# Fracture Toughness of Laminated Steels

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## Introduction

Lamination is found in many commercially available steels which means that the material is built up of layers of different thickness and different mechanical properties. Two main types of lamination can be distinguished, according to their formation: layers of slag and other inclusions represents the mechanical type, whereas ferritic-pearlitic lamination represents the metallurgical type.

When a notch or crack is developed perpendicular to the layers from which the plate is built up, fig. 1, the stresses in the vicinity of the crack tip may become so large that the tensile stress component perpendicular to the layers will break the joint between them causing relaxation of the transverse stress before and during crack propagation.

## Experiments for studying stress mechanism

A plexiglass model was made, the lamination of which was achieved by joining thin wafers with an adhesive which is supposed to have a considerably lower ultimate tensile strength than the plexiglass. Thus, if the adhesive breaks during crack growth a state of plane stress is reached in each plate whereas, in the homogeneous material of the same thickness as the complete laminated structure, plane strain would be dominating.

Strain gauges embedded in the plexiglass are used for determining the stresses near the crack front when the crack propagates. These recordings verify the assumption of partial transverse stress relaxation. On no occasion do the stresses at the strain gauges exceed the elastic limit of the plexiglass.

Under these circumstances, laminated structures may increase the fracture toughness as compared with homogeneous material.

Practical application on steel

The effect predicted above has also been found in steels. The behaviour of steels with "natural" lamination is much the same as that of steels with "simulated" lamination, obtained by joining a number of thin plates. In this work lamination has been achieved experimentally in several ways, namely

1) using a technique known as explosive welding. The ultimate tensile strength of the weld can be varied so that it will determine the properties of the joint ($\sigma_{UTS} \sim 450$–$600$ MN/m$^2$). See for example ref. [1].

2) the plates are brazed together, using a silver alloy for the joint ($\sigma_{UTS} \sim 400$ MN/m$^2$).

3) the plates are soldered together, using a tin alloy with a small percentage of silver ($\sigma_{UTS} \sim 100$ MN/m$^2$).

4) the thin plates can be loosely laid together without any adhesive, hence $\sigma_{UTS} = 0$, corresponding to full lamination from the beginning.

5) for reference, material without lamination is included ("full joint strength").

Object of investigation

The purpose of this study is to determine the influence of layer thickness and joint strength on the fracture toughness of laminated steels.



Principle behaviour

The apparent fracture toughness $K_Q$ as a function of the specimen thickness is illustrated in fig. 2. Under idealized conditions, a laminated plate of thickness 5h, built up from five plates of thickness h, should display the same toughness as a single plate of thickness h. For a 5h specimen, plane strain dominates, whereas the 1h specimen is closely subjected to plane stress.

Material

The testing material was a chromium-molybdenum steel (Bofors RO 651 ≈ SIS 2225) with the following composition, C 0.28% , Cr 1.20% , Mo 0.25% . An appropriate heat treatment will ensure suitable properties in fracture toughness and yield strength in order to reveal any effect of the kind mentioned above.

Results

a) General representation. Since the present material is extremely sensitive to the treatment during quenching and annealing, the apparent fracture toughness $K_Q$ is best represented when plotted against the yield strength $\sigma_s$, fig. 3. For clarity, no individual results have been plotted but only bands covering all the experimental points (59 in all).

b) Joint strength. The dependence of the joint strength is illustrated in fig. 4. Non-dimensional representations were chosen; $K_Q/K_C$, where $K_C$ is the toughness in plane stress, and $x = \sigma_{UTS\,joint}/\sigma_{UTS\,steel}$, where $x = 0$ corresponds to the conditions specified under point 4 above and $x = 1$ to those of point 5 above.

c) Layer thickness. The specimen thickness required for obtaining plane deformation can be estimated from $\sigma_s$ and $K_Q$. The experimental results have been compiled in fig. 5a which also shows the thickness of the different layers used. The thickness dependence is seen in fig. 5b.

d) Charpy impact tests. The results of some impact tests are shown in fig. 6. The influence of the joint strength on the impact energy E is much the same as that on $K_Q$.

## Conclusions

In order to improve the toughness, the transverse strength of the material should be low to allow for lamination. In this respect it should not exceed $0.1 \cdot \sigma_s$. Obviously the thickness strength has to fulfil other requirements, making a higher value necessary. Also, the layer thickness $\delta$ must not exceed a certain fraction of $\delta_{PD}$ which is the plane strain thickness. Preferably, $\delta/\delta_{PD} \leq 0.3$. Specimens of type 3 (with the low joint strength) display several pop-ins before final fracture. Each pop-in can be attributed to crack growth in one layer. In some cases, the maximum load has exceeded the load at the first pop-in by 75%. The tendency in developing new materials nowadays is to increase the yield stress, thereby often causing the toughness to be reduced. The permissible defect size to prevent crack growth is thus rapidly lowered. Lamination offers a possibility to build up structures with high yield stress and high fracture toughness at the same time, thus allowing for a moderate critical flaw size, [2] and [3].

## References:


[1] Lucas, W., Williams, J.D. and Crossland, B., Some metallurgical observations on explosive welding. 2nd int.conf. of the centre for high energy forming, Denver 1969.

[2] Palmer, P.J., British Welding Journal 1961, p.51.

[3] Almond, E.A. et al., J.Iron & Steel Inst. 1969, p.1319.






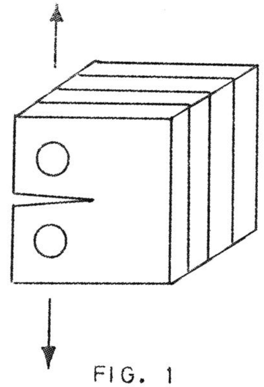

FIG. 1

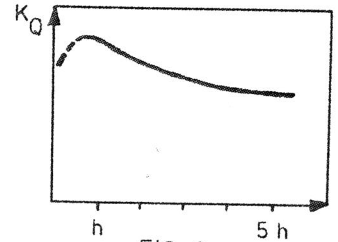


FIG. 2

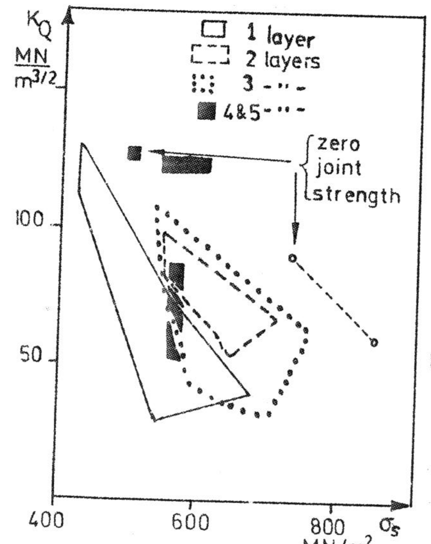


FIG. 3

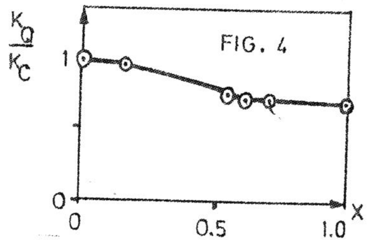


FIG. 4

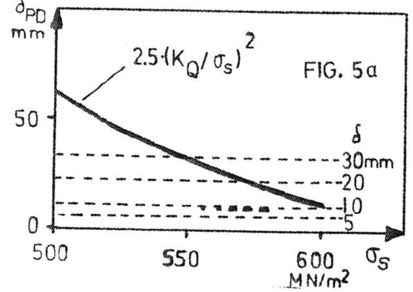


FIG. 5a

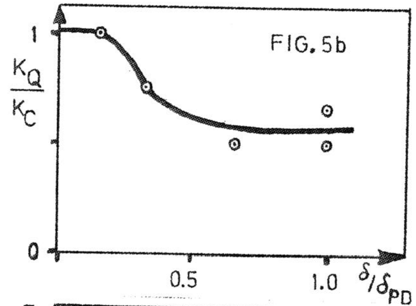


FIG. 5b

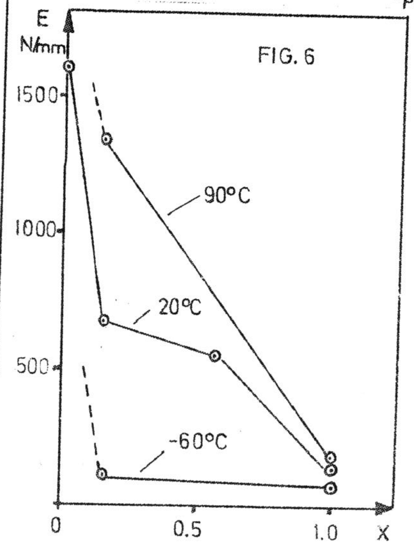


FIG. 6