FATIGUE AND FRACTURE OF MICROALLOYED STEELS: AN OVERVIEW

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ABSTRACT

As one of the most significant metallurgical advances over the last thirty years, microalloyed (MA) steels have been developed as an economical replacement for the traditional quenched and tempered (Q&T) steels. However, the application of these steels is still limited in scale. One main obstacle delaying a wide acceptance of these steels is the lack of systematic and comprehensive research on their fatigue and fracture properties. This paper provides an overview of the research conducted on fatigue and fracture behavior of these materials including low and high cycle fatigue, crack propagation, and fracture toughness. In this process, comparison of MA steels with the conventional Q&T steels is emphasized.

KEYWORDS

Fatigue resistance, crack propagation, fracture toughness, microalloyed steels

INTRODUCTION

Microalloyed (MA) steels, can be defined as basically a carbon or carbon-manganese steel or even a conventional low alloy steel, to which a small amount of microalloying elements have been added. This addition is usually about 0.1% in total and can be singly or in combination to obtain the desirable properties economically. The microalloying elements often used are vanadium (V), niobium (Nb), titanium (Ti) or aluminium (Al) and their role(s) can be one or more of the following: grain refinement, precipitation strengthening, critical temperature adjustment in thermomechanical processing, and scavenging carbon and nitrogen. In MA steels carbon is no longer viewed as a basic strengthening element, but rather increasingly as an impurity element due to its detrimental effect on weldability, formability and fracture toughness.

Basically there are two driving forces behind the development and applications of MA steels: cost savings (better properties at lower costs by elimination of costly heat treatment processes) and properties enhancement for more stringent fabrication and service demands such as formability, weldability, and the resistance to fracture, fatigue and corrosion. While considerable efforts have been expended on optimizing monotonic and impact properties of MA steels, investigations on fatigue and fracture performance have been very limited in scale. It is the intent of this paper to review the existing literature on fatigue and fracture resistance of MA steels as a significant and economical class of materials, replacing the traditional Q&T steels.

FATIGUE RESISTANCE

Several research groups (Engineer et al., 1987; Nomura et al., 1989; Kuratomi et al., 1990) have conducted experimental studies on fatigue performance of smooth and notched rotating bending specimens, comparing performance of V-treated forging steels with the Q&T grades. It has been commonly concluded that with notched specimens, the MA steels exhibit higher fatigue endurance values than the Q&T steel. However, with regards to smooth specimens, experimental results are not consistent as can be seen in Table 1.

Table 1. Smooth and circumferentially notched fatigue strengths of MA steels compared with the Q&T steels.

Steel	Composition (wt %)	Hardness (HRC)	Fatigue limit (MPa) smooth	notched
(Nomura et al., 1989)				
SVd-steel	0.24C-0.24Si-1.45Mn-0.059S-0.37Cr-0.13V	22.3 (Air Cooled)	470	241
SAE 1055	0.55C-0.18Si-0.76Mn-0.14Cr	22.7 (Q&T)	439	225
(Kuratomi et al., 1990)				
S53VC	0.53C-0.22Si-0.76Mn-0.15Cr-0.10V	28.0 (Air Cooled)	331	333
S40C	0.40C-0.22Si-0.76Mn-0.15Cr	28.2 (Q&T)	456	233

Studies on strain-controlled fatigue behavior of flat MA steels were carried out by Landgraf (1977) and later by Bhat (1984). Landgraf found that in the high cycle fatigue (HCF) region, the two MA steel grades in the study (SAE 950X and SAE 980X) offered a substantial improvement in fatigue resistance as compared with hot-rolled low carbon steel. However, only the higher strength MA steel grade (such as SAE 980X) could compete with the heat-treated grade. In the low cycle fatigue (LCF) region, the fatigue properties of both MA steel grades were somewhat inferior to Q&T steel (such as RQC-100) as can be seen from Fig. 1.

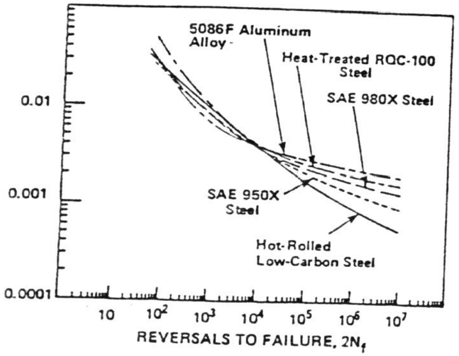

Fig. 1. Comparison of strain-controlled fatigue behavior of two MA steels and other grade metals (Landgraf, 1977).

Bhat compared the fatigue resistance of three SAE 980X steels produced by three different MA compositions (Nb, Nb-V, and Nb-V-Si), and concluded that the Nb-V-Si steel had better fatigue performance than the Nb-V or the Nb steel in the entire fatigue life regim, as can be seen from Fig. 2.

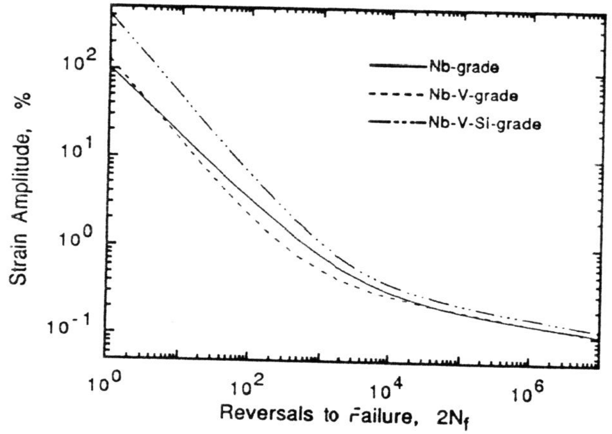

Fig. 2. Strain-life curves for three MA steels (a) Nb steel; (b) Nb-V steel; and (c) Nb-V-Si steel (Bhat, 1984).

Notch effects on fatigue behavior of MA steels were also investigated by Landgraf (1977) and Bhat (1983). Fatigue notch factors were determined for each material with a theoretical stress-concentration factor of 2.5. It was observed that the notch sensitivity increased with increasing strength, and that the notch was less sensitive in the LCF region as compared to the HCF region, as can be seen in Fig. 3.

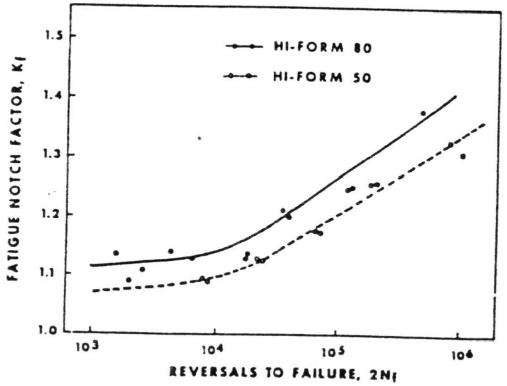

Fig. 3. Fatigue notch factor for two MA steels as a function of fatigue life (Bhat, 1983).

Strain-controlled fatigue tests were also carried out on MA forging steels by Farsetti and Blarasin (1988), Babu et al. (1987), and Davies et al. (1987). It was commonly concluded that the two families of steels, MA and Q&T, exhibit a similar fatigue behavior for the entire fatigue life range. However, the width of the scatter band for MA steels was found to be considerably greater than that for Q&T steels. With regards to the performance in the HCF region, comparison of the fatigue limit to ultimate strength ratios revealed that for a given tensile strength, the ratios for MA steels were usually lower than or close to those for Q&T steels (for which the ratio is around 0.5), but markedly differed from one grade to another. Babu et al. (1987) tested eight different types of MA steels and four Q&T steels, and found that the fatigue life of MA steel family follows the same relationship to hardness as Q&T steels. They also performed axial fatigue tests on circumferentially notched specimens with a theoretical stress concentration factor of 2.9 in the 10^4 to 10^7 cycle life regim. Based on their limited fatigue test results they concluded that the notched fatigue behavior of the V-modified SAE 1541 steel is very similar to that of the SAE 1045 Q&T steel.

Fatigue behavior of cold-rolled MA steels was examined by Yu et al. (1990) and Holt and Charpentier (1984). Significant cyclic softening was observed in both studies. Cyclic yield strengths and fatigue strengths at 10^6 cycles were found to increase with increasing the cold work, whereas the short life fatigue strength was somewhat lower. Notch sensitivity of the cold-rolled grades of a SAE 945X (Nb-based) MA steel was reported to be higher than that of the equivalent hot-rolled steel (Yu et al., 1990). However, the notched specimen fatigue strength only slightly increased by the cold processing.

Comparative fatigue tests have also been conducted on components made of both MA and Q&T steels, such as bolts (Heritier et al., 1984; Namiki et al., 1987), crankshafts (Hashimoto et al., 1982; Kneller, 1987; Cline and McClain, 1987), connecting rods (Kuratomi et al., 1990), front axles (Gunnarson et al., 1987), and steering knuckles (Osuzu et al., 1986; Gunnarson et al., 1987; Blarasin and Farsetti, 1989). All results show that the MA forged components have about equivalent, and in some cases better fatigue strength compared to Q&T forged parts in both the low and high cycle fatigue life regims. These results indicate the promising applications of MA steels for forging products, even for automotive safety critical parts. Taking advantage of the fact that connecting rods made from MA steels exhibited a fatigue limit which was 25% higher than those made from Q&T grades, Kuratomi et al. (1990) successfully developed a light-weight connecting rod by using a MA steel resulting in a 10% weight reduction.

FATIGUE CRACK PROPAGATION AND THRESHOLD BEHAVIOR

Fatigue crack propagation (FCP) and threshold behavior of MA steels have received little attention to date, though these properties become more essential with the increased adoption of these steels. It is difficult to draw general conclusions on the FCP of MA steels based on the limited amount of data available. However, observations presented by several researchers represent a good beginning for the research on FCP aspects of these materials.

Compared to the Q&T grades at similar strength levels, MA steels were found to have an equivalent ΔK_{th} value by Farsetti and Blarasin (1988), and Hertzberg and Goodenow (1977). However, at the intermediate and high ΔK levels, somewhat higher crack growth rates were associated with MA steels. This is due to the lower ductility and toughness of MA steels. Also, while considerable FCP anisotropy usually exists in Q&T steels, only a slight effect of specimen orientation appears in MA grades due to sulfide shape control achieved by rear earth metal addition (Hertzberg and Goodenow, 1977).

Esaklul et al. (1984) investigated the effects of grain size, R-ratio (mean stress), and test temperature on the near-threshold fatigue behavior of two Nb-treated MA steels and concluded that an increase in grain size, a decrease in R-ratio (down to 0.1) or in testing temperature lowers FCP rates and raises ΔK_{th}. Yan et al. (1989) examined the effect of test temperature on

the FCP behavior of a V-treated MA steel. They found the FCP rate to decrease when the temperature dropped down to a certain value (-40 C in their tests), and then to increase with lowering temperature in the intermediate and high ΔK levels. This observation is reflected in Fig. 4, and can also be obtained by interpreting the test results presented by Esaklul et al. (1984). Possible explanations for this behavior can be given based on the combined influence of yield strength, toughness, crack branching, crack closure, and dislocation subcell mechanisms.

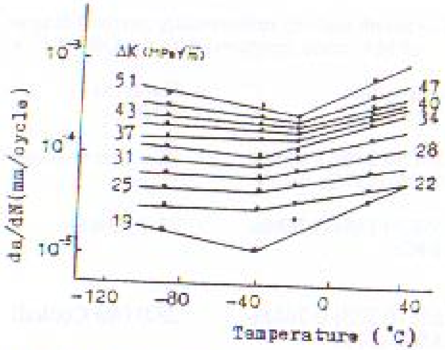

Fig. 4. Fatigue crack propagation rate as a function of test temperature (Yan et al., 1989)

Investigation of the FCP retardation in MA steels was carried out by Drew and Thompson (1985). It was observed that crack growth retardation was of a shorter duration and less extensive in a C-Mn-Nb-V MA steel, than in a C-Mn grade. This can be explained in terms of the higher yield strength and the lower ductility associated with the MA steels. Both yield strength and ductility have a strong influence on plastic zone size and magnitude of crack tip blunting. Tzou and Ritchie (1985), and Thomas (1987) examined FCP in dual-phase (DP) steels containing a low carbon content (less than 0.1%) and found excellent resistance to FCP especially approaching the threshold region due to the microstructural characteristics of DP steels.

Examination of fatigue fracture surface micrographs shows that in medium-carbon MA forging steels, fatigue cracks usually initiate and develop in the softer ferrite phase, and then propagate along pearite/ferrite interfaces (Hertzberg and Goodenow, 1977). Comparison of the fatigue fracture surface features of MA steels with those of Q&T steels indicates that in MA steels, fatigue cracks propagate a rather short distance followed by a predominantly brittle fracture. In Q&T steels on the other hand, fatigue cracks grow through a large portion of the cross-section, leading to dimpled rupture. This may not be surprising due to the lower fracture toughness of MA steels. However, striations were still observed on MA steel fatigue fracture surfaces (Hertzberg and Goodenow, 1977), and compared well with predictions based on Bates and Clark relationship which gives striations spacings as $6(\Delta K/E)^2$.

FRACTURE TOUGHNESS

To evaluate toughness of MA steels, Babu et al (1987) performed a series of CVN impact tests, three-point bend tests, chevron-slotted short-rod tests, and drop-weight tests. To obtain plane strain fracture toughness, K_{IC}, short rod test which is a relatively inexpensive test was used, with good verified correlation with values as measured by the ASTM standard E399 using compact tension (CT) specimen. They concluded that current MA steels are probably inappropriate for those applications which require the ability to yield in a controlled manner. In two other studies (Farsetti and Blarasin, 1988; and Aadland et al., 1987), fracture toughness was evaluated using the J-integral approach with small CT specimens. Results from Farsetti and Blarasin indicate that the room temperature K_{IC} values of the MA steel (M3) and the 900 MPa class Q&T steels to be equivalent, at about 103 MPa (m)$^{1/2}$. Hertzberg et al. (1977) have used CT specimens to obtain plane stress fracture toughness, K_C, based on the R-curve test method. Their comparative tests indicate that the K_C values for the Q&T steel in the longitudinal direction is superior to that of the MA steel. However, the MA steel proved to be superior in the transverse direction. Leep et al. (1987) conducted instrumented charpy impact tests on 1045V MA steel and attempted to correlate the charpy test results with fracture toughness in order to provide a basis for estimating fracture toughness from either standard or fatigue-precracked charpy specimens. They found the defined dynamic fracture toughness of this MA steel to vary between 57 and 79 MPa (m)$^{1/2}$, in the temperature range of 23 to 77 C.

Fracture toughness of ferrite-pearlite MA steels have been generally found to be in the range of 50 to 85 MPa (m)$^{1/2}$, compared with 80 to 120 MPa (m)$^{1/2}$ for heat-treated alloy steels. Consequently, the critical crack size is smaller in MA steels compared to the heat-treated low alloy steels. However, K_{IC} values increase to above 100 MPa (m)$^{1/2}$ in bainite or predominantly bainite-contained MA steels (Farsetti and Blarasin, 1988; Heitmann and Babu, 1987), which is comparable with values from 900 MPa class Q&T steels. This results in an increase in the allowable critical flaw size and provides more tolerance in detecting flaws in MA steel components.

Fractographic examination of fracture facets (Babu et al., 1987; Hertzberg and Goodenow, 1977; Heitmann and Babu, 1987) indicates that the fracture mechanism in MA steels is cleavage, with coarse cleavage appearance in ferrite-pearlite microstructures, and finer cleavage facets with dimpled rupture in bainite microstructures. In contrast, the Q&T steels exhibit a ductile fracture mechanism with large shear lips. Crack jumping behavior (Babu et al., 1987) and pop-in phenomenon (Hertzberg and Goodenow, 1977) have also been observed in fracture testing of MA steels which are characteristics of materials with predominantly a cleavage fracture mechanism.

SUMMARY AND CONCLUSIONS

Property comparison studies of MA and Q&T steels indicate that MA steels are a promising class of materials to replace the Q&T grades with a high potential for significant cost savings. Great efforts have been made in enhancing the fracture toughness of MA steels. However, studies on fatigue and fracture characteristics of these materials are limited in number and scope.

Overall, in the last three decades, especially in recent twenty years, international research activities on the control and evaluation of mechanical properties of MA steels have laid a good foundation for further improvements and optimization of their properties. However, the fatigue and fracture behavior of these materials are not yet well understood. Therefore, research on the fatigue and fracture aspects of these materials is essential, particularly since MA steels are rapidly becoming widely adopted as replacements for the traditional Q&T steels.

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