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EXPERIMENTAL STUDY OF FATIGUE CRACK PROPAGATION MONITORING USING ACOUSTIC EMISSION

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Abstract. *Acoustic Emission (AE) is one of the structural integrity monitoring (SHM) techniques that in recent years has been used for monitoring and fault diagnosis. Given this, this technique is capable of detecting the growth of defects in real-time using a high-sensitivity sensor. In AE applications, different characteristics extracted from elastic waves (such as count, peak amplitude, energy, rise time, duration, etc.) are used to diagnose the damage to the analyzed material. Due to this high effectiveness in identifying failures, AE was applied in this work to monitor the propagation of a fatigue crack in a 1020 steel beam. Three AE sensors were used, coupled to a 25.4 mm thick beam, 850 mm long and 50.8 mm wide, subjected to fatigue due to variable excitation caused by an eccentric disc motor. A "V" notch was made on this beam to facilitate crack propagation (stress concentrator). According to the analysis of the acquired signals, it was possible to identify the growth of the fatigue crack from different parameters of the AE waves. The preliminary results obtained showed that the EA technique was effective in structural monitoring to predict material fatigue failure.*

Keywords: *fatigue crack, structural integrity, acoustic emission*

1. INTRODUCTION

Fatigue cracks are one of the leading causes of structural failures. Fatigue failure occurs when the machine is subjected to varying loads, which cause microscopic fatigue changes in the structure of the material. Crack detection is essential for the mechanical system to operate safely and reliably. Because of this, incipient cracks can be detected through vibration signals using structural health monitoring (SHM) methodologies, reducing maintenance costs and increasing the monitored system's reliability, safety, and performance. Hence, it is crucial to devise a methodology for identifying the growth of cracks that leads to an enhanced assessment of the residual useful life (Junior, 2013; Karimian *et al.*, 2020).

Acoustic Emission (AE) is a non-destructive testing (NDT) technique and passive SHM approach capable of detecting structural deformations across various material compositions. AE is defined as the transmission of elastic waves generated by the rapid release of strain energy from defects (such as crack growth) located within a material subject to stress. AE sensors measure the responses of these waves released by internal damage within the structure in periodically real-time. Subsequently, advanced signal analysis techniques are employed to characterize and diagnose the structural integrity of the monitored material. In recent studies found in the literature, the AE technique has been effectively used in the identification of fatigue cracks and in characterizing the crack growth behavior (Bhuiyan *et al.*, 2019; Hassan *et al.*, 2021; Chai *et al.*, 2022).

A study presented by Bhuiyan *et al.* (2019) involved the experimental utilization of the piezoelectric wafer active sensor (PWAS) to detect AE signals generated by fatigue cracks in a thin aerospace specimen. The PWAS results were compared with signals measured by commercial AE sensors. The study demonstrated that both types of sensors efficiently determine to crack growth by analyzing AE hits and waveform-based analysis. In the work of Pascoe *et al.* (2018), the AE technique was used to predict fatigue crack growth during a single load cycle. The authors showed that crack growth occurs during loading and unloading but only when the strain energy surpasses a threshold value known as the crack growth limit (CG). Consequently, the authors contributed to a better understanding of crack growth physics by analyzing AE signals in their research.

Joseph *et al.* (2021) proposed a novel method for estimating crack length using signals acquired by AE sensors. A finite element model (FEM) was first presented to predict the crack propagation pattern and the acoustic signal received by the AE sensor. As the crack grew, a change in the wave pattern was observed, resulting in increased peaks and valleys in the AE signals. This phenomenon also altered the frequency spectrum of these signals. Therefore, the authors proposed a correlation between the crack length and the peak-valley pattern in the signal frequency spectrum analyses. An experimental study was also conducted, which demonstrated the same behavior observed in the FEM analysis.

Chai *et al.* (2022) presented effective results in identifying crack growth stages using multiple signal parameters obtained from AE sensors. The authors proposed a comprehensive approach, combining qualitative and quantitative methods, to evaluate crack growth based on AE monitoring. Garrett *et al.* (2022) introduced a new methodology for AE signal analysis using a convolutional neural network (CNN) that correlates fatigue crack length with time and frequency domain analysis extracted from AE signals. Then, a database was obtained from a fatigue experiment conducted on a thin metallic plate. The authors presented a novel AI-based crack length prediction method using AE signals, achieving an efficacy of 98.4%.

In this context, the present study aims to investigate the structural monitoring of a clamped-free beam made of 1020 steel, which was subjected to fatigue loading by a motor. The AE technique was employed to analyze and detect the propagation of a fatigue crack that formed at a "V" notch manufactured in the beam. Consequently, specific AE signal parameters were acquired for structural damage identification to predict the crack initiation and detect the occurrence of a complete structural failure.

2. EXPERIMENTAL METHOD

The experimental bench used in this study is shown in Fig. 1. A 1020 steel beam, 25.4 mm thick, 850 mm long, and 50.8 mm wide, and three AE sensors were used, fixed to the beam using double-sided tape and a coupling agent between the surfaces. Sensor 1 was positioned 130 mm away from the notch, with the same spacing between the sensors being maintained. The sensors used were from *Physical Acoustics Corporation* (model R15I-AST), operating in the frequency range of 50 kHz to 400 kHz, with a resonance frequency of 150 kHz.

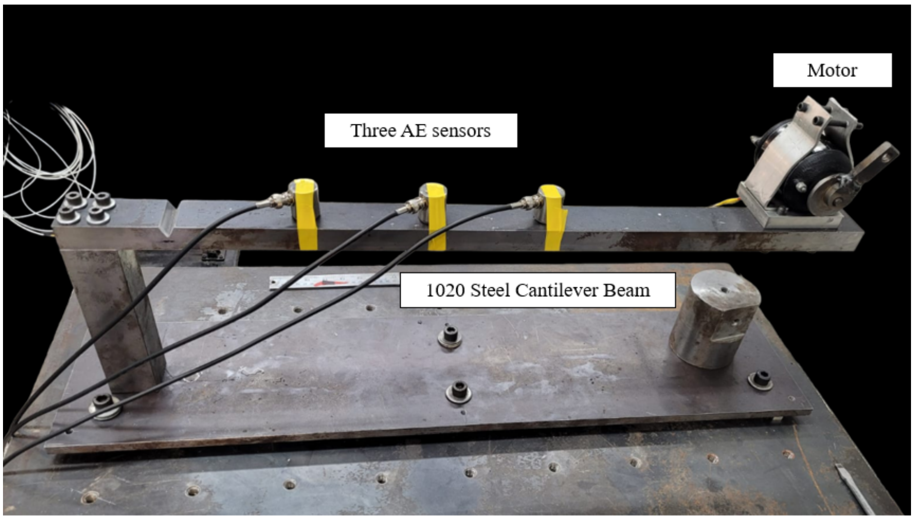
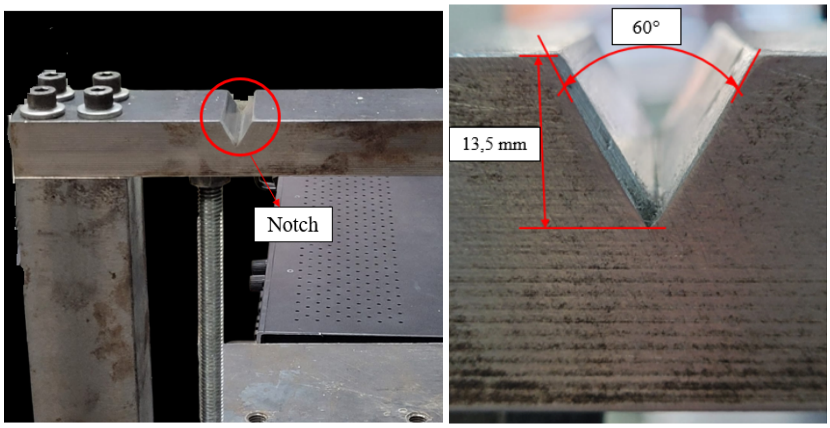


Figure 1. Test rig used in the present work.

To promote crack propagation, a “V” notch was introduced near the nailed end of the beam, serving as a stress concentrator. As shown in Fig. 2, this notch was manufactured to specific design dimensions. At this notch, the crack will initiate and propagate until it reaches a length close to the thickness of the beam. In addition, a threaded bar was inserted at the beginning of the beam to increase rigidity in that area, thus facilitating the formation of cracks (Fig. 2).

A motor with variable power was used to apply the load necessary for beam deflection, securely fastened to the free end of the beam using screws, and an eccentric disc was coupled to its shaft. The rotational motion of this disc induced vibrations in the structure, leading to the generation of a fatigue crack at the notch tip. The motor was controlled using an external voltage and current source from BK Precision® (model 9115/50V/60A/1200W). During the experimental testing cycle, the voltage was fixed at 12 V (the motor’s maximum voltage), while the current was varied each day, allowing for variable vibration amplitudes and power levels.

The initial test cycle aims to assess the detection of the beam structure’s crack propagation through the sensors’ AE signals. The signals were acquired, analyzed, and reproduced using the AEWin software (a program available in the EA equipment from *Physical Acoustics Corporation*). Subsequently, several basic analysis parameters were employed using the AE technique, including amplitude, energy, counts, and hits.



(a) (b)

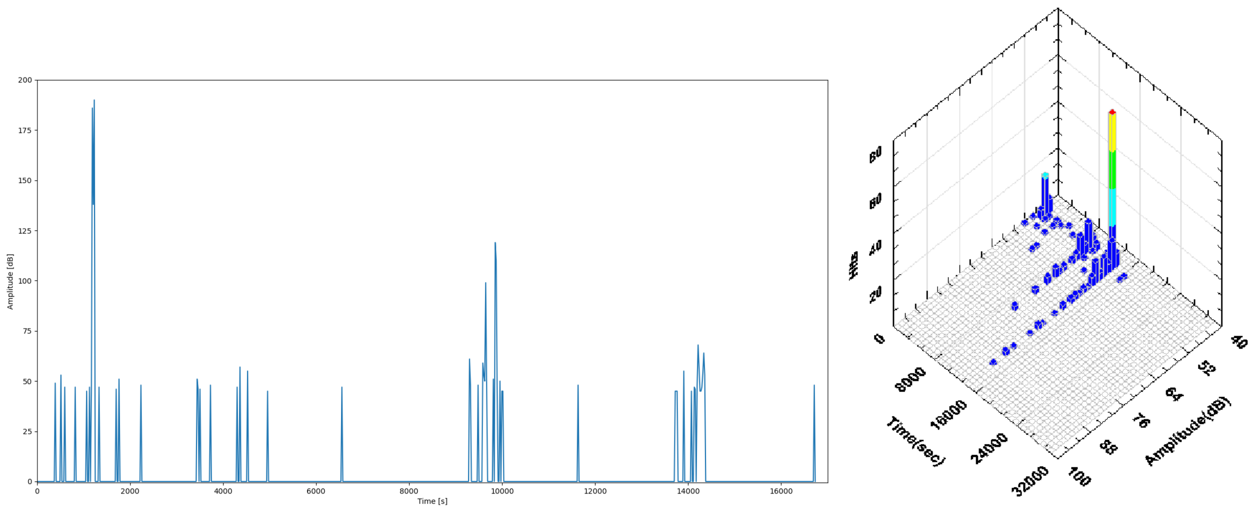
Figure 2. Triangular notch fabricated on the beam structure (a) and its dimensional details (b).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Two checks were performed before starting the AE monitoring technique. The first is to evaluate ambient noise to establish an appropriate detection limit. And the second is to ensure proper coupling of the sensor to the structure and adequate attenuation of the AE signals. This verification was performed using the Hsu-Nielsen font technique, which involved simulating an AE font by breaking a 0.5 mm graphite tip against the structure's surface under pressure (ASTM, 2010). Subsequently, a threshold of approximately 45 dB was determined for all sensors to reduce the influence of noise on responses. The sensors displayed signals indicating satisfactory coupling.

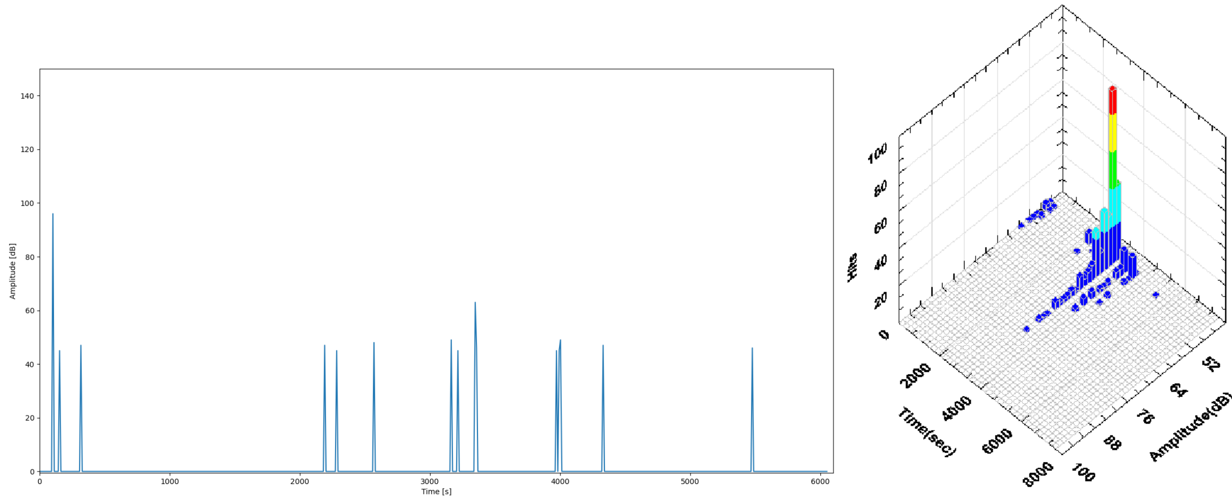
The acquired AE signals from the sensors used in this study were processed and analyzed using the AEWin software. The AE parameters investigated included amplitude (dB), energy, count, and hits (emission events) in the time domain. These tests were conducted for six days, coinciding with the complete structural failure of the beam. The test rig operated for approximately 6 hours per day. During these analyses, variable excitations were employed, adjusting the motor power based on the voltage from the external power source.

On the first day of testing, it was not possible to interpret the results obtained from the adopted parameters. Then, it would have been essential for the equipment to have an AE waveform acquisition module specifically designed to depict the crack propagation waveform. However, by the end of the second day's testing, the initiation of crack propagation was successfully identified in the amplitude and hit signals, primarily due to crack visualization at the notch tip. The results of the parameters considered in this study are illustrated in Fig. 3 to Fig. 7 for the 2nd to 6th day of testing. The signals presented for amplitude and hit in the time domain represent an average of the acquisitions from the three sensors used in the monitoring process.



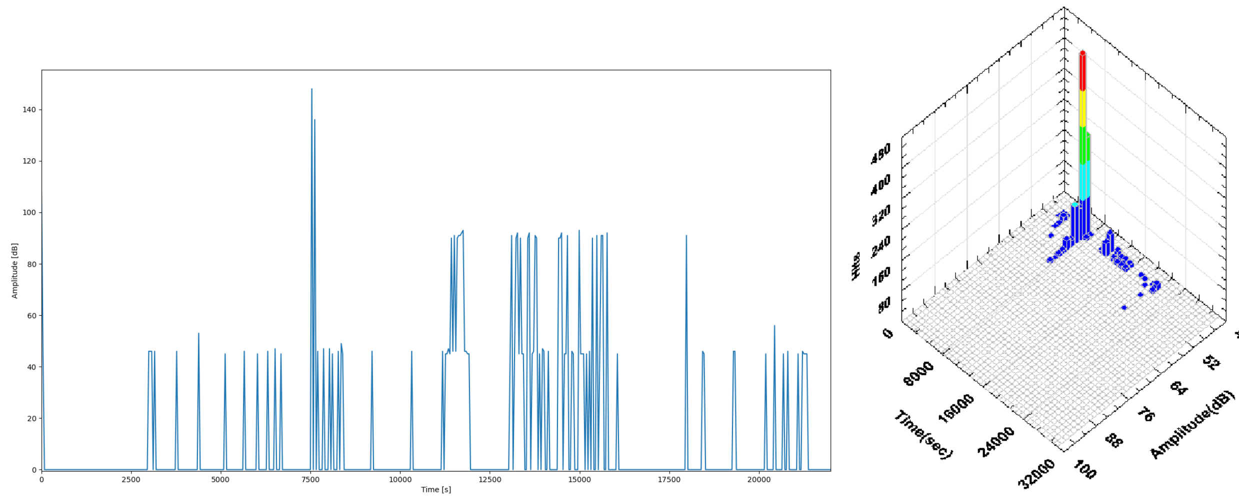
(a) (b)

Figure 3. Average signals from the three sensors for amplitude (a) and hit (b) on the 2nd day.



(a) (b)

Figure 4. Average signals from the three sensors for amplitude (a) and hit (b) on the 3rd day.



(a) (b)

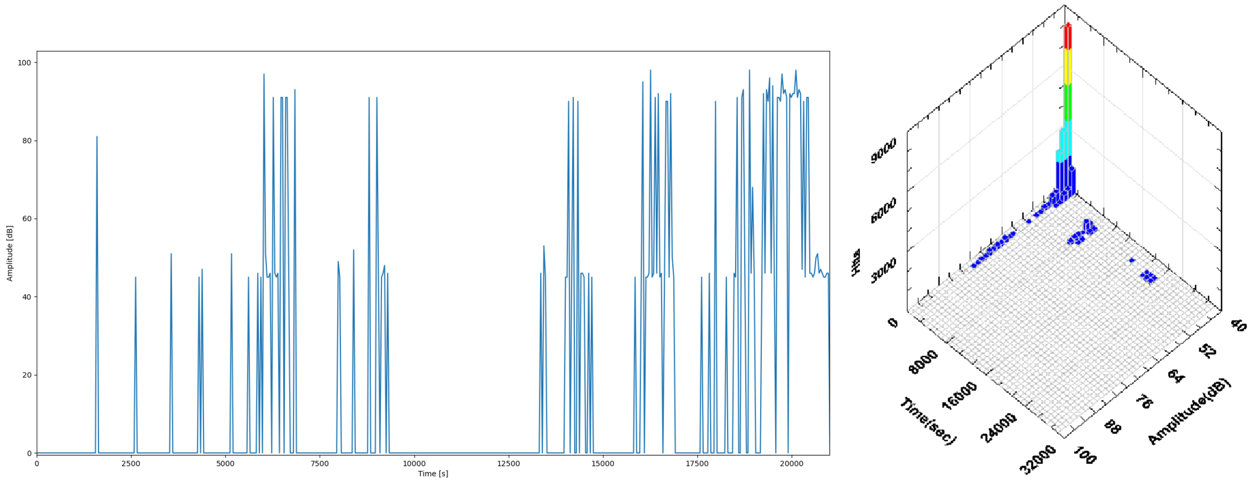
Figure 5. Average signals from the three sensors for amplitude (a) and hit (b) on the 4th day..

The crack propagation can be identified through the emission events displayed in the Hit x Time [s] X Amplitude [dB] graphs (dark blue peaks) and Amplitude [dB] x Time, in an amplitude range between 40 to 52 dB in Fig. 3 to Fig. 7. Additionally, on the sixth day of testing (Fig. 7), an intense activity of amplitude peaks around 20000 s can be observed, indicating an increase in AE events, ultimately leading to the complete structural failure of the beam with a crack opening near the thickness.

Another analysis that can be inferred from these results is the interference of noise on the crack propagation amplitude (ranging from 45 to 52 dB), leading to a significant increase of this signal to 100 dB or more, as observed in Fig. 5 and Fig. 6. The noise predominantly affected the data acquired by sensor 3, which was positioned closer to the engine. On this, the threshold adopted for this monitoring should have been higher.

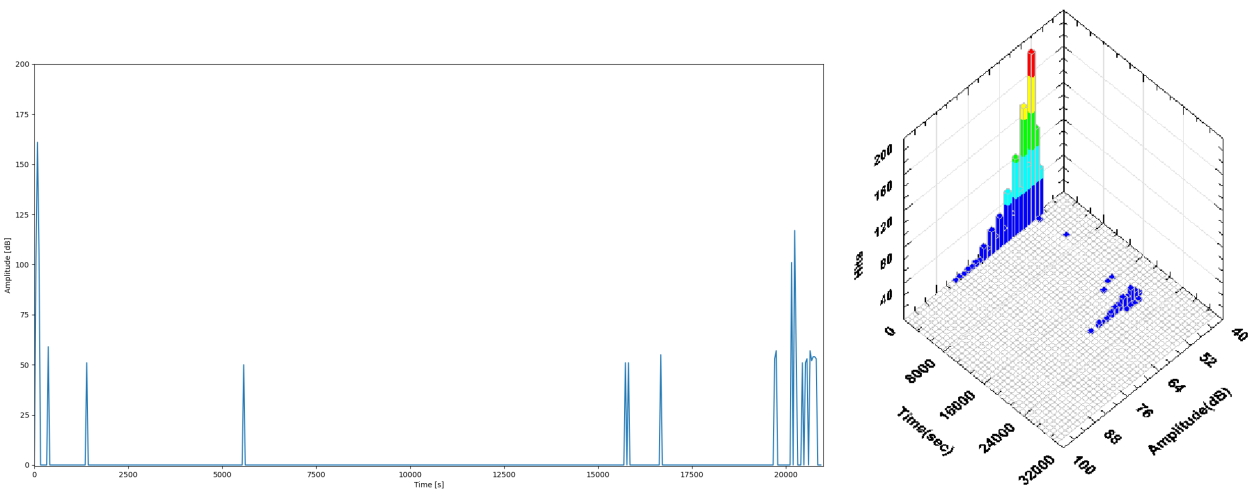
The crack growth was photographed during all days of the experimental tests, as illustrated in Fig. 8. During the experiments, there was a more significant propagation on one side of the notch than the other. This can be attributed to the eccentric mass added to the motor shaft, which resulted in a higher force concentrated on that side of the beam structure.

According to the results presented, the AE methodology proved effective in detecting the initiation of crack propagation in the fatigued beam structure using the selected parameters. Additionally, it was able to predict the imminent failure of the beam structure due to the significant increase in emission activity, characterized by multiple consecutive amplitude peaks observed by the end of the 6th day of testing. However, a correct interpretation of the results was only possible when the crack appeared on the surface. Furthermore, the energy and count data analysis was not feasible due to



(a) (b)

Figure 6. Average signals from the three sensors for amplitude (a) and hit (b) on the 5$^{\rm th}$day.



(a) (b)

Figure 7. Average signals from the three sensors for amplitude (a) and hit (b) on the 6$^{\rm th}$ day.

significant noise interference in these signals.

4. FINAL REMARKS

In this study presented, a preliminary experiment was conducted to investigate the feasibility and limitations of the acoustic emission (AE) methodology for structural integrity monitoring. The experiment focused on a simple dynamic structure to gain insights into the applicability of AE in this context.

In the analyzed case, the acquired monitoring signals could confirm the technique's applicability in detecting the propagation of cracks in this structure. In addition, it was also possible to verify the importance of establishing an adequate noise detection threshold for efficient results of the AE signal.

The methodology in this study presented limitations due to the absence of some advanced post-processing modules in the PAC equipment used for signal acquisition (AE waveform module). It is worth noting that future experiments utilizing the AE technique will take place in test rigs specifically designed for continuous monitoring in rotating machinery.

5. ACKNOWLEDGEMENTS

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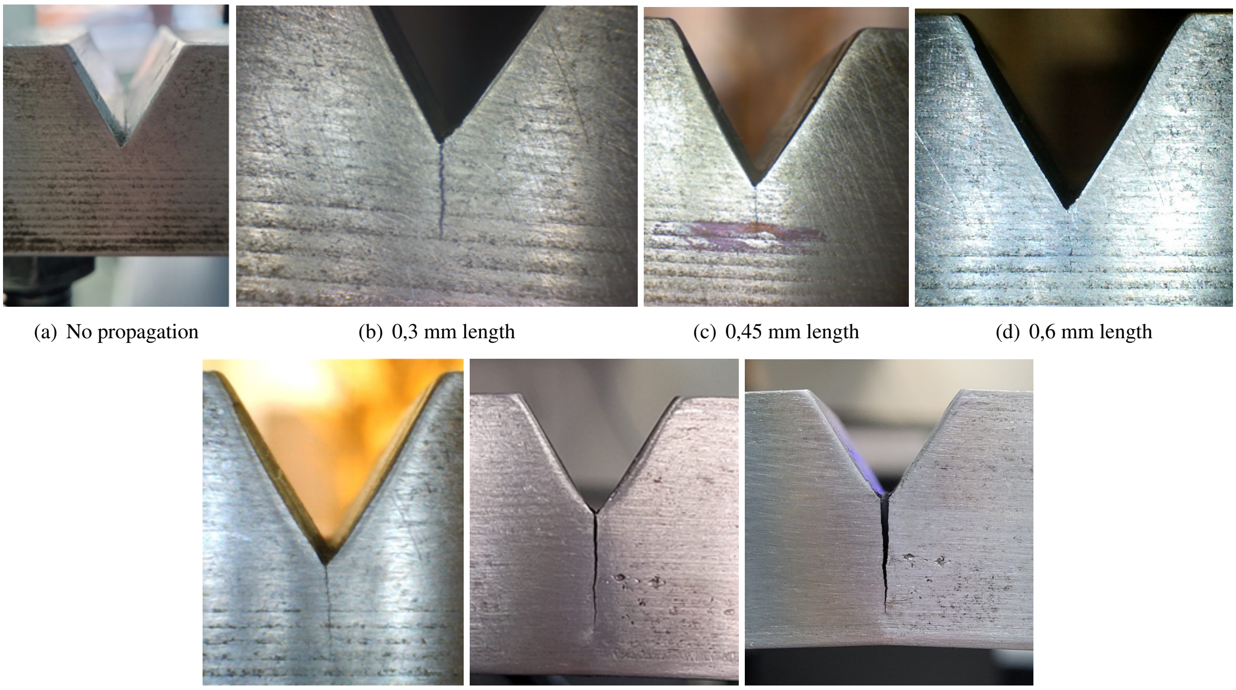

(a) No propagation (b) 0,3 mm length (c) 0,45 mm length (d) 0,6 mm length

(e) 0,8 mm length (f) 1,1 mm length (g) 1,4 mm length

Figure 8. Crack propagation during the days of the experiment: (a) day 1, (b) day 2, (c) day 3, (d) day 4, (e) day 5, (f) beginning of the day 6 and (g) end of the day 6 - total failure.

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7. RESPONSIBILITY NOTICE

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