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Tensile properties of stainless steel-clad aluminium sandwich sheet metals

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The various tensile properties, such as yield strength, tensile strength, strength coefficient, uniform elongation, strain hardening exponent and strain rate sensitivities, of stainless steel-clad aluminium sandwich sheet metals have been analysed on the basis of the fact that the flow stresses of the sandwich sheets follow the rule of mixtures, an average of component properties weighted by the volume fractions. The rule of mixtures can be applied to the tensile strengths and strength coefficients of the sandwich sheets, whereas the yield strengths do not follow the mixture rule. The force weighted average rule, an average of component properties weighted by volume fractions and forces, can be applied to uniform elongations, strain hardening exponents and strain rate sensitivities of the sandwich sheets.

1. Introduction

The flow stresses of stainless steel-clad aluminium sandwich sheets and stainless steel-clad copper sandwich sheet have been shown to follow the mixture rule even though component metals have different anisotropic properties [1, 2].

$$\sigma_{us} = \sigma_{uA} V_A + \sigma_{uB} V_B \tag{1}$$

where σ_u and V are uniaxial flow stress and volume fraction, and subscripts S, A and B stand for sandwich sheet and its component A and B layers.

The flow characteristics were attributed not to negligible transverse stresses compared with longitudinal stresses in the component layers, but to the fact that an increase in the longitudinal stress due to a tensile transverse stress developed in one component layer was offset by a decrease in the longitudinal stress due to a compressive stress in the other component layer.

The purpose of this paper is to examine various parameters characterizing uniaxial tensile properties of the sandwich sheets in terms of component parameters.

2. Experimental procedure

The 304 stainless steel–aluminium–304 stainless steel sandwich sheets of 2 to 3 mm thick were fabricated by rolling at 400 to 500° C, during which stainless steel sheets were reduced by 4 to 10% and commercial purity aluminium sheet by 30 to 48% (Table I). The sandwich sheets were subsequently annealed at 400° C for 15 min to remove residual stresses of the sheets and to improve the bond strength between the layers.

Tensile specimens with gauge lengths of 50 mm and widths of 12.5 mm were cut from the sheets at 0°, 45°, and 90° to the rolling direction. The specimens were tested on an Instron universal testing machine at a constant cross-head speed of 10 mm min^{-1} except when the strain rate sensitivities are measured. The strain rate sensitivities were measured at various strains using a single specimen method in which the cross-head speed was changed from 10 to 200 mm min^{-1}. The strain rate sensitivity, m, at a given strain can be calculated as follows:

$$m = \log(\sigma_2/\sigma_1)/\log(\dot{\varepsilon}_2/\dot{\varepsilon}_1)$$

where σ_1 and σ_2 are flow stresses at stresses at strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$.

The plastic strain ratios or the R values defined as the ratio of the true plastic strains in the width and thickness directions were measured at the engineering strain of 0.15 in accordance with ASTM E 517–74. The strain hardening exponent, n, was calculated from the slope of a best-fit line for a log–log plot of the true stress–strain data between the yield point and the maximum load. Unless otherwise specified, most tensile properties in this paper are average values which are calculated from $(X_0 + 2X_{45} + X_{90})/4$ where X_0, X_{45} and X_{90} are the properties at 0°, 45° and 90° to the rolling direction.

3. Results and discussion

Fig. 1 shows flow curves of commercial purity aluminium sheet fabricated by 39% rolling at 400, 450, and 500° C, followed by annealing at 400° C for 15 min. Tensile tests yielded the flow curves up to about 0.25 true strain, which were fitted to the Hollomon equation, $\sigma = K\varepsilon^n$, to obtain the parameters K and n. The equation was used to extrapolate the flow-curves over 0.4 true strain.

Fig. 2 shows flow curves of a 304 stainless steel sheet as-received and of a stainless steel sheet peeled from a sandwich sheet. The peeled sheet was reduced by about 5% during fabrication of the sandwich sheet. Therefore, the flow curve of the peeled sheet has the higher flow stresses than the sheet as-received. If the

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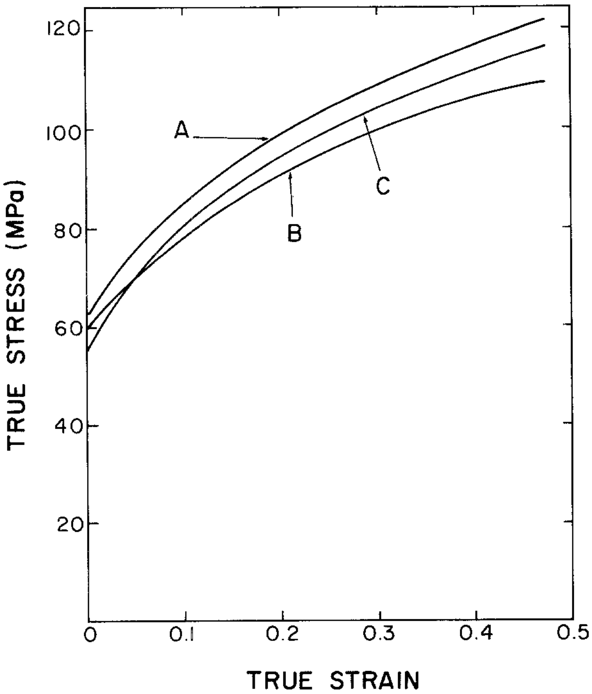

Figure 1 Flow curves of commercial purity aluminium specimens fabricated by 39% rolling at (A) 400, (B) 450, and (C) 500° C, followed by annealing at 400° C for 15 min. (A) $\sigma = 143.2\varepsilon^{0.227}$, (B) $\sigma = 129.4\varepsilon^{0.224}$, (C) $\sigma = 140.2\varepsilon^{0.248}$.

flow curve of the peeled sheet is shifted to the right by 5% strain, then it is almost superposed on that of the sheet as-received.

The yield and tensile strengths of the sandwich sheets are shown in Fig. 3 as a function of the volume fraction of stainless steel. The yield strengths deviate positively from the mixture rule, while the tensile strengths follow the mixture rule indifferent to the fabrication conditions of the sandwich sheets. The yield stresses of stainless steel sheets in Fig. 3 were estimated from the lower curve in Fig. 2 based on the rolling reductions during fabrication of the sandwich sheets. A-sheets were rolled by about 5% during fabrication, whereas B-sheets and C-sheets were rolled by about 7% and 10%, respectively (Table I). Such a

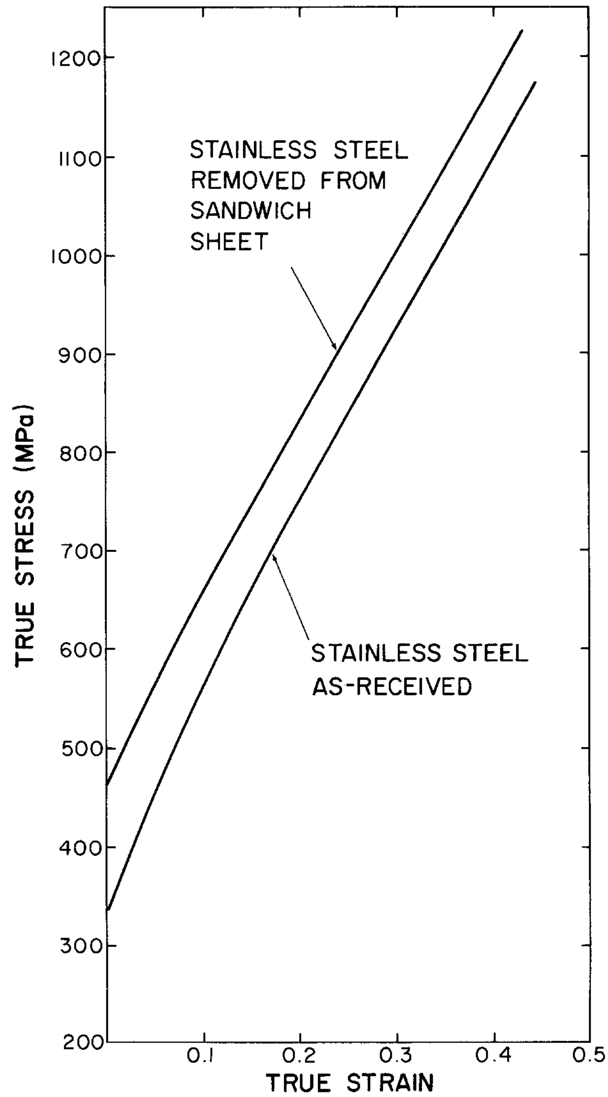

Figure 2 Flow curves of 304 stainless steel sheet specimens.

positive deviation of the yield stresses of the sandwich sheets from the mixture rule may be attributed to big differences between both Young's moduli and yield stresses of aluminium and stainless steel (Young's moduli of aluminium and stainless steel are 7×10^4

TABLE I Stainless steel clad aluminium sandwich sheet metal fabrication conditions

Sandwich sheet metal	Rolling temp. (° C)	Specimen	Initial thickness (mm)		Total reduction ratio (%)	Final thickness (mm)	SLS (vol %)	Al (vol %)	Al R.R. (%)	SLS R.R. (%)
			SLS	Al						
A	400	A-1	0.4 × 2	2.0	28.6	2.0	0.38	0.62	36	9.6
		2	0.5 × 2	2.0	33.3	2.0	0.48	0.52	46	6.2
		3	0.4 × 2	2.5	30.3	2.3	0.33	0.67	36	10.5
		4	0.5 × 2	2.5	28.6	2.5	0.38	0.62	35	9.8
		5	0.4 × 2	3.0	31.6	2.6	0.28	0.72	36	14.0
		6	0.5 × 2	3.0	25	3.0	0.31	0.69	30	7.6
B	450	B-1	0.4 × 2	2.0	28.6	2.0	0.40	0.60	37	7.0
		2	0.5 × 2	2.0	33.3	2.0	0.50	0.50	47	6.0
		3	0.4 × 2	2.5	30.3	2.3	0.34	0.66	38	5.8
		4	0.5 × 2	2.5	28.6	2.5	0.41	0.59	38	5.2
		5	0.4 × 2	3.0	31.6	2.6	0.31	0.69	39	8.6
		6	0.5 × 2	3.0	25	3.0	0.33	0.67	32	5.9
C	500	C-1	0.4 × 2	2.0	28.6	2.0	0.40	0.60	39	4.4
		2	0.5 × 2	2.0	33.3	2.0	0.51	0.49	48	4.2
		3	0.4 × 2	2.5	30.3	2.3	0.36	0.64	39	5.0
		4	0.5 × 2	2.5	28.6	2.5	0.41	0.59	39	4.5
		5	0.4 × 2	3.0	31.6	2.6	0.31	0.69	39	5.0
		6	0.5 × 2	3.0	25	3.0	0.33	0.67	33	4.8

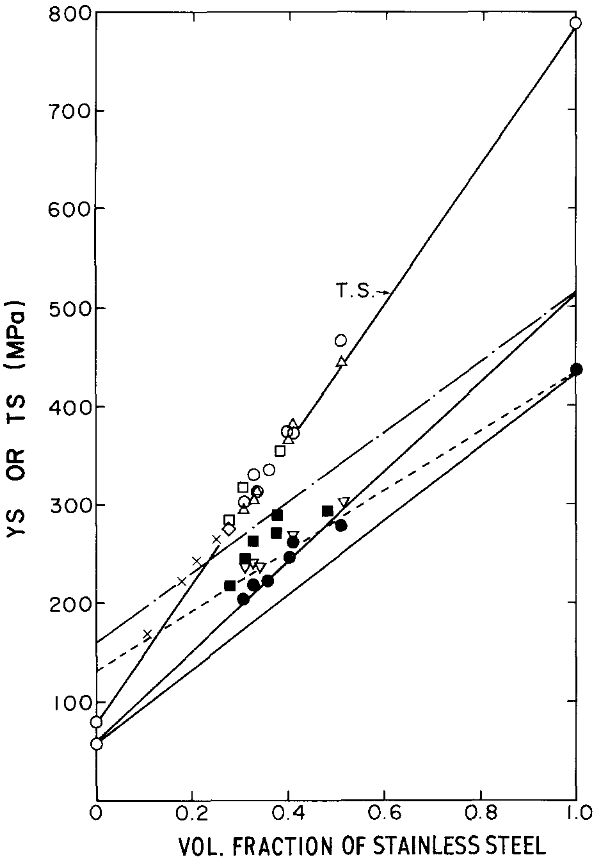

Figure 3 (■, ▽, ●) Yield and (□, △, ○, x, ◇) tensile strengths of stainless steel clad aluminium sandwich sheets as a function of volume fraction of stainless steel. TS and YS stand for tensile strength and yield strength. (■, □) Sandwich sheet A, (▽, △) sandwich sheet B, (●, ○) sandwich sheet C, (x) [5], (◇) [4]. (——) Mixture rule, (- - -) Upper limit YS based on 10% rolled SLS. (- - -) Upper limit YS based on 5% rolled SLS.

and 2 × 10^5 MPa, respectively). Following the mixture rule the yield stress of a sandwich sheet is calculated based on yield stresses at points C and B or A in Fig. 4 depending on the rolling reduction of stainless steel during fabrication. However, measurable detection of yielding can be hardly expected at the strain of point C unless the volume fraction of stainless steel is less than a critical value. The critical value may be estimated on the assumption that yielding of the sandwich sheet is controlled by the aluminium layer, when the force acting on the cross-section of stainless steel layers is smaller than that acting on the cross-section of the aluminium layer. If the yield stresses of stainless steel and aluminium layers are 430 and 60 MPa, the critical volume fraction of stainless steel, V_c, is evaluated to be 0.12 from the relation of $430V_c = 60(1 - V_c)$. At the strain above point C, tensile transverse stress is expected to develop in the aluminium layer while compressive transverse stress develops in the stainless steel layers, because the aluminium layers deform plastically while the stainless steel layers are still in the elastic state. A noticeable yielding would be detected above the strain of point D for the 5% rolled stainless steel sheet and of point E for the 10% rolled stainless steel sheet. In this case the yield stresses at D and E will be the upper bound yield stresses of aluminium because they are estimated based on elastic deformation of aluminium. However, the aluminium layer would be somewhat relaxed by a plastic deformation which, in turn, decreases the yield stresses to smaller levels (effective values in Fig. 4). Therefore, the measured yield stresses would be larger than those evaluated by the mixture rule of uniaxial

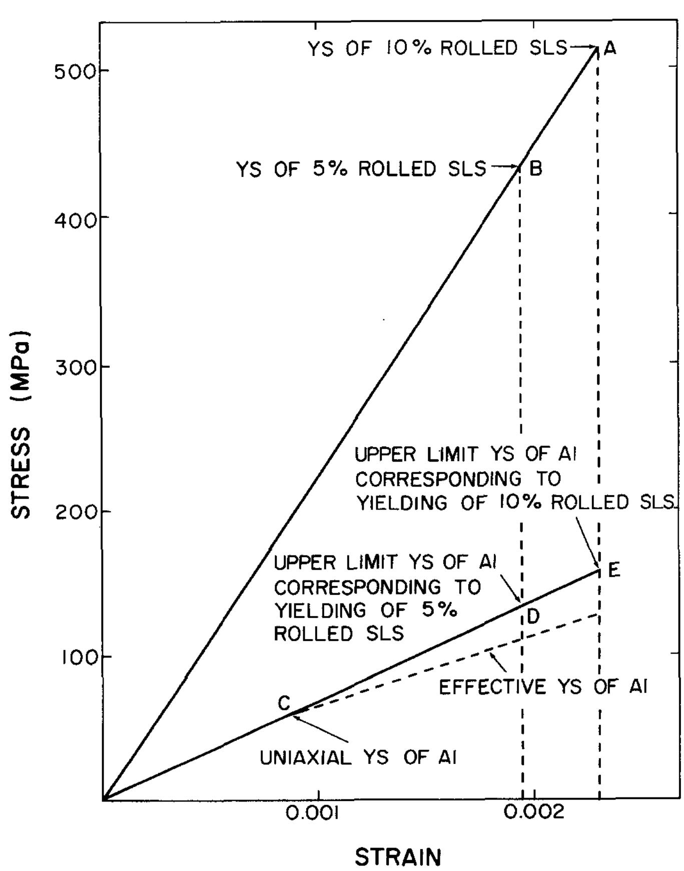

Figure 4 Various yield stresses (YS) for explanation of a positive deviation of measured YS of sandwich sheets from the mixture rule. SLS stands for stainless steel.

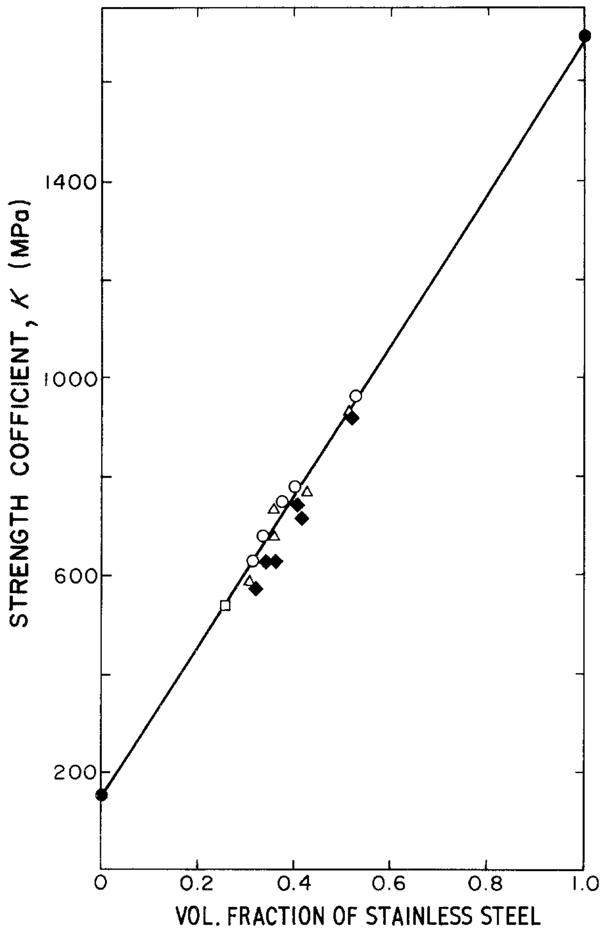

Figure 5 Strength coefficients of stainless steel clad aluminium sandwich sheets as a function of volume fraction of stainless steel. (◆) Sandwich sheet A, (△) sandwich sheet B, (○) sandwich sheet C, (□) after Semiatin [4], (——) predicted.

yield stresses in agreement with the experimental results.

The flow curves are often expressed as the Hollomon equation,

$$\sigma = K\varepsilon^n \tag{4}$$

where K and n are the strength coefficient and the strain hardening exponent, respectively. The strength coefficient, K, is equivalent to the flow stress at the unity true strain, $\varepsilon = 1$. Therefore, the strength coefficient of the sandwich sheet is expected to follow the mixture rule.

$$K_s = K_A V_A + K_B V_B \tag{5}$$

This is the case with the stainless steel clad aluminium sandwich sheets as shown in Fig. 5.

The tensile instability condition or the diffusion necking condition of the sandwich sheet specimen may be expressed as

$$\frac{d\sigma_{us}}{d\varepsilon} = \sigma_{us} \tag{6}$$

Substitution of Equation 1 into Equation 6 gives us

$$\frac{d}{d\varepsilon}(\sigma_{uA} V_A + \sigma_{uB} V_B) = \sigma_{uA} V_B + \sigma_{uS} V_B$$

or

$$V_A\left(\frac{d\sigma_{uA}}{d\varepsilon} - \sigma_{uA}\right) + V_B\left(\frac{d\sigma_{uB}}{d\varepsilon} - \sigma_{uB}\right) = 0 \tag{7}$$

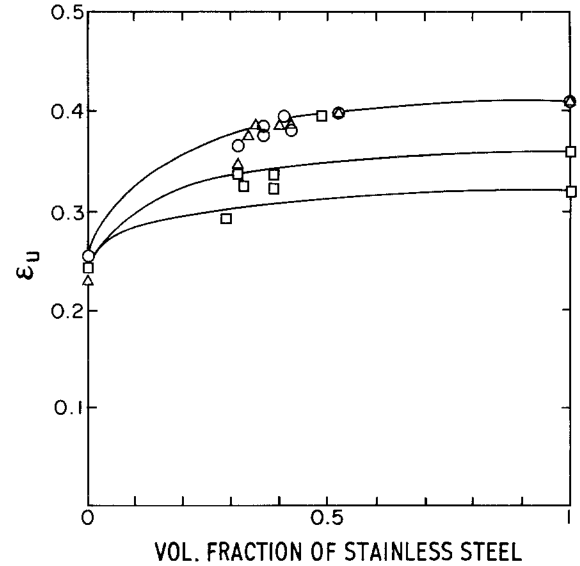

Figure 6 Uniform elongations of stainless steel clad aluminium sandwich sheets as a function of volume fraction of stainless steel. The upper, middle and lower curves indicate values calculated on the basis of data of 5, 7 and 10% reduced stainless steel sheets. (□) Sandwich sheet A, (△) sandwich sheet B, (○) sandwich sheet C.

Substitution of Equation 5 into Equation 7 yields

$$V_A K_A \varepsilon^{n_A}\left(\frac{n_A}{\varepsilon} - 1\right) + V_B K_B \varepsilon^{n_B}\left(\frac{n_B}{\varepsilon} - 1\right) = 0 \tag{8a}$$

The value of ε satisfying Equation 8 is the uniform elongation, ε_u, at which the tensile instability of the sandwich specimen takes place. Therefore, the following relation is obtained

$$V_A K_A \varepsilon_u^{n_A}(n_A/\varepsilon_u - 1) + V_B K_B \varepsilon_u^{n_B}(n_B/\varepsilon_u - 1) = 0 \tag{8b}$$

This equation was used to calculate the uniform strains of the sandwich specimens. The measured data of aluminium and stainless steel specimens were substituted into Equation 8b and the equation was solved by the Newton–Raphson method to yield values of ε_u. The calculated values are in very good ageement with the measured data as shown in Fig. 6. The scattered results in the A-specimens are due to the varied reductions of stainless steel layers during fabrication of the sandwich sheets (Table I). Equation 8b can also be expressed as

$$\varepsilon_u = \frac{n_A V_A K_A \varepsilon_u^{n_A} + n_B V_B K_B \varepsilon_u^{n_B}}{V_A K_A \varepsilon_u^{n_A} + V_B K_B \varepsilon_u^{n_B}}$$

$$= \frac{n_A V_A \sigma_{uA}^* + n_B V_B \sigma_{uB}^*}{V_A \sigma_{uA}^* + V_B \sigma_{uB}^*} = \frac{\varepsilon_{uA} V_A \sigma_{uA}^* + \varepsilon_{uB} V_B \sigma_{uB}^*}{V_A \sigma_{uA}^* + V_B \sigma_{uB}^*} \tag{8c}$$

where σ_{uA}^* is σ_{uA} at ε_u.

The above equation may be rearranged as follows:

$$V_B = \frac{\sigma_{uA}^*(\varepsilon_{uA} - \varepsilon_u)}{\sigma_{uA}^*(\varepsilon_{uA} - \varepsilon_u) + \sigma_{uB}^*(\varepsilon_u - \varepsilon_{uB})} \tag{8d}$$

This equation can be used to calculate the relation between V_B and ε_u when the flow stresses of A and B are known, because σ_{uA}^* and σ_{uB}^* are the flow stresses of A and B at the uniform strain, ε_u. The strain ε_u has a

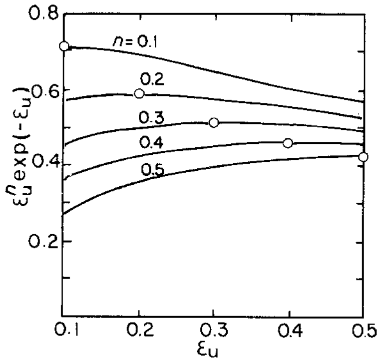

Figure 7 $\varepsilon_u^n \exp(-\varepsilon_u)$ plotted against ε_u. (O) Maximum point.

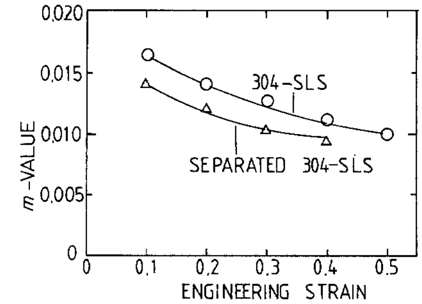

Figure 8 Strain rate sensitivities of 304 stainless steel sheets as a function of engineering strain.

value between the uniform elongations of component sheets, ε_{uA} and ε_{uB}.

The force acting on the sandwich specimen, F, may be obtained by multiplying both sides of Equation 1 by the cross-sectional area of the specimen, A

$$F = \sigma_{uA}A_A + \sigma_{uB}A_B \qquad (9)$$

where A_A and A_B are the cross-sectional areas of the component layers A and B, that is, $A = A_A + A_B$. The area A may be expressed in terms of the initial area, A_0, and strain, ε, as follows

$$A = A_0 \exp(-\varepsilon) \qquad (10)$$

Therefore, Equation 9 can be rewritten as

$$F = (\sigma_{uA}A_{A0} + \sigma_{uB}A_{B0}) \exp(-\varepsilon) \qquad (11)$$

As F reaches the maximum value, F_{max}, at $\varepsilon = \varepsilon_u$, the quantity F_{max} can be expressed as

$$F_{max} = (\sigma_{uA}A_{A0} + \sigma_{uB}A_{B0}) \exp(-\varepsilon_u) \qquad (12)$$

Dividing Equation 12 by the initial cross-sectional area, A_0, we obtain

$$S_T = (\sigma_{uA}V_A + \sigma_{uB}V_B) \exp(-\varepsilon_u)$$

or

$$S_T = V_A K_A \varepsilon_u^{n_A} \exp(-\varepsilon_u) + V_B K_B \varepsilon_u^{n_B} \exp(-\varepsilon_u) \qquad (13)$$

where S_T is tensile strength of the sandwich sheet. The n value of most metals ranges between 0.1 and 0.5. The quantities of $\varepsilon_u^n \exp(-\varepsilon_u)$ at various n values are plotted as a function of ε_u in Fig. 7. The maximum point on a given n curve is associated with the tensile strength of the specimen of the n value, because its tensile strength is $Kn^n \exp(-n)$ for the material whose flow curve can be expressed as $\sigma = K\varepsilon^n$. If the quantity of $\varepsilon_u^n \exp(-\varepsilon_u)$ is insensitive to ε_u, the following expressions are obtained

$$\varepsilon_u^{n_A} \exp(-\varepsilon_u) \approx \varepsilon_{uA}^{n_A} \exp(-\varepsilon_{uA}) \approx n_A^{n_A} \exp(-n_A)$$

If the quantity of $\varepsilon_u^n \exp(-\varepsilon_u)$ is insensitive to ε_u, the tensile strength of the sandwich sheet will follow the mixture rule, because we can express

$$\varepsilon_u^{n_A} \exp(-\varepsilon_u) \approx \varepsilon_{uA}^{n_A} \exp(-\varepsilon_{uA}) \approx n_A^{n_A} \exp(-n_A)$$

and

$$\varepsilon_u^{n_B} \exp(-\varepsilon_u) \approx \varepsilon_{uB}^{n_B} \exp(-\varepsilon_{uB}) \approx n_B^{n_B} \exp(-n_B)$$

This may be the case with the sandwich sheet of this study (Fig. 3) the n values of aluminium and stainless steel are about 0.2 and 0.4, respectively. Therefore, the value of ε_u ranges between about 0.2 and 0.4, in which region the values of $\varepsilon_u^n \exp(-\varepsilon_u)$ at $n = 0.2$ and $n = 0.4$ vary insensitive to ε_u as shown in Fig. 7.

Strain rate sensitivities of aluminium and stainless steel sheets are plotted as a function of strain in Fig. 8. The sensitivities of stainless steels decrease with increasing strain. Fig. 9 shows strain rate sensitivities of the sandwich sheets as a function of volume fraction of stainless steel layers. The calculation of the strain rate sensitivity, m, was made on the assumption that m behaved similarly to the uniform elongation in Equation 8c, that is

$$m = \frac{m_A V_A \sigma'_{uA} + m_B V_B \sigma'_{uB}}{V_A \sigma'_{uA} + V_B \sigma'_{uB}}$$

or

$$V_B = \frac{\sigma'_{uA}(m_A - m)}{\sigma'_{uA}(m_A - m) + \sigma'_{uB}(m - m_B)} \qquad (14)$$

where σ'_{uA} is the flow stress of component A at a strain where m is measured.

The upper curve was calculated based on the data of stainless steel sheet peeled from the sandwich sheet metal C whereas the lower curve was calculated based on an assumed lower sensitivity value which may be applicable to the stainless steel sheet layer of sandwich sheet metal A. It is noted that sandwich sheet metal A was reduced more severely than sandwich sheet metal B (Table I).

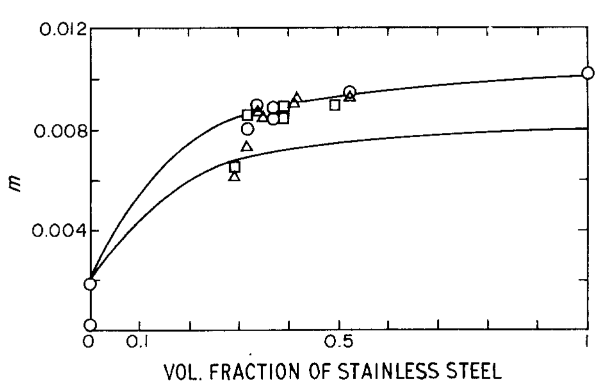

Figure 9 Strain rate sensitivities of stainless steel clad aluminium sandwich sheets as a function of volume fraction of stainless steel. The upper and lower curves indicate values calculated based on the data of stainless steel sheet removed from the sandwich sheets C and A. (□) Sandwich sheet A, (△) sandwich sheet B, (O) sandwich sheet C.

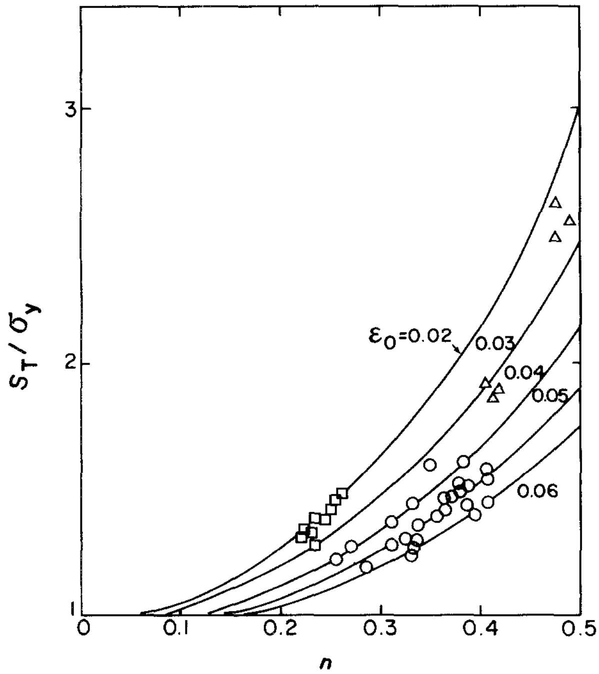

Figure 10 The ratio of tensile strength to yield strength, S_T/σ_y, of (△) 304 stainless steel (SLS), (□) aluminium and (○) stainless steel clad sandwich sheets as a function of their strain hardening exponents for various ε_0 values.

The strain hardening exponent, n, and the ratio of tensile strength to yield strength are often used to evaluated the stretchability of materials. An increase in the exponent is expected as the ratio increases. However, the correlation of the two parameters is not very good as shown in Fig. 10. For materials whose flow curves are fitted for the Hollomon equation (Equation 4), the tensile strength may be approximated by

$$S_T = Kn^n/\exp n \qquad (15)$$

and the yield strength is expressed as

$$\sigma_y = K\varepsilon_0^n \qquad (16)$$

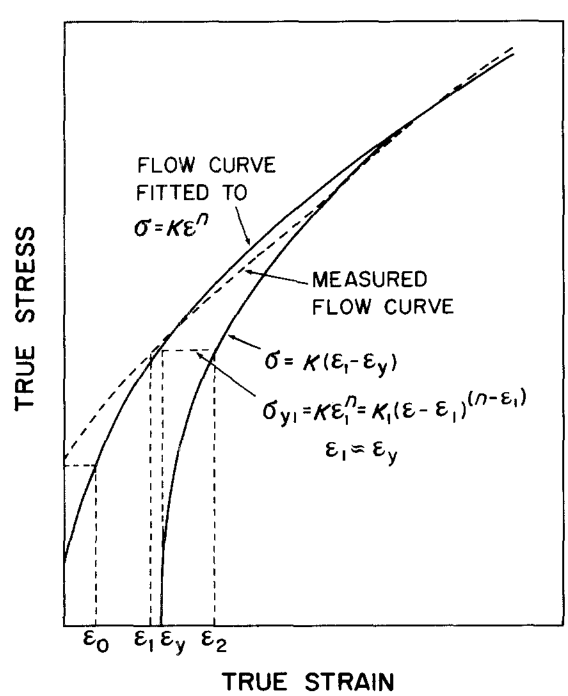

Figure 11 Definition of various parameters.

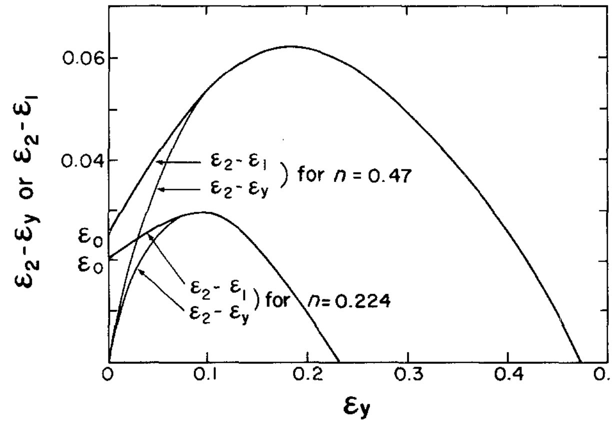

Figure 12 Relation between $\varepsilon_2-\varepsilon_y$ or $\varepsilon_2-\varepsilon_1$ and ε_y.

where ε_0 is the strain which gives rise to the measured yield stress. It follows from Equations 15 and 16 that

$$S_T/\sigma_y = n^n/(\varepsilon_0^n \exp n) \qquad (17)$$

The relation between S_T/σ_y and n at various values of ε_0 is shown in Fig. 10. The data in Fig. 10 indicate that ε_0 is in the range of 0.02 to 0.03 for annealed aluminium and stainless steel specimens. This ε_0, value is shown schematically in Fig. 11.

Supposing that the material is subjected to a cold strain of ε_1, its yield stress becomes σ_{y1}, whereas its tensile strength is still given by Equation 15. The flow curve of the cold worked material is approximated by

$$\sigma = K_1(\varepsilon - \varepsilon_1)^{(n-\varepsilon_1)} \approx K_1(\varepsilon - \varepsilon_y)^{(n-\varepsilon_y)} \qquad (18)$$

where the difference between ε_1 and ε_y is defined in Fig. 11. The true tensile strength, σ_T, and yield stress, σ_{y1}, may be expressed as

$$\sigma_T = Kn^n = K_1(n - \varepsilon_y)^{(n-\varepsilon_y)} \qquad (19)$$

$$\sigma_{y1} = K\varepsilon_y^n = K_1(\varepsilon_2 - \varepsilon_y)^{(n-\varepsilon_y)} \qquad (20)$$

It follows from Equations 19 and 20 that

$$\varepsilon_2 - \varepsilon_y = \frac{(n - \varepsilon_y)\varepsilon_1^{n/(n-\varepsilon_y)}}{n^{n/(n-\varepsilon_y)}} \qquad (21)$$

Equation 21 has been plotted in Fig. 12. The value of $\varepsilon_2 - \varepsilon_1$ or $\varepsilon_2 - \varepsilon_y$ increases with increasing n value. The maximum value of $\varepsilon_2 - \varepsilon_y$ or $\varepsilon_2 - \varepsilon_y$ is about 0.6 and 0.3 for $n = 0.47$ and $n = 0.244$, respectively, which are equivalent to the strain hardening exponents of annealed stainless steel and aluminium. It is noted that ε_0s, which are equivalent to $\varepsilon_2 - \varepsilon_1$, of cold worked stainless steel and most sandwich sheets whose value of n are heavily influenced by stainless steel (Fig. 6 and Equation 8c) do not exceed 0.06 as expected.

When a sheet specimen is uniaxially strained, it is subjected to a diffusion necking at a maximum load, followed by a local necking in which the strain along the neck is zero. The local necking condition is given by [3]

$$d\sigma_u/d\varepsilon_u = \sigma_u/(1 + R) \qquad (22)$$

where R is the plastic strain ratio measured along the tensile axis. The angle ϕ between the tensile axis and

TABLE II Local necking strains

Specimen	Measured	Calculated
304 stainless steel	0.69	0.76
Al–C	0.41	0.4
A–2	0.65	0.68
A–6	0.57	0.58
B–1	0.64	0.68
B–6	0.59	0.65
C–2	0.7	0.72
C–5	0.63	0.64

the local neck axis is given by

$$\phi = \tan^{-1}[(1 + R)/R]^{1/2} \quad (23)$$

The local necking strain along the tensile direction of a sandwich sheet, ε_{ul}, may be expressed in terms of component strains with reference to Equation 8c as

$$\varepsilon_{ul} = (1 + R_s) \frac{\varepsilon_{ulA} V_A \sigma^l_{uA} + \varepsilon_{ulB} V_B \sigma^l_{uB}}{V_A \sigma^l_{uA} + V_B \sigma^l_{uB}} \quad (24)$$

where ε_{ulA}, R_s and σ^l_{uA} are the local necking strain of component A, the plastic strain ratio of the sandwich sheet and the flow stress of A at ε_{ul}, respectively.

Table II compares the measured local necking strains with the values calculated using Equation 24. The local necking strains were measured using gridded circles near the local neck. The calculated strains agree very well with the measured ones.

Table III shows the measured and calculated angles between the tensile axis and the local neck axis. Agreement between the measured and calculated angles is very good.

4. Conclusions

A study on the tensile properties of stainless steel clad aluminium sandwich sheet specimens lead to the following conclusions.

1. The rule of mixtures, an average of component properties weighted by volume fractions, could be applied to the tensile strengths and strength coefficients of the sandwich specimens.

2. The yield strengths of the sandwich sheets showed a positive deviation from the rule of mixtures due to big differences between elastic moduli of components and between yield strengths of components.

3. The force weighted average rule, an average of component properties weighted by volume fractions and forces, could be applied to uniform elongations, strain hardening exponents and strain rate sensitivities of the sandwich sheets.

TABLE III Orientation of local neck, ϕ

Specimen	Measured (deg)	Calculated (deg)
A–1	55	57.7
A–5	62	58.0
B–2	60	57.0
B–6	57	57.3
C–3	54	57.4
C–4	58	56.8

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