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Correlation between steel initiation toughness and arrest toughness determined from small-scale mechanical testing

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Abstract

The ability of a material to arrest a fast-running brittle crack is vital in various industries such as offshore wind, oil and gas, and shipbuilding where cracks can initiate in regions of local stress and put lives at risk. Some modern steels show a high Charpy toughness, but low resistance to crack propagation – i.e. low crack arrest toughness. In this work, the relationship between initiation and arrest toughness is investigated in five different steels, including S355 structural steel, X65 pipeline steel and two high strength reactor pressure vessel (RPV) steels.

Small scale mechanical testing was carried out to determine the material properties, which were correlated against the microstructural characteristics of the materials. The test program included instrumented Charpy, drop weight Pellini, fracture toughess, tensile testing, and microscopy. Nil ductility transition temperature (NDTT) is used as a measure of arrestibility. Initiation toughness showed the expected correlations with upper shelf Charpy and grain size measurements, however these did not correlate with the arrest toughness. The arrest toughness is better correlated against the T_{27J} temperature – i.e. the onset of the lower shelf. This relationship is valid even for steels where the NDTT lies on the upper shelf of the Charpy curve.

Keywords: crack arrest; S355 steel; X65 steel; RPV steel; crack arrest toughness; fracture mechanics

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Nomenclature

CAT	Crack Arrest Temperature
CTOD	Crack Tip Opening Displacement, the maximum of which is referred to as δ_m
CVN	Charpy V Notch test
K_{ca}	Crack Arrest Toughness parameter
NDTT	Nil-Ductility Transition Temperature
RPV	Reactor Pressure Vessel
SEN(B)	Single Edge Notched Bend, fracture toughness test
STRA	Short Transverse Reduction of Area
T_{27J}	The temperature at which the absorbed Charpy energy is 27J

1. Introduction

The ability of a material to arrest a fast-running brittle crack is vital for structures where cracks can initiate in regions of high local stress or low toughness. This is essential in industries such as Oil and Gas, offshore wind and shipbuilding where a structural failure can cause huge loss of life and replacement of expensive assets.

The results of small-scale testing can be used to predict structural behavior using a number of empirical relationships. However, as the plates used for many applications increase in toughness and thickness, these empirical relationships begin to exceed their limits of validation, and the crack arrest behaviour may not be fully understood.

Arrest toughness is considered to be a material property, but in reality it decreases with an increase in the thickness of the plate, the temperature, and the stress applied (Green and Knott, 1975; Wallin, 1985; Sugimoto, 2010; Handa *et al.*, 2016). Additionally, arrest toughness measurements show a dependence on the test plate width (Marschall, 1986; Zhu and Joyce, 2012; JWES, 2014; ASTM, 2016). It also depends on the treatment and preparation of the material, like many other 'material properties'. These factors make it incredibly difficult to predict the structural behaviour from small-scale (typically subsize) samples, and introduce an inherent need for sufficient conservatism.

Due to the temperature dependence of arrest toughness, small scale tests can be carried out to find the transition behaviour of the material such as from Charpy impact energy or nil-ductility transition temperature (NDTT), which can be empirically related to large-scale specimens (Crosley, 1982; Funatsu *et al.*, 2012). A typical parameter used to characterise arrest is the crack arrest temperature (CAT), the temperature above which a brittle crack would be arrested in the material. Resistance to continuous fracture propagation is equivalent to crack arrestibility, characterised by the CAT. The Charpy test is most favoured by the industry because it is cheap and simple and typically already provided as part of the material specification.

The following relations are the culmination of multiple studies of Charpy V-Notch (CVN) impact testing and represent just a few of the many empirical relationships available through literature survey: (Robertson, 1953; Pellini and Puzak, 1963; Hahn, 1980; ASTM, 2014, 2000; Willoughby, 1986; BSI, 1987, 1990; Wiesner, Hayes and Willoughby, 1993)

$$Pellini\ NDTT\ =\ 120\,J\ CVN\ temperature\ +50°C \tag{1}$$

$$Pellini\ NDTT\ =\ 40\,J\ CVN\ temperature\ +60°C \tag{2}$$

$$Pellini\ NDTT\ =\ 27\,J\ CVN\ temperature\ +60°C \tag{3}$$

The scatter in results is considerable, however it is well appreciated that the results of Charpy tests are a result of both fracture initiation and fracture propagation mechanisms and plasticity is introduced during the fracture, which absorbs much of the energy (Völling, Kalwa and Erdelen-Peppler, 2014). In addition, the small size of the Charpy specimen causes a difference in crack-tip constraint as compared with the full plate thickness crack arrest test.

In order to relate small-scale results to crack arrest properties, the following equation can be used, either with Pellini results, or from the converted Charpy results (Wiesner and Hayes, 1995):

$$CAT\ =\ NDTT\ +\ 40°C \tag{4}$$

This promising correlation between NDTT and CAT for different materials and welds is not surprising since the drop weight test is a measure of the resistance against continuous fracture propagation and is rooted in fracture mechanics theory (Puzak, Eschbacher and Pellini, 1952; ASTM, 2000).

Once a crack has initiated in a very high toughness steel, it may have such a high driving force that it continues to propagate until the structure has failed. In this way, the steels which are designed to resist crack initiation may not have sufficient crack arrest properties in the case of accidental damage. This is becoming a problem for some modern steels which have a high upper shelf Charpy energy, but a very low resistance to crack propagation (Moore *et al.*, 2018) which indicates that Charpy energy cannot be used for material certification where brittle cracking is a possibility. This paper correlates the mechanical properties of a selection of modern structural steels to determine the relationship between initiation fracture toughness and crack arrest toughness and the validity of the equations given above.

2. Materials used in this work

The test program was carried out on five steels: two different RPV steels of the same thickness, one pipeline steel, and two plates of S355 structural steel at different thicknesses. The properties of these five steels are summarised in Table 1.

Table 1. Basic properties of the steels used for this research.

Material Reference	M01	M02	M03	M04	M05
Material	RPV A543	RPV A302	X65	S355G10+M	S355G10+M
Thickness	28mm	28mm	30mm	90mm	50mm
Yield Strength	850MPa	638MPa	566MPa	389MPa	444MPa
Tensile Strength	914MPa	764MPa	613MPa	513MPa	535MPa

Materials M04 and M05 (both nominally S355 structural steels) indicate the variability in “off-the-shelf” steels – although they are the same grade, their properties and composition are not identical. This is typical of many steel grades due to the flexibility of the standard specifications (Mehmanparast, Taylor and Brennan, 2018). These five steels show a wide range of different properties, from the very high strength RPV steels to the lower strength structural steels, which suits them to different applications that all have an interest in the crack arrestibility.

3. Test program

Pellini drop weight tests (ASTM E208 (ASTM, 2000)) were carried out to find the NDTT of the materials which is a measure of CAT. Instrumented Charpy (CVN) tests (BS EN ISO 148-1 (BS EN ISO, 2006)) were carried out at a range to temperatures to find the transition curve and upper shelf energy to give a simple indication of fracture toughness commonly used in the industry. Tensile tests were carried out to BS EN ISO 6892-1 (BS EN ISO, 2016).

Additionally, Single Edge Notched Bend (SEN(B)) fracture toughness tests (BS 7448 (BSI, 1991)) were carried out on all the materials at room temperature as a quantitative indication of their fracture toughness in terms of maximum crack tip opening displacement (CTOD δ_m).

The steels shown were etched with 2% nital to show the grain boundaries and microstructure more clearly – then the grain sizes were measured using the linear intercept method (ASTM E112 (ASTM, 2007)) due to the non-equiaxed nature of the grains.

4. Steels' mechanical properties

The mechanical properties of the materials studied are given in Table 2, where the wide variation in properties becomes evident. Figure 1 shows that there is a good correlation between upper shelf Charpy energy and Crack Tip Opening Displacement (CTOD) fracture toughness, except for M03, where the Charpy energy was the highest, but the fracture toughness of this material was the median in this data set.

However, there is no correlation between the fracture initiation toughness parameters and the crack arrest parameters. For example, M01 shows very good arrest properties (NDTT), but has the lowest Charpy upper-shelf energy of any of these steels. M02 has a similar Charpy energy to M01, but the poorest arrest properties (NDTT) of all the steels. This demonstrates the concern that some modern steels may have a high upper shelf Charpy energy but poor crack arrest fracture toughness, as the trend is not well defined.

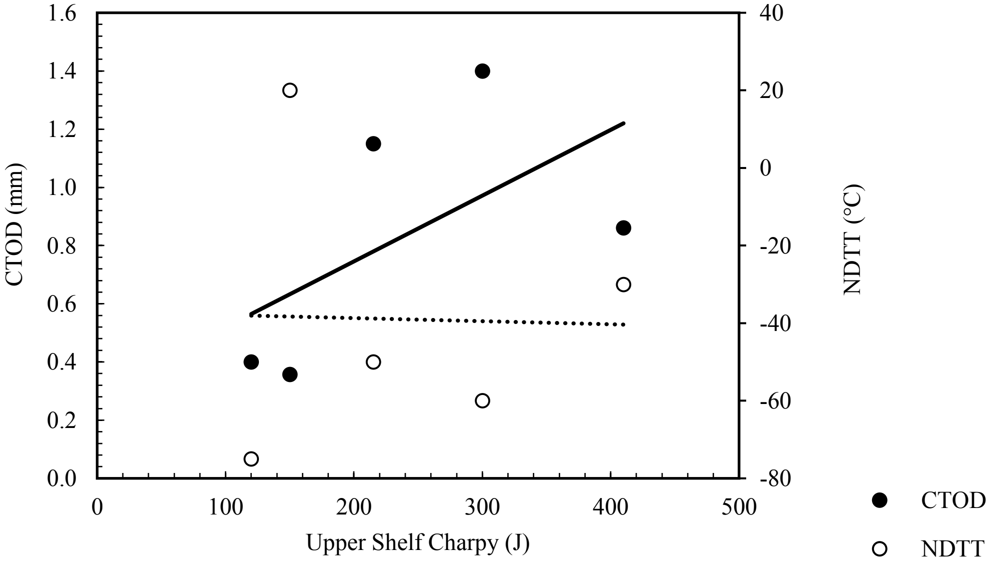

Fig. 1. (a) Correlation between small scale initiation and arrest parameters.

Table 2. Summary of mechanical properties of the steels used for this research.

	M01	M02	M03	M04	M05
Material	RPV A543	RPV A302	X65	S355G10+M	S355G10+M
Yield Strength	756MPa	601MPa	566MPa	389MPa	444MPa
NDTT	-75˚C	20˚C	-30˚C	-50˚C	-60˚C
CVN Upper Shelf	122J	140J	410J	210J	295J
CTOD δ_m	0.40mm	0.36mm	0.86mm	1.15mm	1.40mm
T_{4kN}	-100˚C	14˚C	-90˚C	-113˚C	-112˚C
CVN T_{27J}	-117 ˚C	-13 ˚C	-72 ˚C	-102 ˚C	-113 ˚C
Average Grain Size / µm	9.3	6.9	5.2	5.5	7.4

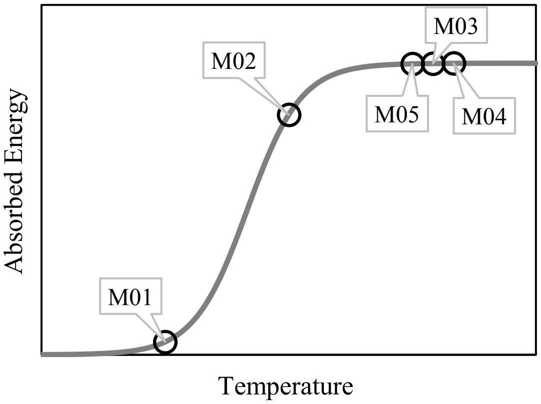

Fig. 2. Relationship between NDTT and Charpy transition curve.

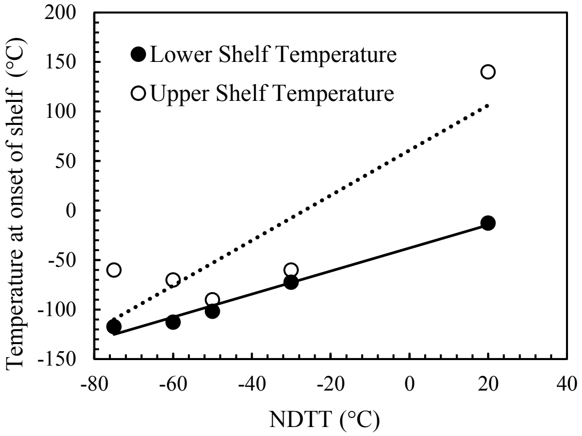

Fig. 3. Relationship between NDTT and Charpy shelf temperatures.

5. Discussion

The steels studied are all very fine grained, which made it difficult to draw meaningful correlations between mechanical properties and microstructure due to high scatter. There is a reasonable correlation between grain size and upper shelf Charpy impact toughness, taken from Table 2, where M03 with the smallest average grain size shows the highest toughness and M01 with the largest grain size shows the lowest toughness. This is a well-established concept for steels, with fine grain size providing both high strength and high initiation fracture toughness, and is the reason why all these modern structural steels have been developed to have very small average grain sizes.

At this time, the arrest properties cannot be correlated strongly to the materials' microstructure. This may be because the approaches are incompatible – comparing the initiation energy to the arrest temperature. This may mean that the CAT approach is not suitable if a quantitative measure of the crack arrest toughness is needed as opposed to a pass/fail result for the specific operation conditions.

Figures 2 and 3 show the relationship between the NDTT and the Charpy transition curve. Only in material M01 does the NDTT lie close to the lower shelf and for most of these steels, the NDTT lies on the upper shelf of the Charpy curve. Although this seems to be contradictory, the results show a very strong relationship between the steels' NDTT and T_{27J}, i.e. the onset of the lower shelf and brittle behavior. This relationship is valid even for the steels where the NDTT lies on the upper shelf. This relationship is weak when the NDTT is compared to the onset of the upper shelf for each of the steels – likely to be due to the steepness/size of the transition region which is very shallow for some of these steels, but very steep for others.

The relationship between NDTT and T_{27J} is not 1:1, therefore equations 1-3 do not hold for modern steels, and would result in an overestimation of the material properties from T_{27J}. For these steels, the difference between NDTT and T_{27J} is between 30°C and 50°C, which mirrors equation 4 between NDTT and CAT. In future work, the CAT will be determined against both NDTT and Charpy transition to determine if T_{27J} can be used as a measure of arrest toughness.

6. Conclusions

It is not recommended to use upper shelf CTOD or upper shelf Charpy energy as measures of crack arrestibilty in a material as there is no correlation between the two. However, there is some potential in using T_{27J} from Charpy tests, suggesting that the crack arrest behavior is affected more by lower shelf or transition properties.

This work has shown that:

- The parameters which influence the crack arrest behavior of modern structural steels are independent of those which provide these steels with upper-shelf fracture toughness.
- The crack arrest behavior is more closely linked to the ductile to brittle transition temperature of the steel (as characterized by T_{27J} from Charpy tests) – even for steels where the NDTT would lie on the upper shelf of the Charpy transition curve.
- High CTOD fracture toughness is not sufficient to determine whether the steel could be at risk of unstable fracture from a localized brittle event, due to poor crack arrest toughness.

7. Future work

This test program will be continued in future work. Quantitative crack arrest testing will be carried out on a selection of the steels to compare to and validate the small scale predictions. Electron Back Scatter Diffraction (EBSD) will be used to characterize fully the texture of the materials by including the grain orientation and correlating the materials' texture to its small-scale mechanical properties. Further correlations between mechanical and microstructural properties will be investigated for each of the materials to determine the relationship between microstructure and arrest. If there remains to be no correlation, it is advised that an energy based approach is investigated to predict the arrest behavior of the materials i.e. K_{ca}.

The five materials studied here will be compared with available material data in the literature to expand the correlations which have been made. The experimental program will be continued on more steels to strengthen the argument for new small-scale test methods for predicting crack arrestibility.

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