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Impact of Crack Growth Behavior on High Strength Steel and Sandwich Metal Panel Using the Constant Stress Ratio, Frequency and Thickness

(Kesan Pertumbuhan Keretakan pada Panel Logam Keluli Berkekuatan Tinggi dan Sandwic dengan Menggunakan Nisbah Tekanan, Kekerapan dan Ketebalan yang Sama)

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ABSTRACT

The armoured vehicle uses a special solid steel that has a heavy vehicle ratio which causes the performance to decrease after being triggered by high velocity impact bullet on rescue missions thus experiencing the phenomenon of fatigue and unstable crack growth flow. In this study, an investigation on crack growth behaviour was carried out for sandwich metal panel and solid High Strength Steel (HSS) which has high ability in terms of residual life. Meanwhile, sandwiched metal panel contains HSS as face sheets and lightweight material as a solid core. The main objective of this study was to determine the crack growth behaviour on two types of structural material by applied frequency (f=10 Hz), stress ratio (R=0.1), and thickness (10 mm) as a constant parameter. The crack growth experiment used compact tension (CT) specimen as followed the ASTM E647 standard. The benchmark for establishing the crack growth behaviour is the (a-N) graph and the Paris law regime, da/dN against stress intensity in order to determine Paris constant (C and m). Based on the results, the sandwich metal panel is more applicable with the number cycle of N = 23300 with an increase in about 27% compared to solid HSS. It can be concluded that the sandwich metal is most practicable and affordable for using higher level of threat for hard armour vehicle panel.

Keywords: Armour vehicle; crack growth; high strength steel; sandwich metal panel; Paris law regime

ABSTRAK

Kenderaan berperisai menggunakan besi keluli khas yang mempunyai nisbah berat yang menyebabkan prestasi kenderaan menurun setelah dipicu oleh peluru hentaman halaju tinggi pada misi menyelamat sehingga mengalami fenomena keletihan dan aliran pertumbuhan retak yang tidak stabil. Dalam kajian ini, penyelidikan mengenai tingkah laku pertumbuhan retak dilakukan untuk panel logam sandwic dan bahan mentah High Strength Steel (HSS) yang mana ia mempunyai kemampuan tinggi dari segi sisa hidup. Sementara itu, panel logam Sandwich pula mengandungi HSS sebagai kepingan muka dan bahan ringan sebagai teras struktur. Objektif utama kajian ini adalah untuk menentukan tingkah laku pertumbuhan retak pada dua jenis bahan dengan menggunakan frekuensi (f = 10 Hz), nisbah tegangan (R = 0.1) dan ketebalan (10 mm) sebagai parameter tetap. Eksperimen pertumbuhan retak menggunakan tegangan padat, spesimen (CT) mengikut piawaian ASTM E647. Penanda aras untuk mewujudkan tingkah laku pertumbuhan retak adalah graf (N) dan undang-undang Paris, da/ dN terhadap intensiti tekanan untuk menentukan Paris berterusan (C dan m). Berdasarkan keputusan, panel logam sandwic lebih terpakai dengan kitaran nombor N = 23300 dengan peningkatan kira-kira 27% berbanding HSS pepejal. Ia boleh disimpulkan bahawa logam sandwic adalah paling praktikal dan berpatutan untuk menggunakan tahap ancaman yang lebih tinggi untuk panel kenderaan perisai keras.

Kata kunci: Kenderaan berperisai; pertumbuhan retak; keluli berkuatan tinggi; panel logam sandwic; undang-undang Paris.

INTRODUCTION

Material structuring is an important part of mechanical design. It works for the exterior, as well as the mechanical design of the finishing items. If the item is required to function properly in troublesome mechanical conditions, an investigation of material structure becomes a priority to provide a certain level of quality. Armored vehicles are one of the items needed to function properly in troublesome mechanical conditions. Research on armored vehicles needs to be expanded to improve the quality impact of the bullet that was released from the fire until fully cracked at some frequent shooting attempts and at the same time able to share the benefit to other industrial sectors. High-strength steel has been widely used in armor applications due to its high quality and cheaper manufacturing quality (Pan 2018; Kılıç & Ekici 2013). Because high-strength steels have a moderately high density, limiting the movement of armored vehicles has become a major drawback and shortcoming for armored vehicles (Ameh & Onyekpe 2016). In order to optimize the strength of armor vehicle, its material structure should be changed by separating solid high strength steel metal with lightweight metals that were set for making the lightweight material structure.

Many studies in the past literature focus on areas associated with sandwich metal structure development. Table 1 explains seven studies on the sandwich metal structure performed over the past five years between 2015 and 2020 with various objectives. Based on Table 1, the sandwich structure between high strength and lightweight materials are two focuses that are frequently studied by the researcher. But not many researchers study on the crack growth behavior. According to Table 1, the first three studies are related to the sandwich panel structure and focused on the crack growth on the sandwich structure while the rest leaned more towards other investigations.

TABLE 1. Studies on sandwich metal approach

No	Reference	Main components		
		Sandwich structure	Crack growth	Others
1	Isahak et al. (2020)	x	x	
2	Luo et al. (2019)	x	x	
3	Mazaheri & Hosseini-Toudeshky (2018)	x	x	
4	N A Rahman et al. (2018)	x		x
5	N A Rahman et al. (2017)	x		x
6	Tan et al. (2016)	x		x
7	S. Bahar Bas¸tu¨rk & Metin Tanog˘lu (2015)	x		x

Theoretically, the sandwich structure is from the combination of the core material and other material of face sheets in layers to give greater strength properties than those of the materials alone.

The process of separating high strength raw material with the lightweight core produces a much lighter structure compared to using only high strength raw material alone. In recent years, many scholars have focused on using the method of combining high strength steel with lightweight materials and study the behavior of developed panels such as composites and aluminum alloys combined with available armored steels to reduce the weight (Yang et al. 2013). (Saleh & Edwards 2011) concluded in their paper that the use of aluminum and its alloys provide great potential for vehicle weight loss. They used a layered mixed plate of high-strength iron with AA7075-T6 as a potential protective structure in their ballistic impact experiments. Generally, the performance of sandwich structure depends on the core material, types of core design, and thickness of core. Recently, core designs such as foam core, honeycomb core, and lattice core structures have been introduced in sandwich panel structure (Rejab & Cantwell 2013). In fact, there is a type of sandwich panel that uses solid plate as their main core for the sandwich panel. These types of core designs are used due to their properties of lightweight, good impact resistance, and good energy absorption (Hou et al. 2010; Baştürk & Tanoğlu 2011).

Thus, this paper aims to investigate the crack growth behavior of solid HSS and sandwich metal panel to determine which one has better ability in terms of residual life.

METHODOLOGY

MATERIALS

The overall methodology for this study is shown in the flowchart in Figure 1. The materials used in the research work were 10 mm thick CT specimen of solid HSS and sandwich metal structure. Magnesium alloy is used as lightweight core material surrounded by the top and bottom plate of HSS.

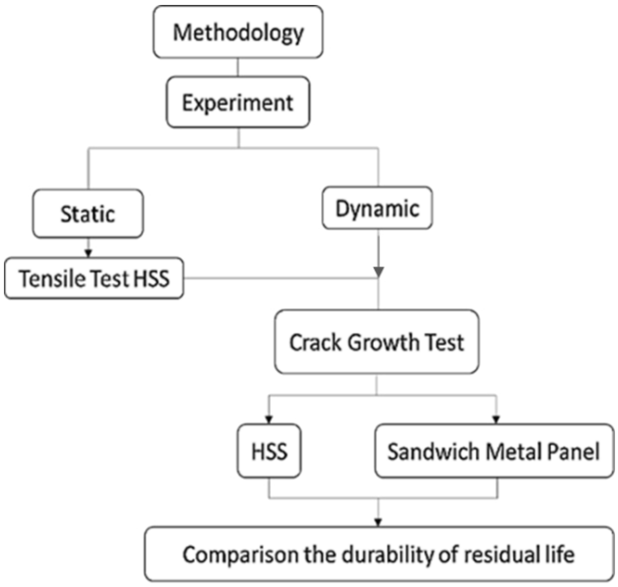


FIGURE 1. Process flow for conducted research study

TENSILE TEST

The tensile test conducted followed (W.N.M. Jamil et al. 2016) by repeating multiple times using a new tensile specimen sample accordance with standard test methods for tensile test of metallic materials (ASTM E8) to obtain the value that approximated the actual values. The selected cross head speed forced on the tensile sample was 1.5 mm/min. During the test, the axial load was consistently applied on the two closures of the example. For each specimen, the dimension was sub-size rectangular specimen, with thickness of 6 mm and 25 mm gauge length iss shown in Figure 2. The ultimate strength, 0.2% yield strength, fracture strength, and the modulus of elasticity were obtained from the resulting stress graph.

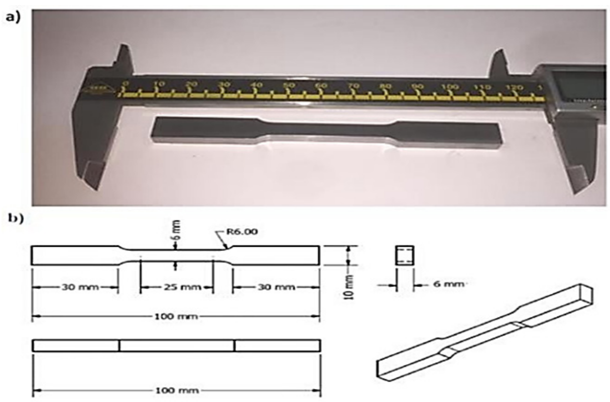


FIGURE 2. Sample HSS specimen and dimensions (mm)

CRACK GROWTH TEST

Crack Growth tests were directed by ASTM E647 "Standard Test Method for Measurement of Fatigue Crack Growth Rate". All the samples utilized for the tests were readied dependent on standard compact tension procedure and measurement showed in Figure 3 and Table 2 separately. 100 kN servo-hydraulic driven testing machine framework at room temperature was utilized for the tests. All the crack growth tests were performed at a constant amplitude loading which stayed fixed all through every crack growth test. The applied loading is 90% yield stress of the HSS material property on both tests. Cycle was led with sinusoidal waveform at a loading frequency of 10 Hz and stress ratio, R equal 0.1. Direct current drop potential strategy was utilized during the tests to gauge the growth of crack length at every 2 mm for the tests.

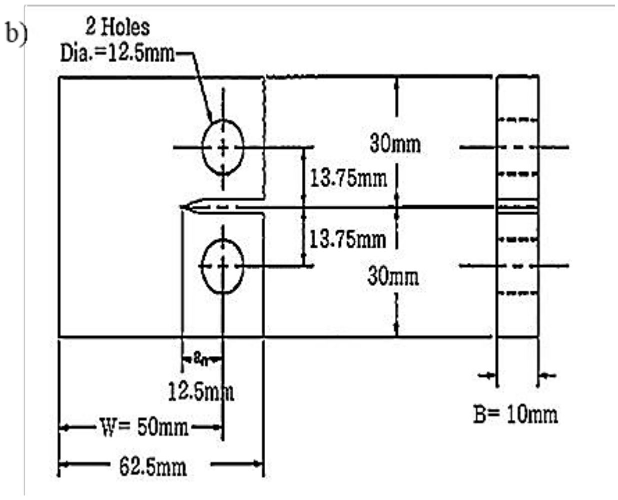


FIGURE 3. Compact tension, CT specimen

TABLE 2. CT specimen dimensions

Quantity	Measured (mm)
Height (H)	1.2*W = 60
Width (W)	50
Thickness (B)	0.5*W = 10
Crack Length (Pre crack +notch)	(10 + 2.5) = 12.5
Notch length (n)	0.2*W = 10
Pre crack	0.25*B = 2.5
Diameter (d)	0.25*W = 12.5
Total Length (L)	1.25*W = 62.5

CRACK GROWTH ANALYSIS

The reported crack length is the projection of the actual crack onto the horizontal direction perpendicular to the loading direction. In the experimental relationship between the crack length and the number of loading cycles, a parabolic curve is used to best fit a set successive data points. By plotting the log-log da/dN versus ΔK, the foundation reaction of the crack growth (CG) was obtained under the constant amplitude loading, CAL. The crack growth rate (da⁄dN) and ΔK was estimated using the mathematical expression:

$$\frac{da}{dN} = C\Delta K^{m} \quad (1)$$

Equation (1) is known as the Paris equation, where m is the slope of the line, and C is the coefficient found by extending the straight line. The range of stress intensity factor, ΔK for CT specimen was calculated with the following equation:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} f(\alpha) \quad (2)$$

Where, the geometry factor f (α) is defined as:

$$f(\alpha) = \frac{(2+\alpha)}{(2-\alpha)^{\frac{3}{2}}} [0.886 + 4.64(\alpha) - 13.32(\alpha)^2 + 14.72(\alpha)^3 - 5.6(\alpha)^4 \quad (3)$$

Where, W is the specimen width, B is the specimen thickness, P is the applied load, and α = a/W, a is the crack length measured from the line of action of the applied load to the crack.

TABLE 3. Two structures of CT specimens with thickness 10 mm

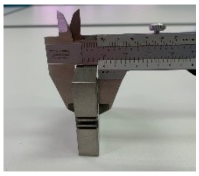
Component	Material	Thickness	CT sample
Solid	HSS	10 mm	
Sandwich	HSS-AZ31B-HSS	(3.2 - 4 - 2.8) mm	

Table 3 shows two different CT structure with constant thickness. The arrangement thickness for sandwich specimen in this study was according to (Rahman, N.A. et al. 2018) for material (AR500 - Al - AR500) which has the thickness of (8 mm - 10 mm - 7 mm). That means the total thickness of the sandwich is 25 mm. Therefore, the main purpose of this research is to produce a new thickness sandwich metal for CT specimen which must be in the range of 2.5 mm ≤ B ≤ 12.5 mm according to ASTM E647. It is important to identify the ratio for each thickness metal to make sure the total of CT specimens' thickness must be 10 mm. By applying the ratio as calculated below:

$$Ratio = \frac{10mm}{25mm} = 0.4$$

*(HSS - AZ31B – HSS) = (0.4*8mm - 0.4*10mm – 0.4*7mm)*

Therefore, the value ratio for each thickness of metal is 0.4. New arrangement thickness for sandwich CT specimen equal to (3.2 mm – 4 mm - 2.8 mm). The specimen then has fulfilled the requirements of thickness in ASTM E647 for standard CT specimen.

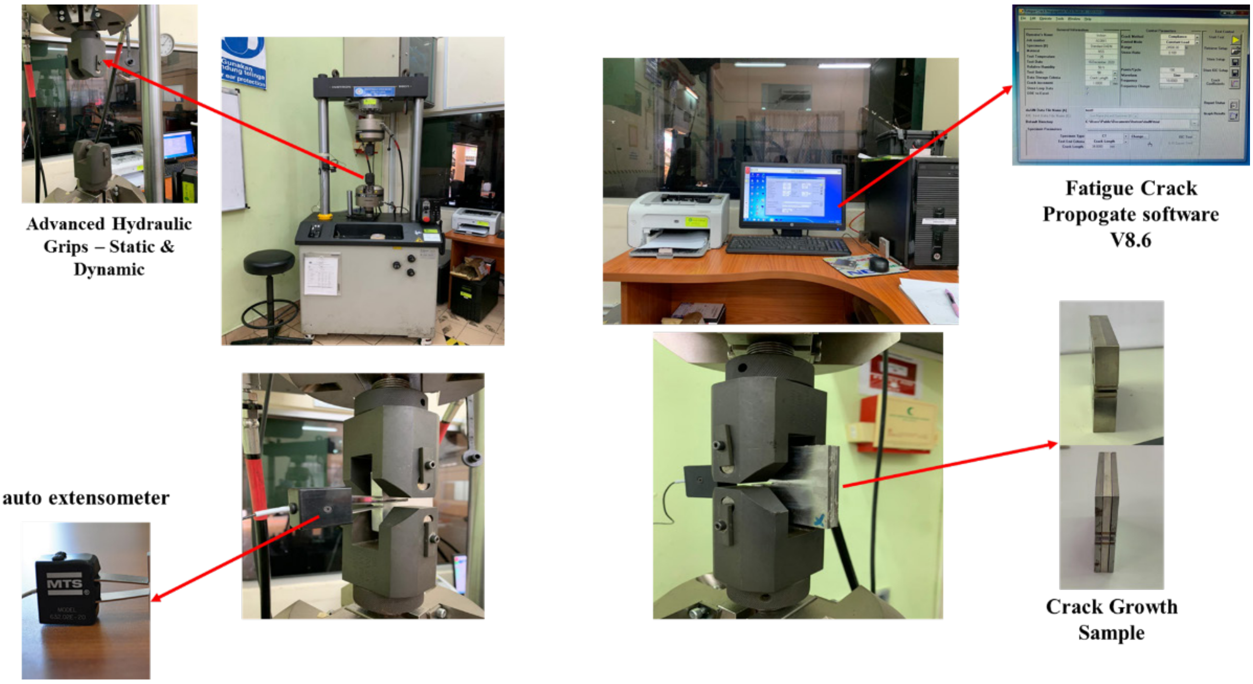


FIGURE 4. Servo hydraulic machine for crack growth test placement

RESULTS AND DISCUSSION

TENSILE TEST ANALYSIS

The stress-strain curve resulting from the samples is shown in Figure 4. The best data of stress strain readings can be obtained from the stress-strain curve, such as 0.2% yield strength, ultimate tensile strength, and Young's modulus of the sample. The value of the 0.2% yield strength and ultimate tensile strength of HSS was 830 and 978 MPa, respectively. Meanwhile, the Young's modulus was 200 GPa. According to the material properties from W.N.M. Jamil et al. (2016), the material properties obtained was compared during the experiment, the HSS has a yield strength and ultimate tensile strength of 847 and 1020 MPa, respectively, and a Young's modulus of 220 GPa which the maximum percentage of less than 9 % error was obtained.

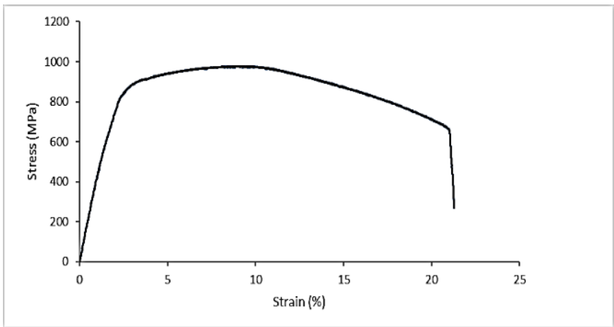


FIGURE 5. Stress-strain curves for HSS

CRACK GROWTH

Crack length, a versus number of cycles, N is shown in Figure 5. It presents the crack growth response HSS and sandwich structure specimens under constant loading at 90% YS up to failure mode. The fracture point for the HSS was located between 33 to 35 mm after the initial crack whilst for sandwich structure were between 31 to 33 mm because of the longer life than HSS. The sandwich structure has showed improvements in terms of durability compared to HSS in number of cycles to failure and crack length grew slower than the HSS under same loading, frequency, and thickness. In this observation, it can be determined that sandwich structure has tremendously increased the life about 22% better than HSS. On the other hand, the method of the sandwich structure has stimulated the crack growth, which can considerably reduce the overall fatigue life. It is also 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 total cycle after completely fracture.

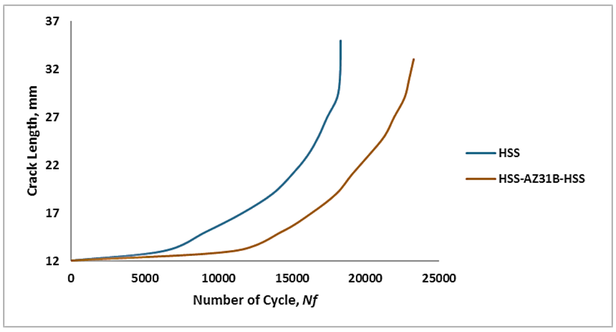


FIGURE 6. Crack length, (a, mm) versus No. of cycles, (Nf) for HSS and HSS-AZ31B-HSS

In both da/dN vs ΔK, C is the intercept while m is the gradient of the line. Value of m indicates the degree of sensitivity of the growth rates to stress.

TABLE 4. The interception, C and gradient, m value for HSS and HSS-AZ31B-HSS

Types	Load	C	m
HSS	90%YS	4E-7	4.5021
HSS-AZ31B-HSS	90%YS	2E-10	6.4206

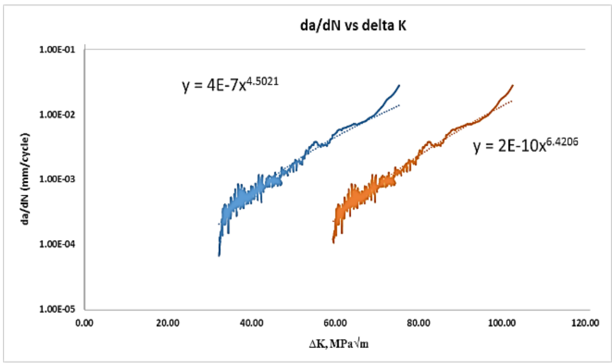


FIGURE 7. Crack length, (a, mm) versus No. of cycles for HSS and HSS-AZ31B-HSS

The value of C and m as shown in Table 4 for sandwich metal structure did not change very much compared to HSS. These graphs of crack length against cycles showed that the life of both structure materials depend on the initial stress intensity factor. Meanwhile, Figure 7 shows the variation of da/dN with ΔK, which was calculated from data in the crack length versus number of cycle for sandwiched structure and HSS using Equation 2 and 3. As a result, the da/dN in the sandwich structure were much lower and increased more slowly with ΔK, compared with HSS. The results for HSS indicated that the crack growth rate is high, but the use of the AZ31B magnesium as a core in sandwiched structure has made a significant enhancement, as the crack grows more slowly. In the graph of da / dN against delta K region 1 is the initial stage of a very slow emerging crack, and requires many cycles before proper growth is detected. This is called the first growth stage where the stress intensity factor is equal to or below ΔK_{th}. Next, region 2 in the second stage which is from the indentation, the growth of cracks is proportional to ΔK and the cracks grow at a fairly close rate. In region 3 which is the last stage, the graph shows an increase in crack growth rate and higher instability.

CONCLUSION

The purpose of this research is to investigate the crack growth behavior was carried out for sandwich metal panel and solid High Strength Steel, HSS to determine which one has the highest ability in terms of residual life. The new structure had been developed by combining AZ31B magnesium alloy as core with HSS. The comparison approach for both structures on crack growth by maintaining the load applied, thickness sample, and frequency. The results showed sandwich metal panel is more applicable with the number cycle of N = 23300 with an increase in about 27% compare to solid HSS. It showed that these new developed structures has good potential to replace and enhance the properties of the structure. Sandwiched panel had found many uses in designs that require low density materials such as in marine vessel. For future recommendation, it is suggested that the effect of crack growth on different temperature to the sandwich metal panel could be studied further to observe the changes of the behavior structure in terms of residual life. In addition, the study of fatigue crack growth based on different frequency in terms of dynamic amplitude loading.

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DECLARATION OF COMPETING INTEREST

None

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