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Evaluating the conditions when warm pre-stressing does not produce a benefit in apparent toughness

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Abstract

Warm pre-stressing (WPS) is the process of subjecting a pre-cracked component to a load cycle at a temperature higher than subsequent operating temperatures. This process is widely acknowledged as being able to enhance the load to fracture, especially in ferritic steels which exhibit lower shelf cleavage fracture. Although accurate estimates of the toughness distributions can be obtained, the accuracy of WPS predictions may be limited by the sample size. It can be argued that the experiments conducted to date are devised to show that the WPS enhancement is always successful, however there are circumstances when a specimen might fail prematurely during the WPS path. Focus is drawn on predicting the number of prematurely failed specimens at different temperatures and pre-load levels.

Keywords: Fracture Toughnes; Monte Carlo Simulation; Warm Pre-stress; Chell model;

1. Introduction

Warm pre-stressing, (WPS), is a process where a cracked metallic component or structure is subjected to a given pre-load in tension at a temperature, termed T_1. This generates localised yielding at existing crack tips. Subsequently, the load required to fracture the warm pre-stressed cracked component at a temperature lower than T_1,

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typically termed T_3, is found to be greater than a component without prior load history [1–7]. This enhancement in apparent toughness has a significant impact on the integrity of nuclear reactor pressure vessels, particularly during severe loading conditions, such as pressurised thermal shock, (PTS), where the vessel is cooled down rapidly with a possible subsequent increase in pressure. The change in apparent toughness depends not only on the load but the temperature paths associated with the prior loading and subsequent operation.

Nomenclature

σ_1, σ_2, σ_3	Yield strengths at Pre-loading, Unloading, Fracture temperatures.
K_e	Elastic component of the Fracture Toughness.
K_{Ic}	Fracture Toughness.
m_K, K_0, K_{min}	Parameters of Weibull distribution.
T_1, T_2, T_3	Temperatures at Pre-loading, Unloading, Fracture.
C(T)	Compact Tension.
CF	Cool – Fracture loading regime – Case 3 of Chell model.
LCF	Load – Cool – Fracture loading regime – Case 2 of Chell model.
LUCF	Load – Unload – Cool – Fracture loading regime – Case 1 of Chell model.
MCS	Monte Carlo Simulation.
PTS	Pressurised Thermal Shock.
WPS	Warm Pre-stress.

Systematic studies have focussed on simplified loading paths using a relatively small number of laboratory specimens. Typical loading paths are shown in Figure 1. Cool and fracture (CF) is the conventional loading path used to carry out a fracture toughness test. However, typical WPS loading paths are load, complete unload, cool and fracture (LUCF) and load, cool and fracture (LCF). Recent WPS studies have explored different pre-stressing conditions in order to evaluate the limitations associated with this enhancement; investigating the effects of biaxiality [8-10], complex loading paths [11], active plasticity [12] and irradiation [13]. The overall conclusion obtained from these experiments suggests that this enhancement is always successful, which, when concerned with a nuclear RPV's structural integrity, is a very desirable outcome. However, there are cases where specimens can fail during WPS loading paths. As such, this raises the possibility that current WPS tests are performed under conditions which always ensure an observable benefit. Whilst the underlying theory governing this enhancement is very well established, since several models have been produced to estimate this effect [7, 16-18];the main issue is determining how to treat prematurely failed data and subsequently understand its effect on the resultant WPS failure distribution.

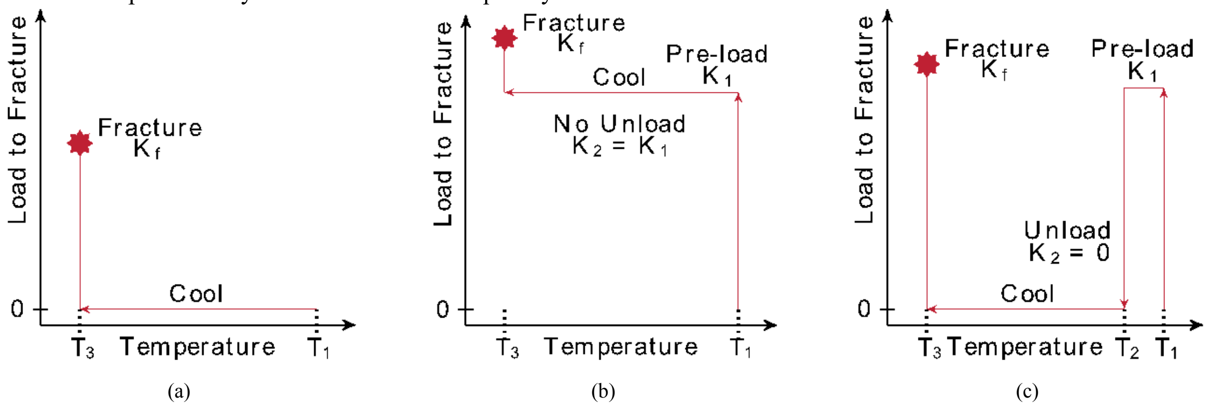


Fig. 1. Schematic of temperature-load cycles applied to fracture specimens: (a) Cool and Fracture (CF) cycle; (b) Load, Cool and Fracture (LCF); (c) Load, Unload, Cool and Fracture (LUCF) cycle.

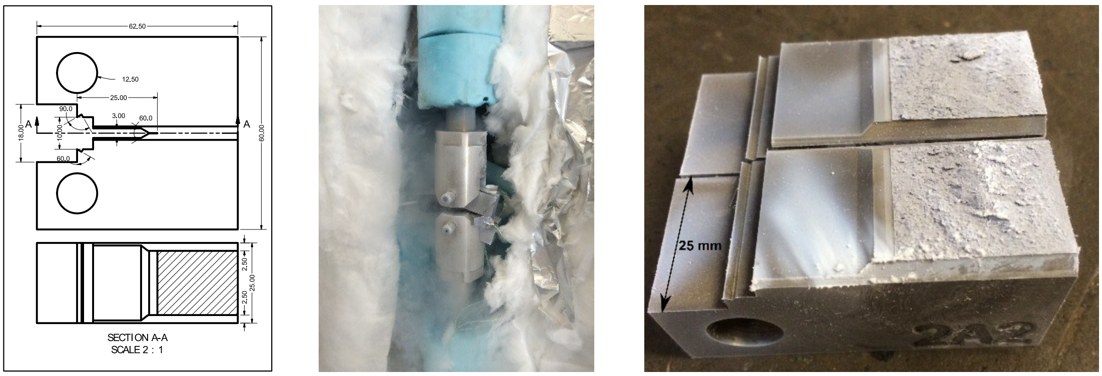
The purpose of this paper is to predict the number of specimens failing prematurely during a set WPS loading path, and identify the conditions when there is no increase in apparent fracture toughness. This is achieved using a probabilistic modelling approach (based on the Chell model [7]) to not only evaluate the minimum pre-load level required to induce an enhancement, but also to estimate based on preliminary fracture toughness results, how many specimens in a sample would fail during the pre-loading sequence at a set temperature.

2. Experimental Results

A substantial fracture toughness data set was generated in order to apply the reformulated Chell model, and perform the predictive analysis, which is described in further detail in Section 3. Compact tension, C(T), specimens, 25mm thick with L-T orientations, side-grooves (to avoid shear lips) and wire EDM pre-cracks, were extracted from 55mm thick steel plates. The fracture tests were conducted at -160°C using a 500kN capacity Dartec hydraulic test machine fitted with a temperature controlled chamber. Figure 2 shows the C(T)'s conceptual drawing and specimens post fracture. The specimens were cooled at a rate of -2°C/min, ensuring no thermal shock was seen, until T_3 = -160°C was reached. Once T_3 had been reached, the specimen would rest at the desired temperature, monitored using 3 type-K thermocouples, for 10mins in order to reach thermal equilibrium. The tests were conducted in displacement control, with a loading rate of 0.2mm/min in order to give quasi-static loading conditions. A calibrated low temperature clip gauge was used to measure the CMOD, in order to evaluate both K_e and K_{JC}. All specimens were manufactured and tested according to the regulations imposed by ASTM E399-09 [19]. Composition and results tables (Tables 1 & 2) are shown below.

Table 1. Chemical composition of C-Mn steel plate BS1501-224 28B.

C	Si	Mn	Al	P	S
0.15	0.28	1.27	0.022	0.007	0.005



(a) (b) (c)

Fig. 2. (a) Engineering drawing of C(T) specimen; (b) Fractured C(T) immediately after test; Fractured C(T) conducted at T_3 = -160°C

Table 2. Fracture Toughness, K_{Ic}, data at -160°C.

Specimen Code	K_{Ic} $MPa\sqrt{m}$	Specimen Code	K_{Ic} $MPa\sqrt{m}$	Specimen Code	K_{Ic} $MPa\sqrt{m}$	Specimen Code	K_{Ic} $MPa\sqrt{m}$	Specimen Code	K_{Ic} $MPa\sqrt{m}$
S1A01	101.26	*S1A02*	71.73	*S1A04*	102.19	*S2A02*	146.52	*S2B02*	101.45
S2A01	88.86	*S2A03*	36.75	*S2A04*	108.96	*S2B01*	101.33	*S2B03*	116.63
S2B04	127.06	*S2A06*	127.47	*S2A10*	69.04	*S2A14*	98.53	*S2A18*	130.99
S2B14	126.72	*S2B17*	127.38	*S2B08*	137.24	*S2B06*	102.30	*S2B10*	122.36
S3B18	144.19	*S2A08*	149.32	*S2A11*	127.83	*S2A17*	117.85	*S2A09*	121.74
S2A12	82.15	*S2A05*	77.95	*S2A07*	73.11	*S2A13*	116.91	*S1B06*	125.80

An additional scoping study was carried out to investigate the fracture transition with temperature for this specific material. The results are shown in Figure 4(a).

3. Monte-Carlo Simulations of Warm Pre-Stress

Monte-Carlo simulation is a numerical method which involves the use of simulated random numbers to estimate some function of a probability distribution, and is often used to model cases where there is a significant uncertainty, e.g. cleavage fracture toughness [20]. The Monte Carlo Simulations (MCS) are applied to the revised Chell model, and the details of this analysis can be found in [21]. A 3 parameter Weibull analysis is used to represent the scatter associated with the fracture toughness data. All three parameters are freely determined, and those which provide the highest linear regression coefficient were selected to govern the Weibull distribution. The distribution mapping the experimental results can be seen in Figure 4(b).

The fracture community cares about low probability events, which corresponds to the tails of the fracture toughness distribution. Generally the master curve [17] is used to evaluate the maximum pre-load level, K_I, by attributing the K_{Ic} value which has a 5% probability of failure. However,it is believed that there is insufficient amount of experimental tests conducted at each temperature step to evaluate such low probability events. As such, an analysis was conducted on the Euro data set [22-23], in order to evaluate a statistically suitable sample size. Specific Weibull parameters were used to generate 100 K_{Ic} data points and 5 to 95 points were randomly progressively removed. A new distribution was fitted to the reduced sample, and the variation in both the shape and scale parameters with the number of specimens in the sample was investigated, as shown in Figure 3. Since the scatter observed is a direct result of the reduction in sample size, this process was repeated 20 times. Applying the Mann-Whitney test [24] to the resulting parameter datasets, it was deemed that a sample size of 30 would be statistically acceptable, in order to minimise the potential variation in these fitting parameters.

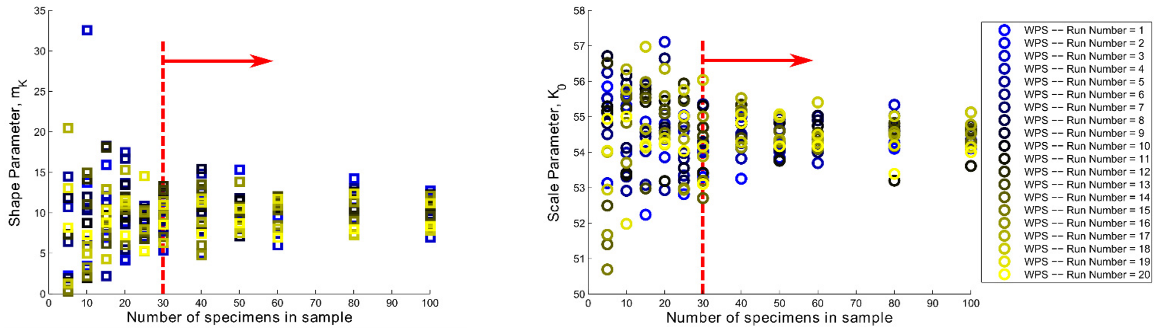


Fig. 3. Scatter in Weibull parameters vs Number of specimens, (a) Shape parameter; (b) Scale parameter.

The input variables required for the Chell model are the virgin fracture toughness (K_{Ic}), pre-load magnitude (K_1), unload magnitude (K_2), and the yield strengths at both the fracture and pre-load temperatures (σ_1, σ_3). As previously mentioned, a 3 parameter Weibull distribution is used to generate the K_{Ic} distribution, however, the elastic component of the stress intensity factor is required in order for the Chell model to be valid. The pre-load magnitude, in this analysis, follows a uniform distribution, with limits of ± 3.2MPa√m. This type of variation is not uncommon, especially if WPS tests are conducted under displacement control [4, 25-26]. Finally, the yield strength values are attributed a 5% coefficient of variation [27]. This analysis also fits 3 parameter Weibull distributions to the K_{Ic} data performed at T_3 = -140°C to -80°C, in order to evaluate the conditions when $K_1 > K_{Ic}(T_1)$, and subsequently eliminate the specimens which would fail prematurely. The pre-load level was increased from K_1 = 100 to 400 MPa√m, and applied at T_1 = -80 to -140°C. The results obtained from this analysis are displayed in Figure 4(c).

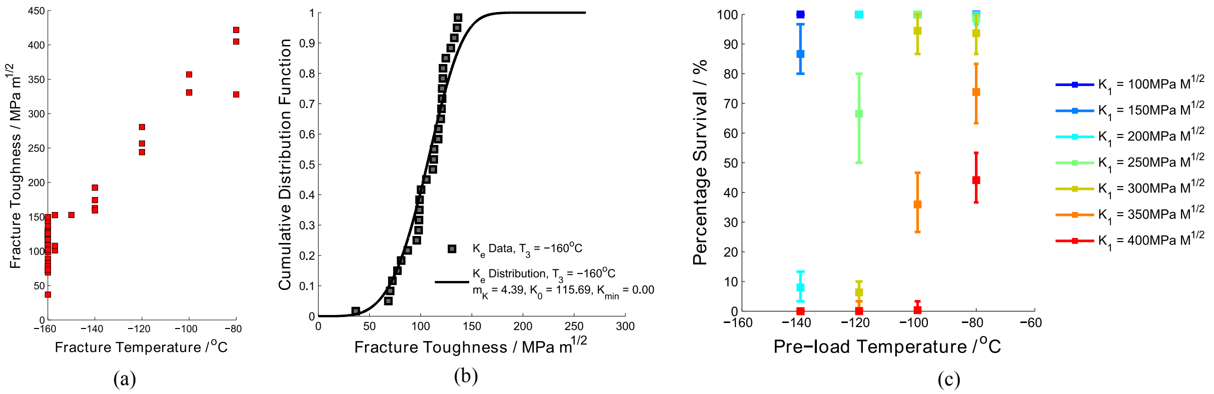


Fig. 4. (a) K_{IC} data vs Temperature; (b) K_e distribution at T_3 = -160ºC; (c) Percentage of survival of sample after pre-load K_I is applied at T_I.

4. Discussion

The results of this analysis have revealed two cases where no benefit is observed after a pre-load has been applied. The first instance occurs when the pre-load reaches a critical magnitude which is larger than the original fracture toughness of that specimen. Whilst the Chell model would normally be used to simply predict the potential enhancement, this analysis takes into account the potential elimination of specimens in a sample if premature failure occurs. Figure 5(a) and (b) show the results obtained from using input parameters K_I = 250 MPa√m, T_I = -120ºC, and T_3 = -160ºC. Figure 5(a) shows the generated K_{Ic} data points and predicted enhancements, and displays the ranked predictions made from eliminating the prematurely failed specimens. Figure 5(b) shows the probability distribution functions made from fitting 3 parameter Weibull distributions to the results displayed in Figure 5(a). The main observation is that the modified prediction shows a curtailing of the original distribution. Since the lower tail (specimens with low fracture toughness) has effectively been removed, it causes the percentage confidence in the enhancement to increase. This gives a false indication of the true distribution, and degree of enhancement. Discarding the specimens which have failed during the pre-loading sequence, would cause the results to be perceived as even more beneficial, which is effectively incorrect as a proportion of the sample has not survived the WPS loading path.

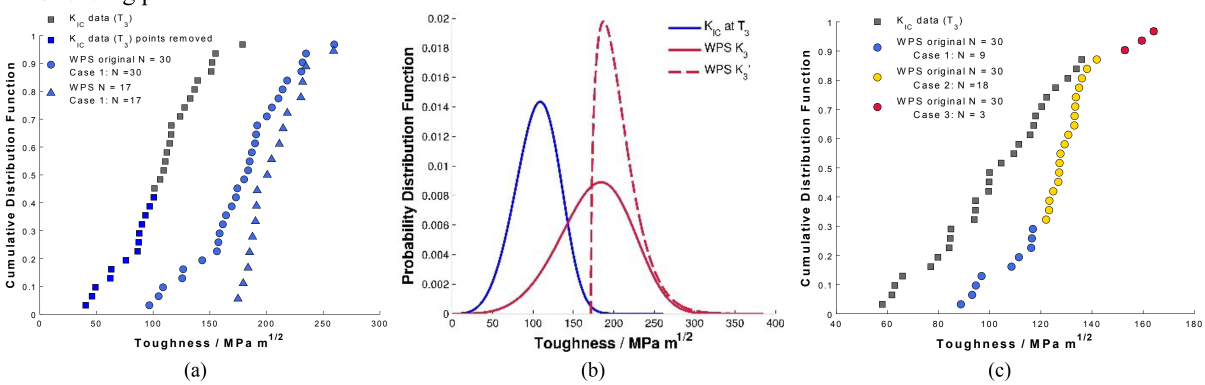


Fig. 5. Results obtained from LUCF simulationT_3 = -160ºC, T_I = -120ºC, K_I = 250 MPa√m, (a) Cumulative distribution; (b) Probability distribution; (c) Results obtained from LUCF simulationT_3 = -160ºC, T_I = -80ºC, K_I = 100 MPa√m.

The second case is identifying the minimum pre-load level required to cause a benefit in the apparent toughness. Theoretically, the Chell model can provide an estimate of the minimum pre-load necessary determined from yield strength ratios [20]. This corresponds to Case 3 of the Chell model, which states that the specimen's fracture toughness, K_{Ic}, is too large for the given pre-load, K_I. However, the analysis results predicts an actual number of specimens in a sample which might not see this enhancement.Figure 5(c) shows that 3 specimens will not see an enhancement, for K_1 = 100MPa√m at T_1 = -80°C, since their fracture toughness would be too high for the applied pre-load. Since the predictions made from this analysis are to be validated experimentally, obtaining an estimate of how many specimens will not see an enhancement is very important. It is impossible to know both the fracture toughness and apparent toughness post WPS of the same specimen, and therefore impossible to know if a given specimen has seen an enhancement or not. However, with an original fracture toughness data set of 30 specimens at T_3 = -160°C, these current predictions will help determine whether a specimen has seen an enhancement or not. Finally, the data collected at T_1 = -140 to -80°C is insufficient to evaluate the tails of its associated fracture toughness distributions. Therefore, the WPS experiments will focus on pre-load magnitudes around the means of the associated Weibull distributions.

5. Conclusions and Future Work

Whilst previous experiments have focussed on loading paths which ensure there is a benefit, this paper has shown that there are 2 cases where no enhancement in apparent fracture toughness is seen. Firstly, there is a risk of premature failure during pre-load. Secondly, it is shown that if the pre-load magnitude is not significantly large enough, there will be no enhancement in the apparent toughness. As such the model used in this analysis defines the parameter space for future WPS experiments. The next step involves experimental validation of the predictions made by the reformulated Chell model. These tests will occur within the transition region using conditions where the risk of premature failure is detectable, whilst the confidence in enhancement is acceptable.

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