On the Influence of Prestraining on the Fracture Toughness of Structural Steels

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Introduction

In a recent paper |1| we have reported on the influence of residual stresses on the fracture toughness K_{Ic}, measured at 77K with CT specimens of a structural steel St 52-3 (engineering strength about 52 kgf/mm^2). The residual stresses have been produced in the specimens by static prestraining at room temperature under the same kind of loading as in the later K_{Ic} tests as well in the same direction of force (sign +) as in the opposed direction (sign -). This prestraining was performed only in the partial scale yielding range with small scale nad full scale yielding as limit cases. The prestraining was measured by a COD clip gauge device and related to the slit+fatigue crack length l: δ_{pr}/l. The mixed elastic-plastic deformation is inhomogeneous and therefore a pure residual stress state results without worth mentioning strain hardening. We have shown that the observed changes in K_{Ic} can be indeed interpretated in terms of the residual stresses.

At these investigations the fatigue crack (index f) had been induced before the inhomogeneous (index i) prestraining: sequence (fi). In further experiments we have changed this sequence, i.e. made the fatigue crack in the specimens already prestrained: sequence (if). Furthermore we have predeformed some plates by a homogeneous (index h) plastic deformation ε_{pr} between 2% and 15% in tension (sign +) and compression (sign -), thus producing strain hardening without large scale residual stresses of the first kind. With the specimens machined from these plates and then provided with a fatigue crack the K_{Ic} tests have

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been made partly in the strain hardened state (sequence (hf)), partly after they had been additionally prestrained by an inhomogeneous partial scale yielding prestrain of the fixed amount $\delta_{pr}/l = +2.5x10^{-3}$ (sequence (hfi)). Finally we have investigated also a structural steel StE 70 (yield stress about 70 kgf/mm^2). The results shall be presented and discussed below. In the figures δ_{pr} or ε_{pr} shall always indicate inhomogeneous partial scale yielding-prestraining or homogeneous large scale yielding-prestraining respectively.

Discussion and experimental results

The fatigue cracking was performed at room temperature by tension-tension loading with a small lower load, exhibiting therefore a loading being principally equivalent to a positive prestraining δ_{pr}. As indicated by the observation of the glide lines at the steel St 52-3 (see Fig.1 in |1|) a small plastic zone preceeds the growing crack[+)]. At the final length of the crack of about 6mm it reaches about 1mm from the crack tip into the material. This length is smaller than the smallest used prestrain-zone-length of about 10mm for $\delta_{pr}/l=0.5x10^{-3}$. For $\delta_{pr} > 0$ and the sequence (fi) it only anticipates a small amount of the prestraining but does not influence the residual stress state, for $\delta_{pr} < 0$ it causes the effective prestraining to be somewhat smaller than the measured one but this is to be neglected already for $\delta_{pr}/l=-0.5x10^{-3}$. The course of $K_{Ic}^{(fi)}$ versus δ_{pr}/l in Figs.1 and 2 results as a consequence of the fact that the residual stress near the crack tip is a compressive stress for $_{pr}$ 0[x)] and a tensile stress for $\delta_{pr} < 0$ as pointed out in details in |1|. Also the appearance of one or more pop-ins in the latter case is characteristic for a tensile residual stress near the crack tip (see Figs.4 and 5 in |1|).

+) The glide lines are too weak to be made visible in a cliché reproduced photograph.

x) The signification of the residual stresses connected with the fatigue crack for the crack closure at positive stresses has been discussed by N.J.I.Adams |2|.

For the sequence (if) it is to be expected that the fatigue crack loading, since equivalent to a positive prestrain loading, somewhat intensifies the existing residual stress state for $\delta_{pr} > 0$ and somewhat weakens it for $\delta_{pr} < 0$. Therefore $K_{Ic}^{(if)}$ should be somewhat larger than $K_{Ic}^{(fi)}$ for both signs of δ_{pr}. This is according to Fig.2 indeed the experimental result for the steel StE 70, but according to Fig.1 for the steel St 52-3 only for $\delta_{pr} > 0$. K_{Ic} reaches the value for nonprestrained specimens for $\delta_{pr} < 0$, i.e. the residual stress state has been completely removed during the fatigue crack generation. In accordance with this pop-ins are no longer observed in this case. To understand this behavior it is to take into consideration that in tensile tests of unnotched specimens the steel St 52-3, contrary to the steel StE 70, exhibits a pronounced Lüders strain. For a steel without Lüders strain, i.e. with a smooth stress-strain curve, the plastic zone caused by fatigue crack loading extends only over the region in which the existing residual stress has nearly its positive maximum value. For a steel with Lüders strain, however, the plastic zone is initiated under the local upper yield stress at this region, but can extend under the local lower yield stress over the whole region of positive residual stress, thus destroying the residual stress state.

By the homogeneous predeformation at room temperature, may this be positive or negative, the strain hardening increases the stress to produce further plastic deformation[+)] at any temperature, since the Bauschinger-effect is negligible for the used amounts of ε_{pr}. The pre-deformed steel may be therefore considered as a new steel of a somewhat higher yield stress[x)]. For the K_{Ic} tests this means that the shear stress to produce gliding is higher, whilst the normal stress to generate cracking is the same, i.e. the effective surface energy and therefore K_{Ic} become lower,

+) This holds also for the load to induce a fatigue crack at the same number of cycles.

x) The reference values are here and furthermore those for the nonpredeformed material.

independent of the sign of ε_{pr}. The experiments exhibit just these results as shown in Fig.3. Evidently an additional fixed inhomogeneous positive prestrain δ_{pr} increases K_{Ic} in the same way relative to the predeformed level as it does for the nonpredeformed steel relative to its initial value for $\delta_{pr} = 0$. The experimental results of Fig.3 confirm this conclusion.

Among the influence on the fracture toughness in structural parts that of residual stresses and of strain hardening may be interpretated by these results. W.Dahl and W.B. Kretschmann |3| have investigated the influence of the grain size and shown that K_{Ic} considerably decreases with increasing grain size. On other factors papers are referred in |1|. By combination of all these results it should be possible to judge the fracture behavior of constructions, especially in the welded state. It was the aim of the present investigations to give a contribution to clarify these problems.

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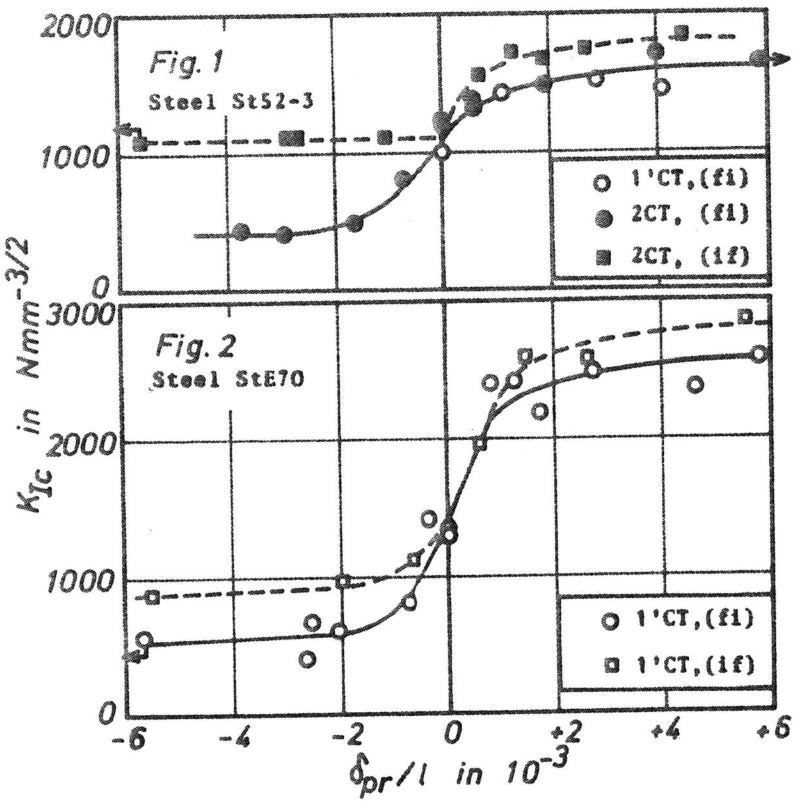

Fig.1 and 2 Fracture toughness $K_{Ic}(T=77K)$ versus relative inhomogeneous prestrain δ_{pr}/l

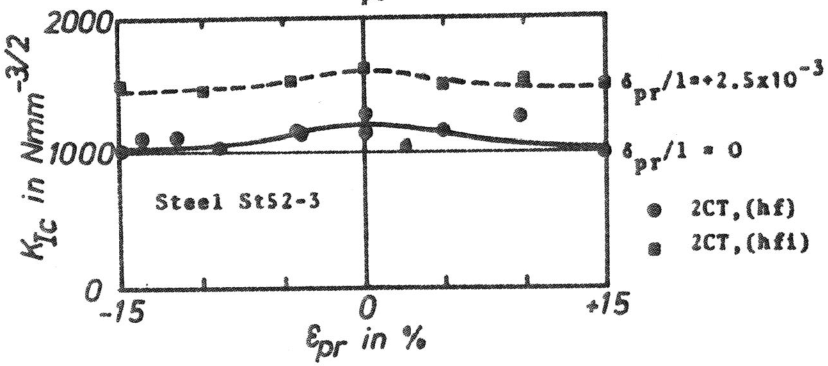

Fig.3 Fracture toughness $K_{Ic}(T=77K)$ versus homogeneous prestrain ε_{pr} and homogeneous + inhomogeneous prestrain