© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Fatigue Crack Growth Behaviour of Sandwiched Metal Panel of Aluminium and Mild Steel under Constant Amplitude Loading

A. H. Isahak, M. F. Abdullah*, M. K. Faidzi, A. Ali, M. M. Mubasyir

Department of Mechanical Engineering, Faculty of Engineering,
Universiti Pertahanan Nasional Malaysia (UPNM) Kem, Sungai Besi, 57000 Kuala Lumpur, MALAYSIA.

*Corresponding author

DOI: https://doi.org/10.30880/ijie.2020.12.05.010
Received 21 May 2020; Accepted 28 May 2020; Available online 30 June 2020

Abstract: This study concerned about the sandwiched metal panel on the fatigue crack growth of mild steel and aluminium. The fatigue crack growth consists of 3 layer of metal sheet or panel that bonded together using adhesive of epoxy resin by hand lay-up technique. The 3 layers are consisting of 2 face metal sheets and 1 metal sheet as a core for the sandwiched; sandwiched of aluminium with mild steel panel (SAMSP) and sandwiched of mild steel panel (SMSP). The specimen was cut using Electrical Discharge Machine Wire Cut (EDM-wire cut) to get tensile test specimen based on American Standard Testing Method (ASTM) E8 before tested with speed rate of 3mm/min using Universal Testing Machine Instron 5569A (UTM). The stress strain curve was plotted in order to analyse the yield strength, Ultimate Tensile Strength (UTS) and the Young's Modulus of the sandwiched. UTS value is used for the fatigue test in the maximum stress applied between 0.50%, 0.60%, 0.70%, 0.80% and 0.90% of UTS. The fatigue test was conducted under ASTM E647 compact tension C(T) standard using Instron 8801 Fatigue Machine with constant frequency of 20Hz and subjected to 1 million cyclic loading to reach failure. The crack growth behaviour of the specimen were discover that indicate the fatigue life, (a-N), fatigue crack growth and failure of the structure by the initial notch. The sandwiched of mild steel panel (SMSP) is compared with the sandwiched of aluminium with mild steel panel (SAMSP) to observe the crack growth behaviour and mechanical properties of the specimen in this study. It can be determined that SAMSP has two times better crack growth behaviour that improve the structure properties compare to the SMSP.

Keywords: Hand Lay-up, Sandwiched Metal Panel, Maximum Stress, Fatigue Crack Growth, Fatigue Life.

1. Introduction

Fatigue is the most problem of failure in engineering structure that exposed to fluctuating loading for metal and composite. Fatigue is a failure in progressive of a component under cyclic and repeated loading. Failure occurs even when the applied stress or strain is well below the value corresponding to failure under cyclic loading [1]. Many mechanisms have been studied to describe fatigue failure and crack initiation are reviewed in this research. This major study of fatigue came in the mid-nineteenth century when railway axles in Europe failed during service [2]. Early 1860, Fairbairn in Britain and Wohler in Germany had conducted laboratory experiments and presented their results as graphs of applied stress (S) vs number of cycles to failure (N) as a research [2]. The research was about the analysis about S-N curves that obtained by loading rotating bar specimens with a fixed moment which is rotating bending. As a result, the similar S-N curves have been used to design parts and structure for metal and composite to avoid fatigue failures.

Nowadays, many research and analysis has been made to reduce and avoid fatigue failure in metal and composite structure. Therefore, new lightweight material should be introduced to improve the mechanical and fatigue properties.

---

*Corresponding author: m.faizal@upnm.edu.my

Since metal structures are often subjected to fatigue loading condition, analysis of the fatigue behaviour for sandwiched metal panel structure need to evaluate the performances. Sandwiched metal panel structure consists of two face metal sheets and a lightweight material sheet as a core for the structure. The advantages of sandwiched structure can be defined as high stiffness, strength, higher energy absorption performance, good thermal, long durability, better crack growth and high structural stability [3]. Therefore, the study of sandwiched structure mechanical properties was crucial in order to achieve of design, safeness and applications.

Sandwiched metal panel have been widely applied in metal structures, research and development of light weight material [4]. Sandwiched structures integrate the strength of the skins and the stiff-ness of the core which has significantly reduced weight than their metal counterparts [4]. This type of structure also has been developed in many industries such as in aerospace, building, marine and railway because of their high specific strength and stiffness, and excellent energy absorption potential [5]. The commonly used cores of sandwiched panels can be classified into two groups, namely continuous that is wood or metallic foams and the other one is discrete which is honeycombs, prismatic trusses, and lattice trusses [6, 7]. Sandwiched structures, which are usually consist of various different combinations of face sheet and core materials have been developed recently to improve their performance and low density [8].

In the 1970s, mostly ship is build using of high tensile steels (HTS) has caused an increase in fatigue cracking in ships [9]. In the modern world, the structural components for applications in the marine, aeronautical, automotive and defense industries are the most important part for every product on the industries [10]. Most of metal structures having a problem on existence and appearance of crack caused by fatigue failure and crack propagation under repeated loading [11]. For example, ship is one of the most critical vessel that having this problem on the hull of the ship. Among the places that may cause the crack is at inner bottoms and boards in the region of deck, outer superstructure walls, bulkheads and most critically at the propulsion part in the ship. Fatigue cracking of structural details due to cyclic loading has always been an important concern in the operation of ships. With the advent of welding as a construction process, fatigue cracking became an even more important consideration Therefore, new lightweight material should be introduced to replace the HTS and improve the mechanical and fatigue properties. Since ship structures are often subjected to fatigue loading condition, analysis of the fatigue behaviour for sandwiched metal panel structure need to be evaluate the performances in amplitude loading in this research.

In this study, the sandwiched structure of mild steel and aluminium were proposed as a new lightweight structure which are subjected to improve the crack growth and mechanical behaviour to fatigue loading. The metal panel of mild steel and aluminium were fabricated with hand lay-up method and cut into specimen using Electrical Discharge Machine (EDM). The sample specimens were tested under constant amplitude loading. Fatigue crack growth were analysed and verified with previous works. The results indicated that the sandwiched metal panel structure of mild steel and aluminium (SAMSP) have a better and improve crack growth behaviour com-pared with sandwiched metal panel of mild steel (SMSP).

2. Methodology

2.1 Preparation Sample

The specimen was fabricated with aluminium sheet were used as core of the studied sandwiched structure whilst using epoxy as adhesive to mount with two face sheets of mild steel. The adhesive consists of epoxy and hardener at a ratio 1:0.4 [14]. The mixture of the epoxy was stirred by using a mixer blade stirrer with speed of 250 rpm for 5 minutes to completely mixed. The sandwiched specimen was fabricated in dimension of 200 mm × 300 mm × 10 mm using hand lay-up technique as shown in Fig. 1 and Fig. 2. The sandwiched metal panel were cured at room temperature for 24 hours.

Fig. 1 - Hand Lay-up Technique

Fig. 2 - Hand Lay-up Technique

The specimens of SAMSP and SMSP were then being cut using EDM-wire cut into standard specimen for tensile test and fatigue test. The samples for tensile test and fatigue test with dimension were shown in Fig. 3 and Fig. 4. The specimens were cut based on the ASTM E8 [12] for tensile test, whilst ASTM E647 C(T) [13] for fatigue crack growth test.

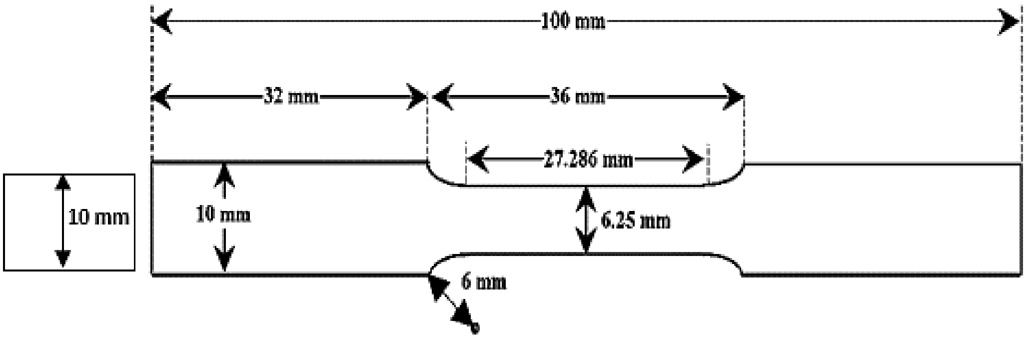


Fig. 3 - ASTM E8 for Tensile Specimen

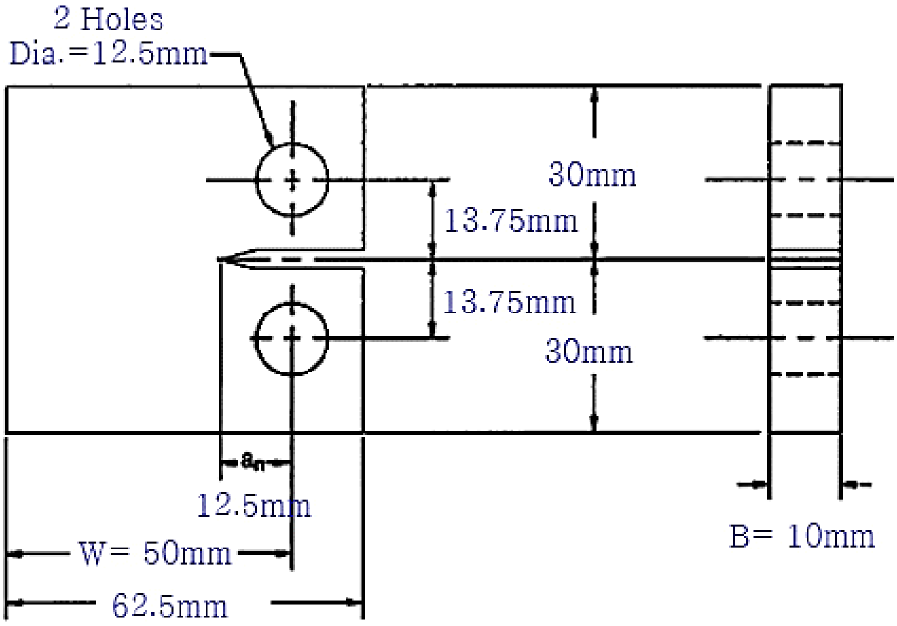


Fig. 4 - ASTM E647 for Fatigue Crack Growth Specimen

2.2 Tensile Test

The samples were prepared and tested using Universal Testing Machine Instron 5569A as shown in Fig. 5. Bluehill 2 Material Testing Software were used with parameters at a crosshead speed of 3 mm/min for the specimen are used. 25 mm gauge length clip-on extensometer and 10 kN load cell were used to record the applied load and elongation data. The mechanical properties such as elastic modulus, strength and failure strain were determined.

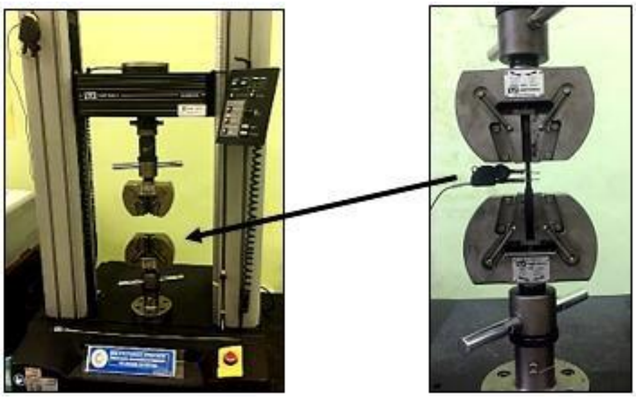


Fig. 5 - Sample attached and ready for tensile test

2.3 Fatigue Test

Fatigue crack growth were done using the 100kN of servo hydraulic testing machine Instron 8801 Test System as shown in Fig. 6.

Fig. 6 - Sample attached and ready for tensile test

The machine was setting to stop automatically when the specimen fails or has reached 1 million cycles which occurs first. The load ratio that were used is 0.1 and 20Hz frequency with constant load amplitude. The different stress levels were used in every specimen started from 0.50 UTS which means 50% of Ultimate Tensile Strength (UTS) and following by 0.60, 0.70, 0.80, and 0.90 UTS.

Table 1 - Stress-Strain Data of the sandwiched of mild steel panel (SMSP) and sandwiched of aluminium with mild steel panel (SAMSP)

Data	SMSP (MPa)	SAMSP (MPa)
Elastic Behaviour	131.20	147.26
Yield Strength	255.97	285.58
Strain Hardening	374.62	305.10
Ultimate Strength	412.06	309.86
Necking Point	383.27	263.01
Fracture Point	328.61	203.79

3. Result and Discussions

3.1 Stress-Strain Curve Analysis

The results for this test for both SAMSP and SMSP showed the fracture on the gage area which is the lateral failure mode. All three layers were break at simultaneous time which indicated that they were break as one solid structure. The data of the tensile test of sandwiched metal panel are listed in Table 1. The stress-strain curves for both specimens are shown in Fig. 7.

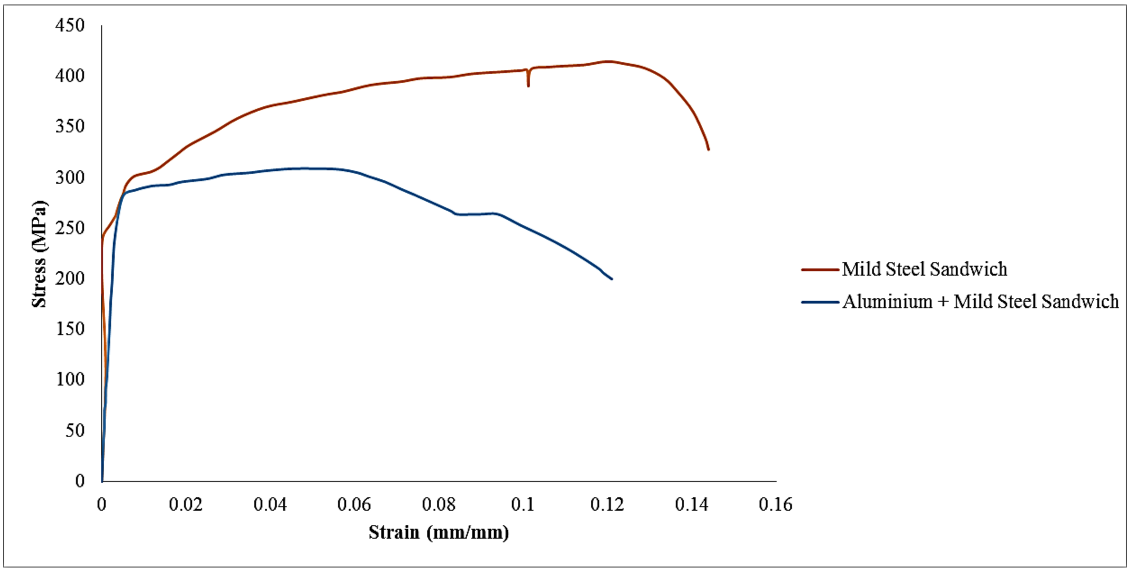


Fig. 7 - Two Sample types for stress-strain curves.

The specimen had experienced the transition region before reaching the ultimate tensile strength and turns to failure as shown in Fig. 7. Yield point were existed earlier and indicated that it is the stage which the sample begins to deform plastically is that point where nonlinear (elastic + plastic) deformation begins. After some point, necking was occurred until fracture point is reached. Thus, it can be concluded that the sample has high ductility that is ability to deform plastically before breaking.

Moreover, it can be seen that although SAMSP has higher yield strength (285.58 MPa) than SMSP (255.97 MPa), the Ultimate Tensile Strength (UTS) for SAMSP were lower than SMSP. Thus, the ability of SAMSP to sustain plastically deformation phenomena were improved than SMSP. There were large amounts of necking observed in SAMSP which is in between 263.01 MPa but lower than mild steel that is 383.27 MPa as shown in Fig. 10 and Table 2. Normally, true strains are of higher values than those of strains. This can be explained by the fact that true strains take place in transverse directions of the gage length. High values of stress and strains in this sample are attributed to strain hardening. Strain hardening occurs at higher values of stress.

Hence, it is indicated that the performance of SAMSP has better mechanical properties than SMSP. Although it has slightly difference in value, still SAMSP got a potential to be used widely in many engineering applications. Fatigue crack growth test were also done to determine stress intensity factor range to the fatigue properties of the sandwiched metal panel and the lead that cause damage mechanisms on the sandwiched metal panel.

3.2 Fatigue Crack Growth Analysis

Fig. 8 showed the image of the samples which has been taken after the fatigue test. The fracture part indicates the specimen has reached the failure point. It is showed that the specimen which has been failure was fracture and delaminate for each layer since its does not experience the tearing failure.

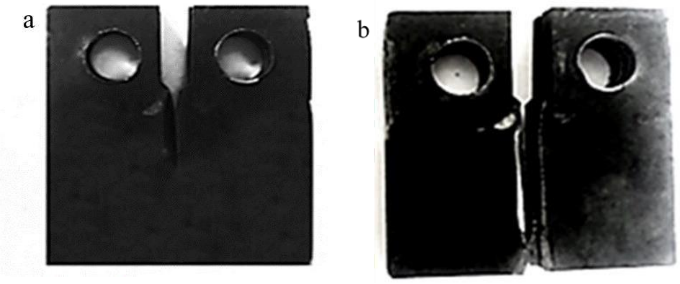


Fig. 8 - Samples a) initial crack; b) after Fatigue Crack Growth Test

It is known that the initially crack at the notch with crack tip length of 22.5 mm before is related to the load amplitude bringing the crack growth. Crack length, *a* versus number of cycles, *N* were shown in Fig. 9 and Fig. 10 presented the fatigue life response SAMSP and SMSP specimens under constant loading start from 0.50 UTS, following by 0.60, 0.70, 0.80 and 0.90 UTS up to failure mode. The fracture point for the sandwiched metal panel of mild steel are located between 37 to 40 mm after the initial crack whilst for SAMSP were between 23 to 26 mm because of the longer fatigue life than SMSP.

Fig. 10 showed the rates of fatigue life has some improvements than in Fig. 9, in number of cycles to failure and crack length were growth slowly than the SMSP under the following loading. In this observation, it can be determined that SAMSP has tremendously increase the fatigue life two times better than SMSP.

Fatigue life improvement is mainly dominated by the high load which accelerated the crack growth rate and almost eliminated the sandwiched metal panel layer strength effect in carrying a part of the load transferred throughout the adhesive layer. On the other hand, the increasing of the fatigue loading amplitude has stimulated the adhesive, partially or totally disbanded, which can considerably reduce the overall fatigue life of the sandwiched structure. It is important to mention that, the usage of compact tension with notch specimen increases the crack growth rate and naturally reduces the sandwiched structure compactness efficiency itself. The compact tension with notch choice in this study was motivated by the need of a fast initial crack initiation and a focus on the crack propagation in mode I.

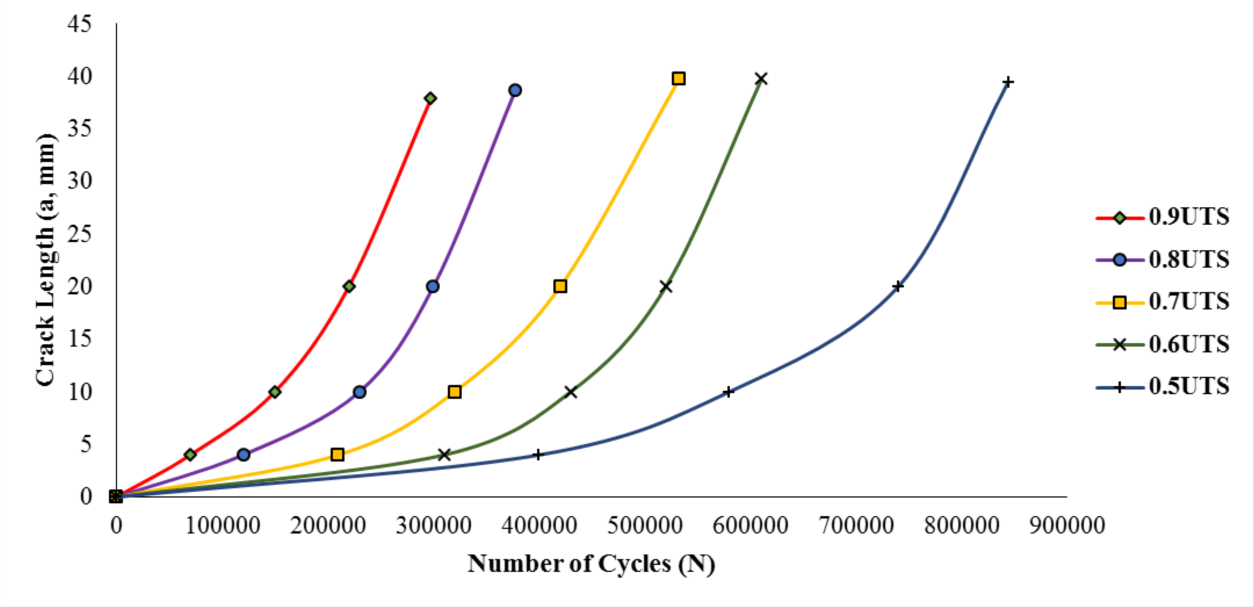


Fig. 9 - Crack length, *(a, mm)* versus No. of Cycles, *(N)* for SMSP

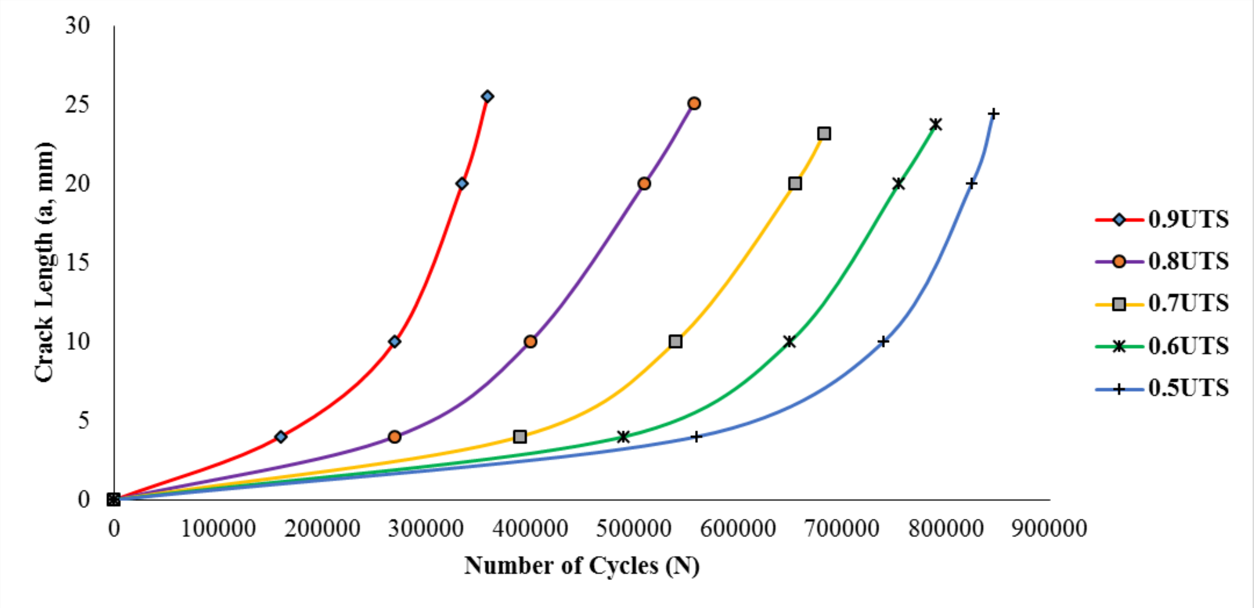


Fig. 10 - Crack length, *(a, mm)* versus No. of Cycles, *(N)* for SAMSP

The fatigue crack growth rates were obtained from the slope of the curve for every point. The stress intensity factor range ΔK were calculated based on the crack length, the applied load and the dimensions of the sandwiched metal panel specimen in accordance to the ASTM E647 standard by using Equation 1. The experimental data for the monolithic alloy were fitted to a crack growth relationship:

$$\Delta K = \Delta\sigma\sqrt{\Pi a}F(a) \tag{1}$$

$$F(a) = 0.886 + 4.64(\frac{a}{b}) - 13.33(\frac{a}{b})^2 + 14.72(\frac{a}{b})^3 - 5.6(\frac{a}{b})^4 \tag{2}$$

$$y = mx + d \tag{3}$$

$$\frac{da}{dN} = C\Delta K^m \tag{4}$$

$$m = \frac{\Delta \log \frac{da}{dN}}{\Delta \log(\Delta K)} \tag{5}$$

$$C = 10^d \tag{6}$$

Where,

ΔK-Stress intensity factor range

$\frac{da}{dN}$-Fatigue crack growth rate

σ-Stress range

$F(a)$-Correction factor

m-Gradient

C-Material constant

y-Y-axis interception

a- Distance from the center of hole to the crack tip (notch)

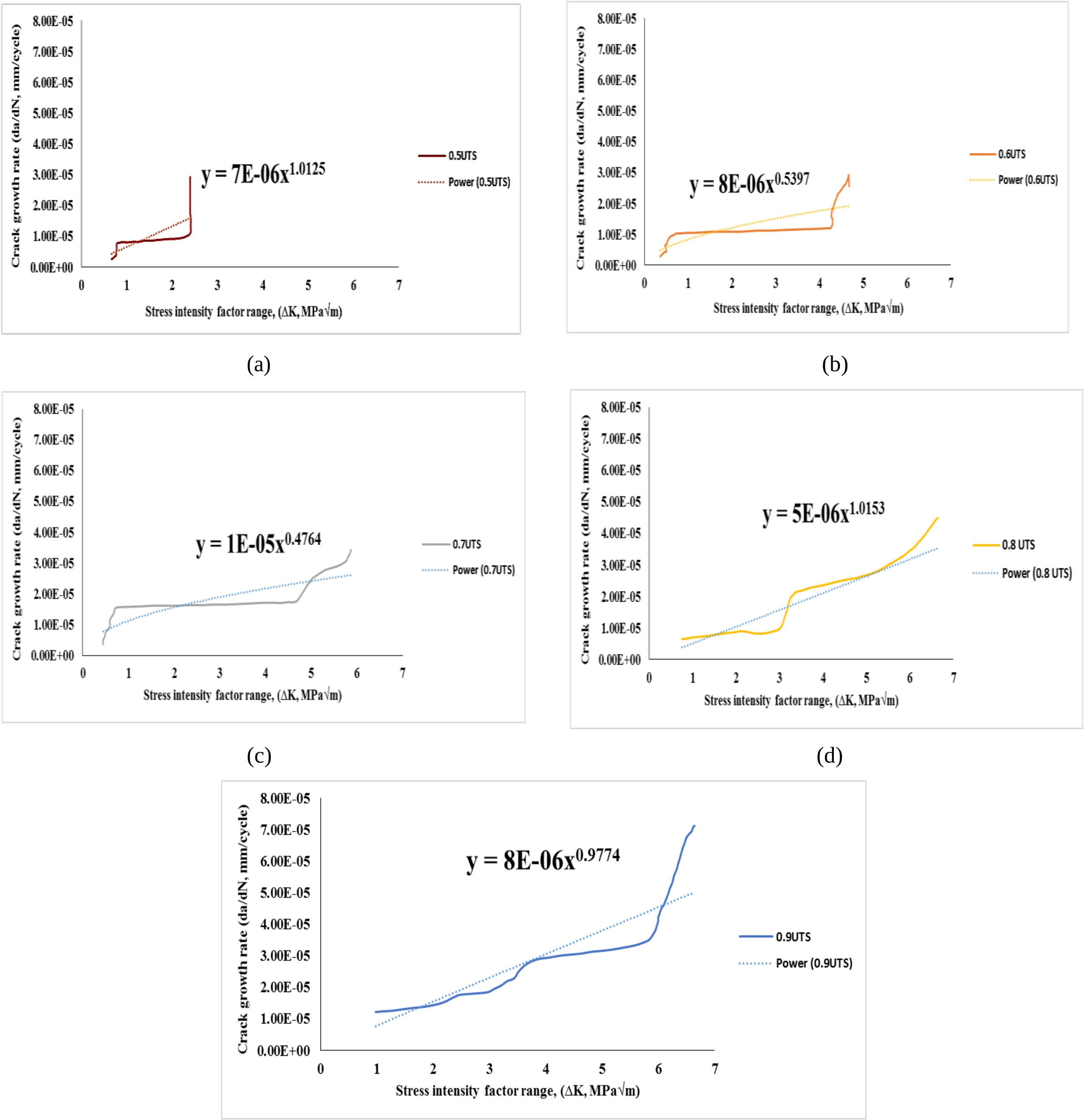
b- Distance from the center of hole to length of specimen

Table 2 - The interception, *C* and gradient, *m* value for sandwiched panels

Types	UTS	*C*	*m*
SMSP	0.50%	0.00001	1.0886
	0.60%	0.00001	0.6804
	0.70%	0.00002	0.4808
	0.80%	0.00001	0.9542
	0.90%	0.00004	0.4852
SAMSP	0.50%	0.000007	1.0125
	0.60%	0.000008	0.5397
	0.70%	0.00001	0.4764
	0.80%	0.000005	1.0153
	0.90%	0.000008	0.9774

Fig. 11 and Fig. 12 shows the variation of fatigue crack growth rate with ΔK, which was calculated from data in the fatigue test on sandwiched metal panel using Equation 1, 2, 3, 4, 5, and 6. As a result, the crack growth rates in the SAMSP were much lower and increased more slowly with ΔK, compared with SMSP.

The results for SMSP indicated that the crack growth rate is high, but the uses of the aluminium as a core of sandwiched metal panel has made a significant enhancement, as the crack grows more slowly. Thus, it can be concluded that SAMSP has much better crack growth rate and slow of crack grows than SMSP. The initial stage which is region 1 showed that the crack appears slowly, and it takes a considerable number of cycles before reasonable growth is detected. This was for the first stage of growth where the stress intensity factor was equal or below ΔK_{th}. In the second stage that is region 2 of the curve, the crack growth was proportional to the ΔK and the crack grew at a considerable rate which was almost constant. The final stage, region 3 of the graph showed higher increase of crack growth rate and instability. This region shown little fatigue crack growth life is involved and controlled primarily by fracture toughness, K_c. The crack length increased with smaller number of cycles. In $\frac{da}{dN}$ vs ΔK, *C* is the intercept while *m* is the gradient of the line as show in the Fig. 11 and Fig. 12. Value of *m* indicates the degree of sensitivity of the growth rates to stress.

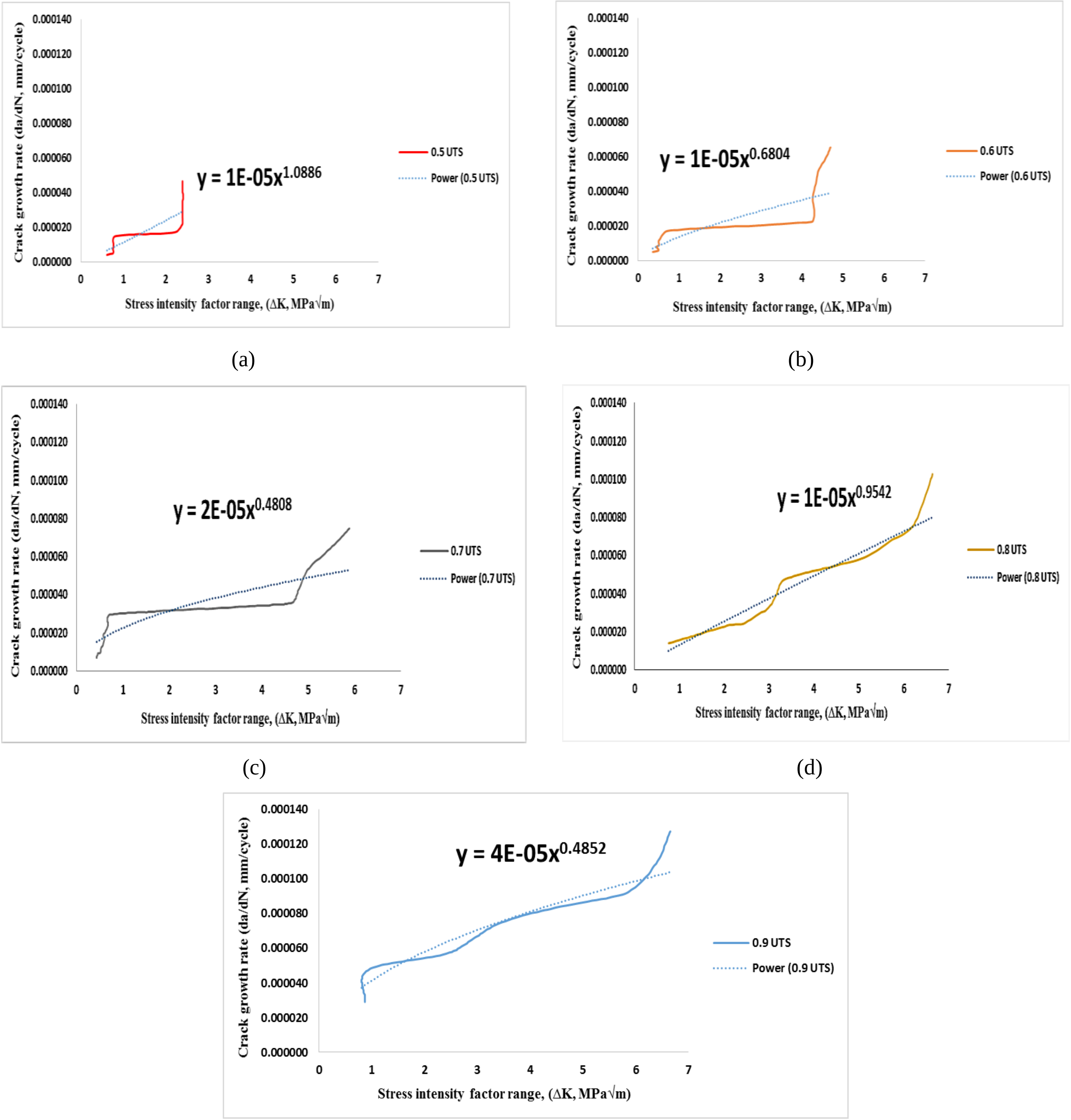


(a) (b)

(c) (d)

(e)

Fig. 11 - Crack growth rate, $\frac{da}{dN}$ vs Stress intensity factor range, ΔK SMSP for (a) 0.5UTS; (b) 0.6UTS; (c) 0.7UTS; (d) 0.8UTS; (e) 0.9UTS



(a) (b) (c) (d) (e)

Fig. 12 - Crack growth rate, $\frac{da}{dN}$ vs Stress intensity factor range, ΔK SMSP for (a) 0.5UTS; (b) 0.6UTS; (c) 0.7UTS; (d) 0.8UTS; (e) 0.9UTS

The value of *C* and *m* as shown in Table 2 for SAMSP did not change very much with compared to SMSP. These graphs of crack length against cycles showed that the life of a material depend on the initial stress intensity factor. From the curve that has been plotted, the SAMSP gives positive effect on fatigue crack growth in which the sandwiched were improved in terms of ductility and mechanical behaviour. The crack growth rate showed that SAMSP has lower crack growth during received the load compared to the SMSP which has higher value of crack growth rate.

According to Zhao et al [15], the mathematical formulations of Paris law were established to describe the relationship of *C* and *m*. *C* and *m* are describing the material parameters as shown in Table 2, the value were almost similar, however has slightly different which also depending on the loading that had to be apply to the sandwiched metal panel samples. Obviously, it is due to the lager curve in the fatigue crack length of sandwiched metal panel and the larger of the parameters *C* and *m*.

4. Conclusion

The purpose of this research is to analyze and investigate the potential of this sandwiched to replace the materials of complex structure such as inner ship hull and others relevant engineering application, in which required toughness but lighter compared others. The new structure had been tested, analyzed and observed the behaviour for crystalline structure of mild steel and aluminium that allows it to withstand high axial loads before fracture can occur. SAMSP are two times better than SMSP in crack growth behaviour. It is showed that these new developed structures had good potential to replace and enhanced the properties of such that structure. Sandwiched panel had found many uses in designs that require low density materials such in marine vessel. For the future recommendation, it is suggested that the effect of before heat treatment and after heat treatment to the samples could be study further to observe the changes in microstructure which is believe has significant affect to the mechanical properties of the structure. In addition, the study of fatigue crack growth based on different frequency in terms of dynamic amplitude loading.

Acknowledgement

The authors would like to express their gratitude and thanks to the Ministry of Higher Education of Malaysia via Universiti Pertahanan Nasional Malaysia (Research funding: FRGS/1/2018/TK03/UPNM/03/1) for funding and supporting this research.

References

[1] R. Idris, S. Abdullah, P. Thamburaja, and M. Z. Omar. (2018). Entropy-based approach for fatigue crack growth rate of dual-phase steel. Int. J. Integr. Eng., vol. 10, no. 5, pp. 1–7.

[2] Finnie, I., and K. Youseffi. (2016). Fatigue Crack Initiation and Propagation in Steels Exposed to Inert and Corrosive Environments.

[3] Balkan, Demet, and Zahit Mecitoglu. (2014). Nonlinear Dynamic Behavior of Viscoelastic Sandwich Composite Plates under Non-Uniform Blast Load: Theory and Experiment. International Journal of Impact Engineering 72

[4] Liu, Chengjun, Y. X. Zhang, and Jing Li. (2017). Impact Responses of Sandwich Panels with Fibre Metal Laminate Skins and Aluminium Foam Core. Composite Structures 182(September), 183–90.

[5] Cheng, Yuansheng et al. (2017). Numerical Investigation on the Dynamic Response of Foam-Filled Corrugated Core Sandwich Panels Subjected to Air Blast Loading. Journal of Sandwich Structures & Materials 105, 109963621770035.

[6] N. M. Amin, S. N. F. Maskor, I. Joohari, and A. Jamadin. (2018). Geometry strength of honeycomb sandwich panel. Int. J. Integr. Eng., vol. 10, no. 9, pp. 85–92.

[7] S. Suryani and N. Mohamad. (2012). Structural Behaviour of Precast Lightweight Foamed Concrete Sandwich Panel under Axial Load : An Overview. Int. J. Integr. Eng., vol. 4, no. 3, pp. 47–52.

[8] Jing, Lin, Zhihua Wang, and Longmao Zhao. (2016). The Dynamic Response of Sandwich Panels with Cellular Metal Cores to Localized Impulsive Loading. Composites Part B: Engineering 94, 52–63.

[9] Xu, T. (2012). Fatigue of Ship Structural Details: Technical Development and Problems. Journal of Ship Research 41(4), 318–31.

[10] Chandran, K S Ravi. (2017). A Universal Functional for the Physical Description of Fatigue Crack Growth in High-Cycle and Low-Cycle Fatigue Conditions and in Various Specimen Geometries. International Journal of Fatigue 102, 261–69.

[11] Ayatollahi, Majid R., Seyed Mohammad Javad Razavi, and Mohd Yazid Yahya. (2015). Mixed Mode Fatigue Crack Initiation and Growth in a CT Specimen Repaired by Stop Hole Technique. Engineering Fracture Mechanics 145, 115–27.

[12] ASTM E8 / E8M-16a. Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, West Conshohocken, PA, www.astm.org

[13] ASTM E647-05. Standard Test Method for Measurement of Fatigue Crack Growth Rates, ASTM International, West Conshohocken, PA, www.astm.org

[14] Gentzkow, Wolfgang von, Jirgen Huber, Heinrich Kapitza, and Wolfgang Rogler. (2014). Epoxy Resin Mixtures For Prepregs And Composites.

[15] Zhao, M. D., Xueling Fan, Qin Zhi Fang, and T. J. Wang. (2015). Experimental Investigation of the Fatigue of Closed-Cell Aluminum Alloy Foam. Materials Letters 160, 68–71.