INFLUENCE OF TEMPERED MARTENSITE CONTENT ON THE FATIGUE CRACK PROPAGATION IN A STRUCTURAL STEEL

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ABSTRACT

A study has been made concerning the effect of tempered martensite volume fraction on the fatigue behavior of quenched and tempered R4 grade structural steel. As this material is largely used for fabricating offshore mooring chains, the study was extended to include quenched and tempered flash welded chain links. Martensite content was varied by varying the austenitization temperature and fatigue behavior of quenched and tempered specimens was determined by following crack growth during constant amplitude cyclic loading. The results indicate that an increase in the tempered martensite volume fraction is associated with a reduction in the number of cycles to failure and that for a given microstructural condition, the fatigue life of the welded joints is invariably shorter than that of the base metal. Finally, the fatigue behavior is presented and discussed considering the mechanical properties and the toughness of the fatigued specimens.

1 INTRODUCTION

An increasingly greater proportion of worldwide oil production currently comes from large offshore fields. The great exploratory potential in deep waters has led companies in the oil sector to search for the necessary technological improvement to make offshore exploration and production feasible. In parallel to searching for new technologies, the reduction in risks of structural failure has become a sector's constant practice. Fatigue assessment of offshore mooring systems, particularly welded joints, is performed by international codes making use of statistical and empirical approaches to evaluate their reliability [1]. Calculations provide a lot of information but experimental work is always necessary to determine this reliability.

The present study was initiated in an effort to evaluate the influence of tempered martensite content on the fatigue behavior of an R4 grade structural steel. As the steel is largely used for fabricating offshore mooring chains, the study was extended to also include flash welded chain links. Martensite content was varied by varying the austenitizing temperature and fatigue behavior was determined by following crack growth during constant amplitude cyclic loading.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

The steel used for this investigation was received in the form of hot rolled round bars of circular cross section with a nominal diameter of 124 mm. The steel contains, in weight percent, 0.24% C, 1.06% Mn, 0.28% Si, 1.05% Cr, 0.55% Ni, 0.22% Mo with the balance being Fe and traces of P, S and other elements.

The circular bars were bent in conformity with the typical studless link geometry before they were butt flash welded [2]. Following the welding process, the links were austenitized at 900^0C for 60 minutes, water quenched, tempered at 680^0C for 60 minutes and then water cooled.

Compact tension (CT) specimens were cut out from the welded side as well as from the opposite side of the heat treated chain links and machining of the specimens was carried out in accordance with

ASTM E647-99 test standard [3]. The specimen width, W, and specimen thickness, B, were taken as 32 and 8 mm, respectively and a starter notch was machined to a depth of 7 mm. Cylindrical tensile specimens were also cut out along the rolling direction, L, from both sides of the heat treated chain links and then machined according to ASTM E37 test standard [4].

The tensile and CT specimens were subjected to one hour austenitization treatment, water quenched and then tempered at 640^0C for one hour. Four different austenitization temperatures of 775, 755, 720 and 685^0C were chosen as they are expected, according to thermodynamic calculations [5], to lead, respectively, to 100, 75, 25 and 0% austenitization of the steel. Identification of the phases present in the as-quenched steel was carried out using X-ray diffraction technique and the percentage of non transformed ferrite was determined as a function of the austenitization temperature.

The CT specimen surfaces were polished and fine lines were drawn parallel to the specimen axis in order to facilitate monitoring crack growth during cyclic loading. Fatigue precracks, 1.5 mm in length, were introduced in the specimens, thus giving rise to an initial crack length to specimen width ratio, a/W, of about 0.26. Precracking of the welded joints was carried out in a way such that the crack plane always coincided with the weld plane.

Constant amplitude (CA) cyclic loading was applied to the precracked specimens so as to establish the typical a-N curves for the tempered specimens pertaining to the base metal as well as to the welded joints. The tests were performed at room temperature using a servo-hydraulic machine, operated at a frequency of 20 Hz. The specimens were submitted to a tension-tension made I loading with a maximum load of 9 kN and a load ratio R of 0.33, and fatigue crack length was monitored using a traveling microscope.

3 RESULTS AND DISCUSSION

The variation of the percentage of primary (untransformed) ferrite with the austenitization temperature is presented in Table 1. One can observe from this table that an increase in the austenitizing temperature is accompanied by a decrease in the volume fraction the untransformed ferrite and that fully martensitic structure can be obtained by quenching the steel from an austenitizing temperature of 775^0C.

The mechanical properties determined by uniaxial tensile testing of the quenched and tempered specimens are given in Table 2, where the symbols A, B, C and D refer to the base metal austenitized, respectively, at 775, 755, 720 and 685^0 C, and A(S), B(S), C(S) and D(S) correspond to the welded joints austenitized at the same where the symbols A, B, C and D refer to the base metal austenitized, respectively, at 775, 755, 720 and 685^0 C, and A(S), B(S), C(S) and D(S) correspond to the welded joints austenitized at the same temperatures. The Vickers microhardness numbers VH are also given in the last column of the same table. The numbers listed there show that both the yield stress, σ_Y, and the ultimate stress, σ_u, decrease with the decrease in the austenitization temperature and that these two stresses are invariably higher for the welded joints in comparison with their respective levels as encountered for the base metal. As to the tensile ductility, an opposite behavior can be observed as manifested by the increase in the percent reduction in area, φ, accompanying the decrease in the austenitization temperature.

Considering the data presented in Tables 1 and 2, one can associate the increase in the strength and the decrease in ductility with the increase in the volume fraction of tempered martensite present in the quenched and tempered specimens.

Table 1: Variation of the percentage of primary ferrite with the austenitization temperatures

Austenitization Temperature (^{0}C)	Ferrite percentage
775	0
755	10 ± 1
720	24 ± 2,1
685	39 ± 1,5

Table 2: Mechanical properties as obtained by tensile testing of the base metal and welded joints

Specimen code	σ_Y (MPa)	σ_u (MPa)	φ (%)	VH (kg/mm^2)
A	734 ± 18	835 ± 17	69 ± 1	281 ± 8
A(S)	742 ± 16	841 ± 17	60 ± 3	-
B	649 ± 21	742 ± 21	73 ± 2	242 ± 10
B(S)	670 ± 18	755 ± 18	69 ± 2	-
C	526 ± 17	646 ± 16	79 ± 2	217 ± 9
C(S)	538 ± 15	671 ± 14	72 ± 1	-
D	509 ± 14	629 ± 15	76 ± 2	206 ± 9
D(S)	539 ± 17	655 ± 12	71 ± 2	-

Fatigue Crack Growth

The base metal fatigue crack growth behavior concerning the base metal and welded joints, exemplified by the variation of crack length with the number of cycles are presented in Figures 1 and 2, respectively. The fatigue life, expressed by the number of cycles to failure, Nf, is presented in Table 3 for the base metal and the welded joints.

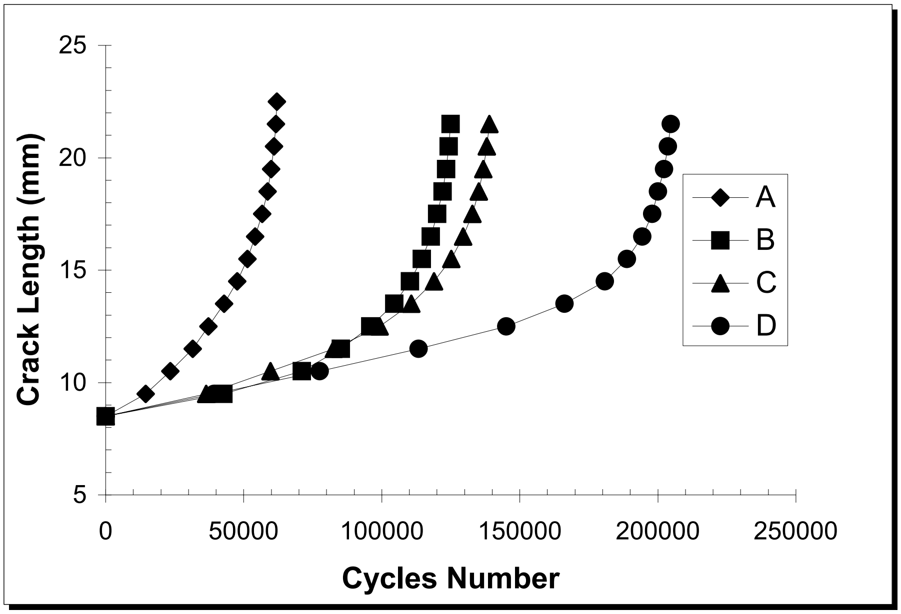

Figure 1: Variation of fatigue crack length with the number of cycles for the base metal.

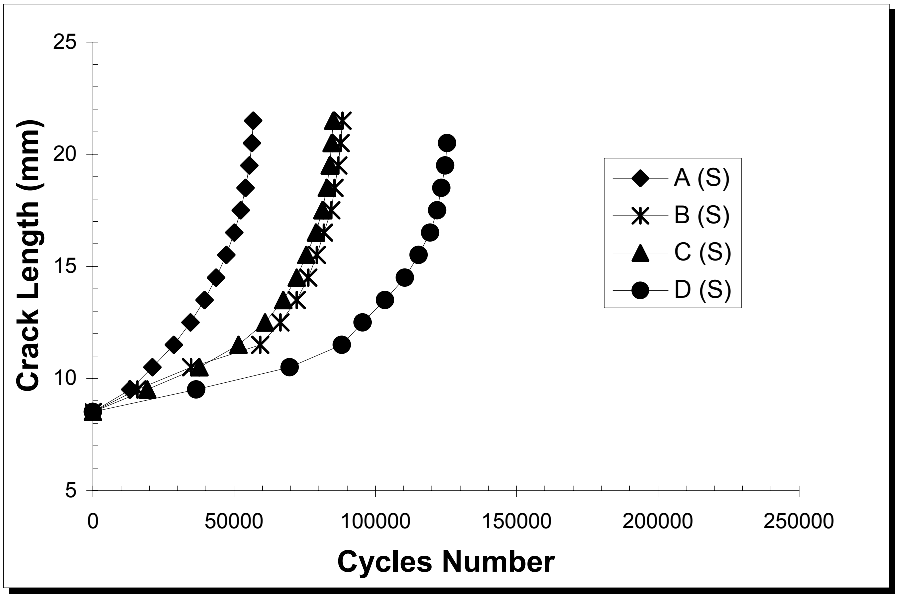

Figure 2: Variation of fatigue crack length with the number of cycles for the welded joints.

Table 3 Number of cycles to failure, N_f, obtained from fatigue testing

Specimen code	N_f
A	61999
A(S)	56763
B	124933
B(S)	88354
C	138919
C(S)	85126
D	204679
D(S)	125431

The results presented above clearly indicate that the fatigue life is considerably improved by decreasing the austenitization temperature. This improvement is brought about by a decrease in the crack propagation rate, da/dN, as well as by an increase in the critical crack size. The critical crack size, which corresponds to the onset of unstable fracture, is determined by the material's toughness, which in turn is strongly dependent on microstructural aspects as well as mechanical properties of the material. Lowering the austenitization temperature, the yield stress drops and the tensile ductility goes up in the virtue of the increase in the ferrite content. As a result, the material's toughness and, consequently, the critical crack length would increase. Similar effects have been reported, by a number of authors [6,7], on high resistance structural steels. Microstructurally modified Al alloys were also found to exhibit the same behavior and the improvement in their toughness was accompanied by an increase in their fatigue life [8].

As to the decrease in da/dN, accompanying the decrease in the austenizing temperature, such a decrease can be attributed to crack meandering through the microstructural composed of a mixture of nontransformed ferrite and tempered martensite.

From the data reported above, one can notice that, for a given microstructural condition, i.e., for a given austenitizing temperature, the fatigue life of the welded joint is considerably shorter than that of the base metal. This degradation in fatigue behavior is caused, in part, by an increase in the crack propagation rate da/dN, in virtue of the fact that crack propagation in the welded joints occurs along the weld plane, which serves as a natural path for fatigue crack propagation. Another factor, which could contribute to fatigue life degradation in welded joints, is the decrease in critical crack size. A decrease in this size is related to toughness degradation, which is inherent to most welding processes.

4 CONCLUSIONS

From the results presented on the fatigue behavior of quenched and tempered R4 grade steel, the following conclusions can be drawn:

- An increased tempered martensite volume fraction is associated with a decrease in critical crack size and an increase in crack propagation rate, thus leading to a reduction in fatigue life.

- The decrease in critical crack size is attributed to a degradation in the steel's toughness, consistent with the reduction in the volume fraction of nontransformed ferrite upon increasing the austenitization temperature.

- A similar behavior is observed for quenched and tempered flash welded joints, with the fatigue life of the joints being invariably inferior to that of the base metal. This is essentially related to the fact that crack propagation rate along the weld plane is higher than that through the base metal.

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