FATIGUE CRACK PROPAGATION PERPENDICULAR TO AN INTERFACE: THE EFFECT OF PLASTIC MISMATCH

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ABSTRACT

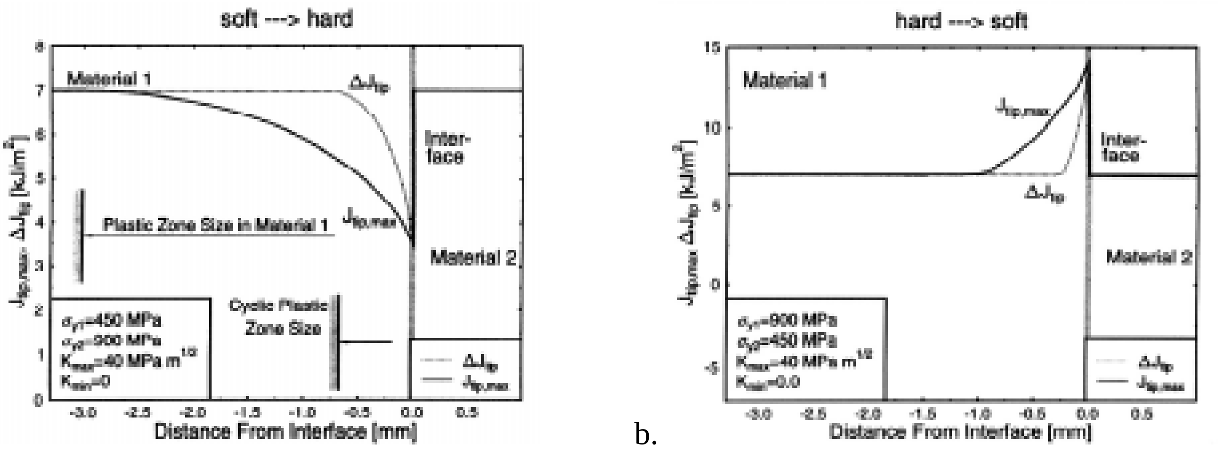
Fatigue cracks approaching an interface in a bi-material are experimentally investigated. Cracks propagating perpendicular to the sharp ferritic steel – ferritic steel interface are studied. The elastic and thermal expansion properties are nearly identical, only the plastic properties are different. The theoretically predicted slowdown of the growth rate in the case of a weak/strong transition and the acceleration in the case of a strong/soft transition are verified. Two surprising results are: The bifurcation of the crack in the vicinity of the interface when the crack propagates from the weak to the strong material, and the relatively large effect of the extremely small thermal mismatch on the crack propagation behavior.

INTRODUCTION

A huge number of engineering components are not made of uniform (homogeneous) material: welded structures; surfaces hardened components; coated structures, etc. The description of the mechanical behavior of such “composites” can be reduced very often to a bi-material problem. The propagation of cracks in such a system is not only determined by the propagation behavior of cracks in the corresponding material; the fracture behavior of the interface plays an additional important role. Furthermore, the driving force of a crack in a bi-material is not only given by the load, the geometry of the component and length of the crack, as in the case of a homogeneous material. One also has to take into account the geometrical arrangement of the two materials and their physical properties.

Especially important are the differences in their thermal expansion coefficients, and the elastic and plastic deformation properties of the two materials. These differences in properties are denoted as thermal, elastic and plastic mismatch, respectively.

In this paper we will study only the effect of plastic mismatch on the fatigue crack propagation behavior of cracks propagating normal to the interface. In the last few years various theoretical analyses (finite element analyses [1,2] and analytical studies [3-8]) have investigated the effect of plastic mismatch on cracks propagating perpendicular to the interface in a bi-material. These studies have shown that the interaction of the plastic zone with the interface leads to significant changes in the effective driving force for crack propagation, even when the elastic and the thermal properties of the two materials are identical (see Figure 1). When the crack propagates from the weaker to the stronger material before approaching the interface, the effective driving force at the crack tip becomes smaller than the applied driving force. This can be interpreted as a shielding of the crack tip from the applied (remote) loading. When the crack approaches the interface from the stronger material, the opposite behavior is observed, i.e. an antishielding of the crack tip occurs and, hence, the crack propagation rate should increase in the vicinity of the interface.



a. b.

Figure 1: Change of local crack driving force expressed in $J_{\text{tip max}}$ and ΔJ_{tip} for a constant ΔK as a crack propagates from the plastically softer material (1) to the plastically harder material (2) (a) and as a crack propagates from the plastically harder (1) to the plastically softer material (2) (b)

Only a relatively small number of experimental studies [1,9,10] have been devoted to the effect of plastic mismatch on fatigue crack propagation of cracks growing perpendicular to the bi-material interface. In these studies a ferritic steel – austenitic steel bi-material has been investigated extensively, but in this material combination a thermal mismatch takes place in addition. In order to study only the effect of plastic mismatch we have investigated a ferritic steel – ferritic steel bi-material with essentially the same elastic properties and nearly the same thermal expansion coefficient, but significant differences in their yield stresses. The measured fatigue crack propagation behavior of cracks growing perpendicular to the interface at constant applied driving force (constant ΔK) will be presented.

TABLE 1

CHEMICAL COMPOSITION OF THE TWO STEELS IN WT.%

	C	Mn	Si	Cr	Mo	Ni	Fe
ARMCO	0.007	0.08	0.008	0.01		0.03	Balance
SAE 4340 (34CrNiMo6)	0.34	0.60	0.3	1.50	0.2	1.5	-“-

TABLE 2

MECHANICAL PROPERTIES

	$\sigma_{0.2}$ [MPa]	σ_{UTS} [MPa]
ARMCO	140	228
SAE 4340	530	672

TABLE 3

COEFFICIENT OF THERMAL EXPANSION (10^{-6}/K)
BETWEEN 20 AND t °C

Temperature t °C	200	400	600	References
ARMCO	12.9	13.8	14.5	[11]
SAE 4340	12.1	13.5	14.1	[12]

MATERIAL

The two materials chosen for this study are ARMCO iron (technical pure iron) and the ferritic steel SAE 4340. Their chemical composition is listed in Table 1. They have essentially the same elastic properties but different plastic behavior. The 0.2% offset yield stress, $\sigma_{0.2}$, of the plastically stronger material, the SAE 4340 steel, is about three times larger than $\sigma_{0.2}$ of ARMCO iron, the plastically weaker material (see Table 2).

These metal/metal composite structures were joined by a special diffusion welding process. The material blocks were machined, laid together, heated up to 1100°C and subsequently deformed under compression where the loading axis was normal to the interface. The heating and deformation was performed under vacuum conditions which enables a diffusion bonding of the two materials. After this procedure the welded blocks were cooled to room temperature. In order to reduce residual stresses and to temper the steel SAE 4340 the welded structures were subsequently annealed at 580°C for 2h. The thermal expansion behavior of the two materials is very similar, as can be seen in Table 3. The difference in the coefficient of thermal expansion is only 3% between 600° and 20°C. Hence, the residual stresses caused by the thermal mismatch should be relatively small. The real calculation of the thermal mismatch stress field is difficult. A simple estimation of the maximum values of these stresses induced by the cooling from 580°C to room temperature gives about 15 MPa compression stresses in the stronger material and about 15 MPa tension stress in the plastically weaker material.

These steel – steel bi-material systems have well-defined sharp interfaces which can be seen in the optical micrograph in Figure 3. In order to proof the strength of the interface (quality of the welding) tensile tests were performed on bi-material specimens with the interface perpendicular to the loading axis located in the middle of the gauge length. Necking and fracture took place in ARMCO before the failure of the interface occurred. From the bi-material and the blocks with an interlayer (see Figure 2) compact tension specimens with following dimensions were machined: width $W = 50$ mm, $B = 8$ mm, initial notch length to specimen width ratio $a_0/W = 0.3$, and the distance from the machined notch to the interface was between 6 and 14 mm. Specimens with notches either in the stronger or in the weaker material were investigated. All fatigue crack propagation experiments were performed at constant applied crack driving forces, i.e., constant far-field ΔK. The smallest value, $\Delta K = 10$ MPa√m, was somewhat larger than the threshold of stress intensity range [17] of both materials, the other two values were $\Delta K = 18$ and 25 MPa√m. The stress ratio, R, in all cases was 0.1.

The crack propagation tests were performed at a frequency of 50 Hz in air. The crack length was measured optically. In order to keep ΔK constant, the load amplitude and the mean load was changed in steps after each extension of about 0.3 mm. Therefore, the necessary reduction of loads was smaller than 5%.

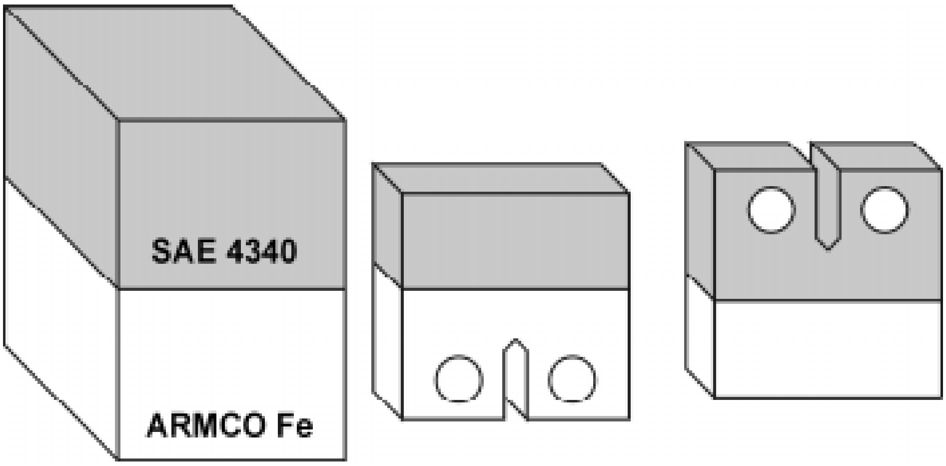


Figure 2: Schematic representation of the used material system and specimens

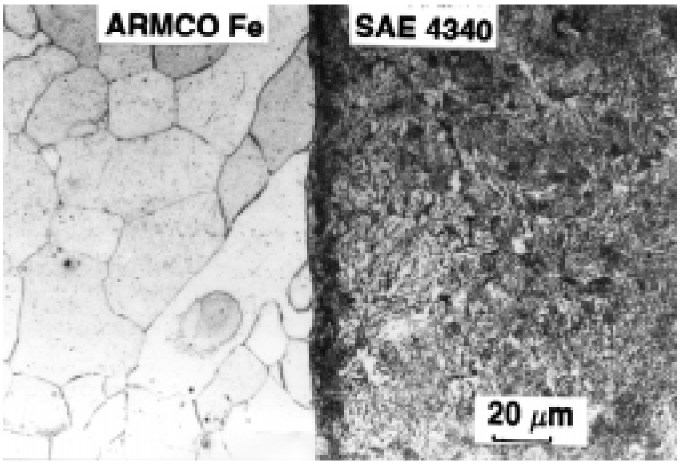


Figure 3: Optical micrograph of the near interface region

RESULTS AND DISCUSSION

Figures 4 and 5 show the measured crack growth rate as a function of the distance to the interface. In Figure 4 the behavior in the bi-material as the crack is propagated from the plastically weaker material to the plastically stronger material, is depicted. In the weaker phase at ΔK = 10 and 18 MPa√m, the crack propagation rate initially remains nearly constant. Only when the crack approaches the immediate vicinity of the interface is a small decrease of the propagation rate visible. This is in agreement with the predicted retardation [1,4,5] for such a case. At ΔK = 10 MPa√m the crack penetrates the interface and propagates at first with a somewhat smaller, and then with a constant growth rate in the stronger material. This has been observed in all three experiments performed at this stress intensity range.

Conversely, at ΔK = 18 MPa√m the crack bifurcates (forming of a branched crack where the branches have about the same length and propagate perpendicular to the initial growing direction) a few microns before reaching the interface (see Figure 7). At ΔK = 25 MPa√m the crack propagates relatively fast at first, but after an extension of about 1 mm from the notch root (at a distance 10 mm from the interface) the growth rate diminishes until it almost reaches the propagation rate of the experiment with ΔK = 18 MPa√m. Before the crack approaches the interface, the growth rate at first accelerates and then decreases again. In the immediate vicinity of the interface the crack bifurcates as in the case of ΔK = 18 MPa√m. The reason for this somewhat unusual growth behavior at ΔK = 25 MPa√m in the weaker material is caused by a change of the plasticity induced crack closure. At ΔK = 18 MPa√m the monotonic plastic deformation is dominated by the plane strain condition, therefore, the effect of crack closure is relatively small. At ΔK = 25 MPa√m the size of the monotonic plastic zone over the whole specimen thickness is predominately controlled by the plane stress condition. In this case the plasticity induced crack closure is much larger. The initial reduction of the growth rate can be explained by a building up of the plane stress closure which reaches a constant value after about 2 mm (this can be estimated by adapting the results of [18,19,20]).

When the plastic zone approaches the interface, the plastic deformation in the thickness direction is constrained by the plastically stronger material. The plane stress plasticity induced crack closure is reduced and, hence, the growth rate approaches the value of the first few millimeters. When the cyclic plastic zone reaches the interface to the plastically stronger material, the cyclic plastic deformation at the crack tip is reduced – or in other words the driving force is reduced as predicted by the models – and the growth rate decreases until the crack bifurcates.

A completely different result is obtained when the fatigue crack is initiated in the plastically stronger material and propagates into the weaker as shown in Figure 5. At ΔK = 18 and 25 MPa√m the crack initially propagates with a relatively large, nearly constant rate. After few mm extension the crack speed continuously diminishes. About 1 mm away from the interface the crack growth rate accelerates again. The maximum crack propagation rate is obtained in the immediate vicinity of the interface; the maximum value is significantly larger than the initial growth rate in the stronger material. In contrary to $\Delta K = 18$ and 25 MPa$\sqrt{\text{m}}$ at $\Delta K = 10$ MPa$\sqrt{\text{m}}$ the crack propagation rate falls to zero. The reason for the surprising initial reduction of the growth rate and the stopping of the crack at $\Delta K = 10$ MPa$\sqrt{\text{m}}$ is the small thermal mismatch between the two materials which causes compressive residual stresses in the plastically stronger material with the somewhat smaller thermal expansion coefficient. This causes an increase of the contribution of crack closure or, in other words, a reduction of the "local" stress ratio acting at the crack tip. If we assume that the growth rate is solely a function of the effective stress intensity range, we can simply estimate from the experiment at $\Delta K = 25$ MPa$\sqrt{\text{m}}$ and $\Delta K = 18$ MPa$\sqrt{\text{m}}$ that the maximum additional shielding caused by the thermal mismatch is about 6 MPa$\sqrt{\text{m}}$ (because the minimum crack propagation rate about 2 mm away from the interface at $\Delta K = 25$ MPa$\sqrt{\text{m}}$ is only somewhat larger than the initial propagation rate at $\Delta K = 18$ MPa$\sqrt{\text{m}}$). Since the effective threshold of the stress intensity range in the stronger material is about 6.5 MPa$\sqrt{\text{m}}$ at a stress ratio 0.1 an additional shielding of about 6 MPa$\sqrt{\text{m}}$ in the experiment with $\Delta K = 10$ MPa$\sqrt{\text{m}}$ causes the observed stopping of the crack.

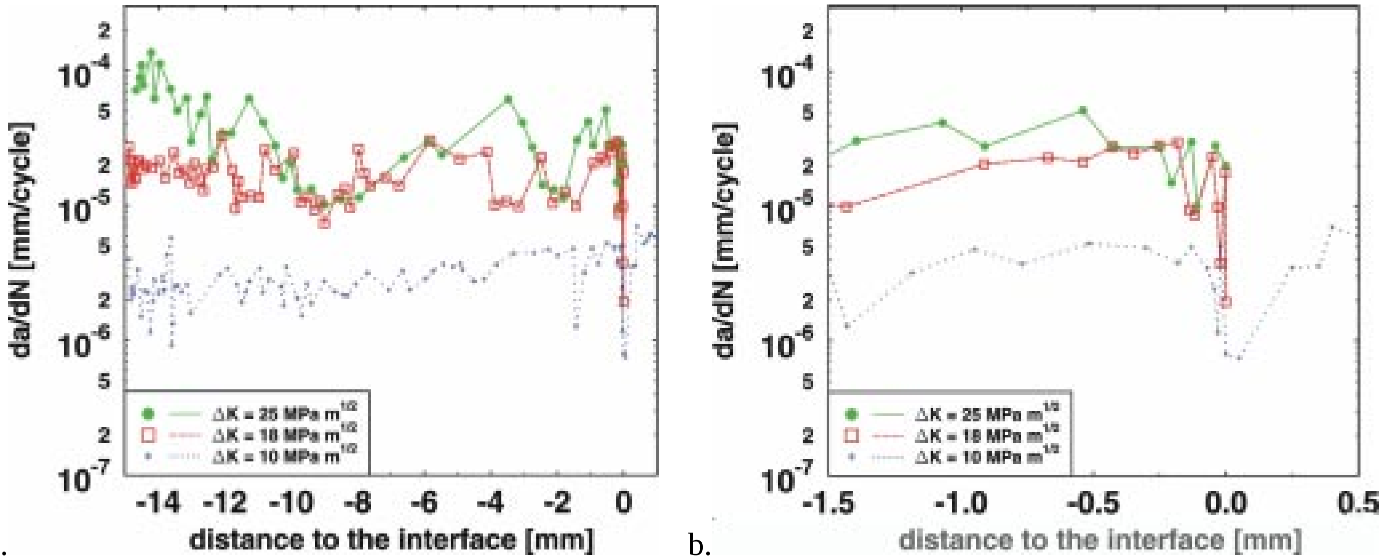


Figure 4: Fatigue crack growth rate, *da/dN*, as a function of the distance from the interface at different ΔK levels in the bi-material specimens, as the crack is propagated from the plastically weaker material, ARMCO, to plasticallystronger material, SAE 4340 (a), and the more detailed view of the near interface behavior (b).

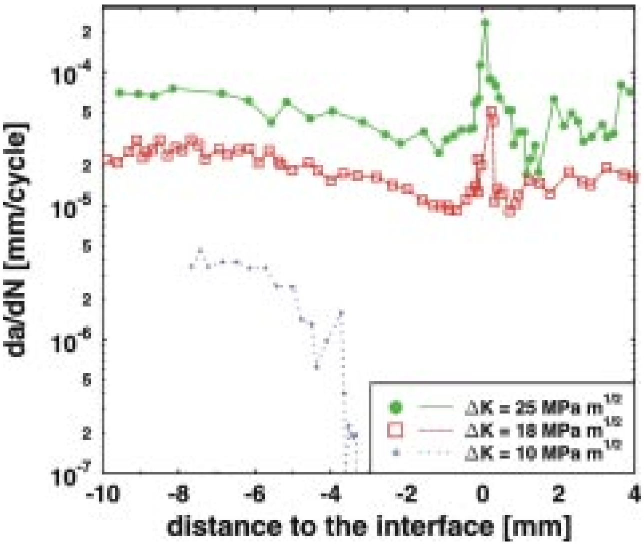


Figure 5: *da/dN* as a function of distance from the interface at different ΔK levels in the bi-material specimens as the crack is propagated from the plastically stronger material to the plastically weaker material

When the crack in the bi-material with the strong weak transition is about 1 or 2 mm away from the interface a plastic zone develops in the weaker material (at first isolated from the plastic zone in the stronger material, see Figure 6), which causes a reduction of the effect of thermal mismatch stresses. This induces the slight increase of the crack propagation rate. When the cyclic plastic zone spreads also into the weaker material a fast acceleration is obtained, which is caused by the antishielding induced by the plastic mismatch. This acceleration in the vicinity of the interface is also observed in the stronger material with weaker interlayer but is less pronounced than in the bi-material case and is in good agreement with the theoretical predictions.

A more extended description of these experiments and the fatigue crack growth behavior of cracks propagating perpendicular to an interlayer - a weaker interlayer in homogeneous harder material and a hard material in a homogeneous weaker material - is described in [21].

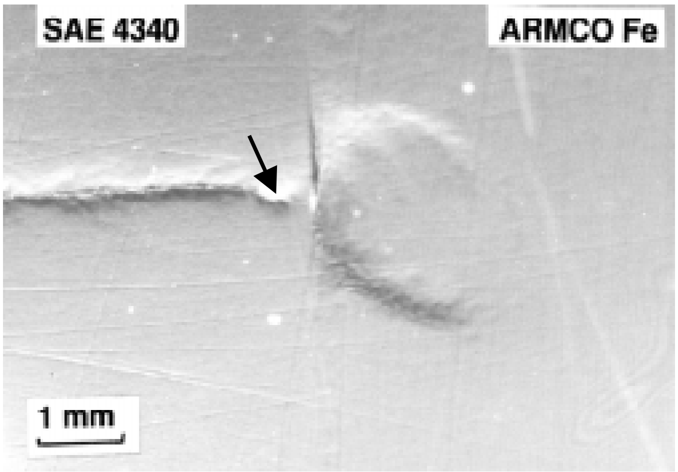


Figure 6: An optical micrograph as the crack is advanced from the plastically stronger to the plastically weaker material, the crack tip is located in the stronger material, the distance to the interface is about 0.5mm, ΔK = 25 MPa√m (the location of the crack tip is marked by an arrow)

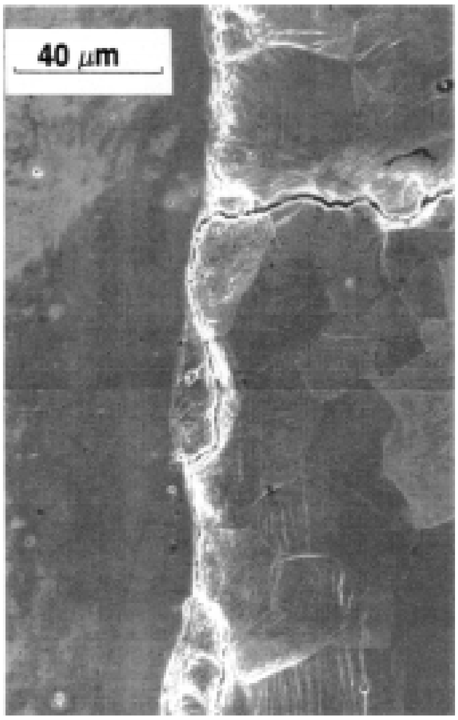


Figure 7: SEM micrograph as the crack is propagated from the plastically weaker to plastically stronger material, at ΔK = 25 MPa√m, it shows the crack bifurcates somewhat in front of the interface, and propagates then in the weaker material along the interface.

CONCLUSIONS

The effect of local changes of the plastic deformation properties on fatigue crack propagation has been studied experimentally. A bi-material was chosen as model systems. The plastically weaker ARMCO-iron (technical pure iron) and the plastically stronger SAE 4340 steel were used as model components, their elastic and thermal expansion properties are nearly identical. The transition from the plastically weaker to the plastically stronger and from the stronger to the weaker components of the bi-materials has been investigated.

- i) The crack propagation rate diminishes in the vicinity of the interface when the fatigue crack approaches the bi-material interface from the plastically weaker material, and accelerates when the crack approaches the interface from the plastically stronger material. This is consistent with the theoretically predicted reduction [1,4,5] or amplification of effective crack driving when the cyclic plastic zone reaches the bi-material interface from the plastically weaker or the plastically stronger material, respectively.
- ii) Surprising is the relatively large effect of the extremely small thermal mismatch, which causes a retardation of the crack growth rate at relatively large distances from the bi-material interface in the SAE 4340 steel with the somewhat smaller thermal expansion coefficient.
- iii) An interesting result is the bifurcation of the crack very close to the interface in the bi-material and interlayer system when the crack approaches the interface from the plastically weaker material (except at the smallest load amplitude in the bi-material). This may be caused by a change of the near crack tip deformation field when the crack tip approaches the immediate vicinity of the interface.

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