

Post-print of “E. Karajibani, [R. Hashemi](https://doi.org/10.1007/s00170-016-9585-1), M. Sedighi, Forming limit diagram of aluminum-copper two-layer sheets: numerical simulations and experimental verifications, The International Journal of Advanced Manufacturing Technology, 2017, Volume 90, Issue 9–12, pp 2713–2722.
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Forming limit diagram of aluminum-copper two layer sheets: numerical simulations and experimental verifications

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Abstract

The aim of this research was to introduce a simulation-based approach for determination of the Forming limit curve (FLC) in two-layer metallic sheets. In this study, the FLC of Aluminum-1100/Copper-C10100 two layer sheets were obtained through numerical simulations and experimental investigations. In order to construct the FLC, two different criteria including the acceleration (i.e., the 2nd order of derivatives) of equivalent plastic strain and major strain were applied to obtain the onset of necking in the materials. Based on these methods, the localized necking would be started when the acceleration of the equivalent plastic strain or the major strain got its maximum value. To verify the numerical predictions, the experimental works were accomplished on the Aluminum-1100/Copper-C10100 two-layer sheets and a good agreement between the proposed methods and experimental works was observed.

Keywords: Two-Layer Sheet; Finite Element Analysis; Forming; Experiment

1. Introduction

In recent years, application of two-layer metallic sheets has been increased to manufacture the products with particular specifications, containing excellent mechanical and functional properties. These kinds of products are utilized in several applications such as industrial (the aerospace, electrical industries, and medical instruments) and domestic application [1-3].

Sheet formability and excessive localized thinning are two relevant problems that both academic and industrial researchers are constantly trying to solve. Due to that, the formability limit prediction in sheet metal forming processes assumes primary importance in all the manufacturing scenarios [4]. A forming limit curve (FLC). Forming limit curves (FLCs) are applied to determine the sheet metals formability. The laboratory tests results has demonstrated that the FLCs are effected by several factors containing strain rate [5, 6], strain hardening index and anisotropy coefficients [7, 8], heat treatment [9, 10], grain size and microstructure [11], strain path changes [12-14] and sheet thickness [15-17].

After the presentation of the forming limit curves concept by Keeler and Backofen [18], many researchers such as Ito et al. [19]; Aghaie-Khafri and Mahmudi [20]; Safikhani et al. [21]; Situ et al. [22]; Mohebbi and Akbarzadeh [23]; Bong et al. [24]; Chalal et al. [25] and Ben Bettaieb et al. [26] developed some numerical and analytical models to determine the sheet metals formability. However, a few attentions have been paid to study the behavior of multi-layer sheets. Semiatin and Piehler carried out the first study on multi-layer materials [27]. Yoshida and Hino [28] investigated the laminated sheets formability both numerically and experimentally. They found that the Forming Limit Curve of the laminates lied between the FLC of its parent material. Weiss et al. [29] tried to determine the laminated sheets formability in different temperatures to specify its effect on the formability of this kind of sheets. Aghchai et al. [30]

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predicted the formability of Aluminum/Steel two-layer metallic sheet both theoretically and experimentally. Their study demonstrated that the formability of two-layer metallic sheet lied between its parent material formability. Tseng et al. [31] investigated the deformation of Ti/Al clad metal sheets. Several significant process parameters, such as holding force, friction, counter pressure history, and blank dimensions, were discussed for improving the formability of Ti/Al clad metal sheets. Bagherzadeh et al. [32] developed analytical models to evaluate instability condition and stress analysis of cylindrical St-Al two-layer cups in hydro-mechanical deep drawing. Yousefi Mehr et al. [33] investigated the influence of annealing on the tensile strength of multilayered Al-Cu composites. Their research illustrated that the tensile properties of material decreased by increasing the annealing temperature and time. Afshin et al. [34] carried out a comprehensive investigation on warm deep-drawing process on Al 1050/St 304 and Al 5052/St 304 laminated sheets experimentally. They accomplished several tests to obtain the influences of grain size on some material characteristics such as stress, elongation and friction coefficient.

Although the fracture occurs by previous necking in several sheet metal forming processes, there are processes or conditions where fracture can develop without previous necking [35]. The scope of this work is limited to situations where necking occurs before failure by fracture.

In this study, two different FE models were utilized to determine the formability of Aluminum-1100/Copper-C10100 two layer metallic sheets. Although many investigations have been carried out to determine the formability of aluminum and copper one layer materials [36-40], according to the knowledge of the authors it's for the first time to determine the FLC of Aluminum-1100/Copper-C10100 two layer sheet using FE modeling and experiment.

The finite element methods using in this research contained: (1) *Acceleration of the equivalent*

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plastic strain (PEEQ) and the forming limit (LE)₁₁ of the major strain (1)¹

limit of two-layer sheets. Although many criterions have been used to predict the formability of one layer metallic sheets [41], the “*acceleration of the equivalent plastic strain*” and “*acceleration of the major strain*” criterions have been employed for the first time to determine the FLCs of Aluminum-1100/Copper-C10100 two-layer metallic sheets in order to determine the efficiency of these criterions in prediction of formability in two layer metallic sheets.

The FLC of two-layer sheets were obtained by a stretch-forming process with hemispherical punch and the simulation results demonstrated a good agreement with the experimental test results. The FEM results demonstrated that the proposed methods were fairly accurate and computationally inexpensive. It could be easily implemented for FLC generation in a laboratory setting with little need for user input and subjectivity.

2. Experimental Work

2.1 Materials

The two-layer metallic blanks (Aluminum-1100/Copper-C10100) were utilized in this research. The composition of the Aluminum-1100 and Copper-C10100 layer are given in Table 1 and Table 2, respectively.

¹ In ABAQUS software, PEEQ refers to the equivalent plastic strain

² In ABAQUS software, LE₁₁ refers to the major component of logarithmic strain

Table 1: Chemical composition of the Aluminum-1100 alloy sheet (wt %)

Al	Si	Fe	Cu	Mn	Mg	Cr	Ni
Base	0.355	0.456	0.0084	0.0803	0.014	0.0017	0.0026
Zn	Be	Ti	Pb	Sn	V	Zr	Sb
0.0091	0.001	0.0041	0.00069	0.0005	0.0088	0.0011	0.0012

Table 2: Chemical composition of the Copper-C10100 alloy sheet (wt %)

Cu	Zn	Pb	Sn	P	Mn	Fe	Ni	Si	Mg	Ti
99.98	0.00015	0.0001	0.0001	0.0016	0.00039	0.0044	0.0026	0.00065	0.00019	0.00014
As	B	Sb	Cd	Bi	Co	Al	S	Be	Zr	Cr
0.00036	0.00017	0.0001	0.0001	0.0001	0.0006	0.0007	0.00069	0.0001	0.0001	0.00014

The Aluminum-1100/Copper-C10100 two layer metallic sheets were fabricated using explosive welding which was utilized for an excellent joining of aluminum and copper sheets [42]. The total thickness of Aluminum-1100 and Copper-C10100 sheet was both 1mm and the two layer blank was made of 0.37mm Copper and 0.63mm Aluminum sheets. A STM-50 (SANTAM Company) electronic tensile machine was employed to accomplish the tensile tests. The mechanical and material properties of each layer were determined by standard test using specimens which were prepared according to ASTM-E8 specification at a constant crosshead speed of 2 mm/min [43]. The tensile test samples and dimension of the specimens used in this research are shown in Figure 1. The mechanical and material properties of each layer are presented in Table 3.

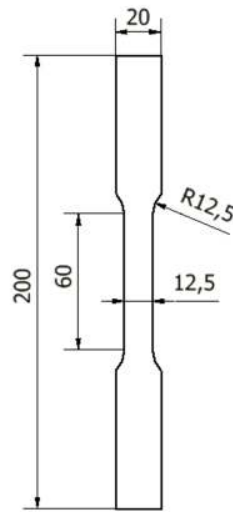


Figure 1: The dimensions of the standard specimens for Aluminum-1100 and Copper-C10100 sheets

Table 3: The material and mechanical properties of Copper-C10100 and Aluminum-1100 sheets from tensile tests

Material	Specific gravity, (Kg/m ³)	Young Module, E (GPa)	Yield Strength, YS (MPa)	Strength coefficient, K (MPa)	Strain hardening index, n
Copper-C10100	8940	115	306	540	0.11
Aluminum-1100	2710	69	122	232	0.12

2.2 Punch stretching test

The punch stretching tests were performed with a hemispherical punch of 100mm diameter according to procedure suggested by Nakazima [44] on a 30 tones hydraulic press (Figure 2). The specimens with different geometries were used to obtain the forming limit curve in this study. Figure 3 shows the geometries of the used specimens to obtain the FLC [45].



Figure 2: A tool set up for FLC

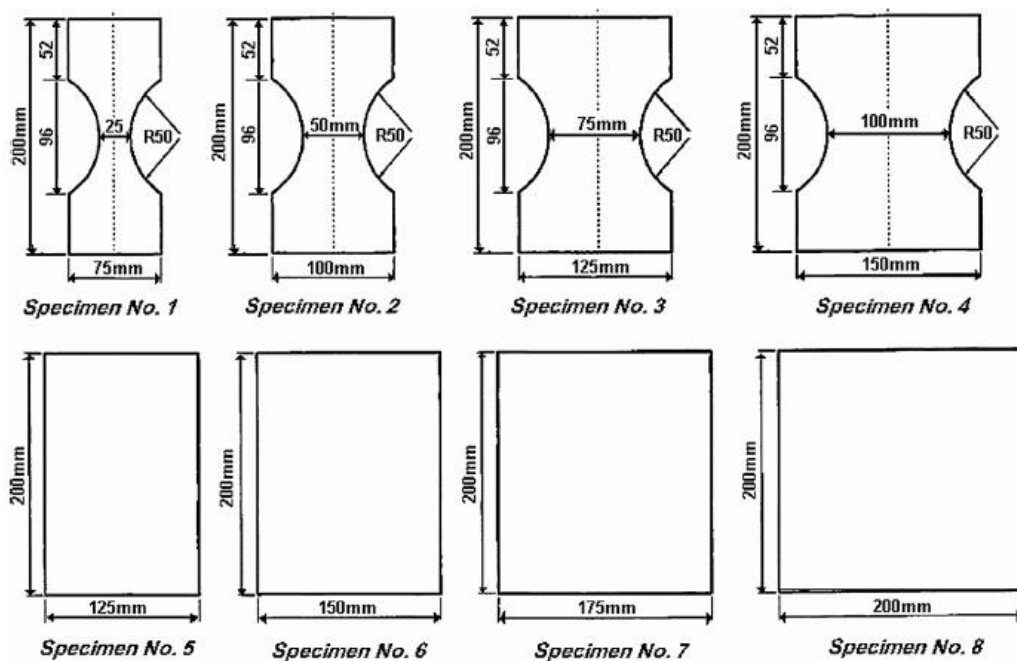


Figure 3: The different specimen geometry to obtain the FLC (all the dimensions in mm) [45]

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Moreover, in order to measure the principal strains after performing of tests to obtain the FLC, the circular grids were marked on the copper side of the Aluminum-1100/Copper-C10100 two-layer metallic blanks by the electro-chemical etching method.

The circles changed to ellipses after deformation. The minor and major diameters of the ellipses were measured using a Mylar transparent tape. The engineering strains were determined using equation (1) and equation (2), respectively and then converted to true strains:

$$\varepsilon_{Major}(\%) = \frac{a-d}{d} \times 100 \quad (1)$$

$$\varepsilon_{Minor}(\%) = \frac{b-d}{d} \times 100 \quad (2)$$

Where a , b and d denote the ellipse's major and minor diameters and the initial circle's diameter, respectively. The FLC was obtained by separating the safe zone from the unsafe zone containing the necked and fractured ellipses.

3. Finite element modeling

The ABAQUS/Explicit FE software [46] was used to model the biaxial stretch-forming test in order to investigate the Aluminum-1100/Copper-C 10100 two layer metallic sheet forming limits. The whole finite element modeling of biaxial stretch-forming test should be based on the actual biaxial stretch-forming test. The setting of the numerical simulation was based on the hemispherical punch and different shapes of specimens as mentioned in experimental section (see Figure 2 and Figure 3). All the analyses were realized using an explicit finite element approach. Figure 4 shows the geometrical setup which was simulated in the FE software. Since the punch, die, and blank holder had negligible deformation, they were simulated as an analytical

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rigid part. Moreover, the blank was considered as a deformable part and it was meshed by shell elements (four nodes, reduced integration elements, ABAQUS type S4R) [47]. It is suggested that the minimum length of element should be higher than the shell thickness (the thickness of test specimens were totally 1.0 mm). For example, based on the mesh sensitivity study, element size with 2 mm was selected as optimum element size for all finite element simulations when the thickness of test specimen was approximately 1 mm [45]. Thus, at the numerical simulations, the element size of the blanks was set to 2mm. For example, based on the selected element size, a 75mm sample contained 4105 elements and 4253 nodes. Also, the tensile properties of each layer were then introduced to the software in order to generate the major and minor strains in punch stretching process. Each layer was used in the power hardening law to model its behavior.

In order to cover full range of the FLC, different specimens with different dimensions were modeled to simulate the tension–compression to tension–tension side of the FLC. Friction coefficient was taken to be 0.15 between the surfaces. The blank holder and the punch could move through the punch’s axis while the die was fixed. Major and minor strains were recorded after each time step to evaluate the numerical FLC.

Figure 5 demonstrates the FE model included of the blank, the blank holder, the punch and the die.

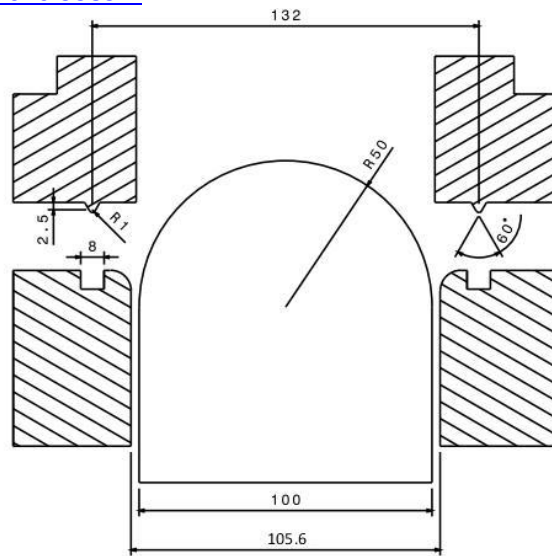


Figure 4: Schematic of the die, the punch and the blank holder (all the dimensions in mm)

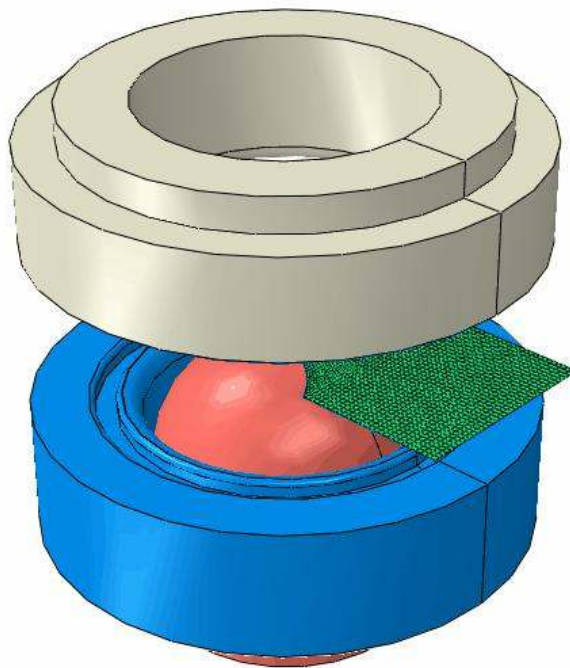


Figure 5: Modeling Nakazima's test in ABAQUS software

3.1. Analytical necking criterion

Selecting an appropriate necking criterion is important to determine the start of plastic instability in sheet metal forming (Figure 6). As previously mentioned, in this research the two necking criteria, containing the *acceleration of major strain* and the *acceleration of equivalent plastic strain* were employed to predict the onset of plastic instability.

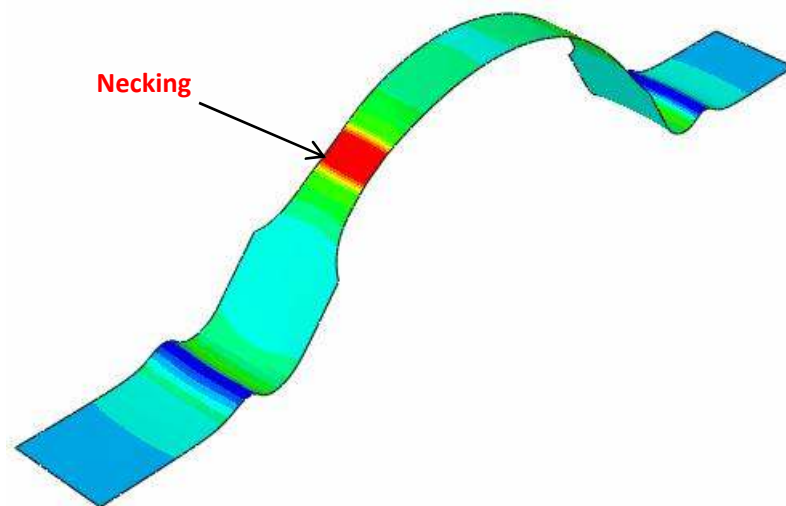


Figure 6: The FE results which show the start of localized necking in an analyzed material

Two novel criteria to detect the start of plastic instability in two-layer sheet were suggested to determine the FLC. The forming limits of the two-layer sheets were predicted considering the history of the equivalent plastic strain and the major strain by taking the second order of derivative. For a given strain path, the limit strain was determined at the maximum value of the strain acceleration. The analyzing of the major and the equivalent plastic strains and their accelerations are presented in detail in the sections 3.1.1 and 3.1.2 below. This analysis was

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repeated for all specimen geometries to obtain the FLC of Aluminum-1100/Copper-C10100 two layer metallic sheets.

3.1.1. The *acceleration of the major strain* criterion

The necking time of a special specimen could be determined by using this method. To obtain the FLC numerically, it was essential to predict at which time and where the necking phenomena occurred in the Aluminum-1100/Copper-C10100 two layer metallic sheets. It was possible to predict the necking time of the analyzed specimen using its acceleration of the major strain. This criterion was first presented by Situ [48] which was based on the major strain acceleration (or second derivative) in the sheet and defined by the following relation:

$$\ddot{\epsilon}_1 = (d^2\epsilon_1) / (dt^2) \quad (3)$$

which ϵ_1 is the major strain, and the logarithmic strain (LE^3) defines as follows in ABAQUS software [49]:

$$\epsilon^L = \ln V = \sum_{i=1}^3 \ln \lambda_i n_i n_i^T \quad (4)$$

Where $V = \sqrt{F \cdot F^T}$ is the left stretch tensor, λ_i are the principal stretches, and n_i are the principal stretch directions in the current configuration. The components of logarithmic strain shows as LE_{ij} for $i \leq j \leq 3$.

First of all the localized necking region was identified. This area could be detected as an unstable local reduction in the blank thickness. After the start of plastic instability in the material, all the strain became focused in this area and in the outside of this zone the strain rate was reduced

³ In ABAQUS software, LE refers to the logarithmic strain

gradually until it finally would be disappeared. The time evaluation of major strain at various aligned points along a section perpendicular to the necking area is shown in Figure 7. It could be seen that the strain level of some points (A and B) enhanced uniformly, while the other points (C, D and E) ceased to strain and even undergo some elastic unloading immediately before fracture. Thus, it could be deduced that the first set of points was situated in the localized necking area, while the second set of points was situated in regions adjacent to the localized necking area. Therefore, the necking zone width could be determined as shown in Figure 7.

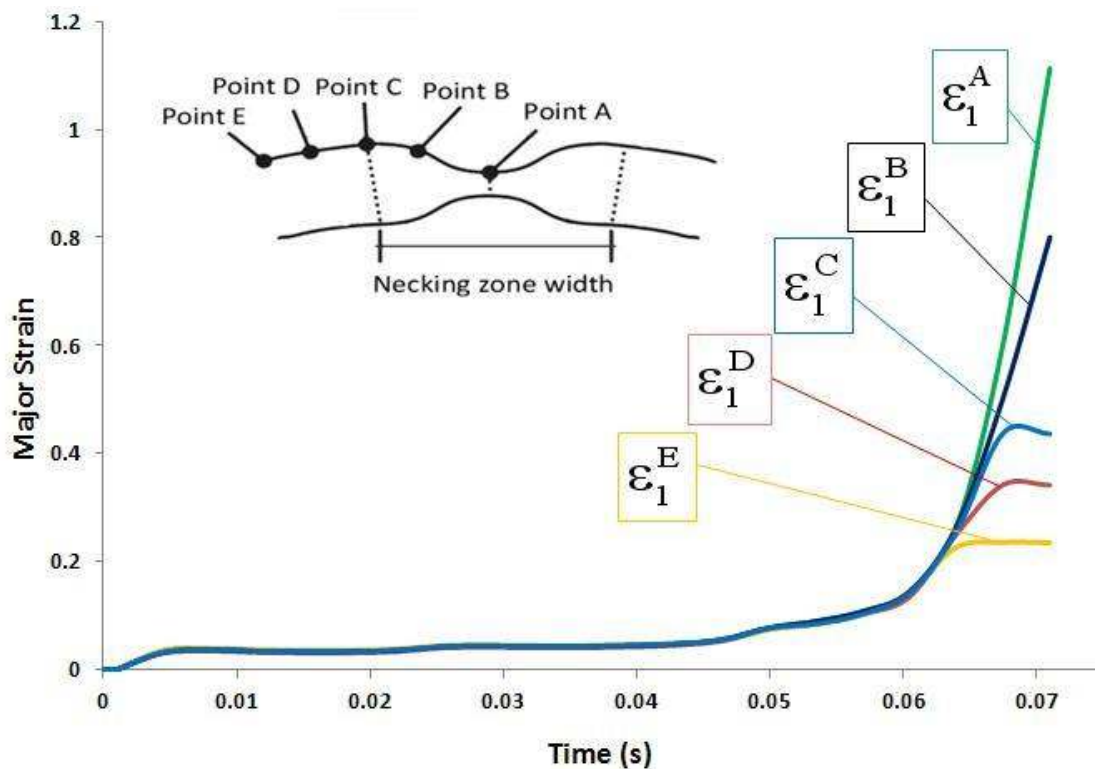


Figure 7: The time evaluation of the major strain at the various aligned points along a section perpendicular to the crack in the simulation to detect the necking region

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The time when the acceleration of the major strain got its maximum value was assumed as the start of necking phenomena in the Aluminum-1100/Copper-C10100 two layer metallic sheets. The element at which the maximum of acceleration of major strain first appeared in the necking area at the critical side of two layer composite sheet was assumed as the element which the onset of plastic instability started. At the end of the simulation, the major strain history was extracted from the output file of the FE model and its second derivative was then plotted (Figure 8). The time of necking (t_{necking}) was predicted from this curve.

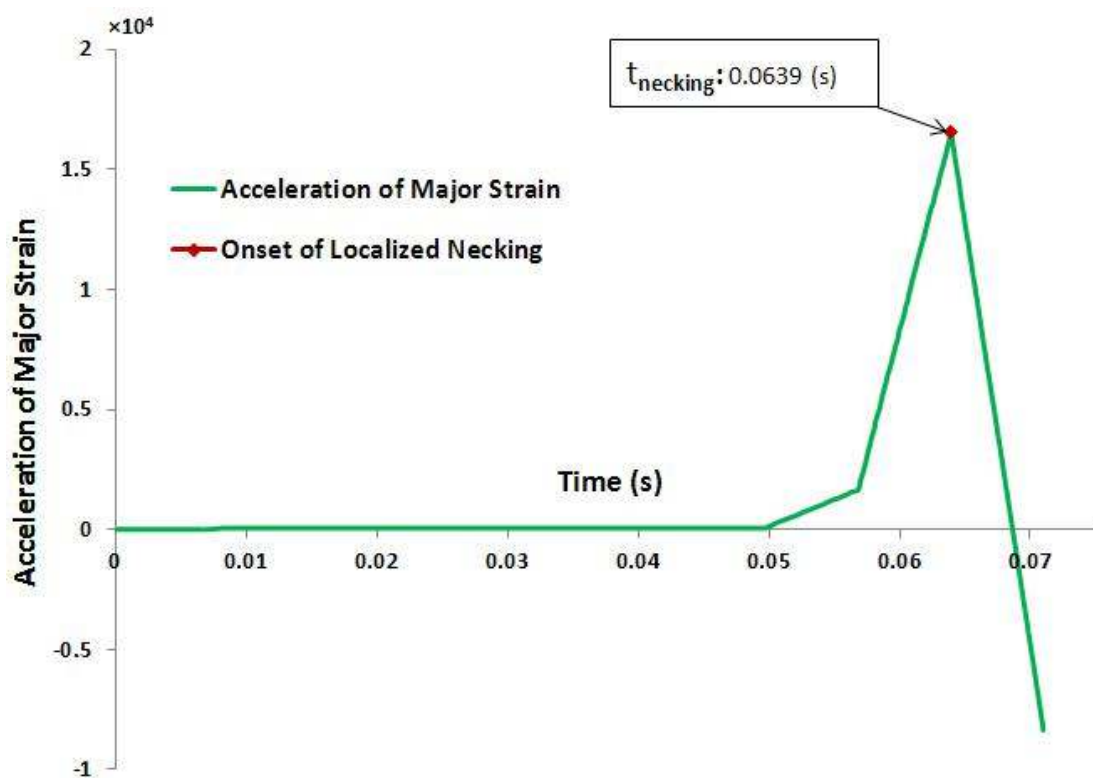


Figure 8: Acceleration of the major strain history information to detect the start of necking

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The major strain and minor strain at the point A and at the time corresponded to the onset of plastic instability ($t_{necking}$) were extracted from the FE result file, in order to construct the FLC (Figure 9). This procedure was repeatedly performed for all simulated specimen geometries of each Aluminum-1100/Copper-C10100 two layer metallic sheets.

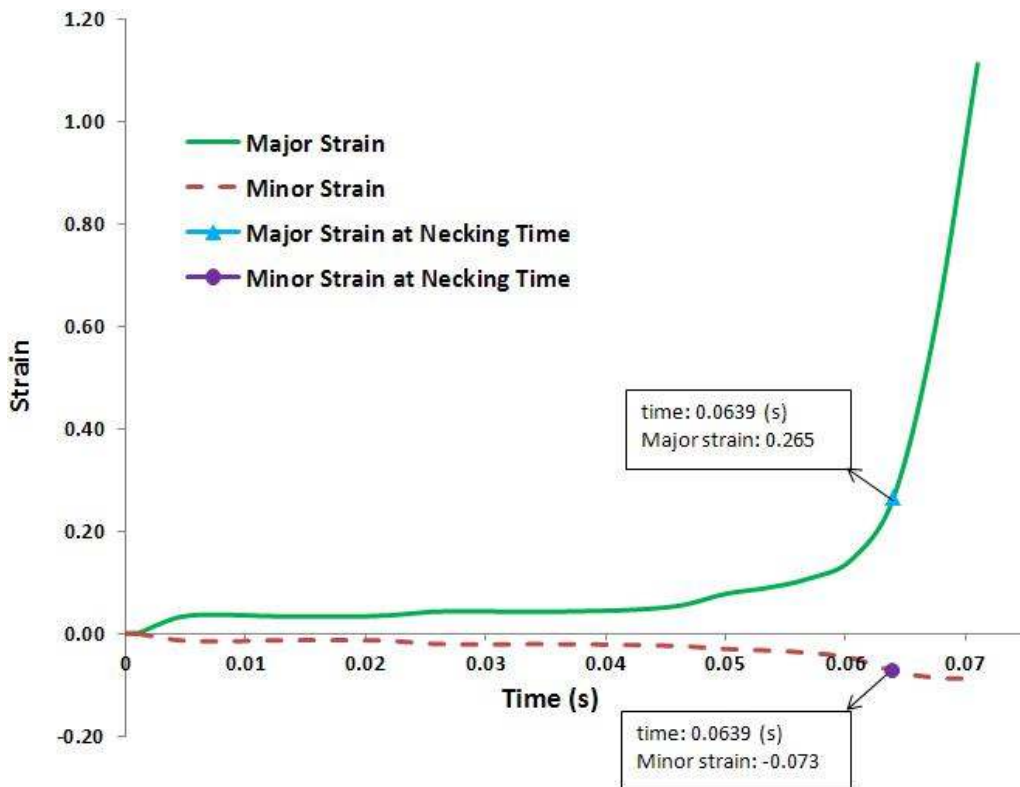


Figure 9: The major and minor strains at the necking time to produce the FLC

3.1.2. The acceleration of the equivalent plastic strain criterion

The procedure to predict the FLC by this criterion was the same as the acceleration of major strain criterion. The corresponding equation could be defined as follows [49]:

$$\bar{\epsilon}^{plastic} = \bar{\epsilon}_0^{plastic} + \int_0^t \sqrt{\frac{2}{3}} \dot{\epsilon}^{plastic} : \dot{\epsilon}^{plastic} \quad (5)$$

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where $\bar{\epsilon}^{plastic}_0$ is the primary equivalent plastic strain and $\dot{\epsilon}^{plastic}$ is the plastic strain rate.

In this research, these two criteria were presented as a necking criterion to determine the FLC in the Aluminum1100-/Copper-C10100 two-layer composite sheets for the first time.

The strain histories of the major and the equivalent plastic strains were compared in Figure 10. Also Figure 11 shows their relation. These Figures illustrate that the relation between these criteria is linear. Thus, the maximum value of their acceleration happens at the similar time and so their FLC would be the same. Thus, it is expected that the two criteria demonstrate the similar results.

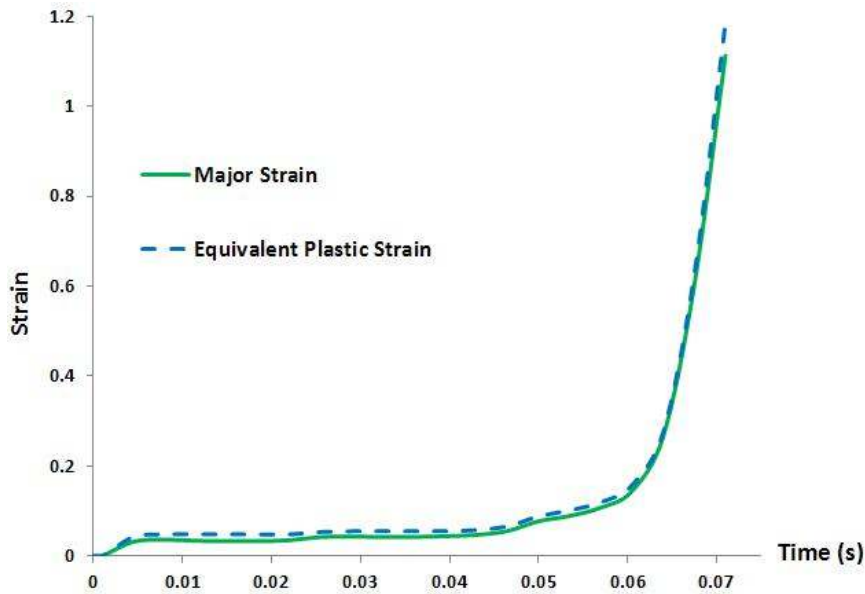


Figure 10: The strain histories of equivalent plastic and major strains

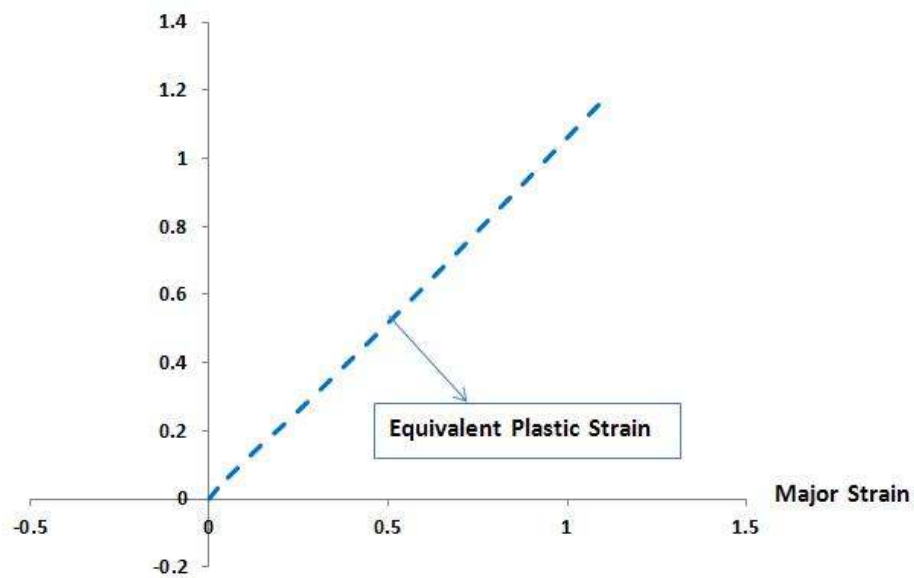


Figure 11: The linear relation between the equivalent plastic strain and the major strain

Strain-based forming limit curves are typically determined under linear loading conditions before the onset of necking. Figure 12 demonstrates the strain path was almost linear up to onset of necking in the FE model used in this work, which implied that the FLCs obtained in this research were acceptable.

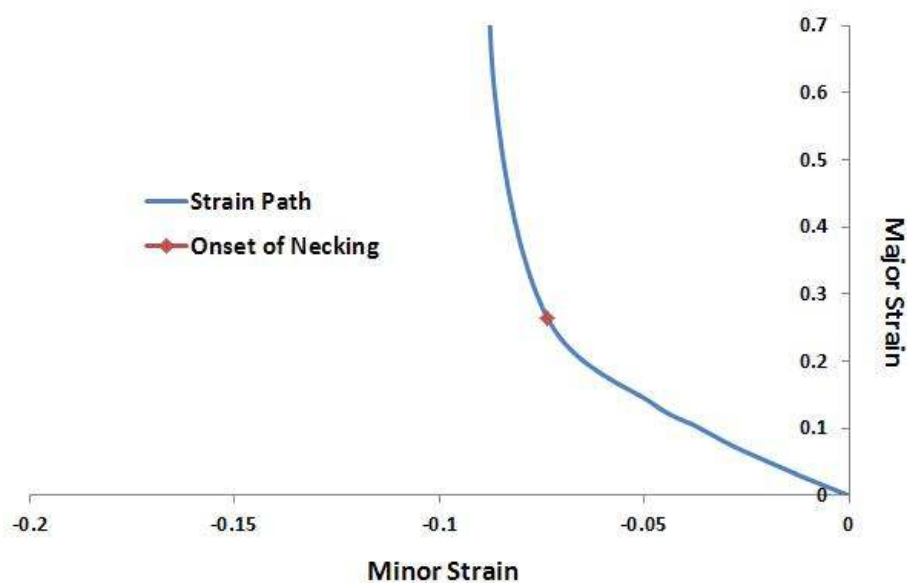


Figure 12: Linearity of strain path before onset of necking in the simulation result

Figure 13 shows the equivalent plastic strain and the major strain distributions for a 75mm wide specimen.

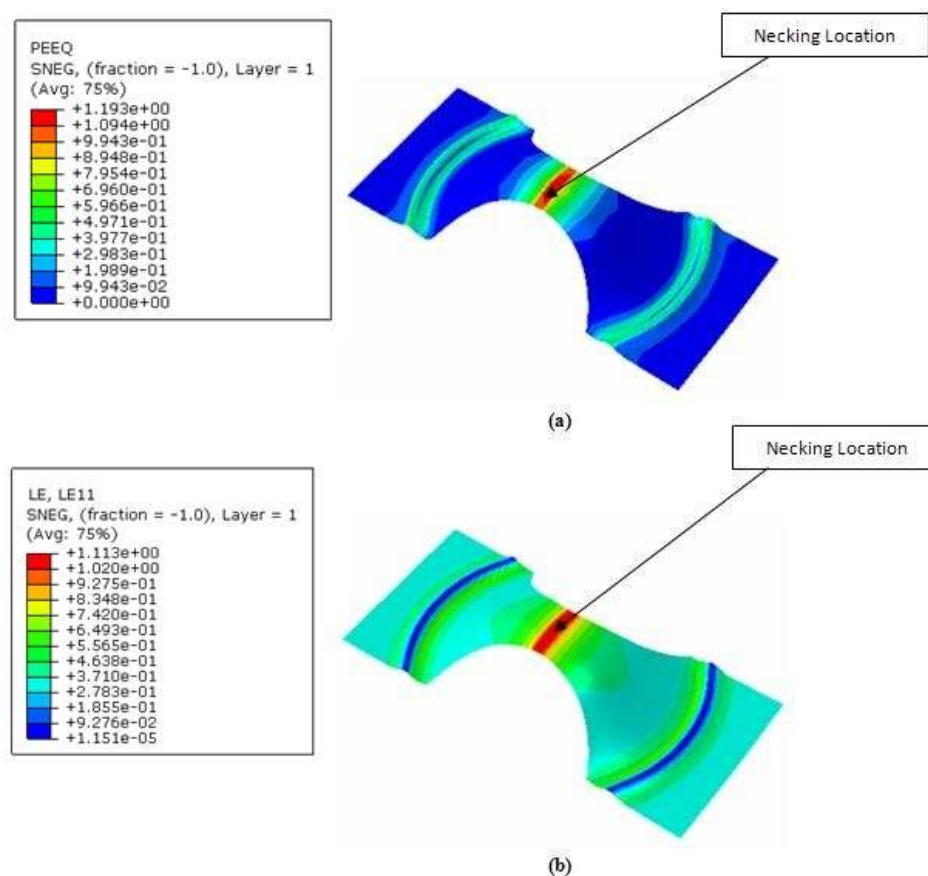


Figure 13: Strain distributions for a 75mm wide specimen: **(a)** Equivalent Plastic strain
(b) Major strain

4 Results and discussion

In this research, the results of the simulated stretch-forming test for Aluminum-1100/Copper-C10100 two-layer composite sheets were presented. The two different necking criterions,

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containing the acceleration of equivalent plastic and major strains, were applied to identify the start of plastic instability in the Aluminum-1100/Copper-C10100 two layer metallic sheets material to construct the FLC. The simulation results illustrated a good agreement with experimental test investigation which verified the applicability of the present necking criterions.

4.1. Comparison of necking locations in two-layer sheets

The equivalent plastic strain and the major strain distributions for a 75mm wide specimen are shown in Figure 13. It could be seen that the strain distributions showed almost similar results for the both necking criterions and the necking locations were almost the same. The necking locations determined by the numerical simulation were compared with the experimental result for the three different strain paths as Figure 14.

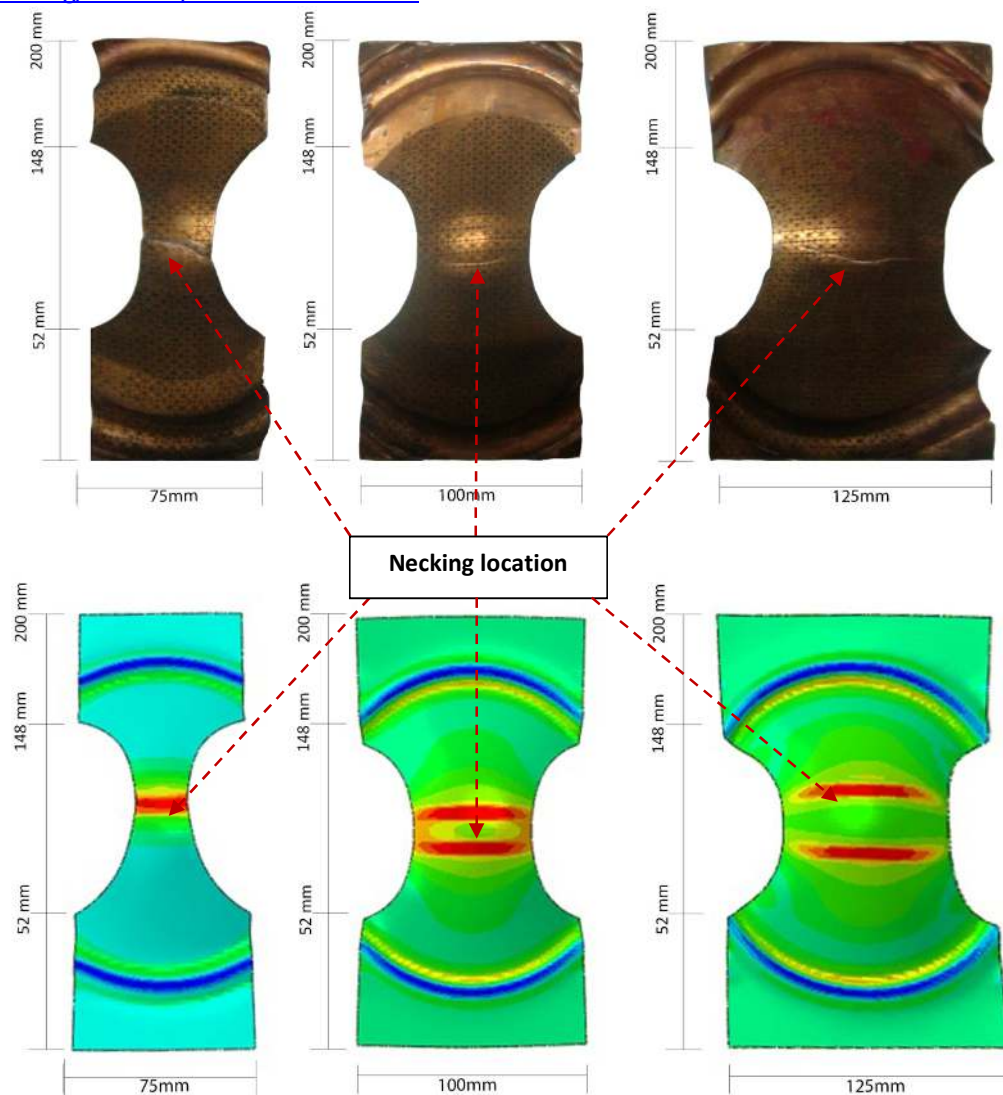


Figure 14: Comparison of necking locations from FE analysis and experiment

4.2. Forming limit curve of Al-Cu two-layer composite sheet

The predicted FLCs were compared with the forming limit curve obtained experimentally for Aluminum-1100/Copper- C10100 two-layer composite sheets (Figure 15). It could be concluded from the Figure 15 that these methods were in good agreement with the experimental test results for Al-Cu two-layer sheets.

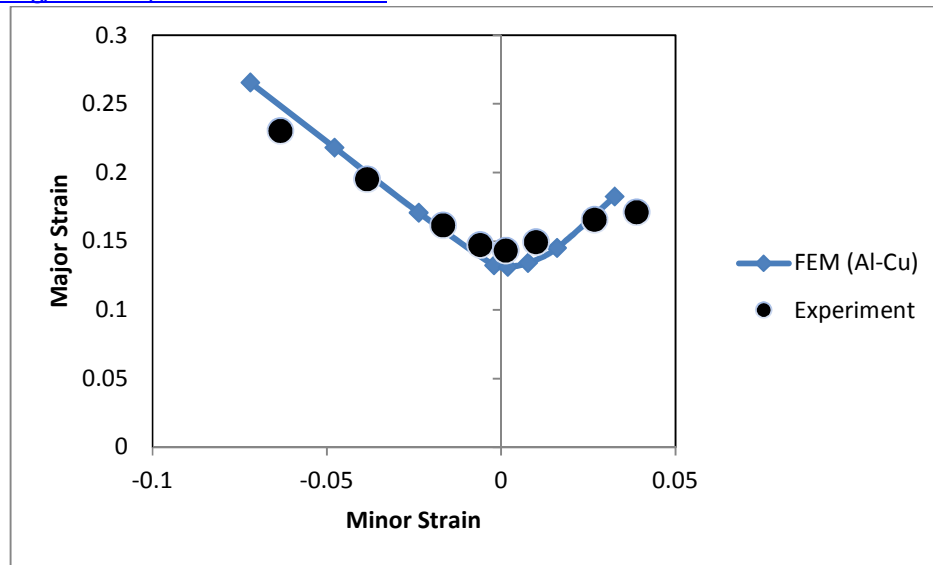


Figure 15: The FLCs for the Aluminum-1100/Copper- C10100 two-layer sheets

The experimental tests were repeated for each mode of forming and two points for each specimen sketch (for each mode of forming) have been determined and a mean values of major and minor strains for each specimen sketch have been reported in Figure 15. This figure showed that there was a low difference between the results of FEM and experiment for the FLD_0 (i.e., major strain in plane strain state). This difference could be due to the errors in strain measurement by the conventional “circle grid analysis” method [50, 51]. Therefore, it could be deduced that the FE results were in acceptable agreement with experimental investigations.

Conclusions

This research presented the study on the FLC’s determination of the Aluminum-1100/Copper-C10100 two-layer composite sheets. The two different numerical methods were applied to obtain the FLCs. The numerical results for the FLCs were verified by comparing them with experimental tests. These numerical models contained: (1) Acceleration of equivalent plastic

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strain, (2) Acceleration of major strain ($\frac{d^2\varepsilon_1}{dt^2}$). These criteria were used for the first time to predict the FLC of the Al-Cu two-layer composite sheets. Both of these models demonstrated the same results. The proposed methods were fairly accurate and computationally inexpensive. Results from the suggested numerical simulations were in fairly good agreement with experimental investigations.

Acknowledgments

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Appendix I: Notation

FLC	Forming limit curve
FLD	Forming limit diagram
FLD ₀	Major strain in plane strain state
K	Strength coefficient
n	Strain hardening index
E	Young Module

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YS	Yield strength
ν	Poisson's ratio
ε	True strain
ε_1	Major strain
ε_2	Minor strain
ε_3	Thickness strain
PEEQ	Equivalent Plastic strain
LE	Logarithmic strain
LE11	Major component of logarithmic strain
V	left stretch tensor
λ_i	principal stretches
n_i	principal stretch directions