A REVIEW OF RECENT WORK ON FATIGUE RESPONSE IN FERRITIC/MARTENSITIC STEELS –

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OBJECTIVE

The objective of this effort is to summarize recent work on fatigue and creep-fatigue response in ferritic/martensitic steels in order to identify those areas where further work would be fruitful.

SUMMARY

The recent literature on fatigue and creep-fatigue response of ferritic/martensitic steels has been reviewed with particular emphasis on that of interest to the fusion materials community. A range of alloys has been studied including low activation martensitic steels developed in Japan and Europe as well as some work on ODS steels of interest. The results show that all these martensitic steels behave similarly, that ODS steels provide improvement, that irradiation tends to reduce fatigue lifetimes, and that simultaneous helium and hydrogen injection can be very deleterious. Work done on 9Cr-1Mo in support of Gen VI demonstrates that creep-fatigue lifetimes will be controlled by cracking of surface oxides. It may be necessary to test in a fusion environment in order to accurately predict ferritic/martensitic steel fatigue response for a fusion machine.

PROGRESS AND STATUS

Review of the literature

This effort is intended to review recent work in the field of fatigue and fatigue-creep interaction for ferritic-martensitic steels of interest to the fusion materials development community in order to indentify those areas where future efforts might be directed effectively.

Since the introduction of a ferritic steel option to the USDOE Fusion Reactor Materials mission in 1979, it has been apparent that the fatigue response in this class of materials would be of considerable interest, due to both thermal and stress cycling. As a result, a number of such studies have been made around the world in support of a fusion energy system. This report will attempt to review the last five or so years of such efforts.

At the 21st American Society for Testing and Materials (ASTM) symposium on Effects of Radiation on Materials, Li and Stubbins [1] reviewed the US and European literature in order to provide comparison with a predictive model based on tensile behavior. The ferritic alloy data they chose to analyze were for MANET (DIN 1.4914), of composition Fe-10.6Cr-0.87Ni-0.82Mn-0.77Mo-0.37Si-0.22V-0.12C-.02N and HT9, Fe-11.5Cr-1Mo-0.55Mn-0.5W-0.4Si-0.3V-0.2C, both before and after irradiation. That review included a plot of fatigue lives for ferritic/martensitic steels MANET and HT9, reproduced in Figure 1. From this work they concluded that pre- and post-irradiation fatigue behavior in ferritic/martensitic is more complex than can be predicted quantitatively from simple tensile test results, (at least in part because fatigue-softening occurred), and that a microstructural-level understanding of the flow mechanisms is necessary to provide guidance about fatigue performance.

The effort to understand fatigue response of ferritic/martensitic steels in Asia has centered on work in Japan based on low activation steels (F82H, Fe-8Cr-2W [2-4] and JLF-1, Fe-9Cr-2W [5-9]), but 9Cr-1Mo [10-11], 12Cr-2W [12] and oxide dispersion strengthened (ODS) alloys [13] were also studied.

The effort on F82H, a low activation martensitic steel developed in Japan and distributed by JAERI to interested researchers was included in Japanese low dose irradiation experiments taken to 0.02 dpa at

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temperatures of 100, 150 and 200ºC [2,4]. Results were similar to those given by Li and Stubbins in Figure 1, about intermediate between HT9 and MANET for unirradiated conditions and similarly reduced following irradiation. A study examining surface finish on fatigue response demonstrated a degradation of ~2 in fatigue life with surface roughness and showed that cracks initiate preferentially on scratches remaining from machining [3].

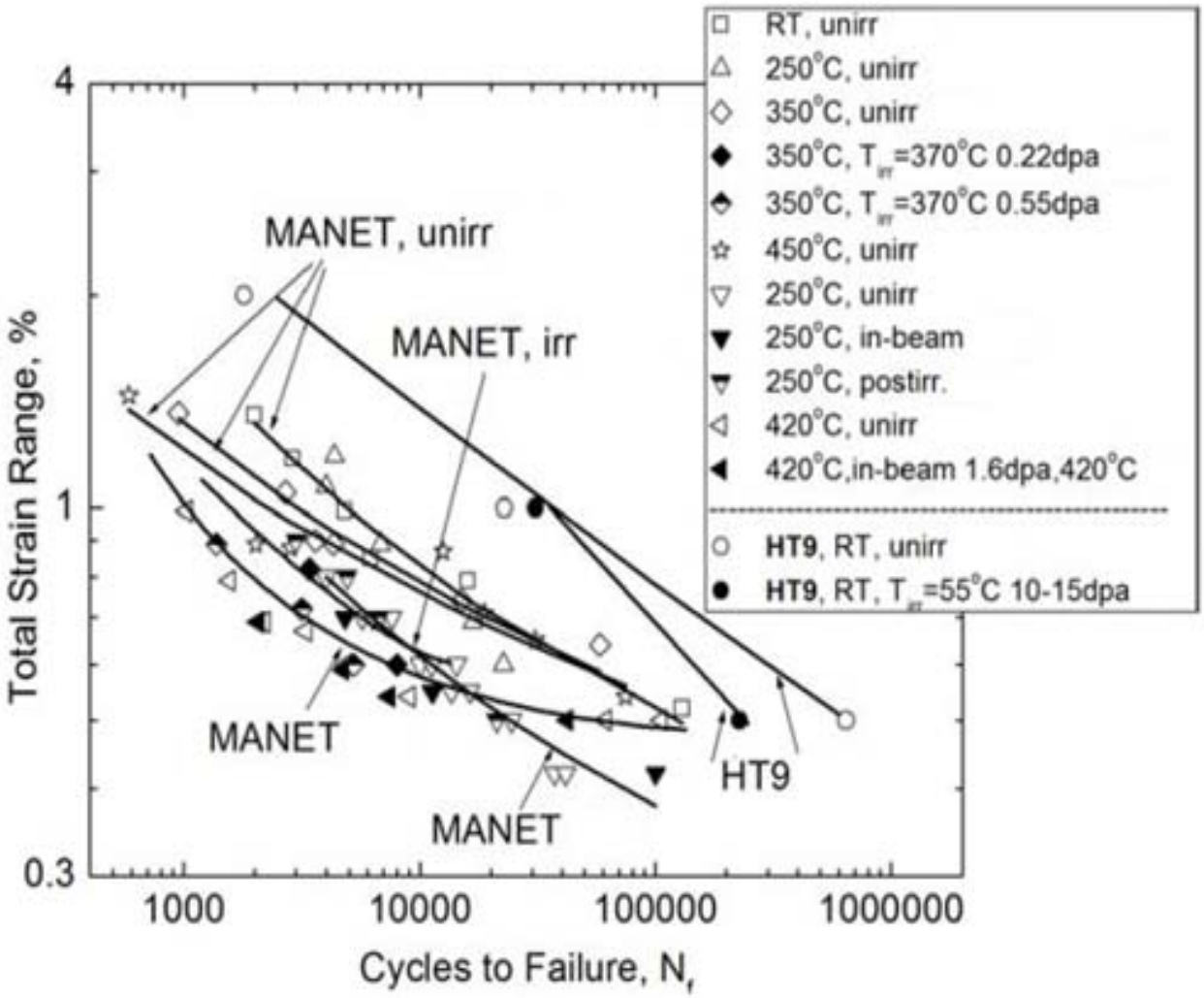

Figure 1. Comparison of the fatigue lives for ferritic/martensitic steels MANET and HT9 in unirradiated and irradiated conditions as a function of temperature, taken from [1].

The JLF low activation martensitic steels were developed by the Japanese University fusion community, and initial experiments were intended to reduce specimen size in order to optimize irradiation experiments [5-7]. Approximately quarter-sized specimens resulted in no significant change in lifetimes at stress amplitudes of ~500 MPa but with a small decrease in slope with stress amplitude. Later experiments demonstrated cyclic softening and reduced lifetimes in TIG weldmetal conditions [6,7]. The JLF steel was also used to provide microstructural analysis of the consequences of fatigue deformation [8-9]. Cyclic softening was found to be caused by reduction of the dislocation density and increase in lath width with no apparent change in carbide size. It was also noted that fatigue life was independent of temperature when plotted against total strain but not against plastic strain (as used by the Coffin model).

There were various efforts on modified 9Cr-1Mo and a 12Cr-2W pipe steel. The first characterized the microstructure during creep-fatigue and showed that the ultrasonic velocity was dependent on the microstructural changes. This was attributed to first a loss in dislocation density and then to a decrease in solute atoms in solution resulting from MX precipitation [10]. As a consequence, non-destructive ultrasonic evaluations can be used to monitor creep-fatigue response. A second effort evaluated a sodium environment on low-cycle fatigue properties and found that the evolution of cyclic stress response was similar to that in air, but lifetimes were significantly increased. This was attributed to the lack of oxidation in the sodium environment and a resulting delay in crack initiation, an effect expected to be more pronounced at lower strain ranges.

Finally, results were provided for low-cycle fatigue properties of ODS ferritic/martensitic steels at high temperatures. Both 9Cr and 12Cr steels were tested with compositions at 2%W, ~0.2%Ti and ~0.3%Y_2O_3, the former containing 0.14%C and therefore martensitic. Both ODS steels were found to have similar fatigue properties but showed superior fatigue life and negligible cyclic softening compared to conventional ferritic/martensitic steels. These differences were attributed to the higher yield strengths for ODS alloys which leads to lower fractions of plastic strain under strain-controlled fatigue conditions.

European efforts were largely centered on low activation steel Eurofer 97, Fe-9Cr-1W-0.2V-0.15Ta-0.1C-0.02N [14-19] but one study included a range of low activation steels [20], as well as 9Cr-1Mo [21-25] and a steel similar to HT9, X12CrMoWVNbN10-1-1 but actually containing ~10Cr-1Mo-1W-0.1C [26]. A modeling effort on the influence of irradiation was also produced [27].

Eurofer 97 was a low activation martensitic alloy prepared for European experimentation. It was found to undergo significant irradiation hardening following low temperature irradiation, as severe as HT9, but provides material comparable to F82H and JLF-1 for fatigue studies. Comparison with Figure 1 reveals that Eurofer 97 has fatigue properties similar to but below those of MANET by about a factor of 2 in lifetime [18]. Early tests in air indicated that oxide formation probably enhanced crack propagation indicating the need for testing in a fusion environment [14]. This issue was then addressed for the case of in-situ testing using 590 MeV protons in a cooling gas, so that H and He were injected during irradiation and fatigue testing [15]. It was found that irradiation strongly reduced cyclic life, concurrent with radiation induced hardening. However, this in-beam damage could be readily recovered by further cyclic deformation with the beam off so that lifetimes were then on the order of tests without irradiation. The influence of hydrogen embrittlement was examined using cathodic charging and testing at room temperature [16]. Both base metal and joints of Eurofer 97 were indeed found to be susceptible to hydrogen embrittlement, but it was noted that such problems might be mitigated by proper microstructural control. A low cycle fatigue study of Eurofer 97 concluded that Eurofer 97 behaved similarly to F82H and MANET at room temperature and showed no significant effect of temperature from 150 to 550ºC on fatigue life [18]. Hold times of 500s were also applied, and at high imposed strains, no strong differences were found even at 550ºC, whereas for low imposed strains there was a strong life reduction and significant softening was noted. Concurrent microstructural studies showed that the major changes during fatigue were a decrease in dislocation density and decomposition of the lath structure into submicron equiaxed subgrains. Multiaxial fatigue behavior has also been studied showing further reduction in lifetime [17,19], and it was demonstrated that fatigue design curves based on uniaxial tests are not sufficiently conservative. Finally, Eurofer 97 was compared to F82H and an ODS Eurofer variant following irradiation at 330ºC up to ~30 dpa [20]. It was found that all alloys showed improved fatigue life following irradiation for low values of total strain range, but Eurofer 97 response was significantly degraded compared to unirradated material at higher values of total strain range.

Fatigue studies outside the fusion community (and in support of accelerator systems or Gen-IV nuclear reactors) were largely based on 9Cr-1Mo compositions. The addition of a FeCrAlY surface modification was determined to result in similar fatigue response at 550ºC for both tests in air and in $Pb_{55}Bi_{45}$ [21]. A series of papers considered creep-fatigue-oxidation interactions and included tensile and compressive hold periods and a lifetime prediction [22-24]. Creep-fatigue tests were found to be more deleterious than equivalent relaxation-fatigue tests and compressive hold periods were worse than tensile ones. Both the mean stress effect and environmentally-assisted crack initiation may be responsible. Note that for

compressive creep-fatigue hold periods, the oxide layer is mainly subjected to tensile stresses (and conversely for tensile hold periods) resulting in enhance oxide scale cracking. Based on an understanding of the controlling physical mechanisms gained from these studies, two scenarios were proposed for the interaction between fatigue, creep and oxidation damage, and a model for creep-fatigue lifetime was developed that accurately predicts pure fatigue lifetimes for $\Delta\epsilon_{fat} \geq 0.4\%$ [24]. This work was further summarized in a later paper and the two cracking scenarios were diagrammed [25]. Studies on Fe-10Cr-Mo-1W-0.1C steels gave cyclic softening results similar to other studies and correlated it with significant subgrain coarsening. Also, cyclic deformation was shown to affect the subsequent minimum creep rate by a factor of 6.

Finally, modeling of fatigue response is being attempted on several fronts. European fusion materials work considers consequences of irradiation damage mechanisms and develops a model to predict behavior in Eurofer 97 [27]. A conference on residual stress and its effect on fatigue and fracture considered low alloy steel behavior but was mainly concerned with assessment of defects [28]. Discrete dislocation dynamics modeling is being used to understand dislocation-crack interactions during fatigue and showed that even during compression with the crack tip closed and the specimen behaving like an uncracked specimen, the dislocation structure can result in lower yield stresses than one would obtain where no cross-slip were allowed [29].

Discussion

Studies of fatigue response for several ferritic/martensitic steels have been performed around the world. Alloying variations resulted in only minor differences in behavior, and irradiation degraded response. Several researchers concluded that behavior was controlled by a breakdown of the martensite lath dislocation substructure and reconfiguration into a coarser subgrain structure, as opposed to carbide coarsening or refinement.

The fatigue response of martensitic steels can be understood based on these reported microstructure changes, as follows. The microstructure of air-cooled martensitic steels is a result of a martensite reaction that leaves a thin layer of carbon-rich retained austenite at lath boundaries [30]. This is because there is sufficient diffusion of carbon to allow the carbon to stay ahead of growing martensite laths. During tempering or normalization, the retained austenite provides sites for carbide precipitation and the high density dislocation structure generated by the martensite reaction relaxes into a substructure pinned by the carbide obstacles. The resultant lath- or subgrain-structure is much finer than that which would result during high temperature creep or fatigue testing, and therefore, the creep and fatigue response are initially reduced by this controlling substructure. However, as fatigue and high temperature creep proceed, this artificially induced dislocation substructure breaks down to one more characteristic of the applied stresses, and the material softens. Reduced fatigue response due to irradiation without simultaneous gas injection is most probably a result of enhanced embrittlement found in these steels.

The fatigue lifetime is dependent on initiation and growth of a crack. These critical cracks generally initiate at specimen surfaces, and therefore surface condition, whether it be from machining artifacts or surface oxide irregularities, will control response. In irradiation experiments where gas was injected during irradiation [15], fatigue lifetimes decreased markedly. Apparently, internal cracking was enhanced by gas injection to the point where critical internal cracks could be developed. However, when irradiation and concurrent gas injection were stopped and the fatigue testing was continued, failure was a result of a critical surface crack.

Opportunities therefore exist in modeling fatigue behavior based on this microstructural description, both for the influence of effective subgrain size on fatigue response and the consequence of injected gas on internal critical crack initiation. Future work could therefore include validating the above description with further microstructural studies and modeling it. Dislocation dynamics modeling of similar behavior has been successful.

However, from this review, it is apparent that the irradiation environment will likely play a critical role in determining fatigue and fatigue-creep response in a fusion machine. We may therefore have to wait until such an environment can be created before fusion relevant tests can be made.

Conclusions

The recent literature on fatigue and creep-fatigue response of ferritic/martensitic steels has been reviewed with particular emphasis on work of interest to the fusion materials community. A range of alloys has been studied including low activation martensitic steels developed in Japan and Europe as well as some work on ODS steels of interest. The results show that all these martensitic steels behave similarly, that ODS steels provide improvement, that irradiation tends to reduce fatigue lifetimes, and that simultaneous helium and hydrogen injection can be very deleterious. The response appears to be a consequence of microstructural changes rather than strength variations. However, creep-fatigue lifetimes in air appear to be controlled by cracking of surface oxides. A fusion environment may be needed in order to accurately predict fatigue response in a fusion machine.

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