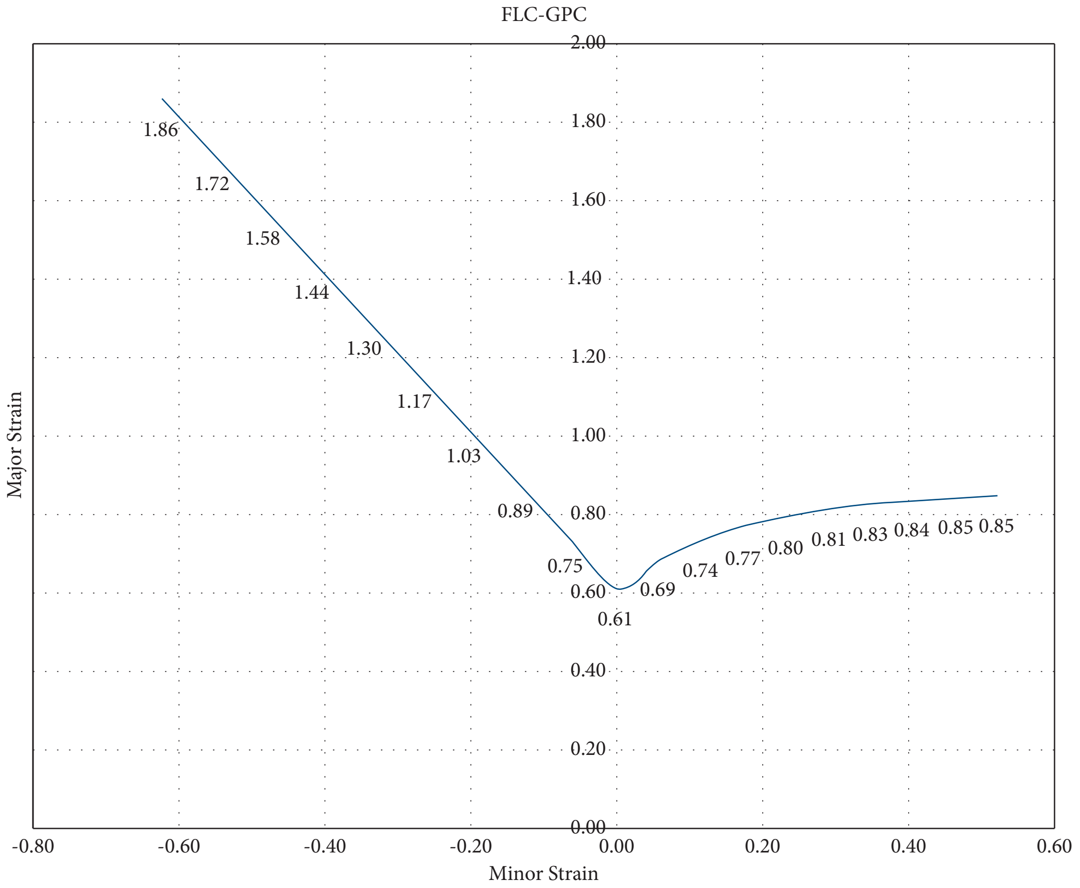
(d)

Figure 6: Engineering stress-strain plots of GSS (a), AS (b), GPG (c), and APA (d).



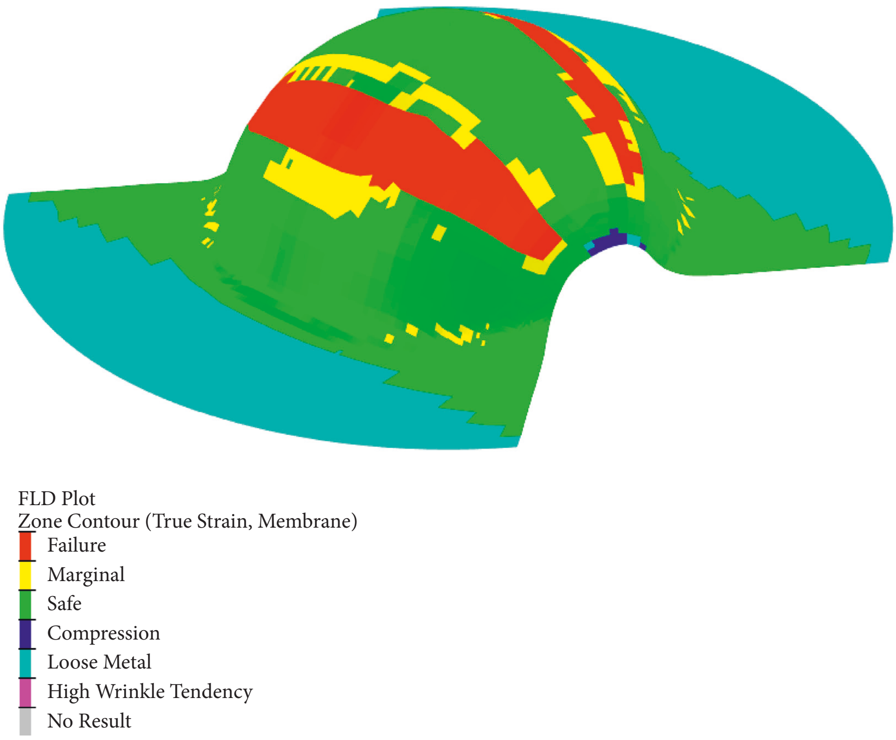
(a)

Figure 7: Continued.



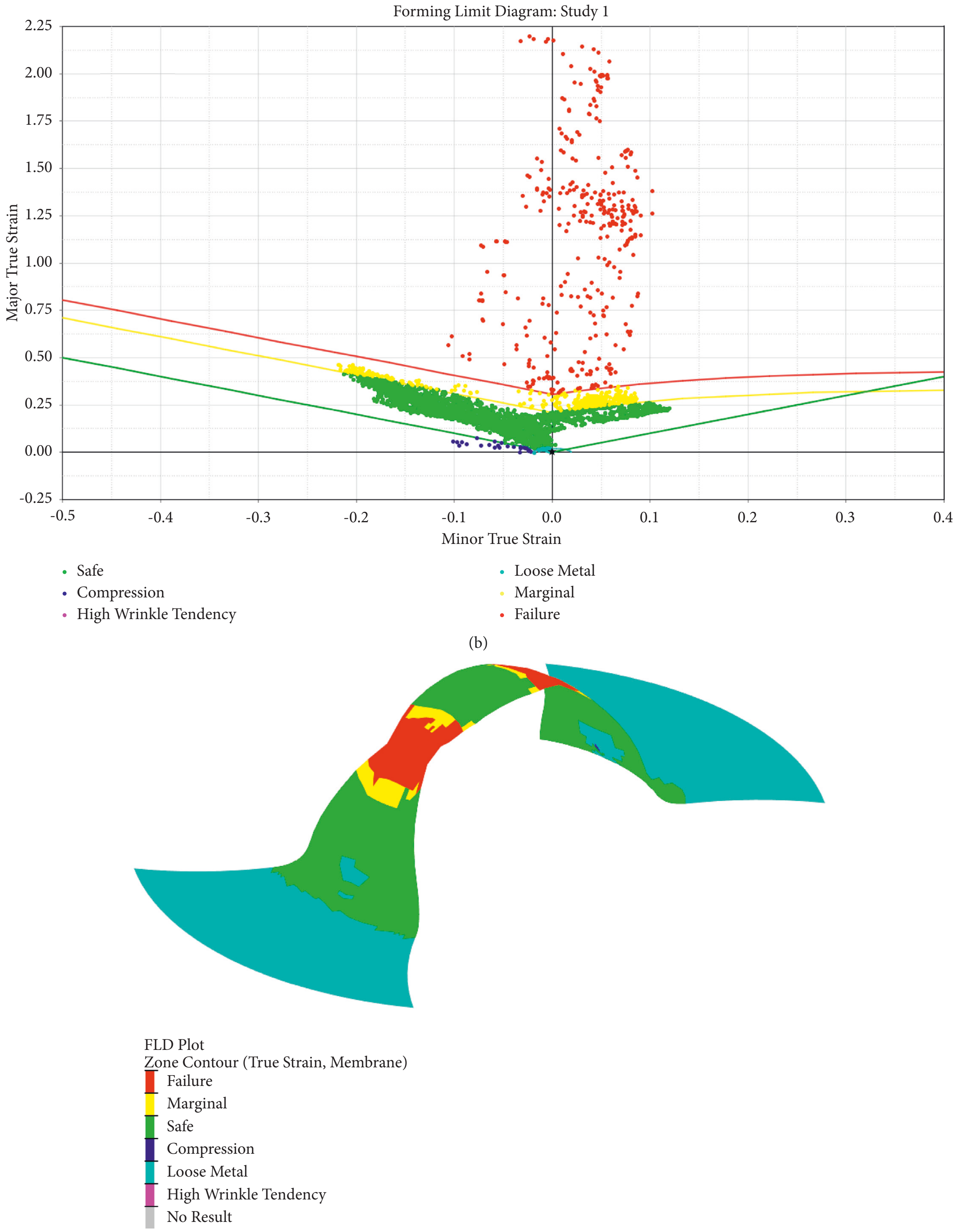
(b)

Figure 7: FLC of APA (a) and GPG (b).



(a)

Figure 8: Continued.



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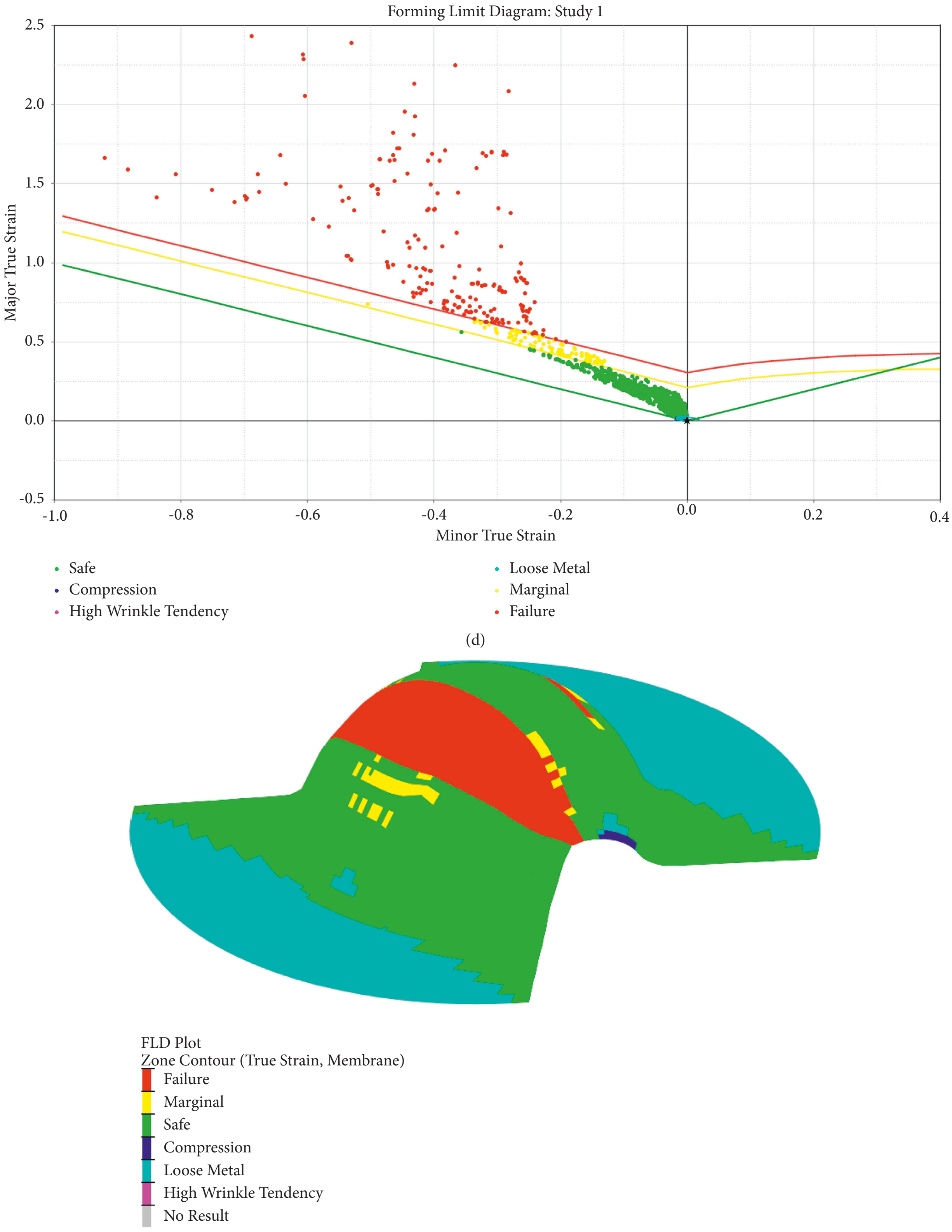
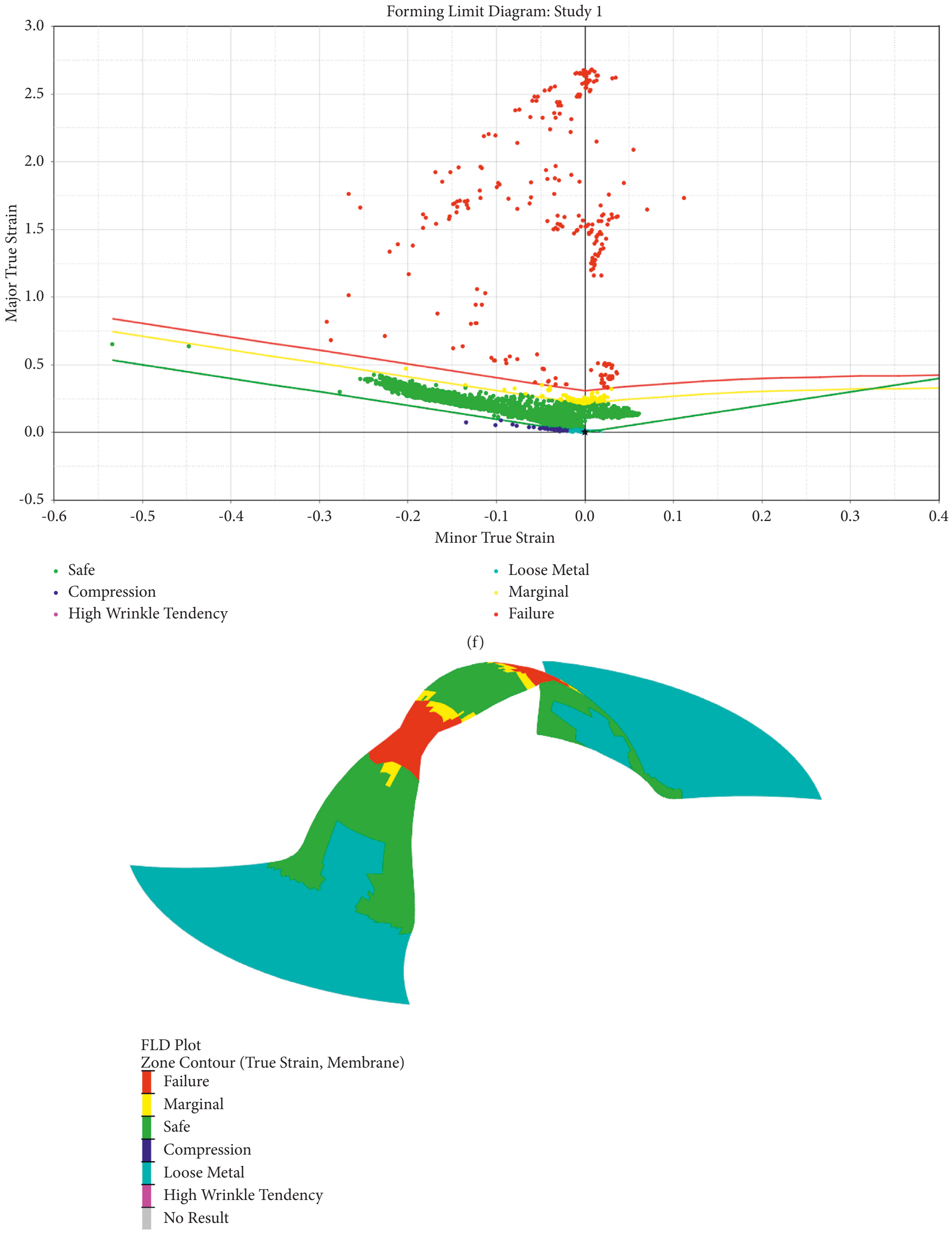


(d)

(e)

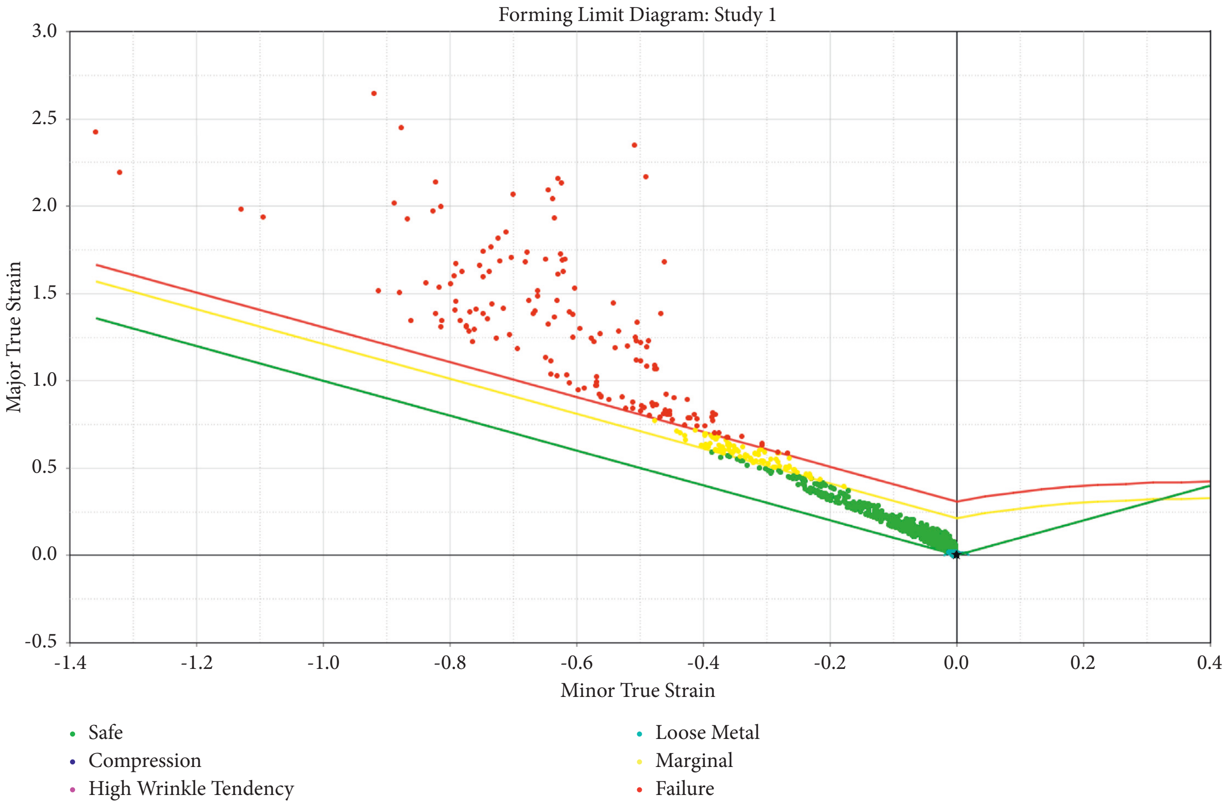
Figure 8: Continued.



(f)

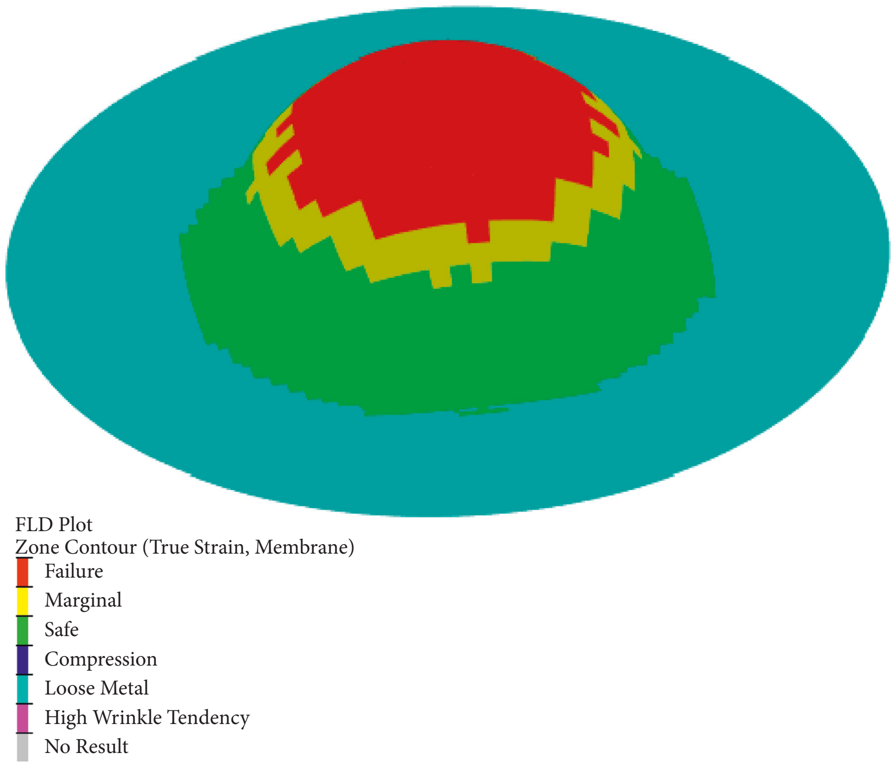
(g)

Figure 8: Continued.



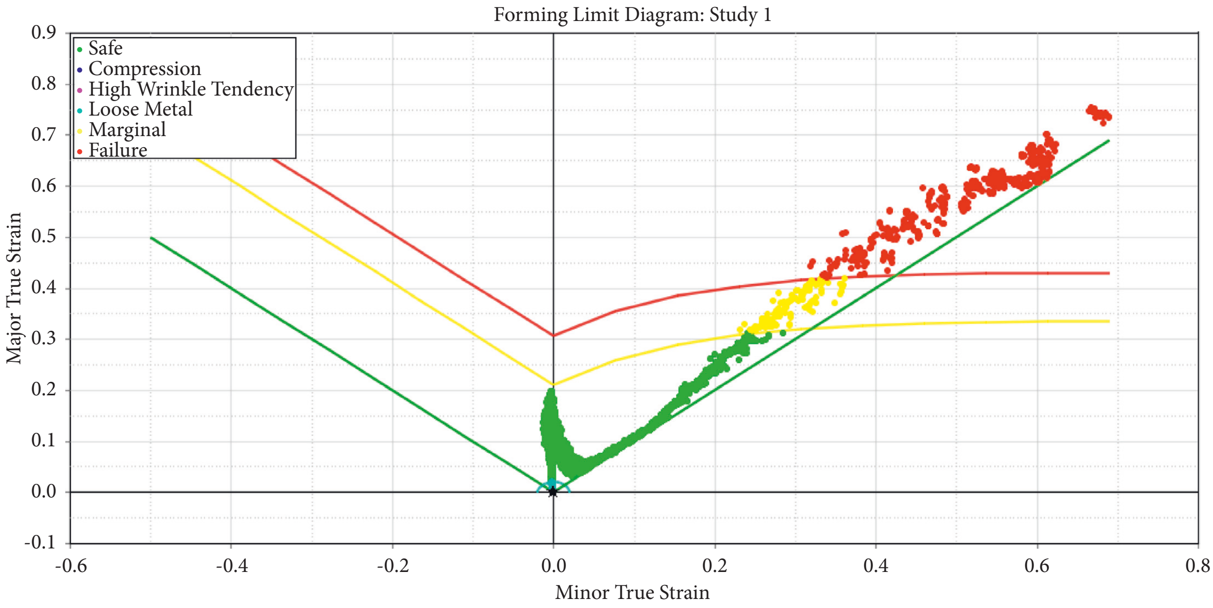
(h)

Figure 8: Contour plot and FLD of APA blank #6 (a, b), APA blank #10 (c, d), GPG blank #6 (e, f), and GPG blank #10 (g, h).



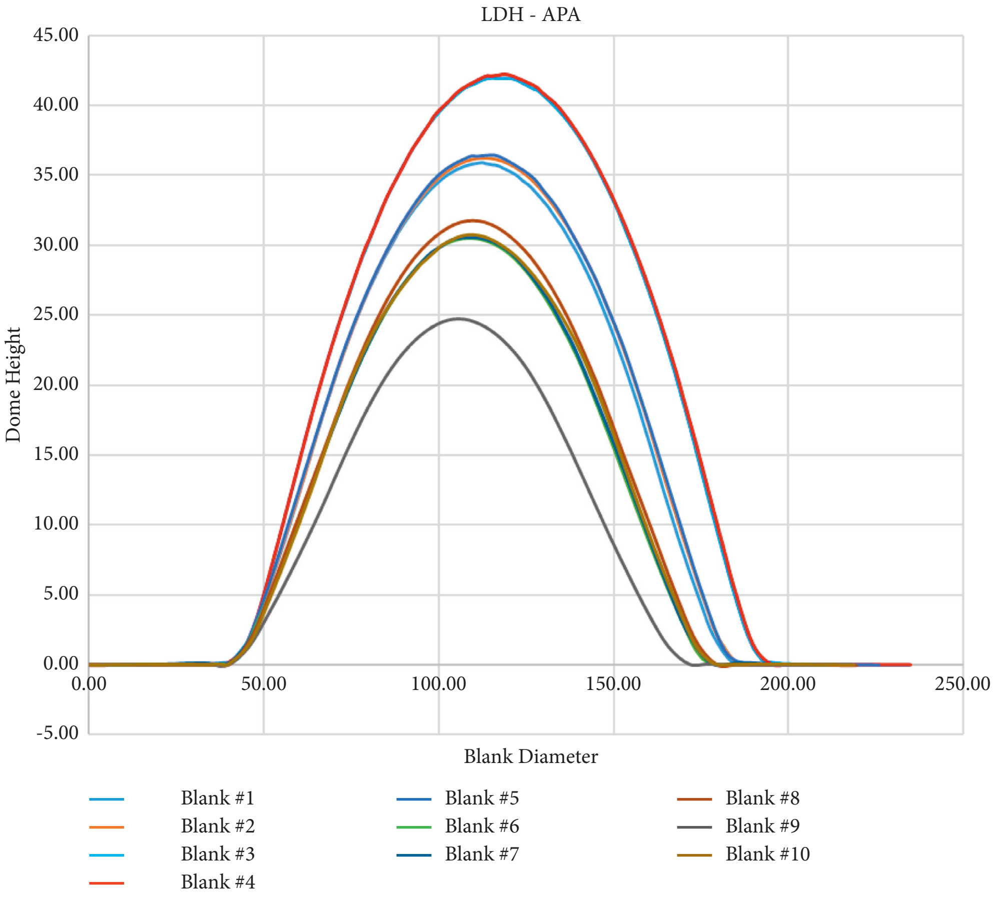
(a)

Figure 9: Continued.



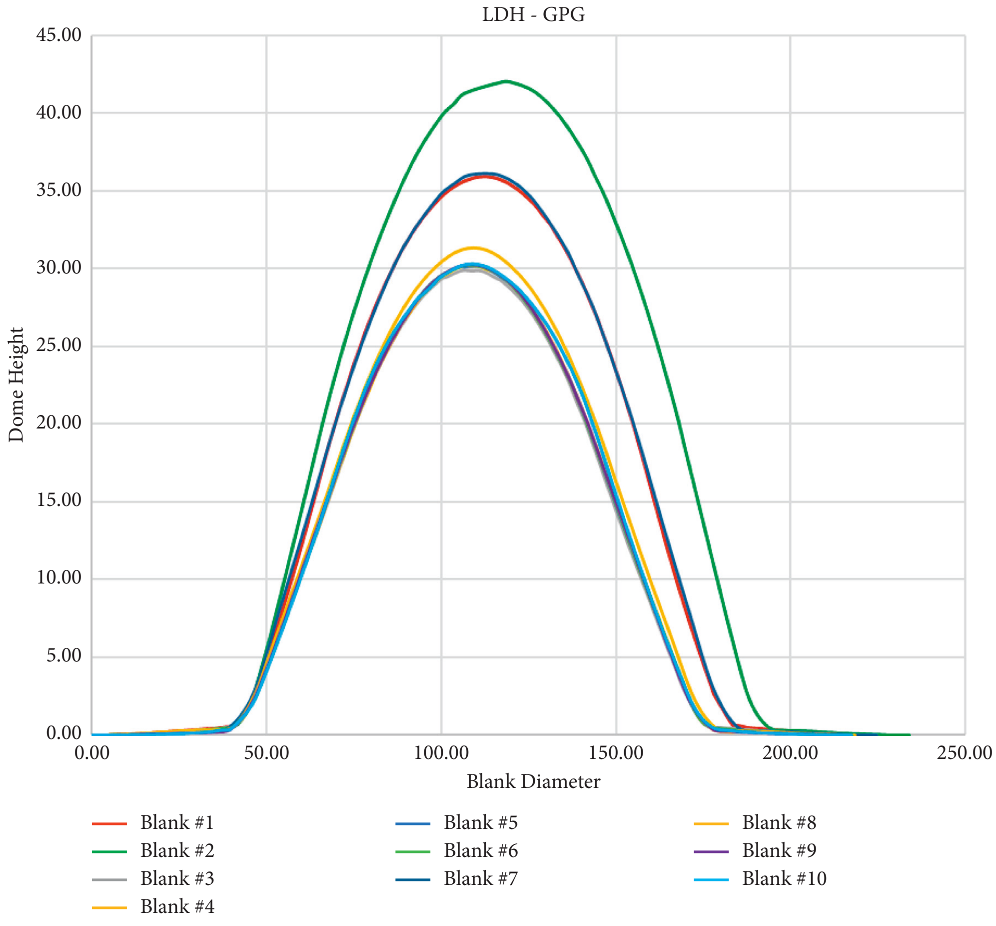
(b)

Figure 9: FLD of APA blank #1 with a zero friction coefficient between the punch and blank.



(a)

Figure 10: Continued.



(b)

Figure 10: Dome height vs process parameters comparison: (a) APA and (b) GPG.

4. Conclusions

In the present work, limit dome height (LDH) simulations for biaxial stretching conditions have been performed using HyperWorks FEA software to study formability of sandwich sheets made up of aluminium (AW 6082) and galvanized steel sheets with PVC, with structural epoxy adhesives as the binding agent. The simulations are conducted under two levels of punch velocities (5000 and 10000 mm/min) and many levels of frictional conditions, starting from zero. The data extracted from all of the simulations are the FLD and maximum dome height. It is observed that the maximum dome height is seen at blank #4 for APA (0.015 friction coefficient) and at blank #2 for GPG (0.005 friction coefficient). In both cases, the punch velocity is 5000 mm/min.

It has also been observed that LDH simulations are very sensitive to friction and have influence on the test outputs. Friction at the tool-blank interface has a considerable effect on formability and thinning distribution. When friction is zero (imaginary and can only be achieved via simulation), the maximum thinning occurs at the tip of the dome. Generally, maximum thinning moves away from the apex of the dome (moves toward the die corner radius) as interface friction increases, and punch force also increases as interface friction increases. Hence, applying a suitable lubricant improves the formability of the sheets.

Data Availability

The data supporting the findings of this study are included within the article which were obtained from numerical simulations and experimentation.

Disclosure

This paper has been submitted as an MSc thesis on "Investigation of Formability Analysis of Metal-Polymer Sandwich Composites Considering the Adhesion Strength." The paper is published as a thesis [18] under the ASTU database.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] J. D. Embury and G. LeRoy, "Failure maps applied to metal deformation processes," in *Proceedings of the 4th International Conference on Fracture*, pp. 15–42, Waterloo, Ontario, Canada, June 1977.

[2] K. J. Kim, M. H. Rhee, B. I. Choi et al., "Development of application technique of aluminum sandwich sheets for automotive hood," *International Journal of Precision Engineering and Manufacturing*, vol. 10, no. 4, pp. 71–75, 2009.

[3] O. A. Sokolova, A. Carrado, and H. Palkowski, "Metal –polymer–metal sandwiches with local metal reinforcements: a study on formability by deep drawing and bending," *Composite Structures*, vol. 94, 2011.

[4] G. Stachowiak and A. W. Batchelor, *Engineering Tribology*, Elsevier, Amsterdam, Netherlands, Fourth edition, 2014.

[5] B. Engel and J. Buhl, "Metal forming of vibration-damping composite sheets," *Steel Research International*, vol. 82, 2011.

[6] R. B. Ruokolainen and D. R. Sigler, "The effect of adhesion and tensile properties on the formability of laminated steels," *Journal of Materials Engineering and Performance*, vol. 17, no. 3, pp. 330–339, 2008.

[7] M. Harhash, R. R. Gilbert, S. Hartmann, and H. Palkowski, "Experimental characterization, analytical and numerical investigations of metal/polymer/metal sandwich composites–Part 2: free bending," *Composite Structures*, vol. 232, Article ID 111421, 2020.

[8] S. Mousa and G.-Y. Kim, "A direct adhesion of metal–polymer–metal sandwich composites by warm roll bonding," *Journal of Materials Processing Technology*, vol. 239, pp. 133–139, 2017.

[9] B. Safaei, R. Moradi-Dastjerdi, K. Behdinan, Z. Qin, and F. Chu, "Thermoelastic behavior of sandwich plates with porous polymeric core and CNT clusters/polymer nanocomposite layers," *Composite Structures*, vol. 226, 2019.

[10] J. K. Kim and T. X. Yu, "Forming and failure behaviour of coated, laminated and sandwiched sheet metals: a review," *Journal of Materials Processing Technology*, vol. 63, no. 1–3, pp. 33–42, 1997.

[11] T. Wollmann, M. Hahn, S. Wiedemann et al., "Thermoplastic fibre metal laminates: stiffness properties and forming behaviour by means of deep drawing," *Archives of Civil and Mechanical Engineering*, vol. 18, no. 2, pp. 442–450, 2018.

[12] A. Carrado, O. Sokolova, G. Ziegmann, and H. Palkowski, "Press joining rolling process for hybrid systems," *Key Engineering Materials*, vol. 425, pp. 271–281, 2010.

[13] A. Jalali Aghchai and S. Khatami, "Experimental and numerical formability investigation of FML sheets with glass fiber reinforced core," *International Journal of Advanced Manufacturing Technology*, vol. 96, no. 9–12, pp. 3881–3891, 2018.

[14] S. Keipour and M. Gerdooei, "Springback behavior of fiber metal laminates in hat shaped draw bending process: experimental and numerical evaluation," *International Journal of Advanced Manufacturing Technology*, vol. 100, no. 5, pp. 1755–1765, 2019.

[15] W. V. Titow, *PVC Plastics: Properties, Processing, and Applications*, Springer, Berlin, Germany, 1990.

[16] Friction factors—coefficients of friction, archived from the original.

[17] A. K. Ghosh and S. S. Hecker, "Failure in thin sheets stretched over rigid punches," *Metallurgical Transactions A*, vol. 6, no. 5, pp. 1065–1074, 1975.

[18] T. Bekele, "Investigation of formability analysis of metal-polymer sandwich composites considering the adhesion strength," MSc thesis, Adama Science and Technology University, Adama, Ethiopia, 2022.