Study of Fatigue Crack Growth Rate for Austenitic Fe-Al-Mn Alloys

Y.-P. Chang, S.-C. Lee, and G.-H. Tang

A study was made of the crack growth rate (*da/dN*) versus stress-intensity variation (ΔK) behavior of Fe-Al-Mn alloys with different percentages of carbon, aluminum, and manganese at ambient temperature. The experimental results are described with respect to a Paris equation, $da/dN = C(\Delta K)^n$, where the exponent n, index for crack growth resistance of materials, was strongly influenced by alloy composition. It was found that higher manganese content provided better crack growth resistance, and that carbon and aluminum had an opposite effect. Scanning electron microscopy, x-ray diffraction, and mechanical properties evaluation were performed and correlated to the change of n values.

Keywords
crack growth rate, Fe-Al-Mn alloy, n value, Paris equation

1. Introduction

THIS STUDY of Fe-Al-Mn alloys focused on the replacement of nickel by manganese and of chromium by aluminum in stainless steel (Ref 1, 2). This type of alloy should also have significant advantages in cost and weight savings. Many authors have conducted experiments on Fe-Al-Mn alloys, including metallurgy, casting, heat treatment, mechanical properties, oxidation resistance, corrosion resistance, stress corrosion, fatigue, weldability, and wear resistance (Ref 3). The reports indicate that Fe-Al-Mn alloys possess lower density, high strength, high toughness, and high-temperature oxidation resistance, depending on alloy addition, heat treatment, and processing.

Altstetter et al. (Ref 4) compared Fe-Al-Mn alloys with stainless steel, but no data were reported on toughness and fatigue properties at ambient temperature. Lou et al. (Ref 5) studied the impact toughness of Fe-Al-Mn alloys, and other authors studied plane-strain and plane-stress fracture toughness (Ref 6, 7), where toughness was discussed from the viewpoint of fracture mechanics. Chang et al. (Ref 8) studied the fatigue properties of Fe-29Mn-9Al-*x*C alloys with different carbon contents. However, data on fracture mechanics parameters of the alloys based on fatigue crack growth rate are lacking. The present study investigated the effect of carbon, aluminum, and manganese content on the fatigue crack growth resistance of Fe-Al-Mn alloys in order to understand the fatigue behavior of the material in terms of fracture mechanics parameters.

2. Experimental Procedure

2.1 *Material Preparation*

Six types of alloys, designated A, B, C, D, E, and F, were produced in this study. A 1000 kg high-frequency air furnace was used to melt the charge materials of Fe-Si, Fe-Mn, and pure aluminum ingot (99.9%). The molten metal was poured into 160 by 160 by 400 mm steel molds. After solidification, the casting ingots were homogenized at 1100 °C for 10 h, then hot rolled to a thickness of 10 mm. The plates were subsequently solution heat treated at 1050 °C for 4 h and then rapidly quenched in water. The chemical and mechanical properties of the six alloys are listed in Table 1.

2.2 *Crack Growth Rate Experiment*

Fatigue crack growth rate (FCGR) testing was performed using 10 mm thick compact-tension (CT) specimens in accordance with ASTM E647 (Ref 11). Details of the specimen configuration are shown in Fig. 1. An MTS 810.13 hydro-servo dynamic testing machine by Materials Testing System Company (Fig. 2) was used for the tests. Crack length measurement was taken automatically by a Fratomat Model 645 instrument by TTI Division Company, along with a Krak Gage affixed to the CT specimen using TTI-353ND epoxy and a bonding jig, then curing at 80 °C for about 90 min. All FCGR tests were performed under tension-tension cycling with sine waveform at room temperature

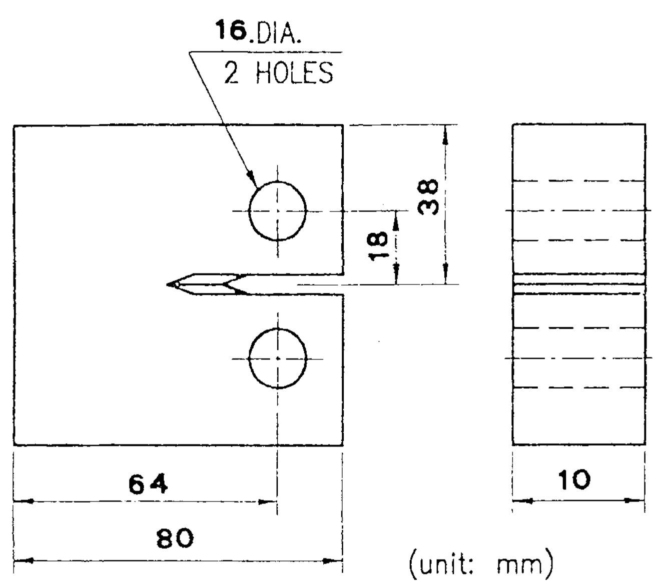

Fig. 1 Dimensions of the CT specimen used for FCGR testing

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(25 °C). The cyclic frequency was 15 Hz, and the load ratio, R, was 0.1 (P_{min}/P_{max}). An MTS 464 data display was connected to a personal computer, which automatically recorded data for every 0.3 mm increment of crack length.

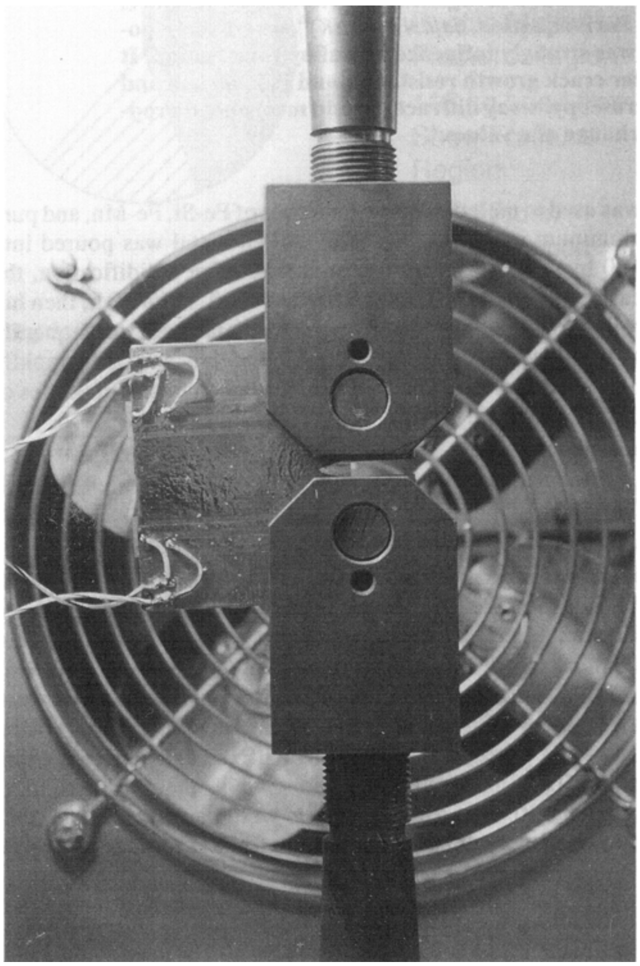

Fig. 2 Dynamic testing machine

3. Results and Discussion

3.1 *Chemical Composition and Fatigue Crack Growth Rate*

Test results for crack length versus number of fatigue cycles are shown in Fig. 3. The precrack length of the six alloys was about 17 mm; as crack length grew to nearly 30 mm, the CT specimens would fracture apart. The relationships of crack growth rate (da/dN) versus stress-intensity variation (ΔK) of the Fe-Al-Mn alloys also were studied and are depicted as log (ΔK) versus log (da/dN) in Fig. 4. The slope of the best-fit line in these plots is referred to the crack growth exponent n in the Paris equation $da/dN = C(\Delta K)^n$, where the range of ΔK was between 25 and 35 $MPa\sqrt{m}$. The smaller value of n generally represents better crack growth resistance, which improves fatigue life (Ref 12). Table 1 lists the C and n constants for the six alloys and for HY-80 steel and 316 stainless steel as deduced from Fig. 4.

Comparing the D and A alloys (both with a manganese content of 20.0%) shows that the aluminum content changed from

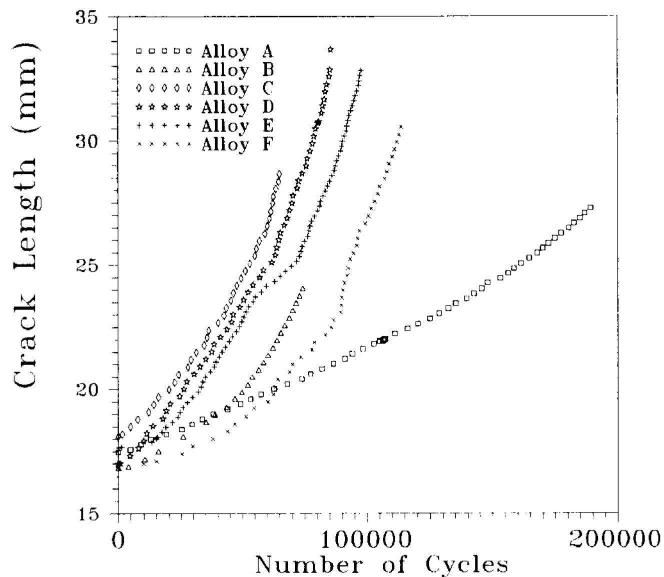

Fig. 3 Typical crack length versus number of cycles

Table 1 Chemical compositions, mechanical properties, and constants (C, n) of the Paris equation for the austenitic Fe-Al-Mn alloys

Material	Chemical composition, wt%				Tensile strength, MPa	Elongation, %	Paris equation [$da/dN = C(\Delta K)^n$]	
	Al	Mn	C	Fe			C	n
Alloy A	8.0	20.0	1.0	bal	1162	32	3.54×10^{-6}	3.78
Alloy B	5.0	25.0	0.8	bal	884	69	1.85×10^{-5}	2.79
Alloy C	8.0	25.0	1.0	bal	1020	40	5.62×10^{-6}	3.67
Alloy D	5.0	20.0	0.8	bal	840	50	1.63×10^{-5}	2.83
Alloy E	10.0	30.0	1.0	bal	1158	24	3.41×10^{-5}	2.63
Alloy F	9.0	29.0	1.0	bal	1050	30	2.20×10^{-6}	3.81
HY-80(a)	...	...	...	...	694	31	1.67×10^{-6}	2.25
316 SS(b)	...	...	...	...	515	30	2.10×10^{-7}	3.80

(a) From Ref 9. (b) From Ref 10

5 to 8% and the carbon content from 0.8 to 1.0%; the n values varied from 2.83 to 3.78. Comparing the B and C alloys (both with a manganese content of 25%) shows that the aluminum and carbon contents changed in the same manner as for the D and A alloys; the n values varied from 2.79 to 3.67. The n values seem to depend on aluminum and carbon content: When aluminum and carbon contents increased, n values also increased. It is apparent as well that the n values were influenced by manganese content: When manganese content increased, the n values slightly decreased. The E alloy possessed higher aluminum and manganese contents than the F alloy, and thus had lower n values.

It was found that manganese addition improves fatigue crack growth resistance. Therefore, manganese can be said to be an austenitic stabilizer for Fe-Al-Mn alloys, provided that its content is less than 30.0%, which ensures that brittle β-Mn will not form. Austenitic structure was ductile and tough in the Fe-Al-Mn alloys, requiring more energy to promote crack growth. Carbon also proved to be an austenitic stabilizer. However, aluminum was a ferritic stabilizer in cases where ferritic structure was known to be a brittle property with high strength, which was unfavorable to crack growth resistance. Gibson and Lillys (Ref 13) have used an experience equation, $X = 6\text{Al} - (0.5\text{Mn} + 50\text{C})$, for austenitic Fe-Al-Mn alloys. When $X < 0$, the lower the X value, the higher the austenite content. Even though the X values for all six alloys are less than zero and the x-ray diffraction pattern in Fig. 5 indicates austenitic phases, experience equation of Gibson and Lillys shows that high aluminum content still has a potential for the formation of ferritic structure.

In summary, n values in the Paris equation for austenitic structure of Fe-Al-Mn alloys with an aluminum content of between 5 and 10% and a manganese content of between 20 and 30% were equivalent to those for HY-80 steel and 316 stainless steel. However, the Fe-Al-Mn alloys had higher strength. Generally speaking, the n values for ductile metal materials were between 2 and 4 (Ref 14). Table 1 shows that n values of Fe-Al-Mn alloys were less than 4 when the stress-intensity factor was between 25 and 35 MPa$\sqrt{m}$. Thus, these alloys can be identified as excellent materials with better fatigue crack growth resistance.

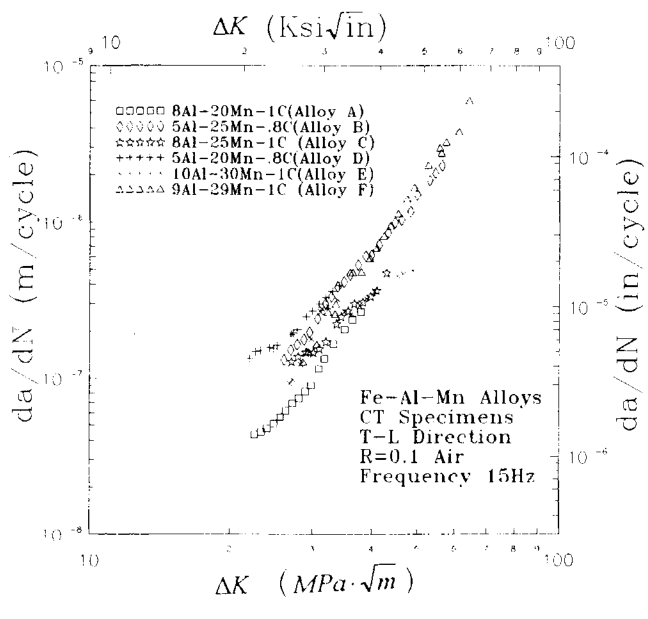

Fig. 4 Crack growth rate (da/dN) versus stress-intensity variation (ΔK) for seven-point incremental polynomial differentiation method, with Δa equal to 0.3 mm

3.2 *Mechanical Properties and Crack Growth Rate*

Mechanical properties in tension for the six alloys as a function of carbon content at ambient temperature are also shown in Table 1. Charles et al. (Ref 1) pointed out that impact energy is excellent as aluminum content decreases. Carbon content has a significant influence on tensile strength, but weakens the elongation property for the alloys. As described in the previous section, carbon and manganese were stabilizers for the austenitic phase. Lower carbon and higher manganese contents improve the ductility and toughness of Fe-Al-Mn alloys. A large plastic zone in the austenitic structure of these alloys improves ductility as well as absorption of the driving energy for fatigue crack growth. Figures 6(a) to (f) show the fracture surface morphology of the fatigue crack growth region of alloys A to F, respectively, as observed by scanning electron microscopy. Figures 6(a) and (c) show the brittle cleavage facets of alloys A and C. These cracks grew in the intergranular fracture mode. Figures 6(b), (d), and (e) show a substantial amount of tearing and dimples, indicating that fracture occurred in the ductile mode, where large plastic zones imply higher toughness for metallic materials. It needs more driving energy to yield plastic zones and unstabilize crack growth so as to possess better crack growth resistance. Figure 6(f) shows the appearance of some plastic zones on the fracture section of alloy F.

4. Conclusions

According to the results of this study on the fatigue crack growth rate of Fe-Al-Mn alloys, the following conclusions can be drawn:

- At higher intensity ranges (25 to 35 MPa$\sqrt{m}$), austenitic Fe-Al-Mn alloys, with n values from 2.63 to 3.81, have a great capability to prevent crack growth, meeting the requirement of the Paris equation for ductile materials.

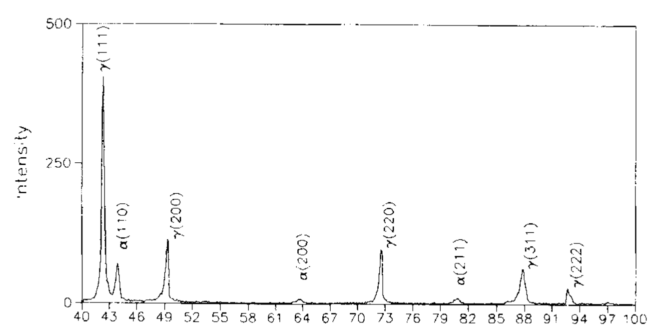

Fig. 5 X-ray diffraction pattern for the austenitic Fe-Al-Mn alloys

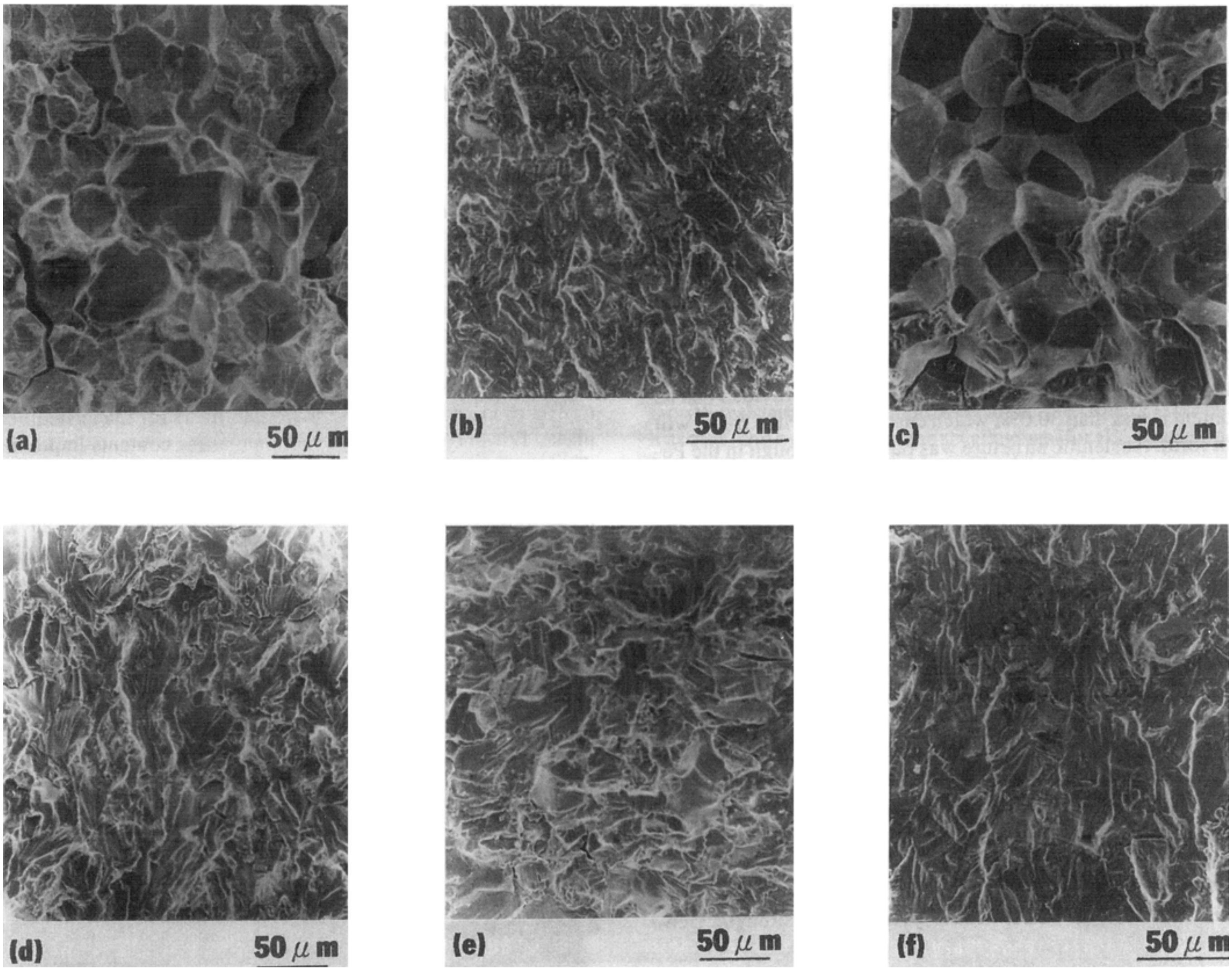

Fig. 6 Fracture surface morphology of the austenitic Fe-Al-Mn alloys. (a) Alloy A. (b) Alloy B. (c) Alloy C. (d) Alloy D. (e) Alloy E. (f) Alloy F

- The large plastic zone in the austenitic structure of Fe-Al-Mn alloys significantly influences fatigue crack growth resistance.
- Carbon content in the austenitic phase of Fe-Al-Mn alloys plays an important role in the possession of high tensile properties. For example, tensile strength would be greater than 1000 MPa for a 1.0% C content. For a carbon content of 0.8%, tensile strength was also greater than 840 MPa and elongation was more than 50%.

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