Analytical study for deformability of laminated sheet metal

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Abstract While a freestanding high-strength sheet metal subject to tension will rupture at a small strain, it is anticipated that lamination with a ductile sheet metal will retard this instability to an extent that depends on the relative thickness, the relative stiffness, and the hardening exponent of the ductile sheet. This paper presents an analytical study for the deformability of such laminate within the context of necking instability. Laminates of high-strength sheet metal and ductile low-strength sheet metal are studied assuming: (1) sheets are fully bonded; and (2) metals obey the power law material model. The effect of hardening exponent, volume fraction and relative stiffness of the ductile component has been studied. In addition, stability of both uniform and nonuniform deformations has been investigated under plane strain condition. The results have shown the retardation of the high-strength layer instability by lamination with the ductile layer. This has been achieved through controlling the aforementioned key parameters of the ductile component, while the laminate exhibits marked enhancement in strength–ductility combination that is essential for metal forming applications.

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Introduction

There has been a strong demand for high-strength steel having an exceptionally good strength–ductility combination. For conventional steel in bulk form, however, there exists a clear boundary drawn in the space of strength and ductility combination, beyond which no conventional steel can go. Considering the rupture modes of high-strength steel, two kinds of elongation limit exist, one is associated with fracture due to lack of toughness and the other is induced by the mechanism so called “plastic instability”. The plastic instability itself has two deformation modes, one is called diffuse necking and the other is localized necking. In order to retard both rupture mechanisms and to overcome the boundary for conventional steel, we have been studying the introduction of a laminated structure composed of brittle high-strength (BHS) and ductile low-strength (DLS) steels, and it has been clarified that the brittle rupture of BHS steel can be suppressed by laminating it with a DLS steel with an appropriate selection of layer thickness, interface fracture toughness, and mechanical properties of the more ductile constituent layer. The experimental studies that have been conducted by Inoue et al. [1] and Nambu et al.
In the present study, an idealized structure is considered: a BHS sheet metal bonded to a DLS sheet metal in two-layer or multilayer laminate that is subject to a tensile plane strain. Key two questions are: whether the BHS sheet can survive larger strains without rupture, and how much would be the associated ultimate strength of the laminate. This is to introduce enhanced strength-ductility combination.

Oya et al. [18] conducted uniaxial tension tests on WT780C as brittle martensitic steel (BHS sheet) and SUS304 as ductile austenitic stainless steel (DLS sheet). The chemical compositions for WT780C and SUS304 are shown therein [18] with a yield strength of 1080 [MPa] and 226 [MPa], respectively. Under uniaxial tension, the metal deforms according to the power law $\sigma = K \varepsilon^n$, where $\sigma$ is the true stress, $\varepsilon$ is the strain, $K$ and $N$ are constants determined from known true stress–strain data before necking. $N$ is also known as the material hardening exponent. It has been reported that WT780C could achieve a hardening exponent $N = 0.05$ associated with $K = 1663$ [MPa]; on the other hand, SUS304 could achieve a hardening exponent $N = 0.5$ associated with $K = 1611$ [MPa]. It is worth noting that the range of laminate parameters that have been considered in this study intends to cover a broad spectrum of potential material combinations for BHS/DLS laminates.

### Uniform deformation stability

The laminate in question has two different hardening exponents, a low hardening exponent of the BHS sheet and a high hardening exponent of the DLS sheet. In a freestanding BHS sheet metal, the geometric softening predominates the material hardening at a small strain, and the uniform deformation becomes unstable. The behavior is similar for a freestanding DLS sheet metal; however, the onset of instability takes place at much higher limit strain. Consequently, at the onset of BHS sheet instability the DLS sheet stiffens steeply and the tensile force increases with deformation by material hardening. So the question is what will happen to a BHS/DLS laminate?

Fig. 1 describes the model, a freestanding BHS sheet metal along with BHS/DLS laminate are analyzed. For the laminate, different values of volume fraction of the DLS component $f$ are studied.

Under uniaxial plane strain stretching, the stress in $x$-direction is related to the applied strain as:

$$\sigma_{\text{BHS}} = K_{\text{BHS}} e^{N_{\text{BHS}}}$$

in the BHS and DLS layers. By volume conservation, as the laminate elongates in the $x$-direction, both the BHS and DLS layers thin by a factor of $\exp(-\varepsilon)$ in the $y$-direction [5,19]. Consequently, the normalized nominal stress $\sigma_{\text{Norm}}$ is given as follows:

$$\sigma_{\text{Norm}} = \frac{\sigma}{\sigma_{\text{avg}}} = \frac{[(1-f)e^{N_{\text{BHS}}} + fK_{\text{DLS}}e^{N_{\text{DLS}}}]}{\exp(-\varepsilon)}$$

By considering the formability of each material layer, it is possible to observe that the laminate is unable to stretch to larger strains without rupture, and how much would be the associated ultimate strength of the laminate. This is to introduce enhanced strength-ductility combination.

Grote and Antonsen [7] studied the deformability of a freestanding metal sheet described by power hardening with strain hardening exponent $N$. They have reported that if the stress state is not uniaxial, as usual in most sheet forming processes, the diffuse necking criterion does not set the limit strain. The localized necking criterion, however, sets the limit strain in practical sheet forming while it predicts well the negative minor strain region of the forming limit diagram. The localized necking limit strain is equal to $N/[1 + e_2/e_1]$; while $e_2/e_1$ is the ratio between minor and major strains in metal forming. It is worth noting that in the forming limit diagram the plane strain represents the critical state where the minor strain vanishes and the localized necking strain ($k_{\text{Necking}}$) becomes equal to $N$ ($k_{\text{Necking}} = N$). The localized necking of the laminate has been analyzed [8] within a forming limit analysis. It was found that the plane strain assumption is still valid in observing the deformability of the laminate, where the minimum necking strain in the forming limit diagram is associated with the plane strain condition.

Hence, in this study the plastic instability associated with the localized necking under plane strain condition has been adopted to evaluate the laminate deformability. In addition, the laminate layers are assumed to be fully bonded; consequently, the interface delamination is beyond the scope of this paper.

Of interest in this paper is the role in retarding the onset of necking of a DLS sheet metal bonded to a BHS sheet metal. Neck retardation allows the laminate to be stretched to larger overall strains. In the range of strains relevant to the BHS sheet metal necking, we anticipate that the incremental modulus of the nominal stress–strain curve of the DLS sheet metal remains constant with stretching while that of the BHS sheet metal decreases steadily. Accordingly, compared to a single (freestanding) BHS sheet metal [9,10] at a given level of stretch, the laminate has lower average stress and higher tangent modulus, both of which promote necking retardation. This is the essence of the phenomenon as similarly introduced [5,11,12] for the polymer substrate-bonded metal film.

There are initiatives that have been investigating the shear and normal stresses in laminated sheet metal [13–15]. The flexural response has been examined [16] for the vibration-damping type of laminated steel (steel/polymer/steel laminate). A comparison has been performed for beam theory predictions with the experimental results, and good agreement has been observed in case of using two layers of shells in the finite element analysis. The formability of multilayer metallic sheets has been evaluated by tensile, V-bending, hat bending and hemming tests [17,18]. Marked enhancement of the bending formability was observed in the bending of type-420J2 stainless steel sheets when they are layered by type-304 stainless steel sheets and composed into a multilayer metallic sheet.
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\[
\sigma_{\text{avg}} = K_{\text{BHS}}(1 - f) \varepsilon_{\text{Necking-BHS}} \exp(-\varepsilon_{\text{Necking-BHS}}) + f K_{\text{NDLS}} \varepsilon_{\text{Necking-DLS}} \exp(-\varepsilon_{\text{Necking-DLS}}) = K_{\text{BHS}} \varepsilon_{\text{Necking}}(1 - f) N_{\text{NDLS}}^\varepsilon \exp(-N_{\text{NDLS}}) + f K_{\text{NDLS}} \varepsilon_{\text{Necking}}(1 - f) N_{\text{NDLS}}^\varepsilon \exp(-N_{\text{NDLS}})
\]

where \( F \) is the resultant force in \( x \) direction, \( \sigma_R \) is the nominal stress, \( \sigma_{\text{avg}} \) is the average of nominal ultimate strength, \( f = H_{\text{DLS}}/(H_{\text{DLS}} + H_{\text{BHS}}) \) is the volume fraction of the DLS component, and \( k = K_{\text{DLS}}/K_{\text{BHS}} \) is the components stiffness ratio. It is worth noting that the dimensionless ratios \( f \) and \( k \) quantify the effect of the DLS component in the laminate.

Fig. 2a plots the normalized nominal stress \( \sigma_{\text{Norm}} \) as a function of the applied strain \( \varepsilon \) for three different values of \( N_{\text{NDLS}} \): 0.5, 0.3, and 0.1 and three different values of the volume fraction of the DLS component (\( f = 1/2, 2/3, \) and \( 3/4 \)), where the laminate components stiffness ratio \( k \) is set to unity and the hardening exponent of the BHS component \( N_{\text{BHS}} \) is set to 0.06. When \( f = 0 \), the BHS sheet metal is in effect freestanding, where \( \sigma_{\text{Norm}} \) peaks at a small strain equal to \( N_{\text{BHS}} \) and then drops. In the analysis, three controlling parameters appear. The first parameter is the volume fraction of the DLS component \( f \), where an increase in \( f \) leads to an increase in the limit strain, through resisting the aforementioned geometric softening for a particular hardening exponent of the DLS component. For instance, in Fig. 2a(ii) the limit strain increases from 6% at \( f = 0 \) to 22.5% at \( f = 3/4 \). The second parameter is the hardening exponent of the DLS component \( N_{\text{DLS}} \), where an increase in \( N_{\text{DLS}} \) leads to an increase in the limit strain, through enhancing laminate hardening against a particular geometric softening. For instance, in Fig. 2a(i and iii) at the same \( \varepsilon \) value that equals to 2/3, the limit strain increases from 8.6% at \( N_{\text{DLS}} = 0.1 \) to 30% at \( N_{\text{DLS}} = 0.5 \). The\( k \) ratio is the third controlling parameter, where an increase in \( k \) leads to an increase in the limit strain, through resisting the aforementioned geometric softening by stiffening the laminate for a particular hardening exponent of the DLS component.

Fig. 2b plots the normalized nominal stress \( \sigma_{\text{Norm}} \) as a function of the applied strain \( \varepsilon \) for the same values of \( N_{\text{NDLS}} \) and \( N_{\text{BHS}} \) and three different values of laminate components stiffness ratio \( k = 1/4, 1/2, \) and \( 1.0 \), where \( f \) is set to 0.5. For instance, in Fig. 2b(ii) the limit strain increases from 12% at \( k = 0.5 \) to 16% at \( k = 1.0 \).

It is worth noting that the rule of averages is considered in this paper as the scale of enhancement in laminate strength and ductility. This is the same enhancement scale for the experimental studies of available laminated sheet metal [1–4]. The limit strain calculated from Eq. (2) at the force maxima, as shown in Fig. 2a and b, is compared further with the prediction of the limit strain based on the rule of averages. As shown in Fig. 3, the comparison with the rule of averages has been conducted for two cases of the hardening exponent of the BHS component (\( N_{\text{BHS}} = 0.01 \) and 0.06), three cases of the volume fraction of the DLS component (\( f = 1/3, 1/2, \) and \( 2/3 \)), four cases of the laminate components stiffness ratio \( k = 2.0, 1.0, 0.5, \) and 0.25), and different values of the hardening exponent of the DLS component \( N_{\text{DLS}} \) ranging from \( N_{\text{BHS}} \) to 1.0. This covers a broad spectrum of designated BHS/DLS laminates. It is obvious that the calculated limit strain becomes closer to that predicted by the rule of averages by decreasing the hardening exponent of the DLS component till a bound of homogenous BHS sheet metal where the ratio \( \varepsilon_{\text{Necking}}(\text{BHS})/\varepsilon_{\text{Necking}}(\text{DLS}) \) approaches unity. It is worth noting that changing the \( k \) ratio affects the limit strain to be less, equal, or even more than the prediction of the rule of averages. It is also clear that by decreasing the ratio \( \varepsilon_{\text{Necking}}(\text{BHS})/\varepsilon_{\text{Necking}}(\text{DLS}) \), the role of the DLS component in retarding the BHS component instability is decreasing. This role vanishes when the ratio \( \varepsilon_{\text{Necking}}(\text{BHS})/\varepsilon_{\text{Necking}}(\text{DLS}) \) becomes very small. These results are compliant with the experimental observations [3], where it has been noted that the tensile ductility of most of the laminated composites is lower than that predicted from the rule of averages when the difference between ductility of the two components is large. This has been attributed to the susceptibility of the less ductile component to an early rupture.

From Eq. (2) and \( \varepsilon \rightarrow 0 \), it follows that:

\[
k/(1 - f) = \varepsilon_{\text{Necking}} - N_{\text{BHS}}\varepsilon_{\text{Necking}}/N_{\text{DLS}}\varepsilon_{\text{Necking}} - \varepsilon_{\text{Necking}}
\]
The results obtained in this section describe a response of critical limit strain associated with a perturbation of long wavelengths. For a freestanding sheet, the prediction of critical strain for long wavelengths gives the lowest critical strain \[6,7\]. Accordingly, it is a common practice to identify the long wavelength limit, \[\varepsilon_{\text{Necking}} = N\], as the rupture strain of a freestanding metal. For a metal laminate structure, there is still a critical strain associated with the long wavelength perturbation limit \[2\]. However, a lower bifurcation strain was observed at finite wavelength \[2,20\] indicating multiple necking in association with interface delamination. It is noted that since the laminate layers are assumed to be fully bonded, the critical strain asso-\[\cdots\text{c}nated with the finite wavelength is no longer a bifurcation mode resulting in a rupture in the laminate\[2,20\]. Hence, the critical strain associated with the long wavelength limit is still identified as the rupture strain of the laminate driving the behavior into a single-necking deformation. The experimental observations of Inoue et al. \[1\] and Nambu et al. \[2\] support this analysis; while, the specimen with high bonding strength experienced large uniform elongation that was followed by a single-necking rupture. Table 1 shows good agreement between the results obtained experimentally \[1,2\] and those obtained based on Eqs. \(2\) and \(3\) of this study.

This is different from what was observed by Li and Suo \[5\] for the polymer substrate-bonded metal film where in the long wavelength limit the critical strain is infinite, then drops precipitously as the wavelength of the perturbation decreases exhibiting a multiple-necking deformation. This difference is attributed to the increasing hardening exponent of the polymer substrate with stretching; meanwhile, the hardening exponent of the DLS component in the BHS/DLS laminate is constant. In addition, the constitutive equation for the DLS component is a power law; meanwhile, for the polymer substrate it is not.

In the next section, the large-amplitude nonuniform deformation in multilayer BHS/DLS laminate has been investigated. The finite element analysis has been performed to investigate the post bifurcation behavior and to identify the deformation mode at the limit strain of the necking, whether multiple-necking (at finite wavelength of perturbation) or single-necking (at long wavelength limit).

Nonuniform deformation stability

The linear stability analysis fails to identify the deformation mode corresponds to the limit strain, where the amplitude of the nonuniform displacement is large compared to the
Fig. 3  The necking strain of the two-layer BHS/DLS laminate compared with prediction based on the rule of averages, for different cases of the hardening exponent of the DLS component $N_{DLS}$, the hardening exponent of the BHS component $N_{BHS}$, the laminate components stiffness ratio $k$, and the volume fraction of the DLS component $f$.

Fig. 4  The necking strain range of the two-layer BHS/DLS laminate for different combinations of the laminate components stiffness ratio $k$ and the volume fraction of the DLS component $f$ at three different cases of the hardening exponent of the DLS component: (a) $N_{DLS} = 0.5$; (b) $N_{DLS} = 0.3$; and (c) $N_{DLS} = 0.1$. 
Table 1

| Laminate description | Experimental results | Analytical results |
|----------------------|----------------------|-------------------|
|                      | Eq. | σ_0,avg (Mpa) | σ_0,avg (Mpa) | Error % | Error % |
|                       |     |   |                 |                 |         |         |
|                       |     |   |                 |                 |   n   |
|                       |     |   |                 |                 |   n   |
|                       |     |   |                 |                 |   n   |
|                       |     |   |                 |                 |   n   |

Inoue et al.[1]

| Twelve BHS Layers of SS420: 40 μm thickness each | 0.6 700 | 0.08 22.40 | 0.52 1192.30 | 1180.00 | 0.99 0.99 | 0.154 1109.71 | 0.93 0.93 |
| Three DLS Layers of SS304: 165 μm thickness each | 0.5 1192 | 0.053 1292 | 0.50 1200.49 | 960.00 | 0.80 0.80 | 0.160 1051.96 | 0.88 0.88 |

Nambu et al.[2]

| One BHS Layer of SCM415: 330 μm thickness | 0.6 1200 | 0.053 1292 | 0.50 1200.49 | 960.00 | 0.80 0.80 | 0.160 1051.96 | 0.88 0.88 |
| Two DLS layers of SS304: 165 μm thickness each | 0.5 1200 | 0.053 1292 | 0.50 1200.49 | 960.00 | 0.80 0.80 | 0.160 1051.96 | 0.88 0.88 |

pertain to the experimental results of published papers and analytical results of this study. The limit strain at the onset of necking has been identified with the point of maximum nominal stress. It is clear that the DLS layer has retarded the necking instability of the BHS layer the point of maximum nominal stress. It is clear that the DLS layer has retarded the necking instability of the BHS layer.
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away beyond its freestanding limit strain (0.06). It is also evident that the absolute layer thickness has insignificant effect on necking retardation, assuming no interface delamination, where the limit strain and the associated ultimate strength are almost identical for the three configurations. The small difference, however, is attributed to the small difference in volume fraction of the DLS component.

Upon the insignificant effect of the absolute layer thickness on necking retardation, only the 11-layer BHS/DLS laminate is used further in the nonuniform deformation analysis. Table
2 illustrates four cases of study for different combinations of ultimate strength \( r_u \) of the BHS and DLS components, and hardening exponent and volume fraction of the DLS component. In all cases, the yield strength and the hardening exponent of the BHS component are 1000 [MPa] and 0.06, respectively; while, the yield strength of the DLS component is 300 [MPa]. The laminate components stiffness ratio \( k \), however, is governed by the selected ultimate strength and the hardening exponent, from the relation:

\[
k = \left( \frac{r_u}{C_{0,BHS}} \right) \left( \frac{N_{DLS}}{N_{BHS}} \right)
\]

Each case includes three sub-cases of investigation which correspond to three different values for hardening exponent of the DLS component (\( NDLS = 0.1, 0.2, \) and \( 0.4 \)).

A finite element plane strain uniaxial tension analysis has been conducted for the four cases, where the same prescribed imperfection on the top surface of the laminate (Fig. 5c) is used. Table 2 lists the FEM analysis results against those obtained analytically using Eqs. (2) and (3) of this study. Fig. 6b plots the same results, where the laminate necking strain \( \varepsilon_{Necking} \) has been plotted versus the associated nominal ultimate strength of the 11 layers laminates in comparison with the analytical results, where the four cases are described in Table 2.

![Diagram](image)

**Fig. 6** Results of finite element analysis for plane strain uniaxial tension of multilayer BHS/DLS laminates: (a) The nominal stress, normalized to the average ultimate strength, versus strain for three different configurations: 15, 11, and 7 layers; and (b) The necking strain versus the associated nominal ultimate strength of the 11 layers laminates in comparison with the analytical results, where the four cases are described in Table 2.

It is clear that both results are close to the prediction of the rule of averages with a noticeable deviation usually observed at the third sub-case of each analysis case (\( N_{DLS} = 0.4 \) and \( N_{BHS} = 0.06 \)). This is attributed to the observation of Figs. 2 and 3, where the ultimate strength and the associated limit strain deviate from the averages by increasing the hardening exponent of the DLS component (\( NDLS \)) relative to that of the BHS component (\( NBHS \)), where the ratio \( \varepsilon_{Necking(BHS)}/\varepsilon_{Necking(DLS)} \) tends to be small. It is also clear that the limit strain increases by increasing \( NDLS \), when comparing the three sub-cases of each case. Fig. 6b informs also that the analytical results obtained in this study represent a conservative estimate for laminate limit strain and ultimate strength which are adequate for the design purpose of sheet metal laminates. Further investigation is needed for the sensitivity of deformation mode to material parameters and interface delamination.

**Concluding remarks**

The deformability of laminated sheet metal has been studied analytically in this paper. The plastic instability associated with the localized necking under plane strain condition has
been adopted to evaluate the laminate deformability. Stability of both uniform and nonuniform deformations has been investigated for two-layer and multilayer high-strength/ductile metal sheets (BHS/DLS) laminates. It is assumed that laminate layers are fully bonded, and metals obey the power law material model. It is worth noting that the present study is adequate for the design purpose of sheet metal laminates; meanwhile, further investigation is needed for the sensitivity of deformation mode to material parameters and interface delamination.

The results are summarized as follows: (1) the key controlling parameters for the BHS/DLS laminate formability are: the hardening exponent of the DLS component $\eta_{\text{NDLS}}$, the volume fraction of the DLS component $f$, and the laminate components stiffness ratio $k$, where the deformability is increased by increasing these parameters; (2) the layer absolute thickness (component thickness) has insignificant effect on laminate stability, assuming no interface delamination; (3) for different laminate $f$ and $k$, the range of the laminate limit strain is bounded by the freestanding limit strains of both the BHS component and the DLS component as lower and upper bounds, respectively; (4) the laminate limit strain becomes closer to that predicted by the rule of averages by decreasing the hardening exponent of the DLS component till homogenous BHS sheet metal where the ratio $\varepsilon_{\text{Necking}}(\text{BHS})/\varepsilon_{\text{Necking}}(\text{DLS})$ approaches to unity; (5) the laminate limit strain becomes closer, equal, or even more than that predicted by the rule of averages by increasing the $k$ ratio; (6) the laminate ultimate strength is close to the average of components ultimate strengths as predicted by the rule of averages; (7) the deformation instability is different between a freestanding sheet and multilayered sheet because the former exhibits only single-neck mode; meanwhile, the latter exhibits also multiple-neck mode. However, the most critical mode that is leading the final rupture in both of the sheets is the single-neck mode.

It is found that the DLS sheet metal retards the deformation instability of the BHS sheet metal to an extent that depends on the abovementioned three controlling parameters. Hence, enhanced strength–ductility combination can be achieved by laminated structure compared with the freestanding one. Such combination is essential for metal forming applications.

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