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Investigation of the Fracture Behavior of Steel/Steel Laminates in Crack Divider Orientation

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Abstract

A study is carried out to examine the applicability of J_{IC} testing for laminates that behave in an elastic-plastic manner. Laminates made up of layers of low-C and medium-C steels are tested in crack divider orientation with a single specimen technique using a partially unloading compliance method. The study shows that the method can be applied for laminates for comparative purposes, but the values of J_{IC} derived are not as reliable as those in monolithic materials. This is mainly due to difficulties faced with the estimation of crack growth data that are not accurate enough due to composite nature of the samples.

Key words: Fracture toughness, J_{IC} testing, Partially unloading compliance technique, Steel laminates.

Introduction

Various methods have been proposed over the years to measure the fracture toughness of engineering materials (Griffith, 1924; Irwin, 1957; Rice, 1968). Of these, plane strain fracture toughness, K_{IC}, has found wide application as a standard method of measurement. These methods based on linear elastic fracture mechanics can be used for high strength materials that are essentially brittle or have very limited ductility. For materials that behave in an elastic-plastic manner, strain energy release rate, as proposed by Rice (1968), is the most common method.

While both K_{IC} and J_{IC} test procedures were originally developed for monolithic materials (Begley and Landes, 1972; Hickerson, 1976; Underwood, 1976; Schwalbe *et al.,* 1985), in recent years the procedures have been applied to composite materials (Manoharan *et al.,* 1990; Balton and Gant 1998; Pandy *et al.,* 2001; Chung *et al.,* 2002; Rohatgi *et al.,* 2003). For laminates, most of these studies have aimed to determine the fracture toughness of systems with brittle reinforcements, e.g., metal-intermetallic and metal-ceramic composites (Bloyer *et al.,* 1998; Hwu and Derby, 1999), and used mainly K_{IC} testing. For laminates where both phases are tough, Manoharan *et al.,* (1990) measured fracture toughness in terms of J_{IC} of Al laminates, made up of layers of Al and Al reinforced with SiC. In general, studies of J_{IC} testing are rare for laminates.

The current study was therefore undertaken on a composite system, i.e. steel laminates, where both phases are tough. The study aims to examine the applicability of J_{IC} testing to composites that behave in an elastic-plastic manner.

Materials and Methods

Steel laminates were made up of layers of medium carbon (0.6% C) and low carbon (0.12% C) steels. Layers used in the production of laminates (see below) were in heat-treated condition. For medium C-steel, this involved austenitization at 830 °C (15 min) and quenching in oil, followed by tempering at 550 °C for 6 h. For low C-steel, the treatment consisted of annealing at 550 °C (4 h).

The mechanical properties of the layers are given in Table 1. The properties were measured by tensile test in the rolling direction in accordance with ASTM E 8M-93. Stress-strain (σ -ε) data obtained in the test were fitted into an equation of the form $\sigma = \kappa\varepsilon^n$, where κ is the strength coefficient and n is the strain hardening exponent.

For the production of laminates, steel layers were combined, yielding volume fractions (hard phase) Vr = 0.4 and Vr = 0.8. For this purpose, steel layers were first surface cleaned (a solution of 3.7 g of hexamethylenetetramine, 500 ml of hydrochloric acid and 500 ml of pure water) and then ground sequentially with 320, 600, 800 and 1200 emery paper, and finally washed and dried. The layers were then stacked in the sequences shown in Table 2 and hot pressed at 550 °C. A typical example of steel laminates is shown in Figure 1. The duration of hot pressing was determined based on measurement of the interfacial strength (see below).

Interfacial shear strengths of hot pressed laminates were evaluated by both bend test and direct shear test. The bend test was carried out in accordance with ASTM D2344-76. The sample used in the direct shear test is given in Figure 2. The sample was notched from opposite faces, which terminated at an interface between the layers at a certain depth. By assuming that stress is uniform in the shear lap (in reality it is not), shear strength is calculated by dividing the failure (maximum) tensile load by the area between the notches.

Table 1. Mechanical properties of layers used in the production of steel laminates. κ and n values describe the true stress-true strain relationship in the form $\sigma = \kappa\varepsilon^n$.

Materials (thickness)	σ_{ys} MPa	σ_{UTS}, MPa	% elong. at fracture	κ MPa	n
Medium-C steel (2.5 mm)	858	959	10.4	1244	0.0722
Low-C steel (1.5 mm)	232	328	42.4	557	0.212

Table 2. Stacking sequence of layers for steel laminates.

Laminate	Stacking sequence (*M: medium-C steel, L: low-C steel)*
Vr = 0.4	L L M L M L L
Vr = 0.8	M M L M L M M

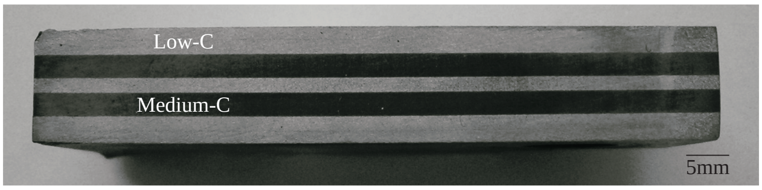


Figure 1. Cross section of a typical steel laminate. The sample refers to the laminate with Vr = 0.4.

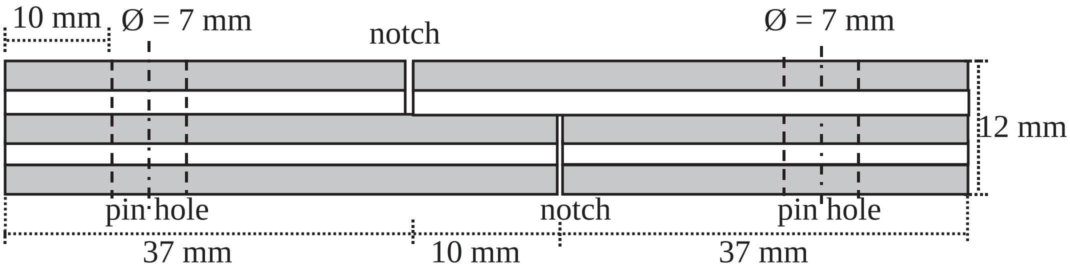


Figure 2. Geometry of test piece in direct shear test. The sample is loaded under tension at 2 pinholes, width = 20 mm.

The variation of the interfacial shear strength as a function of the bond time in steel laminates is given in Figure 3. Based on these data the bond (annealing) time was selected as 4 h, which yielded the maximum interfacial strength. The value of interfacial shear strength at this condition was about 59 MPa (average of 4 measurements, bend tests and direct shear tests). Typical microstructures of the laminates across the interface and hardness profile (Knoop) are given in Figure 4a and b, respectively.

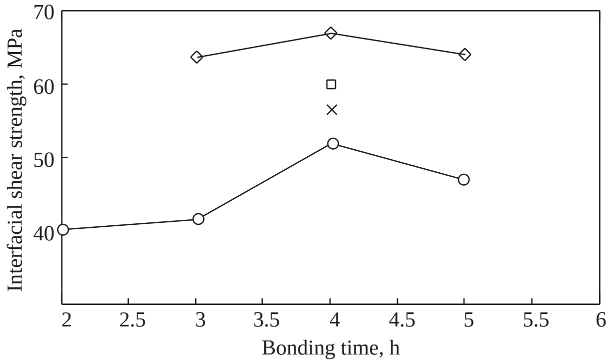


Figure 3. Interfacial shear strength versus bonding (annealing) time at 550 °C. ◇ and o refer to bend tests (in 2 sets of samples) and x refer to direct shear tests for 4 h bonding time (2 samples).

Measurement of fracture toughness

The fracture toughness of the laminates was measured in terms of J_{IC}. A single specimen technique, as described in ASTM E 813-89, standard, was used. Sample geometry and dimensions are given in Figure 5. Thus samples had an initial crack length to width ratio of $a_o/W = 0.65$ (after fatigue loading, see below), and a width to thickness ratio (W/B) of 4. Samples were tested in a hydraulic test machine under stroke-control with a constant crosshead speed of 0.008 mm/s.

The specimens were first loaded under fatigue to generate a sharp crack. For this purpose, the load was alternated between a positive load (300 N) and a value less than 0.4 of limit load P_L as defined in ASTM E 813-89. Fatigue loading was stopped when the crack length, a_o, reached a value of $a_o/W = 0.65$.

Measurement of J_{IC} first involved the estimation of the original crack length a_o. For this purpose, the specimen was loaded <0.4 P_L and unloaded to >0.1 P_L3 times with a relaxation time of 10 s. Original crack size was estimated in accordance with the relevant standard.

Having determined the original crack length, the load was decreased to the lowest possible value while maintaining the fixture alignment. The specimen was then loaded and unloaded in a sequence such that at each step load line displacement was 0.1 mm higher than the previous loading. At unloading the displacement was decreased by 0.15 mm with respect to the current loading position. A relaxation time of 10 s was used at each step of loading and unloading.

Having gone beyond a maximum in the load-load line displacement curve, the test was stopped. To determine crack growth length a heat tint method was applied. For this purpose, the sample was heated at 300 °C for about 10 min. The sample was fatigued under tension-tension condition and finally overloaded and broken. The crack extension values were measured both at the edges and at the middle for each layer and averaged for the laminate as a whole.

From the sequence of loading and unloading described above, data on load-load line displacement were recorded. From these data, fracture toughness J_{IC} was determined via a compliance method. The compliance, C_i, at an unloading is defined as

$$C_i = {}^{\Delta\delta}/_{\Delta P} \tag{1}$$

where $\Delta\delta$ is the change in load line displacement, and ΔP is the change in load measured during unloading. After C_i values were determined at each unloading, crack length, a_i, relevant to each step was calculated based on the relevant standard as follows:

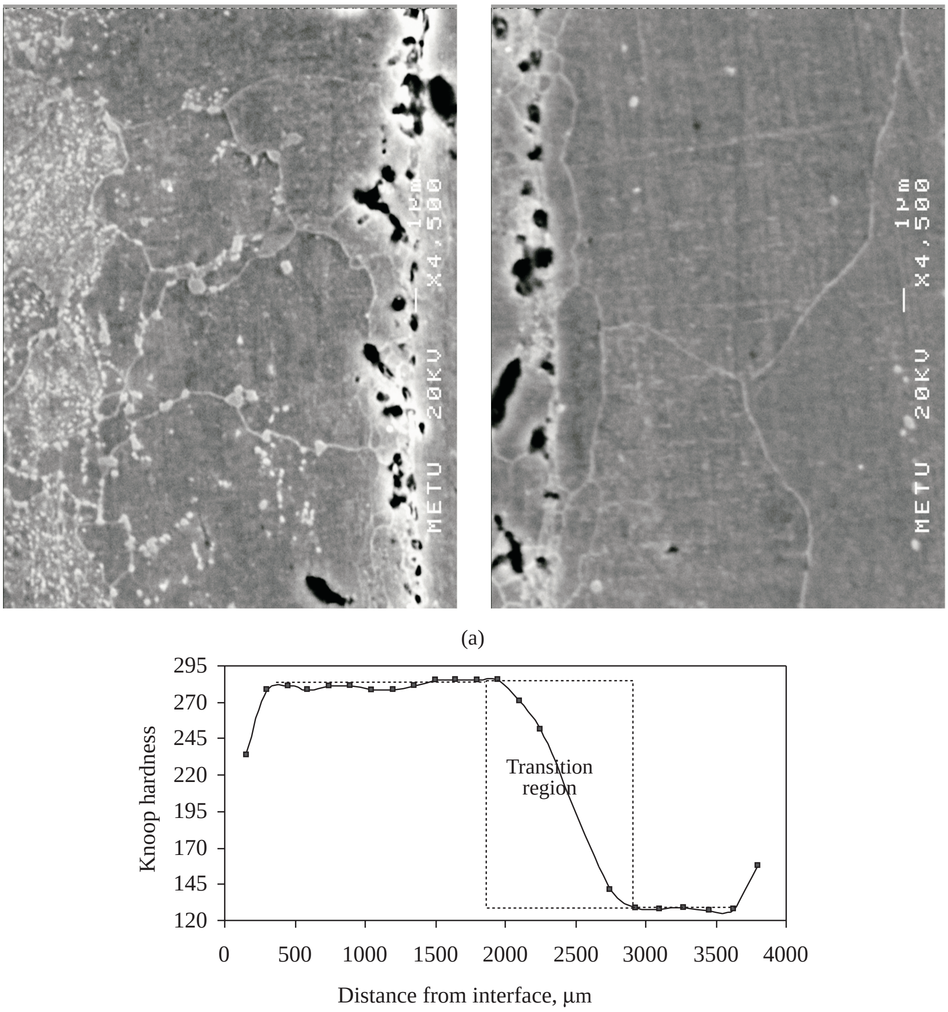
$$\begin{aligned}\frac{a_i}{W} &= 1.000196 - 4.06319u_{LL} + 11.242u_{LL}^2 - \\ &106.043u_{LL}^3 + 464.335u_{LL}^4 - 650.677u_{LL}^5\end{aligned} \tag{2}$$

where U_{LL} is defined as (B is the thickness and E is Young's Modulus):

$$u_{LL} = 1\Big/\left[(BEC_i)^{1/2} + 1\right] \tag{3}$$

The same equations were employed for estimation of the original crack length, whereby the amount of crack extension was evaluated as

$$\Delta a_i = a_i - a_o \tag{4}$$



(a)

(b)

Figure 4. **a)** Typical microstructure in steel laminates close to the interface. The structure on the left edge (medium-C steel) is tempered martensite and that on the right (low–C steel) is essentially ferrite. Note a gradual change in the microstructure across the interface.
b) Variation of Knoop hardness as function of distance from the interface in the laminated composite. Data on the left refer to locations across the medium-carbon layer and those on the right refer to those in the low-carbon layer. Note that the transition layer has a thickness of about 1.0 mm.

Having determined crack extension values Δa_i, the J integral is evaluated based on the fact that it is the sum of elastic and plastic contributions:

$$J = J_{el} + J_{pl} \tag{5}$$

At a point of loading, P_i, corresponding to a displacement,δ_i, the elastic and plastic parts are evaluated based on the load-load line displacement curve relevant to that step, as given in ASTM E 813-89 standard.

Thus from data on load-load line displacement J values versus crack extension data are determined. Exclusion lines drawn at crack extension values of 0.15 and 1.5 mm with a slope of $2\sigma_Y$ and a third line drawn at a slope of 0 at a value $J_{max} = b_o\sigma_Y/15$ define the area of valid data. A power law curve was fitted to J versus Δa data in this area.

The procedure assumes a critical crack extension value of $\Delta a = 0.2$ mm, i.e. the J value corresponding to this extension, designated as J_Q, is considered to be the fracture toughness of the material. $J_Q = J_{IC}$ provided it satisfies

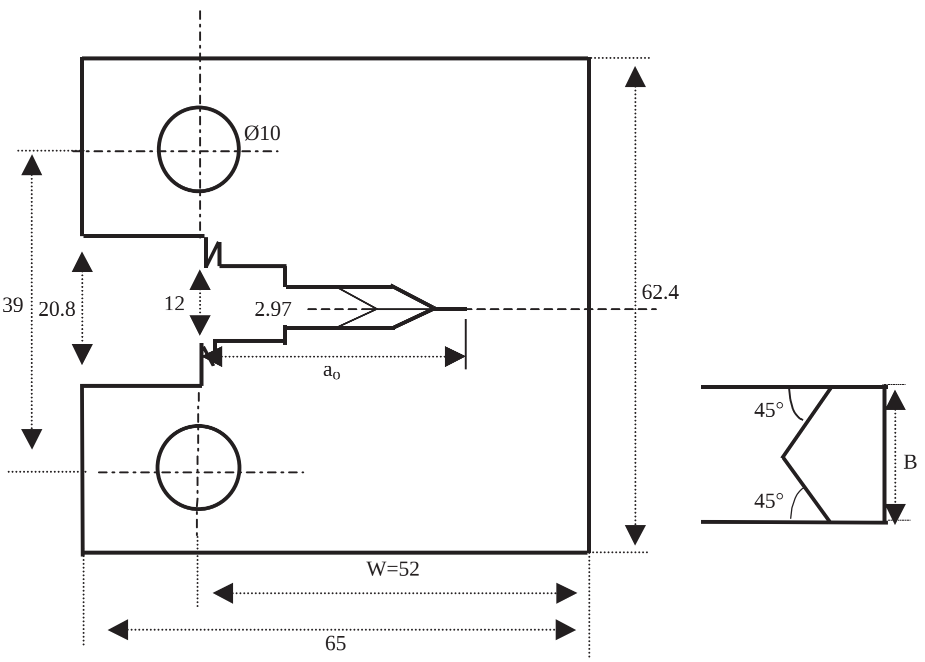


Figure 5. Compact tension specimen for J$_{IC}$ testing for a$_o$/W = 0.65, W/B = 4, B (Thickness) = 13-10 mm. Details of the chevron notch are shown on the right.

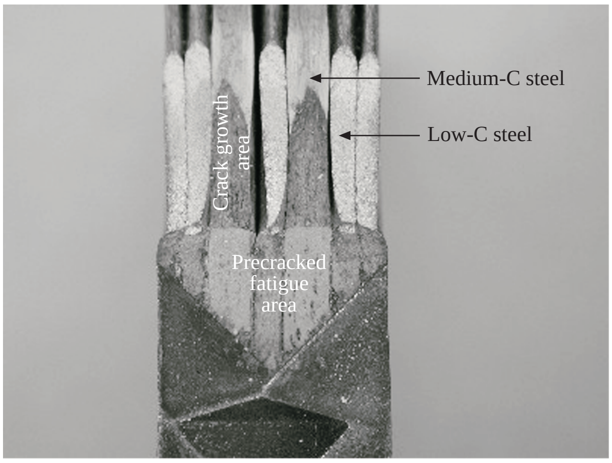


Figure 6. Fracture surface of laminates for Vr = 0.4. Note that crack growth occurred only in the hard (medium-C) layer while the soft layer was subject to deformation only. Note also delamination, which occurred only between the soft and hard layers, but not in between the 2 soft layers.

$$B \text{ and } b_o > 25J_Q/\sigma_Y \tag{6}$$

where B is the sample thickness and b$_o$ is the uncracked ligament length.

Certain precautions are necessary to measure the fracture toughness, J$_{IC}$, accurately. One is related to the minimization of friction in the pinholes so that the pin is free to rotate while loading. If the free rotation of clevises is prevented because of, for instance, increased friction, load line displacement values are underestimated. This might lead to negative values for the crack extension. Negative values of crack extension may also be obtained as a result of the use of insufficient relaxation time.

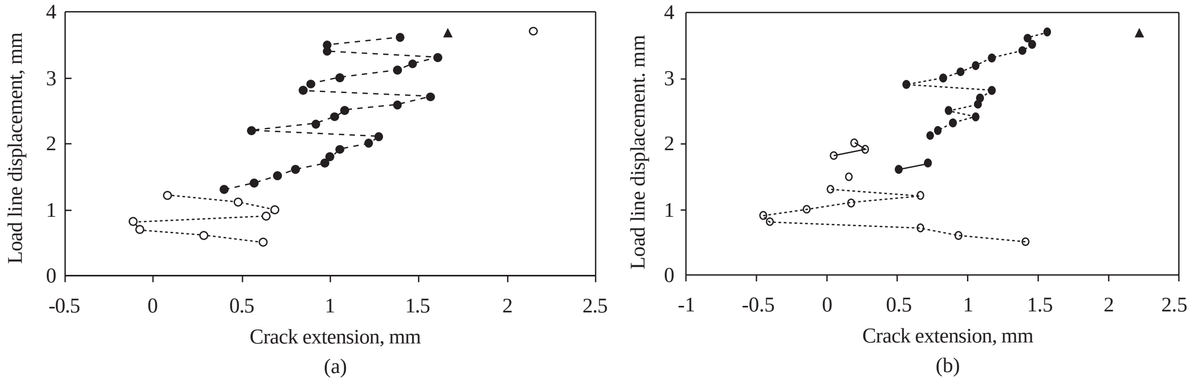
Results and Discussion

A typical example of fracture surface in the laminates is given in Figure 6. The surfaces refer to a sample after J_{IC} testing and failure via overloading after fatigue. It is seen that the soft layers were subject to plastic deformation without crack growth, whereas the crack advanced considerably in the hard layer. There was also severe delamination between the layers, which was confined to the interfaces between the soft and hard layers. Delamination length, d, in front of the crack tip extends to a value as high as d/B = 0.60 for Vr = 0.4 and to d/B = 0.34 for Vr = 0.8. There was no delamination at the interface between 2 soft layers that were in contact with each other.

Returning to J_{IC} testing, crack extension values estimated with the compliance method at various values of load line displacement are given in Figure 7a. The data refer to the laminate with Vr = 0.4. It is seen that even when the invalid data are discarded the relationship between crack extension and load line displacement is not smooth. Such scatter is not uncommon in the literature even for monolithic materials (Andrews and Shih, 1979: Shih *et al.,* 1979). When the terminal value of crack extension is considered, this value is more than what was physically measured (see Table 3). It is known that the compliance method normally underestimates the crack extension (Gudas and Davis, 1982; Neale and Priest, 1985) although there are cases of overestimates, as reported by Gudas and Davis (1982) and Neale and Priest (1985). Data for the laminate Vr = 0.8 are given in Figure 7b. Here scatter in LLD versus Δa is much less, and the physically measured terminal value of crack extension is less than what was predicted with the compliance method. Scatter in LLD versus Δa as well as differences between physically measured data and those found with the compliance method may be attributed to several sources. During the test, friction in the pinhole, which prevents the free rotation of clevises, as well as the use of insufficient relaxation time during measurements are common causes (Voss and Mayville, 1985) that may also be valid for the current experiments, but part of the reason may be attributed to the composite samples themselves. It is expected that because of residual stresses setup in different layers, the relaxation in the composite should be more complex than that in the monolithic materials.

Table 3. Crack extension data for laminates. Δa (phys) refers to the terminal value of crack extension found with the heat-tint method and Δa (compliance) are the same calculated from the partial unloading compliance method.

Specimen, Vr	Δa (phys) mm	Δa (compliance) mm	Δa (phys) /Δa (compliance)
0.4	1.6619	2.1536	0.7717
0.8	2.2256	1.5703	1.4173



(a) (b)

Figure 7. Load line displacement versus crack extension data for laminates. ●are valid and o are invalid data according to test evaluation procedure. shows the terminal value for crack extension measured with the heat-tint method.

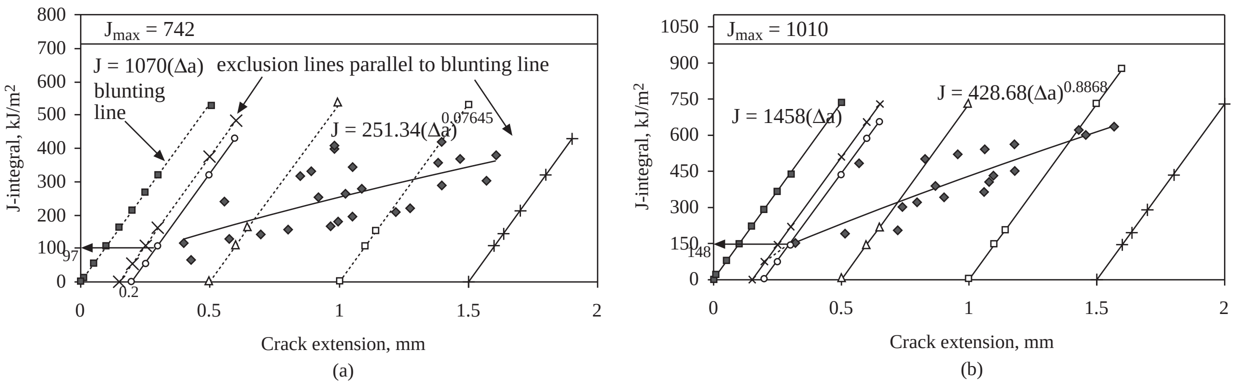


Figure 8. J-crack extension curve for laminates. J integral values crack extensions of 0.2 mm are also shown in the figures.

A requirement in J_{IC} testing is that (Δa(compliance)-Δa(phy) $<$ 0.15Δa(phy). In the current study the values are 0.4917 and 0.6553 for Vr = 0.4 and Vr = 0.8, respectively, and therefore the requirement is not satisfied. On the other hand in terms of Δa(phys)/Δa(compliance), values reported in the literature vary in the range 0.42-2.92. Therefore the present measurements with values of Δa(phys)/Δa(compliance) of 0.77- 1.42 are quite acceptable from that point of view but need to be improved according to the relevant standard.

J integral versus crack extension curves for the laminates are shown in Figure 8a and b. J values corresponding to a critical crack extension value of Δa = 0.2 mm are 97 kJ/m^2 and 148 kJ/m^2 for Vr = 0.4 and Vr = 0.8, respectively. The values satisfy the requirement with respect to the uncracked ligament and thickness. Therefore, the laminate with Vr = 0.4 has a fracture toughness value of J_{IC} = 97 kJ/m^2 and that with Vr = 0.8 has a value of J_{IC} = 148 kJ/m^2.

The current results show that there is a pronounced increase in the fracture toughness of the laminates with an increase in the volume fraction of the hard phase. In most laminates, however, this relationship is the opposite, i.e. fracture toughness decreases with volume fraction (Rohatgi *et al.,* 2003), but such cases refer to laminates where the reinforcing layers are hard and brittle. In the current sample, the reinforcing layer as well as the soft layers are both tough, and so the observed relationship is not unexpected. This is particularly true considering the fact that there is severe delamination between the layers, which leaves layers to behave on their own.

Conclusion

The current study on the facture toughness of steel laminates where both constituents are ductile and tough has shown the following:

1) Methodology developed for the measurement of J_{IC} for monolithic material that behaves in an elastic-plastic manner can be adapted for steel laminates. Measurement of J_{IC} via the compliance method yields values that can be used for comparative purposes, but the values are not as accurate as those obtained in monolithic materials. This is mainly due to difficulties in the estimation of crack growth data for the laminates via the compliance method.

2) On a comparative basis, it appears that the fracture toughness of steel laminates where both phases are tough and interfacial strength is low increases with increases in the volume fraction of the hard phase.

Although the compliance method as used in the current work is quite sufficient for a comparative evaluation of fracture toughness, there is a need for a reformulation of the compliance method specific to composite materials so that it yields better estimates of crack growth data.

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