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# The effect of low temperatures on the fatigue of high-strength structural grade steels

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## Abstract

It is well-known that for fracture, ferritic steels undergo a sudden transition from ductile behavior at higher temperatures to brittle cleavage failure at lower temperatures. However, this phenomenon has not received much attention in the literature on fatigue. The so-called Fatigue Ductile-Brittle Transition (FDBT) has been identified in the literature as the point at which the fracture mode of the fatigue cracks changes from ductile transgranular to cleavage and/or grain boundary separation. The current paper contributes to understanding this phenomenon by presenting both ductile to brittle fracture transition data and fatigue crack growth rate curves for two modern high strength steel base plate materials: S460 and S980. The data in this paper suggests that fatigue at lower shelf temperatures may have a higher rate than in the transition or upper shelf temperatures for Regions I and II of the  $da/dN$  versus  $\Delta K$  curve.

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## 1. Introduction

Fatigue behavior of metals is often characterized by the  $da/dN$  versus  $\Delta K$  curve. This curve is typically presented in log-log coordinates and represents the crack growth per cycle ( $da/dN$ ) on the vertical axis against the stress intensity range ( $\Delta K$ ) on the horizontal axis. An example is given in Fig. 1a. This curve is known to have three

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distinct regions. Region I corresponds to low stress intensity ranges. This region contains the vertical asymptote known as the threshold stress intensity range ( $\Delta K_{th}$ ), below which no or negligible crack growth occurs. Region II is a region in which the relationship between the crack growth rate and the stress intensity range is approximately linear in log-log coordinates, as is often expressed in the Paris law:

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

Region III is the region at which the unstable crack growth is present. The current paper will focus on the threshold stress intensity range and the Paris regime because they are the most relevant to practical applications.

As ferritic steels becomes colder, they undergo a transition from a shear-dominated (ductile) fracture mode to a cleavage-dominated (brittle) fracture mode. This is measured through fracture mechanics testing, such as CTOD,  $K_{Ic}$ , Charpy, or  $J$ -integral testing. A similar effect has been documented for fatigue at low temperatures (e.g. Baotong and Xiulin, 1991, Moody and Gerberich, 1979, Stephens et al., 1980, Tobler and Cheng, 1985, among others) and has been called the Fatigue Ductile-Brittle Transition (FDBT). The temperature at which this transition occurs is known as the Fatigue Transition Temperature (FTT). It has been observed that lower temperatures generally cause decreased fatigue crack growth rates until the FTT is achieved. Below the FTT, the trend is reversed, and higher fatigue crack growth rates are encountered (Stephens and Chung, 1980). A more nuanced explanation is that temperatures below the FTT induce a higher slope in the  $da/dN$  versus  $\Delta K$  curve, thus meaning that the fatigue crack growth rate may be lower for low  $\Delta K$  values and higher for higher  $\Delta K$  values than for room temperature (Stephens and Chung, 1980). This is shown in Fig. 1a for a low-carbon steel. Fig. 1b from the same source shows the slope of the  $da/dN$  versus  $\Delta K$  curve (the value  $n$  from Eq. (1)) increasing until a set temperature, and then decreasing sharply thereafter. Fig. 1b also shows a number of other attributes ( $da/dN$  at  $\Delta K=120$  MPa $\sqrt{m}$ , cycles to failure, and critical stress intensity to fracture for fatigue) becoming more favorable as the temperature decreases, and then becoming less favorable after a certain set temperature. Clearly, this effect could become important for structures operating at low temperatures. Designers and classification societies assure safety against brittle fracture by checking that their steel has a Charpy Ductile to Brittle Transition Temperature (DBTT) below the operating temperature (plus or minus a shift to account for various factors). The FDBT should not be important for designers if this happens below their lowest design temperature or their Charpy DBTT. Therefore, there is interest in knowing the relationship between the fatigue and fracture ductile to brittle transition temperatures. Tobler and Cheng (1985) have partially answered this call by plotting the  $K_{Ic}$  fracture toughness and the Paris exponent ( $n$ ) against temperature on the same plot. This plot is shown in Fig. 2a, and it shows that the slope of the  $da/dN$  versus  $\Delta K$  curve increases as soon as the  $K_{Ic}$  value starts to decrease in the fracture ductile to brittle transition. However, one would expect a higher slope of the  $da/dN$  curve to occur in the lower transition or lower shelf, where the cleavage fracture is not first preceded by ductile crack growth in fracture tests. Indeed, a number of authors have observed that the FDBT occurs low in the fracture transition or even in the lower shelf. For example, it is mentioned by Baotong and Xiulin (1991) that the transition usually occurs at a lower temperature than the Fracture Appearance Transition Temperature (FATT). Furthermore, Stephens et al. (1980) indicate that the FTT tends to be lower than the Nil-Ductility Temperature or the Charpy transition temperature (though the authors leave the precise definition of Charpy transition temperature vague). Moody and Gerberich (1979) contribute by plotting the Paris exponent versus the test temperature minus the fracture DBTT. Their plot is shown in Fig. 2b. Their plot shows a clear relationship between the Paris exponent and the relative position of the DBTT over a range of the DBTT $\pm$ 50°C. This paper makes the first steps to resolving some of the ambiguities as to where the FDBT is relative to the fracture transition curve.

## 2. Materials

Two materials are considered. The first is an S980 grade plate with a thickness of 25 mm. The second is an S460 grade plate with a thickness of 40 mm. Some key properties of both materials are presented in Table 1. In both cases, the materials were assessed in the un-welded condition. The yield strength ( $\sigma_y$ ) and ultimate tensile strength (UTS) that are presented in Table 1 came from the material certificates. The  $T_{27J}$  and FATT values are described in the following section.

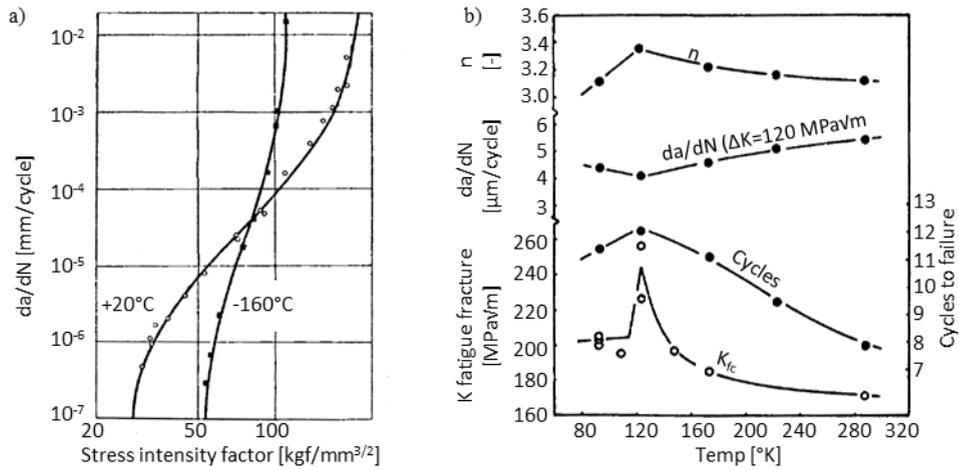


Fig. 1. a) A  $da/dN$  versus  $\Delta K$  curve for a low-carbon steel above and below the FTT (from Stephens and Chung, 1980); b) Several fatigue parameters for a 5.5% Ni steel showing increasingly favorable performance as temperature decreases until a critical temperature (presumably, the FTT), and then becoming markedly less favorable. (From Stephens and Chung, 1980)

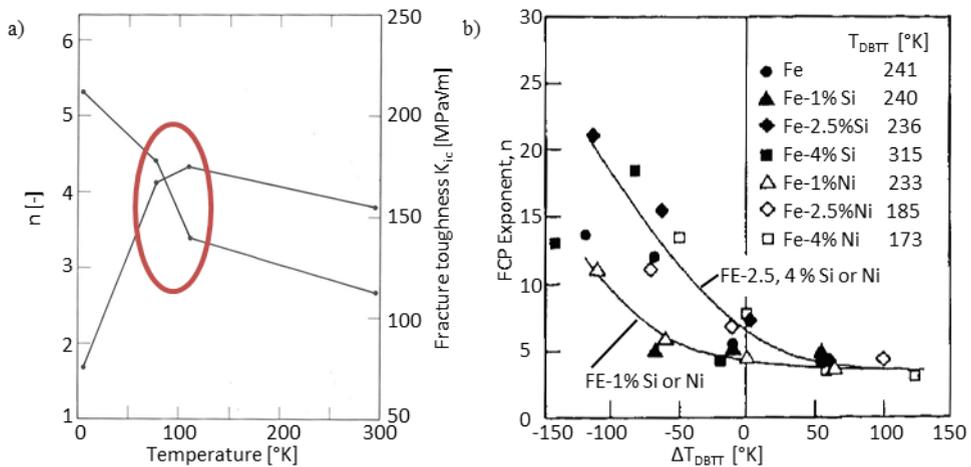


Fig. 2. a) The Paris law exponent and the fracture toughness plotted against temperature, showing a relationship between the fracture and fatigue ductile to brittle transitions for 9% Ni ferritic steel (from Tobler and Cheng, 1985); b) The Paris exponent plotted against the test temperature minus the fracture Ductile to Brittle Transition Temperature (DBTT) for iron and iron binary alloys (from Moody and Gerberich, 1979). This shows a relationship between the temperature at which fracture and fatigue undergo their respective transitions.

Table 1. Summary of key material parameters

Name	Thickness [mm]	$\sigma_y$ [MPa]	UTS [MPa]	T27J [°C]	FATT [°C]
S980	25	986	1039	-65	-31
S460	40	479	566	-79	-50

### 3. Fracture data

The full ductile to brittle transition curve was measured with Charpy impact tests for both materials according to ISO 148. The Charpy energy transition curve is presented in Fig. 3. The Charpy energy transition curve was fit with a  $\tanh$  function according to the least squared fit method, and the  $\tanh$  function was used to evaluate the temperature

at which the Charpy energy is 27J (the  $T_{27J}$  value) that is presented in Table 1. The surface appearance was recorded according to the method of comparison with a chart, but it is not presented here. The surface appearance data was fit with a  $\tanh$  function according to the least squared fit method, and it was used to find the FATT (Fracture Appearance Transition Temperature, or temperature at which 50% of the fracture surface has the cleavage mode) that is presented in Table 1. CTOD tests were performed according to BS 7448-1 in the SENB (Single Edge Notched Bending) configuration, and it is also presented in Fig. 3, where data is available.

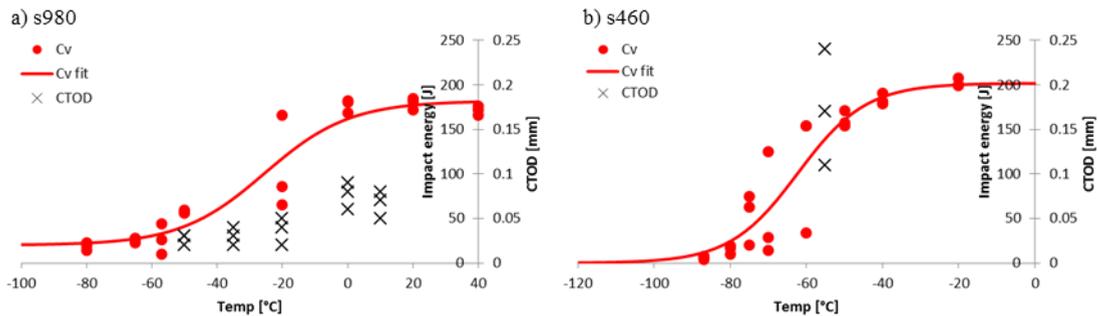


Fig.3. Charpy transition curves with CTOD data superimposed for the (a) S980 mater and (b) the S460 material (right).

#### 4. Fatigue data

Testing of the fatigue crack growth rate was performed according to ASTM E647-08. For all specimens, the full-thickness SENB configuration with an R ratio of 0.10 was used. The crack length was measured to the nearest 0.001 inches (0.0254 mm) by the DC potential drop method, and the  $da/dN$  was calculated according to the incremental polynomial method. A sinusoidal wave form of 5 Hz was used. In all cases, the experiment was started with an intermediate stress intensity range (15-17  $\text{MPa}\sqrt{\text{m}}$ ). The specimen was fatigued at that stress intensity for a number of cycles. A lower stress intensity range was chosen, and it was fatigued at that range. The process was repeated until sufficient data to estimate the  $\Delta K_{th}$  was obtained. After that, a new test was started at a stress intensity in the range of 4-6  $\text{MPa}\sqrt{\text{m}}$ , and the stress intensity range was progressively increased in the same way that it was lowered. Ascending and descending tests were carried out at room temperature (RT) and  $-70^\circ\text{C}$  for both materials. The results of are shown for both materials in Fig. 4. This data shows that the low temperature seemed to increase the fatigue crack growth rate for the S980 material but decrease it for the S460 material.

#### 5. Discussion

For the S980 material, room temperature corresponded to the upper shelf, and  $-70^\circ\text{C}$  was on the lower shelf (below both  $T_{27J}$  and the FATT). This material showed an acceleration of the crack growth rate with lower temperature. For the S460 material, room temperature corresponded to the upper shelf, and  $-70^\circ\text{C}$  was in the transition of the material. This is seen both by the Charpy ductile to brittle transition curves presented in Fig. 4 and because  $-70^\circ\text{C}$  is between the  $T_{27J}$  and the FATT. The S460 material experienced a lower crack growth rate with the lower temperature.

The results of the S980 material show that fatigue crack growth is accelerated at a temperature lower than both the FATT and the  $T_{27J}$ . The results of the S460 material show no crack growth acceleration for the lower temperature, which is indeed lower than the FATT, but still higher than the  $T_{27J}$ . Therefore, based on the results of both materials together, there is preliminary evidence that the  $T_{27J}$  may be a better indicator of fatigue ductile to brittle transition than the FATT, which had been suggested by Baotong and Xiulin (1991). However, more research is necessary to determine the statistical significance of these findings, what the full consequences are, and further refine the temperature of the fatigue ductile to brittle transition relative to the fracture ductile to brittle transition.

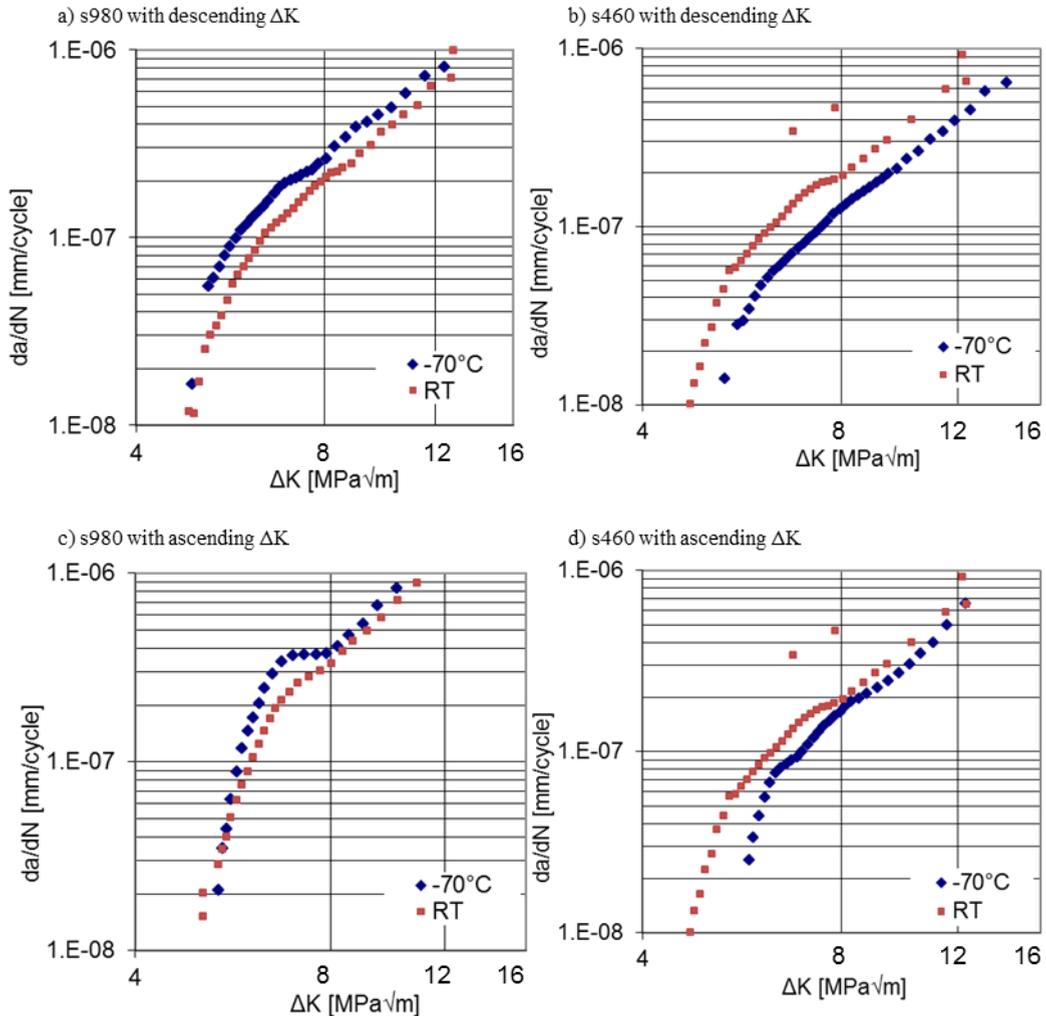


Fig. 4. Room temperature fatigue data compared to low-temperature fatigue data for descending values of  $\Delta K$  (a and b) and ascending values of  $\Delta K$  (c and d). These were calculated for S980 material (a and c) and for S460 material (b and d).

The work of Tobler and Cheng (1985) showed a change in the slope of the  $da/dN$  versus  $\Delta K$  curve that correlated with the upper portion of the transition for  $K_{Ic}$  testing; see Fig. 2a. Tobler and Cheng (1985) presented results in terms of  $K_{Ic}$  results, and this paper presents them in terms of Charpy results, so no specific comparison can be made with respect to the relationship between the fracture and fatigue ductile to brittle transition curves. While no specific comparison can be made, it is notable that the results of Tobler and Cheng (1985) present a change in crack growth in the upper transition, and the results presented in this paper show an accelerated fatigue crack growth rate only on the lower shelf. Specifically, it can be seen that the S980 steel had an accelerated crack growth rate at a lower shelf temperature, but the S460 steel (still in the transition but below the FATT) did not yet have an accelerated crack growth rate. Considering that fracture specimens tend to feature ductile tearing before the onset of cleavage fracture in the transition region and that fatigue cracks grow by very small increments, one might expect that accelerated fatigue crack growth due to cleavage would only occur very low in the transition or on the lower shelf. This intuitive explanation is more consistent with the data presented in this paper than that of Tobler and Cheng (1985). The belief that the FDBT occurs low in the transition is also consistent with the suggestion by Baotong and Xiulin (1991) that it is below the FATT and those of Stephens et al. (1980), who believe that it is below the Nil-Ductility Temperature and the Charpy transition temperature.

The low temperature considered in this study was very low for air temperatures ( $-70^{\circ}\text{C}$ ) and therefore impractical for structures exposed to the outside environment. However, the main goal was to explore the relationship between the fatigue ductile to brittle transition and that of fracture. It is noted that the ductile to brittle transition occurs at a much higher temperature (often in the range of low ambient air temperatures) for welds. Therefore, this affect may become important for civil, offshore, and maritime structures if welded structures are considered. The preliminary evidence presented here shows that the fatigue ductile to brittle transition occurs at a temperature below  $T_{27J}$ , which means that current design practices would be safe. While this data is preliminary, more tests are currently planned.

## 6. Conclusions

The Paris regime and threshold stress intensity range ( $\Delta K_{th}$ ) have been measured for S460 and S980 structural grade base plate material at room temperature and  $-70^{\circ}\text{C}$ . These results support the conclusions found in the literature that the fatigue crack growth rate decreases with lower temperatures until the FDBT, and then it increases again. Contrary to the example of Fig. 1a, it appears that temperatures below the FDBT also cause a lower  $\Delta K_{th}$ . From this data set, it would appear that the FDBT is lower than the  $T_{27J}$ , thus very low in the fracture ductile to brittle transition or on the lower shelf. While the temperatures considered in this paper were relatively low compared to atmospheric air temperatures, this may point to a problem in Arctic application of steels for welds or other steels that present higher ductile to brittle transition temperatures. More research is required to establish if this effect is important for structures that have a sufficiently low  $T_{27J}$  and what the consequences are.

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## References

- ASTM (2008) "ASTM E647-08: Standard Test Method for Measurement of Fatigue Crack Growth Rates" ASTM International, West Conshohocken, PA, USA.
- Baotong, L and Xiulin, Z (1991) "Predicting fatigue crack growth rates and thresholds at low temperatures. *Materials Science and Engineering*," A148: 179-188.
- BSI (1991) "BS 7448-1: 1991: Fracture mechanics toughness tests – Part 1: Method for determination of  $K_{Ic}$ , critical CTOD and critical  $J$  values of metallic materials." British Standards Institute.
- International Standards Organization (2009) "ISO 148-1: Metallic materials – Charpy pendulum impact test – Part 1: Test method," ISO, Geneva, Switzerland.
- Kitsunai, Y. 1985. Fatigue Crack Growth Behavior in Mild Steel Weldments at Low Temperatures. *Fatigue at Low Temperatures*, ASTM STP 857, edited by Stephens, American Society for Testing and Materials, Philadelphia.
- Moody, NR and Gerberich, WW (1979) "Fatigue Crack Propagation in Iron and Two Iron Binary Alloys at Low Temperatures," *Materials Science and Engineering*, 41, pp 271-280.
- Stephens, RI, Chung, JH, Glinka, G (1980) "Low Temperature Fatigue Behavior of Steels – A Review," SAE Technical Paper 790517, 1979, doi:10.4271/790517.
- Tobler, RL and Cheng, YW (1985) "Midrange Fatigue Crack Growth Data Correlations for Structural Alloys at Room and Cryogenic Temperatures." *Fatigue at Low Temperatures*, ASTM STP 857, edited by Stephens, American Society for Testing and Materials, Philadelphia.