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Fracture Testing of Energy Materials for Application in Electrical Engineering

Abstract. *The aim of this paper is to analyse the fracture behaviour of energy materials for application in electrical engineering, and also to determine the relevant parameters that contribute to higher critical values of fracture toughness. The quality assessment of high temperature resistance steel used for pressure vessels of innovative construction of a linear oscillatory synchronous generator designed to be used in a free-piston Stirling engine was determined. For all testing of pressure vessel and the steel specimens the standard test procedures were used.*

Streszczenie. *Celem artykułu jest analiza zachowań niszczących materiały energetyczne w elektrotechnice, jak również określenie istotnych parametrów, mających wkład w wyższe wartości krytyczne wytrzymałości na złamania. Przeprowadzono ocenę jakości stali odpornej na wysokie temperatury używanej w naczyniach ciśnieniowych innowacyjnych konstrukcji generatorów synchronicznych do beztłokowego silnika Stirlinga. W celu wykonania testów naczyń ciśnieniowych oraz próbek stali użyto standardowych procedur badawczych.* ***(Testy wytrzymałościowe materiałów energetycznych stosowanych w elektrotechnice)***

Keywords: fracture test, energy materials, Stirling engine, synchronous machine, electrical engineering
Słowa kluczowe: test wytrzymałościowy, materiały energetyczne, silnik Stirlinga, maszyna synchroniczna, elektrotechnika

Introduction

The basic operation topology of Stirling engine is implemented when the engine receives thermal energy and converts it into mechanical movement. Conversion is possible with three different types of Stirling engine, alpha, beta or gamma type. All three types need an external source of thermal energy. It can be provided by different conventional energy sources or renewable energy sources in applications with external combustion. Stirling engine is most often used in micro Combined Heat and Power (μCHP) applications, which are mostly based on renewable energy sources. Versions with mirrors, using solar energy, and versions with external combustion of e.g. biomass, are used.

A pressure vessel is a component of Stirling engine as container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. Pressure vessels can be dangerous, and fatal accidents have occurred in the history of their development and operation, thus in present research determination of quality assessment of high strength steel used for pressure vessel design is necessary [1-4]. Pressure vessel of prototype Stirling engine operated under 210 ^{O}C as a hot cylinder and it is made by high temperature resistance steel 10CrMo10V5 and welded together with two undermached welds (Fig. 1). In the assessment of pressure vessels as a welded structures the consideration of both strength mismatching and transferability cannot be avoided. In this paper we first review the effects of the mismatch observed in pressure vessel with two welded joints on strength and fracture, and show that the plastic constraint due to strength mismatching plays an important role in fracture-initiation behavior for ductile and brittle cracks which appeared in the pressure vessels [3]. Finally, for all testing of pressure vessel and the steel specimens the standard test procedures were used for determining the weldability and quality assessment of high strength steel.

The fracture performance of welds is affected by various factors and their complex combined incidence, the following two controlling factors of brittle fracture strength of welds are essential: (I) the embrittlement in HAZ and the weld metal in the vicinity of pre-existing defects, and (II) inhomogeneity in strength, such as hardening and softening in HAZ and matching between the weld metal and base metal. The various factors control the embrittlement in welds (Fig. 2). Mechanical heterogeneity is also a result of the same kind of controlling factors, [2, 3]. In particular, as mentioned above, the embrittlement results in problems with the existence of local brittle zones (LBZs) in multi-pass welds.

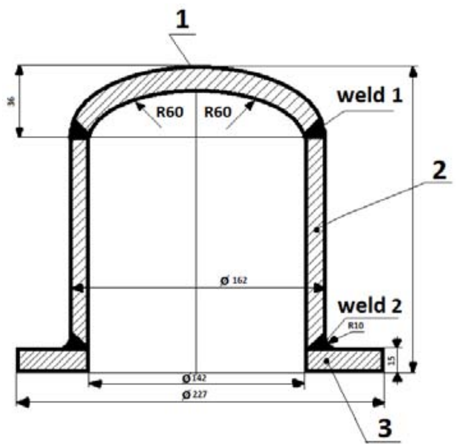

Fig. 1. Pressure vessel of prototype of Stirling engine operated as a hot cylinder with torispherical head, welded together with two undermached welds.

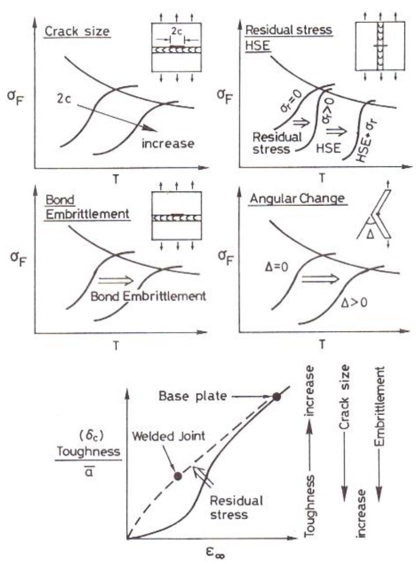

Fig. 2. Various controlling factors on fracture performance of energy materials.

Strength Mismatching in Heterogeneous Materials and its Effect on Fracture

Heterogeneous regions as a welded joints inevitably have some special characteristics which make them different from the base metal. The most important characteristics in terms of the fracture behavior of welded joints are change due to local plastic deformation resulting from the weld's thermal history, metallurgical and mechanical changes and existence of a geometrical discontinuity. In these characteristics, the mismatching in welded joints sometimes plays an important role in the fracture-initiation behavior in terms of both fracture toughness and the deformation behavior of cracked joints. Typical sizes of brittle zones in common multi-layered welded joints are in the sub-millimeter range. This is the reason for the local brittle zone (LBZ) problem [5]. In the common-fracture mechanics concept, the fracture parameters including the applied stress and geometrical conditions such as crack size have been adopted for evaluating the fracture behavior of a cracked body. The critical value of the parameters is called the fracture toughness. The fracture toughness obtained by using a certain method is called a material constant. The upper part of Figure 3 shows the conventional fracture-mechanics concept for evaluating whether the critical condition for brittle fracture occurs or not. In other words, the possibility of the occurrence of a fracture can be evaluated by comparing the magnitude of both values.

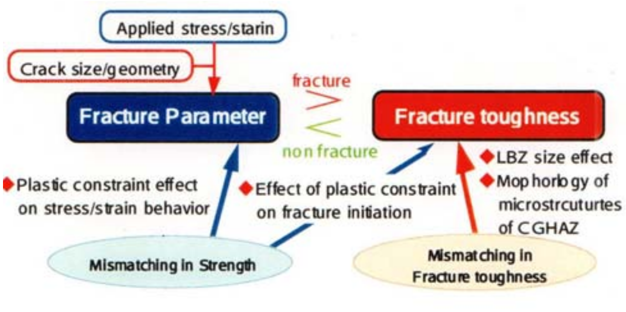

Fig. 3. Effect of mismatching on fracture-mechanics approach

The mismatching in both strength and fracture toughness observed in welded joints affects both fracture parameters and critical fracture values, as shown in Figure 3. The strength mismatching mainly influences the fracture parameters that control the stress-strain behavior.

Consequently, it is most important to find an appropriate parameter that controls stresses and strain in the vicinity of a crack tip regardless of the degree of strength mismatching and the geometry of the specimens.

If the common parameters such as the J integral and the crack-tip opening displacement (CTOD) - δ , are adopted, the critical toughness values such as J_c and δ_c are apparently influenced by the strength mismatching through the change of the plastic constraint [3].

The existence of the mismatching in strength is the cause of the transferability problem with fracture toughness data obtained by conventional toughness tests in the evaluation of the fracture performance of practical structures. On the other hand, the problem related to mismatching in fracture toughness consists mainly in the question of how to evaluate the fracture toughness of welded joints with LBZs.

In ductile crack initiation, the plastic constraint should influence the critical situation of ductile crack initiation due to the existence of strength mismatching. It is important to find appropriate transferable fracture criteria by considering the change in the plastic constraint due to the existence of typical characteristics for welded joints.

The plastic constraint in the lower strength region adjacent to hard materials plays an important role in the static and fracture strength behaviors.

Experimental Procedure

The crack tip opening displacement (CTOD) test was developed in the U.K. during the 1960s. The first draft for the methods for CTOD testing were prepared as British Standard DD19 (1972). The CTOD test specimen (Fig. 4) contained a fatigue-pre-cracked notch and was loaded in a three-point bending to fracture.

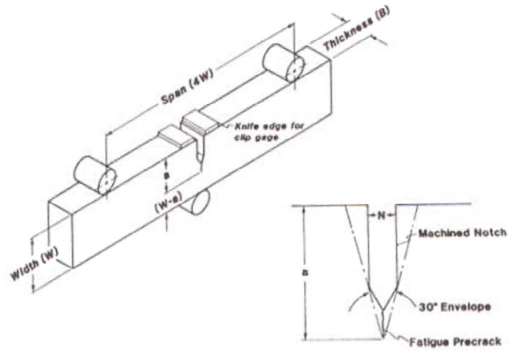

Fig. 4. Three-point bending CTOD test specimen.

The critical CTOD was obtained via the clip-gauge displacement *Vg* measured across the notch mouth by using a certain converting equation. In 1979, the above testing method was specified as BS 5762 [1]: British Standard Methods for Crack Opening Displacement (COD) Testing (1979). In the current British Standard, the CTOD be calculated from the new equation, where the first term is the elastic component of CTOD, the second term is the plastic component, and *Vp* is the plastic component of the clip-gauge displacement. The stress intensity factor for the elastic CTOD calculation is obtained from the relationship, where *P* is the applied load, and *Y* is the stress intensity coefficient given as a function of the crack length-to-width ratio.

In this standard, the type of critical CTOD was clearly defined according to the nature of the observed fracture event. The four kinds critical CTOD, i.e. δ_c, δ_u, δ_m and δ_i, are measured (Fig. 5). At low temperatures, the steel fails by cleavage and δ_c is measured empirically.

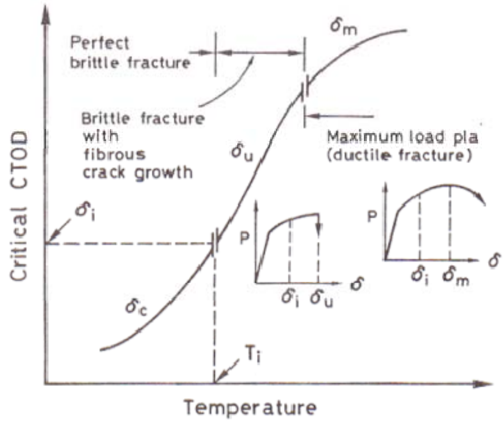

Fig. 5. Definition of critical CTODs in BS 5762.

As the test temperature increases, cleavage becomes less favorable and the fracture toughness increases. The fracture mode changes to microvoid coalescence, and the crack grows in a stable manner. δ_i is defined as the value of CTOD at the onset of tearing. At temperatures slightly above the fracture mode change, stable tearing can be followed by unstable cleavage. In this case, the critical measure is δ_u at the instability point. On the upper level of toughness, the steel reaches a point of plastic collapse when the work-hardening cannot keep pace with the decrease in ligament area caused by stable crack growth. δ_m is then measured at the point of maximum load in a bend test.

The fracture toughness of heterogeneous regions of HSLA steels was evaluated using a standard static Crack Tip Opening Displacement (CTOD) test at the Geesthacht Research Center [5]. All CTOD tests were conducted using Zwick (20t) and Schenk (100t) testing machines. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was -10°C, following the recommendation of the OMAE (Offshore Mechanics and Artic Engineering) association. For CTOD testing, the single specimen method was used. To evaluate the fracture toughness of under-matched welded joints, standard bending specimens, [2-4] with deep (a/W = 0.5) and shallow (a/W = 0.25 - 0.4) notches in the weld metal and HAZ were used, [1,5]. For all specimens, fatigue pre-cracking was carried out with the Step-Wise High R ratio method (SHR) procedure, [5]. During the CTOD tests, the potential drop technique was used for monitoring stable crack growth, [1]. The load line displacement (LLD) was also measured with a reference bar to minimise the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with BS 5762, [1], and also directly measured using a clip gauge on the specimen side surfaces at the fatigue crack tip over a gauge length of 5 mm (Fig. 6), [5].

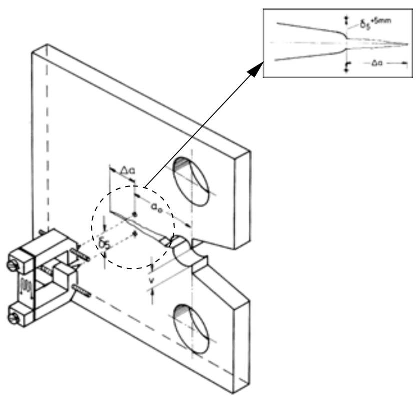

Fig. 6. Direct measurement of CTOD values at crack tip of fracture mechanics specimen

For fracture mechanics, standards for the treatment of welded joints suitable are not yet available, but different procedures exist, [1,5], recommending different ways of fatigue crack positioning in weld joints. Different positions and depths (a/W) of fatigue cracks in welds were chosen, taking this into account.

Dynamic tensile tests and numerical simulations have been performed for the above under-matched weld joint by using various strain rates and test temperatures. The effects of the relative thickness of the under-matched joints on yield stress and tensile strength are shown in Figure 7. The effect of relative thickness on the tensile strength of under-matched joints is the same as in our previous studies [3] even under dynamic loading. The strength of the welded joint approaches that of the base metal when the thickness of the soft interlayer becomes smaller, and this tendency does not depend on strain rate. On the other hand, the plastic constraint must affect the fracture behavior of welded joints with under-matched layers. The effects of temperature and strain rate on the crystallinity of under-matched joints are shown in Figure 8. The ductile-to-brittle transition curve shifts to high temperatures when the relative thickness becomes smaller, and it does not depend on strain rate.

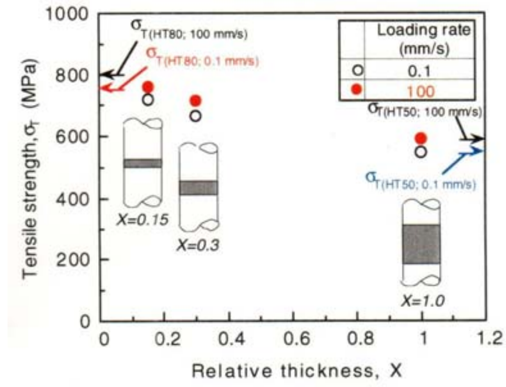

Fig. 7 Relationship between tensile strength and relative thickness in undermatched joints.

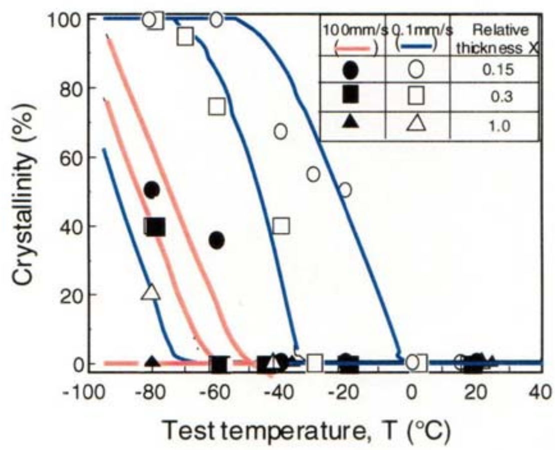

Fig. 8. Comparison of ductile-to-brittle transition behavior in undermatched joints.

This phenomenon is considered to be the reason why the plastic constraint in the center of the cross-section in the soft interlayer affects the fracture initiation. Furthermore, the transition curve under dynamic loading is located at the lower temperature side compared to the curve for static loading.

This phenomenon seems to contradict conventional results. The shift to lower temperatures under dynamic loading compared to static loading can be explained by the curves in Figure 9. The ductile-to-brittle transition curve under dynamic loading receives not only the shift to higher temperatures due to the increase of strain rates but also a shift to lower temperatures due to temperature increases resulting from plastic deformation.

In order to evaluate the fracture performance of welded joints with a strength mismatch, the appropriate criteria for the change of plastic constraints have to be clarified.

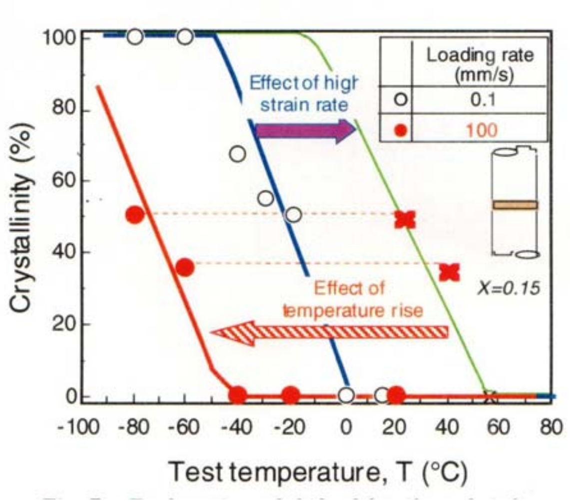

Fig. 9. Explanation of shift of ductile-to-brittle transition temperature in undermached joints.

It is well known that ductile crack initiation is mainly controlled by the critical strain, which is strongly influenced by the stress triaxiality at the fracture initiation point. The criteria for ductile crack initiation are widely used in situations where the equivalent plastic strain reaches the critical value as a function of stress triaxiality. The applicability of the above concept has been confirmed so far by using notched specimens for various structural steels. In the present experiments, the applicability of the two-parameter (equivalent strain versus stress triaxiality) criterion has been clarified in the case of ductile crack initiation for welded joints with a strength mismatch as well as for cracking under dynamic loading. Figure 9 shows the relationship between the equivalent plastic strain and the stress triaxiality in fully ductile fractured specimens under static and dynamic loading for both homogeneous and under-matched weld joints. Also shown are the results for homogeneous round bars with circumferential notches.

Conclusions

The main aim of this paper is to analyse the quality assessment of high temperature resistance steel (10CrMo10V5) used for pressure vessels of innovative construction of a linear oscillatory synchronous generator designed to be used in a free-piston Stirling engine. Pressure vessels can be dangerous, and fatal accidents have occurred in the history of their development and operation, thus in present research determination of quality assessment of high strenght steel used for pressure vessel design is necessary.

Experimental results shown that ductile crack initiation is mainly controlled by the critical strain, which is strongly influenced by the stress triaxiality at the fracture initiation point. The criteria for ductile crack initiation are widely used in situations where the equivalent plastic strain reaches the critical value as a function of stress triaxiality.

Finally, the designed hot cylinder pressure vessel can be used for operation of prototype Stirling engine.

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