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High-Rate Fracture by Fixed Energy Input (Pendulum) and Speed Controlled (Servo-hydraulic) Procedures

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Abstract

It is generally easier to break alloys at high speeds; in other words, fracture toughness reduces as strain rate increases. Understanding of these dynamic properties, by experimentation, reduces excessive conservatism in structural design, allowing for safe life extension of existing components and more efficient new constructions. This work investigates procedures to determine fracture toughness at elevated loading rates. Specific testing, used examples of different properties from Zinc, Aluminium and SA508-III pressure vessel steel, highlighting challenges in standard methods.

Two methods of 'rapid' toughness testing have been contrasted – pendulum (Charpy) and servohydraulic (Very High Speed [VHS] Instron) test rigs. Charpy pendulums have a set energy input, hence a *non-constant speed*. Servohydraulic machinery adds energy to the system, *maintaining speed*. Both methods utilised sub-sized (10mm square bending specimens) specimens are recommended for high speed, minimising inertial effects and align with load capacities of high-rate instrumentation.

Elevated speeds also make crack growth more difficult to monitor, compared to well understood static methods. Normalisation crack length monitoring (as recommended in standards) and a linear growth assumption from peak load have been utilised in this testing. Both methods produce similar crack length histories. Normalisation method anticipated the same crack growth initiation as peak load and showed a non-linear crack growth that aligns well with fracture surface features. However, the normalisation method is open to personal interpretation to fit data to a standard model.

Results showed both testing methods to be dynamically invalid for brittle materials (Zinc and SA508-III steel at low temperature). Dynamic invalidity occurred as fracture occurred before (less than 93µs) kinetic energy effects are minimised - a requirement from standards for valid high-rate testing.

Ductile materials (Aluminium and SA508-III steel at high temperature) were dynamically valid. Peak loads in Charpy data were clipped by relatively low sample rate. Peak loads in VHS testing were emphasised by high levels of ringing caused by impact shockwave resonating through the test rig. This let Charpy and VHS data to present different responses. Aluminium testing (low stiffness) loaded slow enough and damped ringing enough to produce comparable toughness data. Steel (higher stiffness) experienced these effects so much that data was incomparable. Improved system by higher sample rate Charpy instrumentation and higher mass and rigidity in the VHS test rig would reduce ringing (signal noise) and allow for better identification of accurate material response. The discrepancies between testing machines overwhelmed the effect of fixed energy input or speed controlled procedures.

Key Words

Rapid, High-rate, Fracture, Toughness, RPV, Steel, Charpy, VHS Instron

Bio – Ben Sargeant

Ben Sargeant is a PhD student at Imperial College London, Mechanics of Material and Structural Integrity group. His work focuses on high-rate fracture toughness assessment in steel and involves development of testing methods, considerations on high levels of plasticity and sub-sized specimens.

Introduction

Strain rate sensitivity has been observed in the mechanical properties of most metals; typically, rapid loading increases yield stress, limiting plasticity, promoting more brittle fracture modes, and reducing critical fracture toughness. Dynamic fracture occurs at lower loading conditions than would be expected from static testing. However, there is less experience in testing materials to fracture at accelerated rates, particularly for ductile metals at intermediate rates (impact strain rates approximately 1 – 1000 /s). Hence, overly conservative toughness properties are used in structural design.

This work investigates whether loss of speed during fracture impacts load history and toughness results by comparing fixed energy input and speed controlled test machines. Developments in experimental techniques aims to further understanding of material response at elevated rates, allow less excessively conservative material properties to be confidently employed for more effective utilisation of critical component.

Method & Material

Two methods of 'rapid' toughness testing have been contrasted. Pendulum (Charpy) impact testing applies a fixed energy impact and is a widely used in industry. Less utilised, servohydraulic (very high speed Instron [VHS]) test rigs actively add energy, by hydraulic pressure control, to maintain speed during testing. i.e. VHS tests in the same manner as traditional static fracture testing, just faster.

Following equivalent fracture tests on both machines, load and displacement histories are processed, along with physical measurements of initial crack length (a_0) and final crack length (a_{end}), to assess critical fracture toughness, following ASTM-E1820-23b standard for fracture toughness assessment [1]. Methods and assessment procedures across standards organisations [1–7] agree well; with detail focusing in different areas but no major discrepancies that would lead to hugely differing results.

Dynamic assessment uses the same procedure as for static fracture. Standards [1–7] emphasise use of instrumented Charpy tests over servohydraulic, likely as Charpy testing utilises a more mature technology.

Sample Materials

Sub-sized specimens are recommended for high-speed testing, *minimising inertia effects*. 10mm square v-notch bending specimens were used. Such samples fit available high-rate testing machines and load capacities. Such small samples are prone to *plastic collapse* (dominance by global yielding over local crack tip stresses). Fatigue pre-cracking to 0.5 a/W ratio aids to increase constraint, restricting collapse, and aligning specimen geometry to larger static counterparts. Standards acknowledge plastic collapse as an issue, stating *"such tests do not comply to valid specimen sizes but can be used as part of research and quality control"* (ASTM-E1820-23b [1]).

Tests were conducted on three materials (Illustrated in Figure 1).

Zinc represents a brittle material. Samples were cast at size.

Aluminium represents a ductile material. Samples were extruded bar and machined to size.

SA508-III steel is a higher strength material and exhibits brittle and ductile behaviour at different temperatures. Samples were machined from bulk material and fatigue pre-cracked, with peak stress intensity factor of 30 MPam$^{0.5}$, to produce a 5mm crack (0.5 a/W ratio). Pre-cracking was selected to follow standards and ensure fracture within machine load capacity.

Figure 1 - Illustration of Samples Zinc & Aluminium (10mm v-notch Charpy) and SA508-III Steel Samples (10mm v-notch and 5mm pre-crack) [Width = Thickness = 10mm]

Test Machines

Two machines were used. Where possible, test procedure was maintained across both test sets.

PENDULUM (CHARPY)

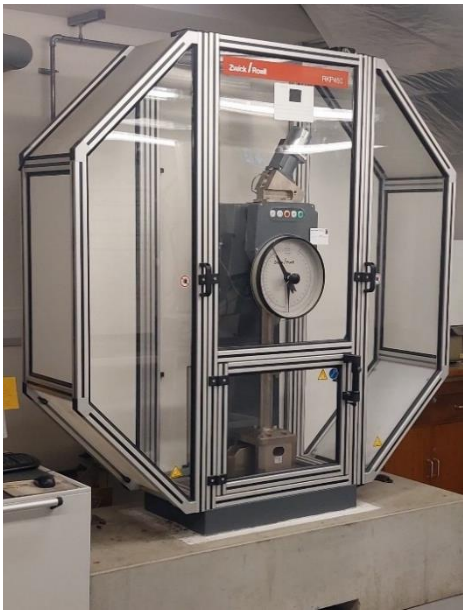

Figure 2 - Zwick 450J pendulum impactor.

- Instrumented impactor – strain gauges 20mm from point of impact
- 450J hammer, impacting at 5.24 m/s

SERVOHYDRAULIC (VHS INSTRON)

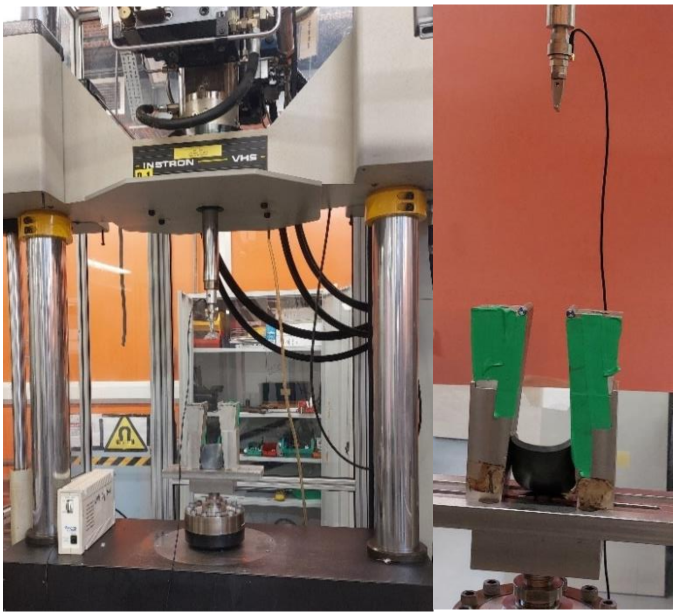

Figure 3 - Instron Very High Speed (VHS) test machine.

- PCB 222B piezoelectric load cell on the impactor – 17mm from point of impact
- Speed control by hydraulic systems set to 5.24 m/s

Dynamic Stability

Rapid fracture toughness assessment use the same equations as static, with an additional criterion. All results were assessed for dynamic validity, employing work by Nakamura [8]. They found dynamic (inertial) effects can be considered negligible after a given period ($tm > 2\tau$), enabling static calculations to remain valid. This work inspired minimum time limitations (t_m) but limits differ between standards, shown in Table 1. Dynamic loading must also have reached stress equilibrium; taken as requiring 3 reflections of stress waves between instrumentation and specimen. This is why is instrumentation is located as close to specimens as possible. These times are also shown in Table 1 and are sufficiently below t_m.

ASTM E399 [7] is shown to be highly conservative, compared to other standards. Values from Nakamura's [8] original work were used as a satisfactory medium between methods.

Table 1 - Dynamic validity minimum test times

Time to assume negligible dynamic effects (Static equations valid) for 10mm Charpy (SEN(B) test)				
	t_m condition	**Zn**	**Al**	**SA508**
Nakamura [8]	$t_m \geq 2\tau \quad \tau = DS\frac{H}{C_0} \cong 23.8\frac{H}{C_0}$	128μs	151μs	93μs
ASTM E399 [7]	$t_m \geq 1ms$	1,000μs	1,000μs	1,000μs
ASTM E1820 [1]	$t_m \geq 2\pi\sqrt{{}^{m_{eff}}/_{k}}$	122μs	88μs	89μs
BS ISO 26843:2015 [3]	$t_m \geq 3\tau$	192μs	227μs	139μs
Time to reach stress equilibrium $\left(3\ \text{Reflections} -\ \mathrm{t} \geq 3 \cdot {}^{\mathrm{D}}/_{\mathrm{C_{0\_impactor}}}\right)$				
Charpy	D = 20mm	12μs		
VHS	D = 17mm	10μs		

Crack Monitoring

For full fracture rapid testing, normalisation and peak load (linear) methods are recommended. Other well established crack monitoring methods, potential drop and interrupted/compliance methods are not recommended for rapid testing as methods must be non-contact (to not entangle or add inertia) and high speed machines are very difficult to interrupt part way through fracture.

Linear crack growth model assumes a linear crack growth rate, initiating at peak load. This method only required load history, including clear identification of the end of test, and measurement of crack lengths (a_0 and a_{end}). Samples that do not fully fracture (a_{end} < total width) were heat tinted at 350°C for 30min before impacting at liquid nitrogen temperature, colouring exposed crack surface (the 'test' crack length) and completing fracture in a brittle mode (preserving the 'test' surface). This method is simple to implement but highly conservative.

Normalisation model required load and displacement histories as well as a_0 and a_{end} measurements. This method (detailed in ASTM-E1820-23b [1] and illustrated in Figure 4) iterates crack length, from a_0, to fit normalised values to a fitting curve. Fitting curve was set according to values using a_0, apart from final data point that uses a_{end}. Then crack lengths, at each time step, are adjusted to make the data match the fitted curve exactly. This method offers more adaptable results for crack growth rate and does not assume the critical point of crack initiation but is open to personal interpretation.

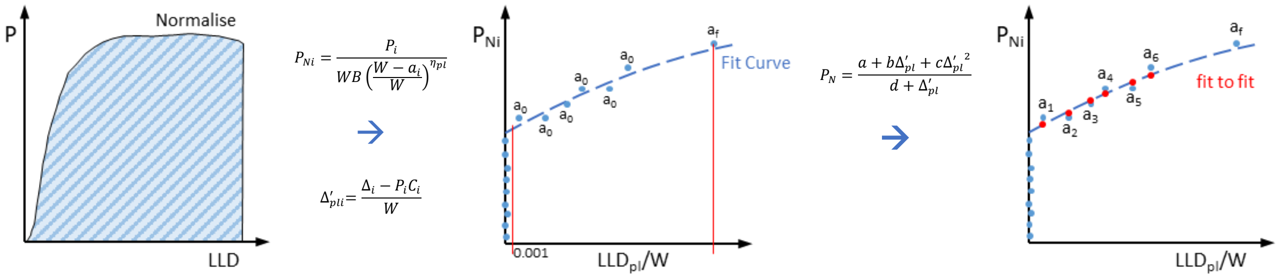

Figure 4 - Illustration of the Normalisation method of Crack length approximation. [1]

Results & Discussion

Zinc – Brittle Material

All Zinc tests were dynamically invalid, snapping too quickly to eliminate dynamic effects. Therefore, a non-standard analysis would be required to assess fracture toughness.

Valuable observations, however, can be made from the results and comparison between test methods.

Both systems had good rate control, maintaining an initial strain rate of 310 /s and consistent velocity. Zinc specimens absorbed very little energy (approx. 2J) to fracture, so both systems were maintained by their momentum. Observations of fracture surfaces (Example in Figure 5) were identical, suggesting very little difference experienced between machines.

Charpy force data removed peak loads as the relatively slow sample rate (200 kHz) does not capture the impact peak. The assessed toughness (45 MPam$^{0.5}$) is, hence, likely lower than truth. VHS data recorded at a higher rate (1 MHz) captured peaks but appeared above expected values, artificially increased by the reverberating shockwave causing a 'ringing' effect. The assessed toughness (166 MPam$^{0.5}$) was much higher than expected.

Figure 5 - Zinc Fracture Surface

Aluminium – Ductile Material

Aluminium tests were found to be dynamically valid as the ductile material takes more time to undergo plastic deformation before fracture. Both systems continued to exhibit good control of strain rate and showed the same variation in velocity during fracture (approx. 0.15 m/s). Velocity variation cannot be reduced in the Charpy machine. However, added mass (increasing momentum) and fine tuning would aid to reduce variation in the VHS machine.

Both toughness values for Charpy (167 MPam$^{0.5}$) and VHS (174 MPam$^{0.5}$) are reasonable for Aluminium and comparable to each other. Load profiles (Figure 7) are indicative of plastic collapse and make the point of collapse (end of test) difficult to identify.

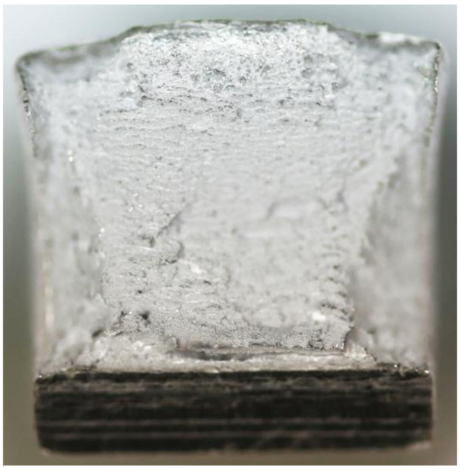

Figure 6 - Aluminium Fracture Surface

Unlike in brittle fracture, there was enough sample data points to fully capture the Charpy load response, building confidence in this result. Like in brittle fracture, the force profile from VHS tests are elevated by ringing – adding a large amplitude sinusoidal wave to the material response. Material stiffness damps this shockwave enough for the material response (signal) to still be distinguished from the ringing (noise). This explains the higher toughness result from the VHS analysis.

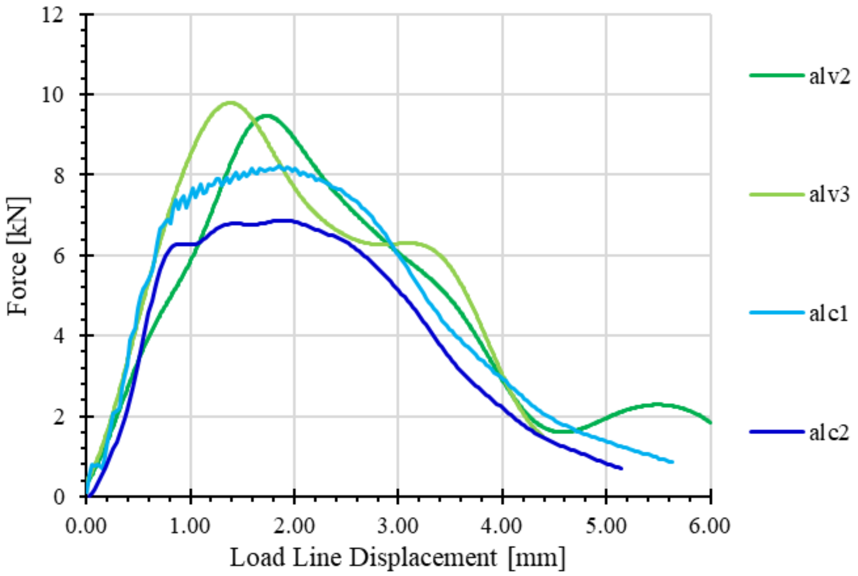

*Figure 7 - Load, Displacement Profiles for Aluminium tests for Charpy 'al**c**_' (blue) and VHS 'al**v**_' (green)*

Steel

Results, once again, demonstrated good strain rate control (Figure 10). Both systems maintained similar average rates and the same range. This was also reflected in velocity variation.

SA508-III steel tests were repeated at several temperatures to observe brittle to ductile transition (Figure 8). Transition points were expressed as mid-transition temperature (referred to as *BDTT*) and reference Temperature (T_0). T_0 is defined as the temperature at which 50% of samples would fail below 100 MPam$^{0.5}$ (when scales to standard size) – expressed by Wallin [9] and outlined in ASTM-E1921-22 [10]. The observed transitions were vastly different between test machines (BDTT -36 °C for VHS and 15 °C for Charpy - T_0 -135 °C for VHS and -65 °C for Charpy). Charpy results matched well with previous work at static tests.

At low temperature, results mimicked observation from Zinc. Fracture was brittle and results were dynamically invalid. Charpy data was likely clipped by relatively slow acquisition and VHS loads were higher than expected.

High Temperature brought ductile fracture. Like Aluminium, collapse made identification of the end of test difficult and ringing made VHS loads (and therefore toughness values) far higher than Charpy assessment. Increased ringing with temperature embellished material response, hence reduced transition curve. However, where steel was stiffer than Aluminium, ringing was less damped and overwhelmed the material response – Figure 9.

At highest temperature (room temperature) VHS toughness results dropped. This would indicate total plastic collapse – where stress concentration leads the material to yield almost instantly. Stiffness reduced as the material readily deformed; this dampens shockwaves more, reducing the amplitude of ringing (also seen in force history). Toughness values at collapse matched Charpy upper-shelf data, suggesting the upper-shelf Charpy data, at this temperature, is also plastically collapsed – tearing apart instead of fracturing.

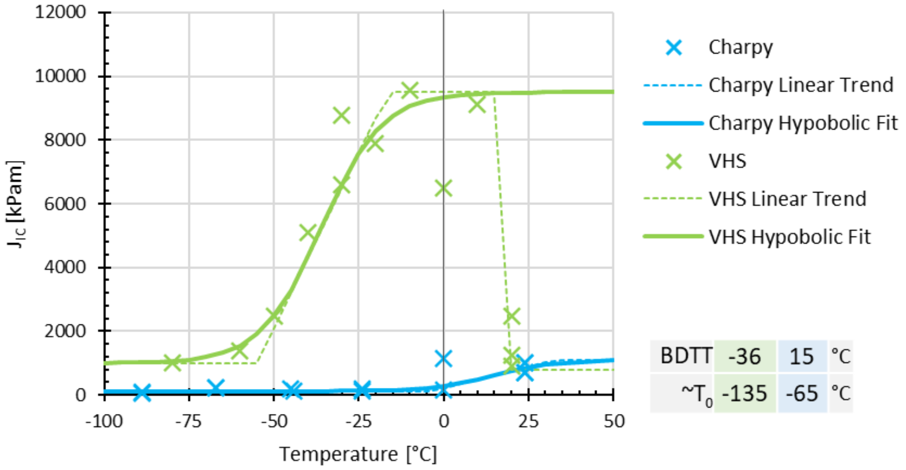

Figure 8 - SA508-III steel toughness results with Temperature, using Charpy (blue) and VHS Instron (Green) test machines

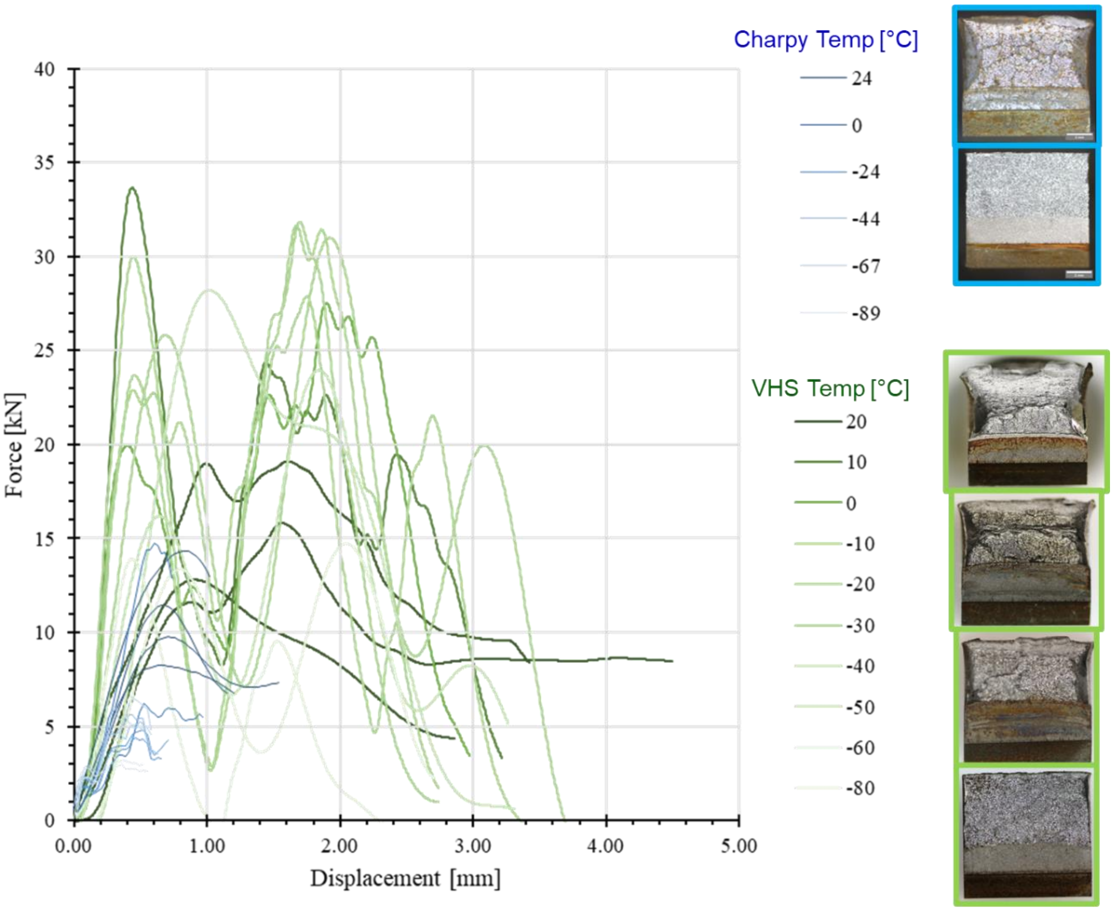

Figure 9 - Force Histories of SA508-III Charpy (Blue) and VHS (Green), at temperatures, Right - Example fracture surfaces

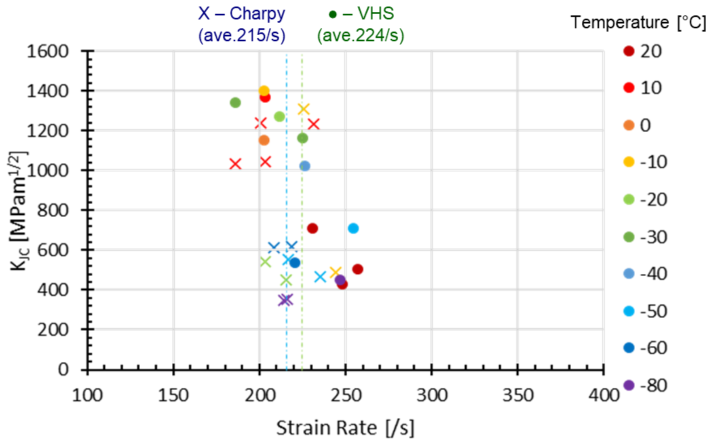

Figure 10 - Test strain rate form SA508-III Steel test, at varying Temperatures

Crack monitoring methods

Both normalisation and linear methods yielded similar crack length profiles - Figure 11. These methods are both impacted by identification of the test end point; a clear drop in load would have been an optimum indicator but was lacking in the experimental data. Careful interpretation of load histories and comparison to time-stamped high-speed photography was used to accurately represent the test duration.

Normalisation method initiated crack growth near peak load. This reinforces that, for this material, peak load is an appropriate assumption for crack initiation. Spikes prior to initiation were caused by initial load up and potential crack tip blunting. Modelled crack length from normalisation also showed plateaus or changes in growth rate; these features aligned well with features seen on fracture surfaces. However, model fitting was very open to personal interpretation, allowing these results to be altered and requiring experience to fit appropriately. The method worked less well for brittle fracture and VHS results, where noise in load history distort the fitted crack length approximation. Contrastingly, linear crack length approximation presented a similar initiation and was much more robust method, less open to adjustment or distortion.

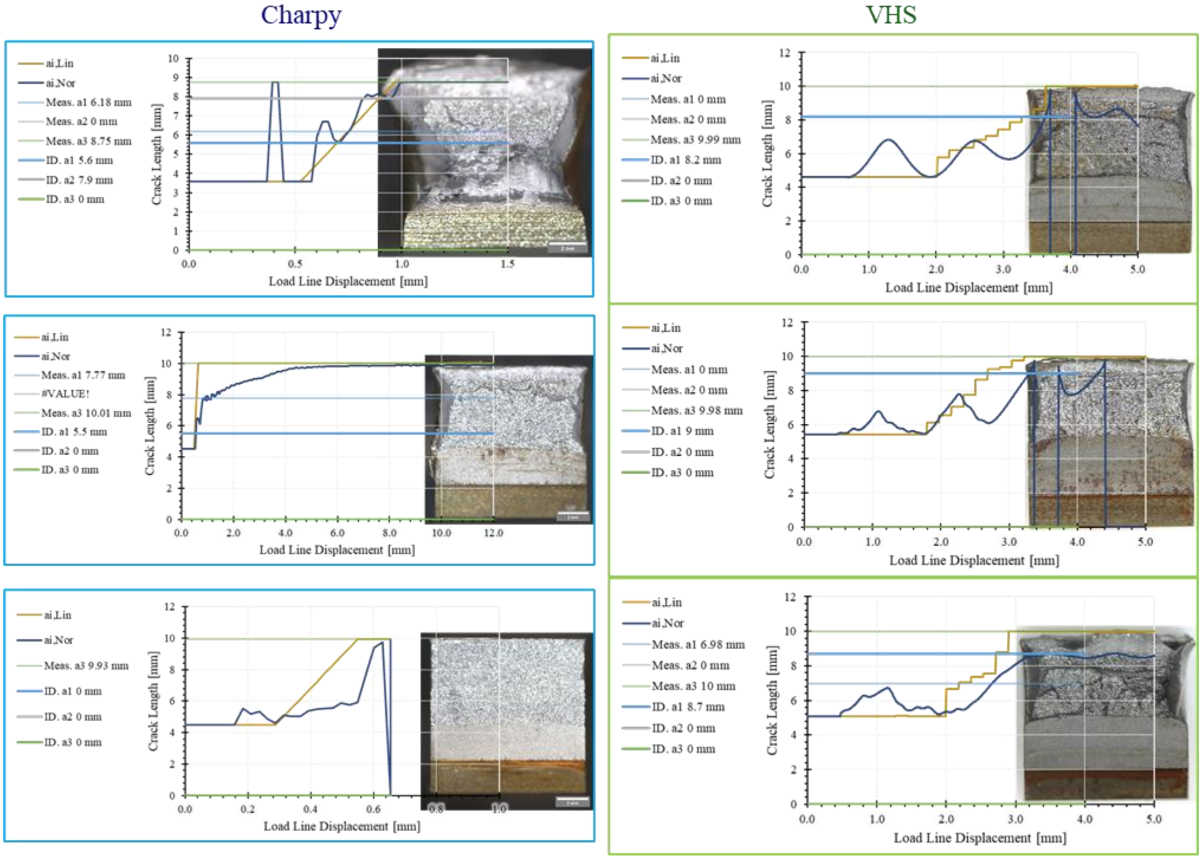

Figure 11 - Crack length models, with accompanying fracture surface and highlight lines with surface features

Conclusion

This work compared fracture results from two testing machines, across three materials (Zinc, Aluminium and SA508-III steel). No observable difference could be found between fixed energy input and speed-controlled actuator testing. Both systems had good control on strain-rate and matching variation of speed during testing. Differences in hardware (sample rate and system ringing) made a larger effects on results than speed control type had, if any.

Crack modelling by normalisation and linear peak load approximations had similar profiles, including similar initiation points. Compared to the simplistic linear assumption, normalisation offered the benefit of more detailed profiles but required experienced tuning to acquire the most realistic profiles. The method was, however, prone to noise in data.

This work required low stiffness ductile metal to be effective. Brittle tests were dynamically invalid for fracture assessment, snapping before standard assessment methods are valid, and low sample rates would clip peak loads. Brittle tests require more detailed (non-standard) computer modelling to compute fracture toughness coupled with dynamic response. All materials were subject to ringing in servohydraulic testing, artificially increasing load data. High stiffness materials, like steel, were overwhelmed by ringing. Aluminium demonstrated the most comparable load data with a dynamically valid ductile response and ringing was damped by the material.

Further work will reduce the effect of ringing in the VHS servohydraulic machine (more ridged test rig) and improve speed control (adding mass and system fine-tuning). Trials of potential drop method for crack growth approximation will assess the impact of thin electrical cables on dynamic response. This work can also be extended to contrast interrupted testing methods by the so called ‘low-blow’ pendulum test and novel servohydraulic testing rigs.

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