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Effect of the fabrication process on fatigue performance of U_3Si_2 fuel plate with sandwich structure

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Abstract

U_3Si_2–Al fuel plate is one of the dispersion fuel structure materials recently developed and widely used in research reactors. The mechanical properties of this structural material, especially the fatigue performance, are strongly dependent on its fabrication process. To investigate the effects of these processing technologies, the fatigue tests for the different specimens were carried out. The *S–N* curves indicate that the fabrication processing technologies of U_3Si_2 fuel plate, such as the addition of U_3Si_2 particles into aluminum powder to form the fuel meat, holding and rolling the processes of meat and cladding of 6061-Al alloy, plays an important role in improving the mechanical properties and fatigue performance of this fuel plate. In addition, some factors that influence the crack initiation and propagation are summarized based on the fatigue images that are in situ observations with SEM. The critical criterion for fatigue damage is proposed based on the fatigue data of the structural material, which were obtained at the different conditions.

1. Introduction

A typical composite structure material, the dispersion U_3Si_2–Al fuel plate with sandwich structure, was produced by the Nuclear Material Institute (NMI) in China and has been used in research reactors since the recent decennia [1]. Wiencek (1995) summarized the efforts of the fabrication technology section at Argonne National Laboratory in the program of Reduced Enrichment Research and Test Reactors (RERTR) (1978–1990) [2,3]. These researches indicated that the fabrication of the fuel plate was the key aspect of fuel assembly and application. The fabrication quality of fuel plate directly affects the safety and reliability in applications. The main drawbacks that have to be overcome are the interfacial strength and poor wettability between the U_3Si_2 particles and the matrix as well as the cladding and the meat with sandwich structure during processing. The high mechanical properties or good fatigue behavior can be obtained when fine and thermodynamically stable U_3Si_2 particles are dispersed homogeneously in the matrix [4,5].

To meet such demands, the effects of fabrication process on the mechanical properties were investigated [6].

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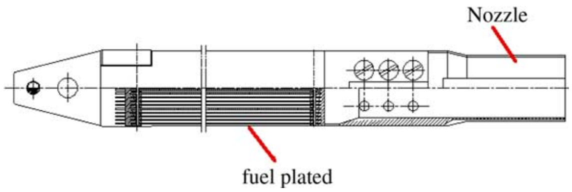

Fig. 1. Schematic of the fuel plate elements assembly.

Especially, the fatigue properties of fuel plate in research reactors have to be considered in service. This is the reason that the fuel plates have to be subjected to the repeated loading when the research reactor frequently turns on or off. This frequent number is about thousands. Another reason is that the fuel plate elements to be held in the two ends are usually subjected to the cooling water fluctuation at high temperature so that these fuel plates will be subjected bending fatigue loading. These two ends of fuel plate elements are held as shown in Fig. 1. Therefore, the fuel plates in research reactor are subjected to the lower thermal–mechanical bending fatigue stresses at higher cycles and the higher impacting stress at thousands of cycles as well as the unforeseen effect of assembled residual stress in service [7–9]. In addition, the brittle fracture of the fuel plate element possibly occurs when the research reactor turns on and off repeatedly but the fracture may be impossible for the generic reactor. This is because the elongation of this fuel plate is no more than a maximum value of 3.54% [4]. However, not many investigations on the fatigue performance of this fuel plate have been reported for research reactor. For these reasons above mentioned, it becomes essential to investigate the fatigue behavior of the dispersion U_3Si_2–Al fuel plates, especially to determine the fatigue crack initiation and propagation mechanism, in order to improve the fabrication process of the structural material and to evaluate the safety of research reactor. In this context, the fatigue tests of the U_3Si_2–Al fuel plate with sandwich structure are performed at different conditions. And the effects of the process factors on fatigue data are discussed based on the fatigue fracture criterion.

2. Preparation of material and experimental method

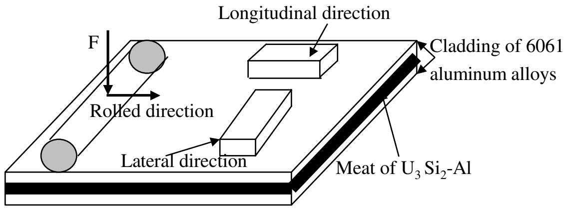

Fig. 2. Schematic showing samples taken from U_3Si_2–Al fuel plate with sandwich structure.

The samples with the sandwich structure used in fatigue tests are taken from the U_3Si_2–Al dispersion fuel plates as shown in Fig. 2. The flat dog-bone shaped specimens have the following dimensions: 10 mm gage length and a gage cross-section of 1.38 mm by 2.40 mm, or 50 mm gage length and a gage cross-section of 1.54 mm by 7.56 mm, respectively. To consider the effect of directions on mechanical behavior of the fuel plate and to estimate the strength of the fuel plate, axial tensile tests and fatigue tests were carried out from the different directions. The effects of directions on the mechanical properties mainly indicate that the tensile strength of samples parallel to the rolled direction, which is defined as the longitudinal direction, is slightly higher than that of samples perpendicular to the rolled direction, which is defined as the lateral direction. But the toughness of the sample of the former case is relatively lower than that of the latter. The mechanical properties of the fuel plate are shown in Table 1. There is significant difference in the mechanical properties (except the Young's modulus) depending on the rolling directions. The main reason, which causes the difference is discussed in detail elsewhere [4].

The preparation of the fuel plate involves the following: the U_3Si_2 particles, with an average particle size of about 70–80 μm, were dispersed into the aluminum powder, and compounded into U_3Si_2–Al fuel meat. The U_3Si_2–Al meat was put into the cladding frame of 6061-Al, soldered and rolled repeatedly, and then blister tested at a medium temperature for about 1 h to obtain relatively good mechanical properties and good compatibility between the U_3Si_2 particles and Al powder matrix, as well as to form a relatively symmetrical interface between the fuel meat and cladding so that the formation of a typical dog-bone meat in the sandwich structure is avoided. This fabrication process of the fuel plate with sandwich structure is similar to that reported in Ref. [3,10]. The degree of compatibility between the fuel meat and cladding is the most important parameter for any fuel plate. It is particularly important to understand the reaction conditions of the U_3Si_2 particles with Al powder matrix when U_3Si_2 particles make direct contact with the Al powder matrix. When the rolling fuel

Table 1
Mechanical properties of the fuel plates with sandwich structure

Code	Samples	UTS (MPa)	Yield (MPa)	Long. (%)	*E* (GPa)
1	Longitudinal samples	154.88	141.00	2.06	67.80
2	Lateral samples	112.91	84.00	3.75	66.27

plate produced under typical conditions [3] was dissected, a slight reaction surrounding the U_3Si_2 particles was observed and the formed reaction zone was also observed on the fracture surface. If the temperature of heat treatment is over 600 °C, U_3Si_2 particles in the fuel plate rapidly react with Al powder. The reaction product was determined to be UAl_x by the X-ray diffraction (XRD) powder technique. The main mechanical properties of the fuel plate are: yield stress $\sigma_{0.2}$ of about 140 MPa, tensile strength of about 150 MPa, and elongation of about 2–4%. All fatigue tests were carried out at 10 Hz, at room temperature and were controlled by load. The servo-hydraulic testing system was designed by MTS and Shimadzu companies, which provide pulsating (sine wave) loading. The stress ratio was $R = 0.1$.

3. Results and discussion

3.1. *Effect of fabrication process on fatigue life of the fuel plate*

Considering the effect of fatigue performance of fuel plates in actual application of research reactor, the samples for the fatigue tests were classified into two types: A type samples are subjected to simulated conditions, which are in water flowing impacting at a pressure of 1 MPa and at a frequency of 10 Hz, at about 100 °C and continuously working for 1200 h and B type samples are from the raw fuel plates, which is in the general processed condition. These samples are then cut from the fuel plate elements for fatigue tests.

Fig. 3 shows the *S–N* curves of these samples with a greater geometric size, such as 1.54 mm by 7.56 mm gage cross-section. As the fatigue test at 10^6 cycles is a rare in research reactor, the fatigue test was stopped manually when the cycles arrived at 10^6 cycles and using the small arrows to be defined as these fatigue data as shown in Fig. 3. The fatigue data are represented by ○, □ and the solid lines represent the predicted results, respectively. The predicting method is based on the following:

$$\lg N_{50} = \frac{1}{n}\sum_{i=1}^{n} \lg N_i, \qquad (1)$$

where N_i is the fatigue fracture cycles of the ith sample, n is the number of samples, N_{50} is number of fatigue fracture cycles with a reliability of 50%.

No matter what the cycles of fatigue fracture are for A type or B type samples, these results indicate that the reliability is rather higher when the stress ratio ($\sigma_{max}/\sigma_{0.2}$) is less than about 0.857 as shown in Fig. 4. At the same time, the fatigue lives of A type samples are longer than that of B type samples at lower cycles, but the difference of fatigue lives for A type and B type are not obvious at the higher cycles. This means that the fuel plate to the operational environment can properly extend the fatigue lives at low cycles. In general, the fatigue cyclic criterion of fuel plate with sandwich structure for a research reactor in service is defined as about 2×10^4 at the higher stress level. Therefore, the critical stress can be estimated based on the *S–N* curves in different conditions. Especially, when the stress ratio ($\sigma_{max}/\sigma_{0.2}$) is over 0.857, the fatigue data of pretreated samples after 1200 h (A type samples) is also able to satisfy the criterion but that of the B type samples is unable to satisfy this criterion. This hints that the aging technology is important for the fuel plates. One of the main reasons is because the simulated condition is at about 100 °C for about 1200 h. Therefore the toughness and resistance of fuel plate are able to have been improved. Another reason is that although the results indicate that the dispersion U_3Si_2 fuel plate with sandwich structure

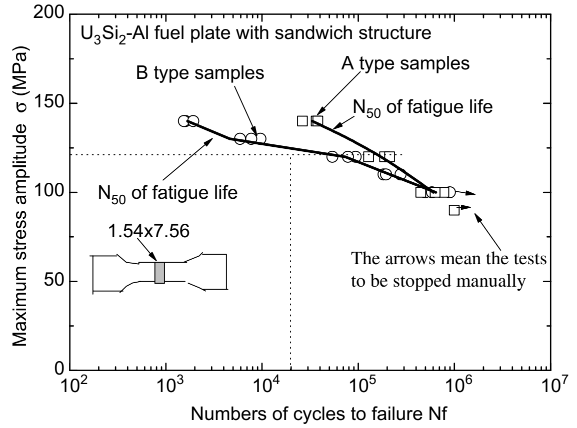

Fig. 3. *S–N* curves for U_3Si_2–Al fuel plate with A type and B type samples.

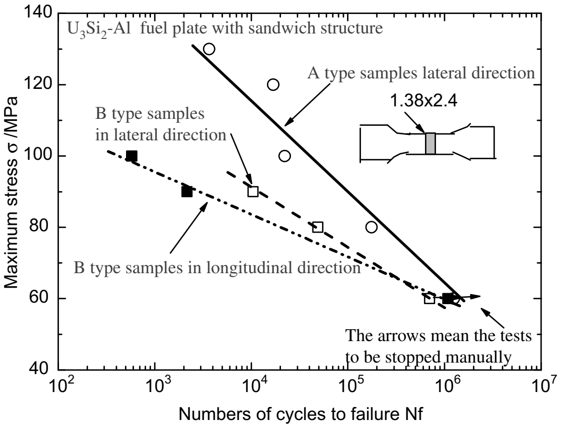

Fig. 4. *S–N* curves for samples from different directions (with respect to rolling).

has an elongation of only about 3.54% in annealed state and 2.30% in tempered state [4], their toughness and wettability between the particles and matrix can be improved if given an aging treatment at about 100 °C for about 1200 h.

Therefore, if the elongation of fuel plates is greater than 2.50%, the fatigue performance is able to meet such demand, which the fatigue cycles are 2×10^4, even if the raw fuel plate are not aged prior to fatigue tests as shown in fatigue data of B type samples. When the fatigue cycles of samples increased to over 10^5 cycles, the fatigue behavior of A and B types were approximately identical. The simulated conditions for dispersion U_3Si_2–Al fuel plates with sandwich structure are like the higher cycles and lower stress level conditions for research reactors. Therefore, the fatigue performance of the current dispersion U_3Si_2–Al fuel plates with sandwich structure is suited for the actual application in research reactors. But, the difference of the fuel plates at high stress level and the techniques used in the preparation of U_3Si_2–Al dispersed fuel plates should also be considered in order to avoid fatigue brittle fracture at lower cycles.

3.2. Effect of rolled direction on the fatigue life of fuel plate

Fig. 4 shows that the effects of rolling directions on the fatigue life of fuel plate are obvious at the lower cycles. Comparing the both results in Figs. 3 and 4, the main differences are due to the rolling directions and the sizes of samples. The sample is of cross-section 1.38 mm by 2.40 mm as shown in Fig. 4. The rolling direction may lead to the difference of fatigue resistance of fuel plate as the U_3Si_2 particles distribution in the fuel meat, especially when the larger particles are concentrated at the interface of both the fuel meat and cladding. In other words, this depends on whether the U_3Si_2 particles are isotropic in the fuel meat and the sizes of U_3Si_2 particles are approximately equal as well as well the interfacial strength or wettability between these particles and the aluminum powder matrix. The distribution of larger sized U_3Si_2 particles may produce anisotropy in the mechanical properties of the fuel plate so that their fatigue performances are affected. It has been observed earlier [4,6,11] that the average size of the U_3Si_2 particles in the meat is about 70–80 μm but there are also large differences in the shape and sizes of these U_3Si_2 particles. The fatigue crack initiation mainly occurred at the larger particle in the vicinity of the interface between the fuel meat and 6061-Al alloy cladding as well as the interface between the larger particles and the matrix in the meat [6,11]. At the same time, the wettability at the interface is rather weaker. How to reinforce the interfacial strength and improve the wettability may be a potential issue based on the fabrication processing technology [6,11–13].

The fatigue data also indicate that the fatigue lives of samples in the direction perpendicular to rolling are longer than those along the rolling direction, such as B type samples, as shown in Fig. 4. One of the main reasons for this is the toughness of sample along the direction perpendicular to rolling is larger than that along the rolling direction even if the strength of sample along this direction is relatively lower. However, the fatigue fracture of the sample depends on the mismatch of deformation between the U_3Si_2 particles and Al powder matrix when the stress ratio is in a range from 0.60 to 0.95 as above mentioned such as interfacial strength and wettability. Therefore, the toughness of sample is more important and essential than the strength of sample at higher stress level or lower cycles when the stress ratio is not over 0.95. The better the toughness of the fuel plate, the greater the fatigue resistance it has. This is because the strength of the cladding framework of the 6061-Al alloy is greater than that of the fuel meat, and the toughness of the fuel plate is far lower than that of the 6061-Al alloy. This hints that it is necessary for the forced vibration tests for the fuel plates.

3.3. Effect of sample size of fuel plate on fatigue life

Fig. 5 shows the *S–N* curves for two cross-sectional sizes along the same rolling direction. The effect of sample size on the fatigue life of fuel plate is clearly seen. The fatigue life of samples with larger cross-section is longer than that with smaller cross-section. However, the trends of these curves are identical with increasing or decreasing the applied stress amplitude. The fatigue cycles can be defined as consisting of two parts viz. the fatigue cracks initiating cycles and the fatigue cracks growth cycles. According to earlier studies [6,11,14–17], the fatigue crack growth rate in the meat is rather fast when the stress ratio is in the range of 0.60–0.95 as shown in Fig. 6. Therefore, the effect of sample size

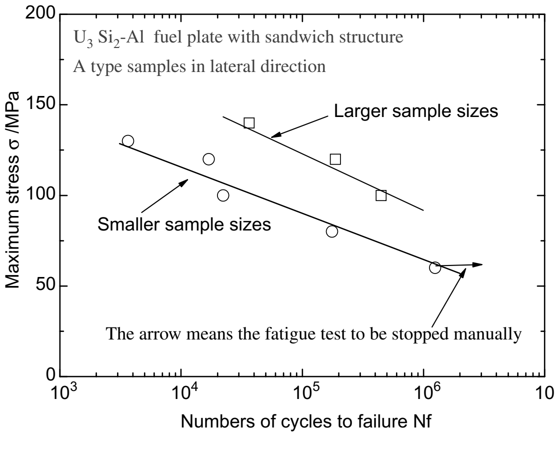

Fig. 5. *S–N* curves for different sample sizes.

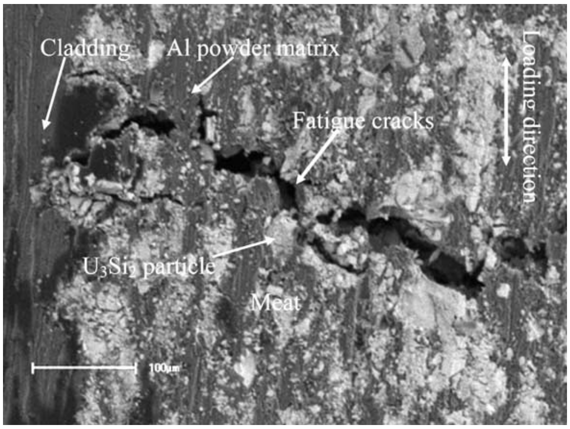

Fig. 6. SEM image of fatigue crack initiation and propagation in situ observation with SEM.

on fatigue life is mainly due to the difference of fatigue crack initiation life because cycles representing fatigue growth are small compared to the total fatigue fracture cycles. As the smaller sized sample is more sensitive to the roughness at the edges than the larger sized sample [12], fatigue crack initiation occurred easily in the smaller sized sample. The stress concentration effect for the smaller sized sample at the edge is greater than that for the larger sized sample. In addition, the surfaces of these samples were not carefully polished prior to fatigue tests. Therefore, there could have been some small notches due to the cutting process causing a notch effect in the vicinity of larger U_3Si_2 particles. The results imply that a fatigue fracture criterion should be defined as the fatigue cracking size, which is not more than twice the size of the U_3Si_2 particle.

3.4. Analysis of fatigue fracture of fuel plate with sandwich structure

Fig. 7(a) and (b) show the SEM images of fatigue fracture sections of the fuel plate. Three distinct macroscopic fracture surfaces are seen: two shear-lips occurring at the cladding and the brittle fracture surface in the meat. The fundamental physical mechanisms responsible for the observed fracture phenomena can be summarized based on the experimental results. The fracture process at the meat may alter the fracture toughness. Thus, fracture toughness from plane strain Mode I may be below those for a plane stress. Crack advance is more rapid in the plane strain region as a result of the smaller plastic zone size and the triaxial stress state, and it results in the reduced fracture toughness. In addition, an analysis of fatigue fracture indicates that the crack growth rate in the fuel meat portion is faster than that at the cladding because of the plane strain condition prevailing at the center. The lower fracture toughness is associated with this fracture mode. The flat interior fracture surface is bounded on the sheet edges and in the slant fractures of the clad surfaces (where the two shear lips are formed). Shear lips are formed during tensile fracture because the surface of the sample is incapable of supporting a stress and because a thin rim is formed around the previously fractured interior of the test sample.

4. Conclusions

Based on fatigue tests of the U_3Si_2–Al dispersion fuel plates with sandwich structure, the effects of influential factors on fatigue strength, at $R = 0.1$, are analyzed. Some conclusions are drawn below:

(1) Based on the current processing method and fatigue testing data, the fatigue performance of the fuel plate with sandwich structure satisfies the criterion of fatigue strength under stress amplitude of about 80 MPa at $R = 0.1$.
(2) It was found that the elongation of the structural material depends strongly on the fatigue life when the stress ratio ($\sigma_{max}/\sigma_{0.2}$) is in the range from 0.60 to 0.95. Therefore, it is important to improve the toughness of fuel plate by the heat treatment tech-

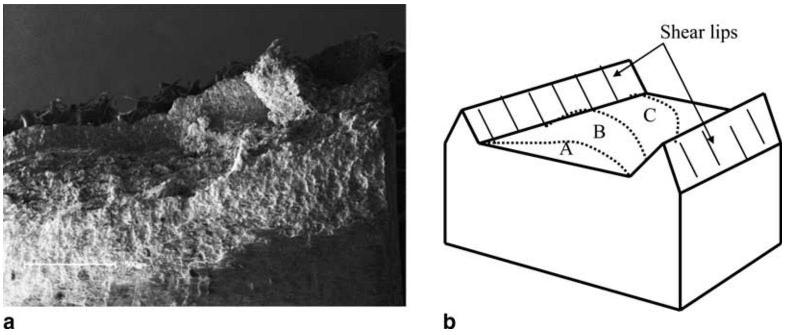

Fig. 7. Fracture progress in a finite sheet: (a) Fracture surface of fuel plate; (b) schematic of crack growth. A, B and C represent the progressive crack growth through the sheet.

niques. When the elongation of the fuel plate is over 2.5%, the fuel plate based on the current process is safe.

(3) In actual applications for research reactors, the fatigue performance of the fuel plate is likely to be enhanced at lower cycles because the fuel material is aged during service. However, the phenomenon is not obvious at the lower stress level, when the stress ratio ($\sigma_{\max}/\sigma_{0.2}$) is less 0.50.
(4) The effect of sample size on fatigue performance indicates that the notch effect is more sensitive in the smaller sized sample than in the larger sized sample.
(5) The effect of rolling direction on fatigue performance of fuel plate is also obvious. In addition, an analysis of fatigue fracture indicates that the crack growth rate in the central portion is faster than that at the cladding because of the plane strain conditions prevailing at the center and the lower fracture toughness associated with this fracture mode.

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