SIGNIFICANCE OF POP-IN FRACTURE IN HIGH NICKEL CRYOGENIC STEEL WELDMENTS

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ABSTRACT

In fracture toughness tests on the heat affected zone in welded joints of high nickel steels for cryogenic application, pop-in fracture takes place often. For checking whether catastrophic fracture can result directly from the pop-in fracture or not, a series of well designed wide plate test was conducted on welded joints of 5.5 percent nickel steel.
From this investigation the pop-in fracture in cryogenic steel weldments is considered not to be significant in actual structures.

KEYWORDS

Brittle fracture, Design criterion, Pop-in fracture, Cryogenic steel, LNG storage tank, Wide plate test.

INTRODUCTION

Fracture toughness tests by Tenge and Solli (1971, 1973), Sarno, Bruner and Kampschaefer (1973), Murayama, Pense and Staut (1976) on welded joints of 5 to 9 percent nickel steels for LNG storage tanks revealed that "pop-in fractures" often took place at considerably low stress intensity, especially when the test was conducted on the heat affected zone of the joints. The stress intensity factor at the pop-in was in some case as low as 70 $MN \cdot m^{-3/2}$ or 0.02mm in terms of COD (crack opening displacement). For a long time, researchers (Pense and Staut, 1975; McHenry and Reeds, 1977; Sarno, Bruner and Kampshaefer, 1973) have argued the significance of this type of fracture, sometimes applying R-curve concept or examining the fracture surface. Non the less the evaluation of the pop-in fracture does not seem to be established from the viewpoint of practical application as stated in the following.
For the evaluation of this kind of fracture phenomenon, the basic design concept for prevention of catastropic fracture should be examined in detail. Although the "leak before failure concept" is a typical example of such a concept and has been applied to the design of LNG storage tanks (Tenge and Solli, 1971, 1973; KMN comittee, 1973; Sakai and co-workers, 1975), pop-in type fracture has never been analyzed deeply from the view point of the design concept. In this report, several basic fracture design concepts are presented and the pop-in fracture is analyzed by means of one of the basic concepts.

DESIGN CONCEPT AGAINST CATASTROPHIC FRACTURE

Various concepts for fracture safe design have been proposed for cryogenic storage tanks. From the viewpoint of avoiding a catastrophic fracture the next four concepts seem to be practical when industrial steel structures are considered.

(A) No initiation by means of proof of no defect in the structure
(B) No initiation from cracks tolerated by the structure
(C) No propagation based on the arrest of short cracks.
(D) No propagation based on the arrest of long cracks.

The term of "initiation" here means onset of unstable crack propagation and the term of "no propagation" means no crack propagation leading to a catastrophic failure.

With the concept (A) the present authors intend to mention the traditional design method which relies on the experiences in the past. Very careful non-destructive testing should be required in this concept in the sense that there is no fracture toughness assessment available. Concept (B) is based on fracture mechanics which consists of fracture initiation toughness and stress analysis together with the appropriate non destructive testing to detect defects longer than the allowable crack size determined by fracture mechanics. In the no propagation concept based on the arrest of short cracks, a running brittle crack, even though it originates in a brittle zone, is aimed to be arrested in a high toughness zone before it becomes a very long crack. This concept requires no possibility of a long crack formation in any form, such as a brittle fracture along a brittle zone of welded joint.
Suppose that a long brittle crack is created along a welded joint or in a brittle base plate in an accidental case. Criterion D aims at arrest of these kinds of long cracks by placing a very tough plate, a thick plate, discontinuous joints as rivet joints or any another effective measure at adequate locations of both ends of the long crack. Although tough plates may arrest the brittle fracture once, the possibility of reinitiation and propagation of a brittle or even ductile fracture due to subsequent increment of stress intensity caused by the stress redistribution should be proved not to exist.
Concept B, when combined with the condition that it permits a through thickness defect, concept C and concept D, when the structure is designed not to collapse despite of the long crack creation, are all considered as kinds of the leak before failure concept. In the following paragraphs practical investigation is made whether any one of the three criterions can be applied to the low stress intensity pop-in in the welded joint of high nickel steel.

FRACTURE TOUGHNESS OF HAZ OF 9 PERCENT NICKEL STEEL WELDMENTS

Actual heat affected zone (HAZ) of a welded joint is highly heterogeneous in the microstructures and toughness because of the various complex thermal cycles by the welding which obstruct measurement of the minimum value of fracture toughness in a simple series of test. The minimum value is controlled by the most embrittled region. In order to know the real fracture toughness of the embrittled region investigations are often carried out on specimens subjected to synthetic thermal cycles similar to the heat affected zone of the relevant materials. Table 1 shows the COD test results on the synthetic HAZ of two heats of nine percent nickel steel. This table summarizes the COD value at the maximum load in load-clip gauge displacement curves as shown in Fig. 1. From this result it is clear that the steel has considerably low fracture toughness in the HAZ compared with the base plate.

Table 1 Result of COD test on synthetic HAZ of 9% nickel steel plate

Condition of thermal cycle		Maximum load COD value at −165℃ (mm)	
Peak temperature of the 1st cycle, ℃	Peak temperature of the 2nd cycle, ℃	Heat A	Heat B
1400	——	0.037, 0.074	0.089, 0.130
1200	——	0.048, 0.072	0.194, 0.340
1000	——	0.052, 0.083	0.170, 0.283
1400	1000	0.085, 0.135	0.151, 0.193
1400	800	0.070, 0.125	0.065, 0.137
1400	650	0.103, 0.172	0.055, 0.144
1400	500	0.082, 0.111	0.069, 0.132
1400	250	0.045, 0.099	0.067, 0.422

Note
1) COD test specimen size: B=10mm, W=20mm, Span=80mm.
2) Cooling rate for synthetic thermal cycles: Equivalent to manual arc welding with the heat input of 35kJ/cm.
3) COD values in the table are the minimum and the maximum in five test results.

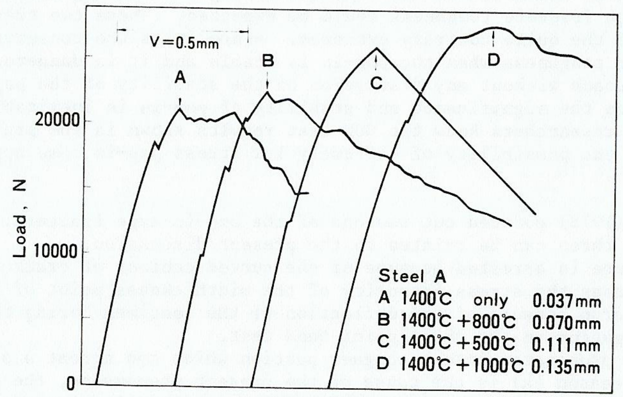


Fig. 1. Load-displacement curve in COD test on synthetic HAZ of 9% nickel steel.

Figure 2 illustrate examples of load-clip gauge displacement records in the COD test on the welded joint of 9 percent nickel steels. Almost all of the records for 5.5 percent nickel steels and nearly one tenth of those for 9 percent nickel steels showed the pop-in as shown in the figure. Indication of the pop-in was also found on the fracture surface of the specimen except for the very low stress intensity pop-in at which discontinuity in the record was usually very small. This kind of pop-in behaviour can be easily expected, since the fracture toughness of the HAZ itself is considerably low as shown above.

NECESSITY OF REALISTIC WIDE PLATE TESTS

The low stress intensity pop-in has been argued by many researchers. Tenge and Solli (1971, 1973) used the pop-in fracture toughness for safety assessment

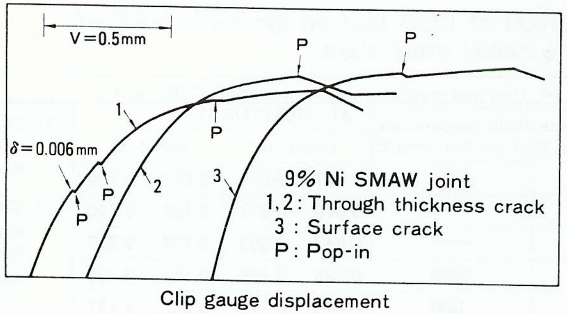


Fig. 2. Load-displacement curve in COD test on 9%Ni steel welded joint.

whereas Sarno, Bruner and Kampschaefer (1973) applied the R-curve analysis to the phenomenon of intermittent and consequtive pop-ins and emphasized that comparatively high fracture toughness could be expected. These two treatments would be considered the quite contrary extremes. Since it is too conservative to adopt the pop-in toughness when the pop-in is stable and it is dangerous to use the R-curve approach without any discussion on the stability of the pop-in, the investigation on the significance and stability of pop-in is inevitable. This is very true when researchers knew the COD test results shown in the previous paragraph, and admit the possibility of extremely low stress pop-in some appropriate condition.

Harrison (1978) pointed out reasons of the pop-in type fracture. Among them the following three can be related to the present discussion.

a) Fracture is arrested because of the curved contour of crack front which decreases the stress intensity of the midthickness point of the crack tip.
b) Load drop because of the deflection of the specimen during the crack propagation in the three point bend test.
c) Crack propagates into a tougher portion which can arreat a short crack.

When the reason (a) is the cause of the present phenomenon, the pop-in fracture toughness should be taken into account as the critical value for the structure where cuclic loading is applied and the shear lip like ligament aroung the pop-in could be fractured by fatigue. In such case, possibility exists for re-initiation of brittle crack before detection. When (b) is the reason, the fracture arreat such as a pop-in can not be expected in actual structures in which load drop caused by the small deformation such as pop-ins is negligiblly small. If the reason (c) is the cause investigation should be carried out to confirm that the fracture is arrested regardless the load condition. Arrest ability depends not only on toughness itself but also on load condition which may be quite different between a small test piece and a real structure with complex weld joints and residual stress field.
For the investigation on any item, the overall conditions including applied stress, residual welding stress, accuity of the existing crack, plate thickness and so on should be similar to those in the actual structure. Present authors employed a series of well designed wide plate tests to answer these questions and solve the problems.
In wide plate test, load drop during crack propagation is negligible when the running brittle crack is shorter than one fifth of the specimen length, since the elastic wave originated at the pop-in can not travel roung the specimen end and to the fracturing part in that condition. If the cyclic loading is applied on the specimen and fractures the shear lip like ligament, the stablity of the pop-in can be investigated. Examination of crack path is, of course, one of the main interest in the present wide plate tests.

DESIGN OF WIDE PLATE TEST SPECIMEN

Wide plate test specimens employed in the present investigation are illustrated in Fig. 3. Specimen A is designed so that a pop-in takes place at a low applied stress close to that in actual structures and a realistic condition for fracture propagation is obtained. Specimen B has a surface crack along the fusion line of the welded joint. This specimen was designed to investigate whether a pop-in from a long surface crack can penetrate a plate thickness or not. For all the specimens a fatigue crack was developed at the tip of the machined notch. For

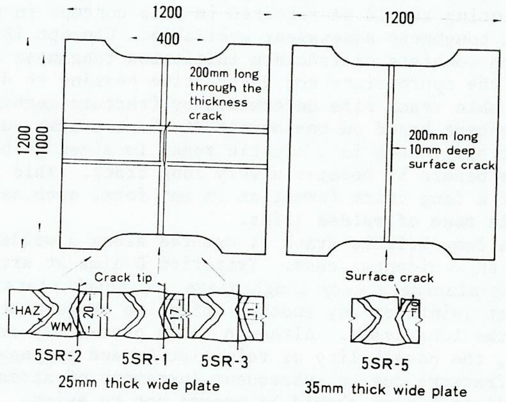


Fig. 3. Wide plate specimen for brittle fracture and cyclic loading.

this investigation a 5.5 percent nickel steel plate was applied. This choice was made since a low stress pop-in could more easily take plate in the lower nickel steel which was known from numerous COD tests on the welded joints of 5.5 and 9 percent nickel steels.

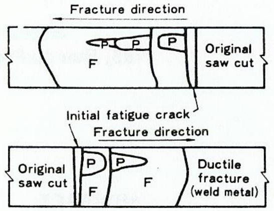
WIDE PLATE TEST RESULTS

The test procedures for specimen number 5SR-3 is described in detail as an example. This specimen was at first given a cyclic loading with the maximum stress of 86 N/mm^2 for fatigue crack development at the tip of machined notch. Then the specimen was cooled down to −170°C and an increasing load was applied. Then the gross (nominal) stress, σ_g, reached 144 N/mm^2 the first pop-in took place. Immediately after this, the specimen was unloaded and cyclically loaded with the maximum stress of 144 N/mm^2 at the same temperature. During this cyclic loading, no fracture was observed except fatigue crack propagation. After several tousands of load cycles a monotonic increasing load was applied up to the next pop-ins took place. Specimen 5SR-3 showed pop-ins at σ_g of 189, 236 and 256 N/mm^2 sequentially and was unloaded immediately after the last pop-in. Furthermore this specimen was cyclically loaded with the maximum stress of 256 N/mm^2. During this loading there was no crack extension except fatigue crack growth. Finally tensile test to fracture was carried out and additional three pop-ins were observed at σ_g of 409 435 and 469 N/mm^2. At final fracture σ_g and net section stress were 499 and 789 N/mm^2 respectively. After the test the fracture surface was investigated and the result is illustrated in Fig. 4. As seen in this figure the trace of pop-in is very clear but the identification of the individual pop-in is very difficult. Fatigue crack development around the pop-ins is clear.

Table 2 Result of the wide plate test on 5.5% nickel steel (Specimen No 5SR-3)

Step and test item	Result
1st step: Tensile test at -170℃	Pop-in at σ_g=144 K=83 Unloaded after this pop-in
2nd step: Cyclic loading at -170℃	σ_{max}=144 K=83 6395 cycles No pop-in observed
3rd step: Tensile test at -170℃	Pop-in at σ_g=189 K=119 Pop-in at σ_g=236 K=149 Pop-in at σ_g=256 K=161 Unloaded after the last pop-in
4th step: Cyclic loading at -170℃	σ_{max}=256 K=161 1900 cycles No pop-in observed
5th step: Tensile test at -170℃	Pop-in at σ_g=409 K=305 Pop-in at σ_g=435 K=325 Pop-in at σ_g=469 K=350 Final fracture σ_g=499 σ_{net}=789 (K=373 invalid)

σ_g : Gross stress (N/mm^2), K : Stress intensity factor (MN·m$^{-3/2}$)



P : Pop-in(s),
F : Fatigue crack propagation

Fig. 4. Fracture surface at the both tips of original crack for specimen 5SR-3.

Similar test procedure was applied to other three specimens. The results of those, as shown in Table 3, were much the same as that of the first example. The specimen with a surface crack also showed a pop-in which propagated by only 2mm in the short transverse direction. In the subsequent tensile test, this specimen fractured at the weld metal at a stress close to the tensile strength of the weld metal. Summarizing the results of these wide plate test, the following points become clear.

1) Also in the wide plate test, pop-ins took place and the size of the pop-ins were nearly the same as those in COD tests.
2) Consecutive formation of pop-in did not take place even though the shear lip like ligament around the pop-in was fractured by fatigue crack propagation and a comparatively straight contour of the crack was created.
3) Both the pop-ins and fatigue cracks have a tendency to deviate from their original direction into the weld metal or the base plate. The reason for this seems to be a much higher hardness of the HAZ than those of the weld metal and the base plate.
4) The surface cracked wide plate test revealed that there is little possibility of formation of a through thickness crack following a pop-in fracture at the surface crack. Even if a through thickness crack is formed, it is to be arreated because of the deviation of the crack into the weld metal.
5) Final fracture was controlled by either the tensile strength of the weld metal or the fracture toughness of the base plate.

Table 3 Result of the wide plate test on 5.5% nickel steel (Other specimens)

Step \ Specimen	5SR-2	5SR-1	5SR-5
1st step: Tensile test at -170℃	1st pop-in σ_g=76 K=43 Last pop-in σ_g=217 K=123 Unload after this	Pop-in σ_g=190 K=109 Unload after this	1st pop-in σ_g=302 K=59 2nd pop-in σ_g=484 K=94 Unload after this
2nd step: Cyclic load at -170℃	σ_{max}=217 4160 cycles No pop-in after several pop-ins at early stage	1) σ_g=190 650 cycles No pop-in after several pop-ins at early stage 2) σ_g=119 15625 cycles No pop-in	σ_g=484 1700 cycles No pop-in
3rd step: Tensile test at -170℃	Fracture at σ_g=486 σ_{net}=771 Well over the yield stress of the weld metal	Fracture at σ_g=282 K=195 Same toughness as the base plate	Fracture at σ_g=670 σ_{net}=711 Well over the yield stress of the weld metal
Final fracture path	Weld metal	Base plate	Weld metal

Note
σ_g: Gross stress (N/mm^2)
K : Stress intensity factor (MN·m$^{-3/2}$)

DISCUSSION

From the wide plate test results, it becomes now clear that the reason of the pop-in is not the load drop caused by the specimen deflection. The main reason is the deviation of pop-in to the tougher weld emtal or the base plate. This tendency exists even in the fatigue crack propagation. Hence, the final fracture is not controlled by the HAZ toughness. In other words a pop-in at low stress intensity found in a COD test has no relevance to overall fracture of the welded joint. Although the load holding capacity of a COD specimen after a pop-in took place may become lower than the load at the preceding pop-in, this is true only in the COD specimen whose ligament size is designed to investigate the first incident of the fracture.

From the above consideration the integrity of the actual tank of 9 percent nickel steel can be discussed on a convincing basis. Since the test condition of the wide plate test applied in the present series of investigation is much severer than that in the actual structure, it would be reasonable to assume that a pop-in does not even take place in the welded joint in actual structures. Even if a pop-in or several pop-ins would take place, the total integrity of the structure could not be affected by them, because all the fracture initiation in the HAZ will be arrested and remain as a very short crack. When cyclic loads are applied the very short crack might grow in a crack penetrating the plate thickness and leakage might take place. But the crack can not become long before detection when appropriate detection system for the leakage of LNG is installed. In this sense, it can be said that the leak before failure concept based on the arrest of short cracks is valid in the welded joints of these high nickel cryogenic steel plate.

It is also noteworthy that there is no appreciable difference in fracture behavior between the present series of wide plate test and the conventional wide plate test for which no cyclic loading is applied. Then the conventional wide plate test seems to be sufficient to investigate whether the fracture path deviates into the weld metal hence resulting in a high fracture stress, when the weld metal is soft and tough such as in a 70 percent nickel austenite weld metal.

CONCLUSION

A series of wide plate test was carried out in order to investigate the significance of pop-in fracture which is often observed in small scale fracture toughness tests. Through the careful and well designed wide plate test, the following conclusions have been obtained.

1) The reason of the pop-in fracture in COD test is not the load drop caused by the specimen deflection but the curved contour of the pop-in fracture and the deviation of the fracture path into the tougher portion.
2) When the shear lip like ligament around the pop-in is fractured by some reason, several pop-ins may take place. But long brittle fracture or accelerated fracture by the combination of intermittent pop-ins and fatigue crack propagation can not take place. The reason of this is that the fracture path deviates into the soft and tough weld metal of austenitic microstructure.
3) Leak before failure concept based on the arrest of short cracks can be applied to the welded joint of 5 to 9 percent nickel steel. To confirm this both the sophisticated wide plate test and the conventional wide plate test are suitable.

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