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Fatigue crack growth analysis in Al/Ti layered material in ambient and cryogenic conditions

Dariusz Boroński[a]*, Maciej Kotyk[a], Paweł Maćkowiak[a], Robert Sołtysiak[a]

[a]*UTP University of Science and Technology, al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland*

Abstract

The paper deals with the process of crack growth in a layered material made by explosive welding from AA2519 aluminum alloy and Ti6Al4V titanium alloy. The tests involved loading CT type specimens parallel to the weld surface so as to cause simultaneous fatigue crack growth in both layers. Independent optical measurement of the crack growth lengths enabled comparison of the crack growth behavior for both layers and relating them to the results of a crack growth analysis performed by the compliance method with the use of a COD extensometer and FEA crack length analysis. Tests of crack growth lengths by the compliance and FEA methods were also performed in a liquid nitrogen which made it possible to compare the crack growth behavior in ambient temperature and cryogenic temperature.

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Keywords: explosive welding; layered material; AA2519; Ti6Al4V; fatigue; crack growth; cryogenic conditions

1. Introduction

Metal layered materials find a very wide range of applications. There is a variety of technologies used to manufacture them including the explosive welding method (EXW). This method involves using the energy of high-energetic materials explosion for welding particular layers. Figure 1 shows a scheme of the explosion welding process where flayer layer is welded with the base layer. This method of building layered materials provides the possibility of welding alloys with very different physical and mechanical properties. In literature we can find examples of Al/Al [1], Al/Cu [2,3], Al/Mg [4,5], Al/Fe [6,7], Al/steel [8,9], Al/Ni [10], Ti/Mg [11], Ti/Ni [12,13],

* Corresponding author. Tel.: +48 52 340 82 16; fax: +48 52 340 82 71.
E-mail address: dariusz.boronski@utp.edu.pl

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Ti/Cu [14] or Ti/steel [15,16] alloys welding. One of the application areas where joining different materials is beneficial is aviation and aerospace industry as the environment where technical objects operate imposes numerous requirements on construction materials which include very high strength properties in relations to the density as well as low radiation permeability, high ballistic resistance [17] and high heat resistance.

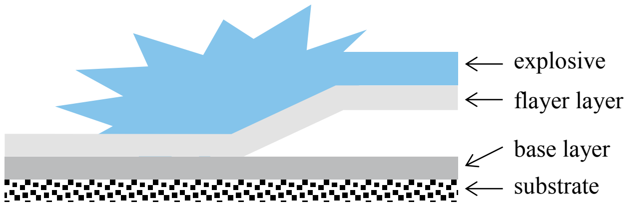

Fig. 1. Scheme of explosive welding with longitudinal layer configuration.

This study presents results of crack growth behavior tests for a new layered material AA2519-AA1050-Ti6Al4V to be used for spacecraft structures, which was developed in cooperation with Military University of Technology in Warsaw, Warsaw University of Technology, Institute of Non-Ferrous Metals, Space Research Centre of the Polish Academy of Sciences, UTP University of Science and Technology in Bydgoszcz and Explomet company.

Many available works deal with explosive welding of aluminum and titanium alloys. They usually present analyses of the transition zone properties including its impact on the crack growth rate for cracks perpendicular to the surface of weld. There are also tests connected with fatigue life of layered materials, whose example is work [18]. However, there are not many studies of fatigue crack growth behavior of layered materials made of high strength aluminum and titanium alloys with the cracks propagating simultaneously in particular layers of the laminates.

Tests of metal construction materials indicate that generally, cryogenic temperatures improve and stabilize the structure of a crystal grid in alloys of metal materials which results in their strengthening [19]. Taking into account the range of application of developed material, it is important to have knowledge of the influence of cryogenic temperature on a layered material crack growth behavior.

2. Experimental procedure

Base materials used in AA2519-AA1050-Ti6Al4V construction are AA2519 alloy aluminum and Ti6Al4V titanium alloy. Their chemical compositions are given in Table 1. Nominal mechanical properties of both alloys are presented, among others, in [20]. A detailed analysis of static properties of a base material and a layered material determined in ambient temperature and under cryogenic conditions is subject to another test and will be presented in a different work of the authors of this paper.

Table 1. Chemical composition of AA2519, Ti6Al4V and AA1050 [20,21]

Chemical composition of AA2519, wt %									
Si	Fe	Cu	Mg	Zn	Ti	Sc	Zr	V	Al
0.06	0.08	5.77	0.18	0.01	0.04	0.36	0.12	0.12	balance
Chemical composition of Ti6Al4V, wt %									
O	V	Al	Fe	H	C	N	Ti		
<0.2	3.5	5.5	<0.3	<0.0015	<0.08	<0.05	balance		
Chemical composition of AA1050, wt %									
Si	Fe	Cu	Mg	Mn	Ti	Zn	Al		
0.25	0.4	0.06	0.05	0.05	0.05	0.07	balance		

AA2519 alloy is an age hardened, high strength aluminum alloy with very good mechanical properties, high impact strength and ballistic resistance. These properties are used in construction of lightweight ballistic covers for military vehicles with high mobility. Prior to welding the alloy of AA2519 aluminum undergoes treatment through hot rolling and annealing in temperature of 400°C, for 1h. In effect its plasticity increases and internal stresses are reduced. Due to such a treatment AA2519 alloy has a coarse grain structure with big homogenously distributed particles of Al_2Cu.

The alloy of Ti6Al4V titanium is a widely used construction material which finds application, among others, in aviation. Its high strength and relatively good plasticity makes it a useful material for making mechanical carrying elements for the structure of an airframe as well as components of a power transmission system. Ti6Al4V alloy has a structure of α+β type which consists of thick grains of α phase and, rich in vanadium and aluminum precipitates of β phase, located on the boundaries of the grains.

In order to improve mechanical properties of the transition zone which is formed in effect of explosive welding, an additional, thin layer of AA1050 aluminum alloy was plated on AA2519 aluminum alloy layer using a metallurgic method.

The sheets used for tests, whose nominal thickness was 10 mm, were prepared by Explomet. Explosive welding of Ti6Al4V titanium alloy and AA2519 aluminum alloy was performed for a parallel plating arrangement where the deposited layer (flayer) was a 5 mm thick sheet made of AA2519 aluminum alloy with a 0.2 mm thick soft layer of AA1050 aluminum layer rolled on its one side.

In effect of welding a layered construction material with non-homogenous properties is formed. The transition zone is a special zone of welded material, characterized by a complex structure containing intermetallic compounds formed in result of the energy of impact and temperature. Work [21] presents a detailed analysis of the transition zone for the analyzed layered material. Figure 2 shows images of a layered material under thickness measurement and the image of the sheet transverse cross-section.

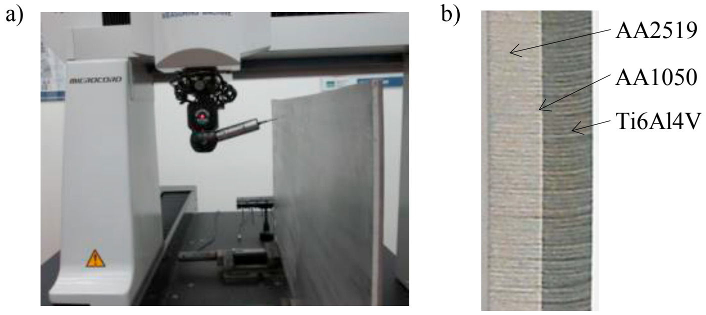

Fig. 2. AA2519-AA1050-Ti6Al4V layered material

In order to improve mechanical properties of the layered material, in particular, the layer of aluminum alloy pre-treated before welding, it undergoes thermal treatment after welding which involves heating in temperature 530-550°C for 2 hours and cooling in ambient temperature 165°C for 10 hours. The treatment does not affect the structure of titanium alloy.

Specimens of the compact tension type (CT), shown in Figure 3 were used for tests of crack growth rate. The specimens were cut out of a 10 mm thick sheet of a layered material. The specimens were loaded in the direction parallel to the surface of welding which provided simultaneous loading of the aluminum and titanium layers.

Fatigue tests were performed on a fatigue testing machine Instron with constant frequency of loading equal to 5 Hz and for constant amplitude values and constant values of stress ratio R. For tests under cryogenic conditions, additionally a special chamber was used which made it possible to immerse the entire specimen with grips and COD extensometer in liquid nitrogen. An image of this test stand is presented in Figure 4.

FatigueVIEW (Fig.5) developed in cooperation of UTP University of Science and Technology and The Institute for Sustainable Technologies – National Research Institute [22,23] was used for measurement of strains. The measurement method involves applying a digital image correlation (DIC) for a displacement distribution analysis on both specimen surfaces. Gradients of crack displacements in the direction of the force loading the specimen was used to make an analysis of the actual location of the crack tip.

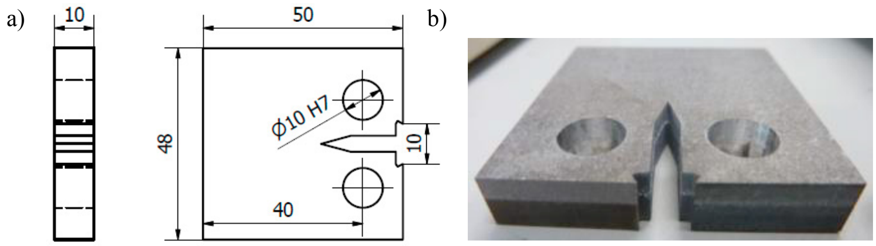

Fig. 3. AA2519-AA1050-Ti6Al4V layered material: a) dimensions, b) layers configuration in the CT specimen.

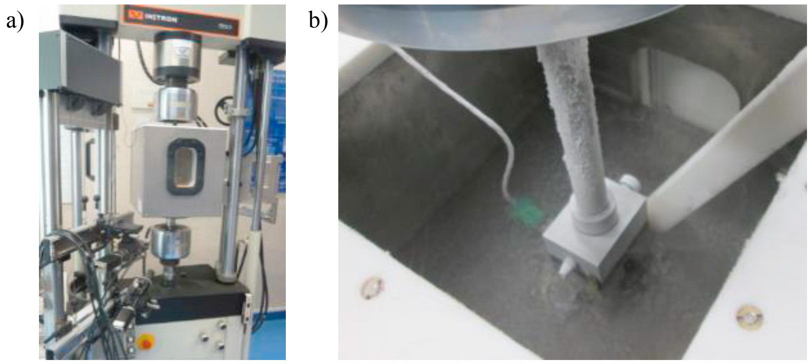

Fig. 4. Research stand: a) general view, b) specimen immersed in the liquid nitrogen

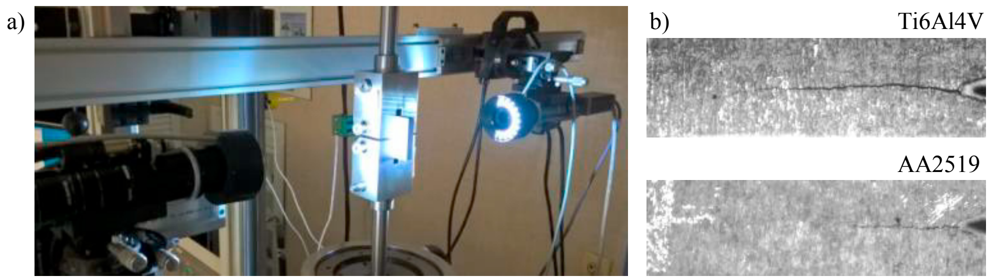

Fig. 5. Crack length measurement system: a) general view of FatigueVIEW system, b) specimen surface images.

3. Results and discussion

The main result of carried out fatigue tests with the use of CT specimens in ambient temperature, under constant force amplitude and constant value of the cycle asymmetry coefficient R, were histories of the crack length changes and the crack opening displacement COD changes in the function of the number of loading cycles. For tests carried out under cryogenic conditions only COD values were measured.

Figure 6 shows exemplary crack length change histories determined by the optical method for the aluminum and titanium layers. A dimension *a* marked in Figure 7 (distance between load line and crack tip) was accepted as a crack length to be used for analyses of CT specimen crack behavior.

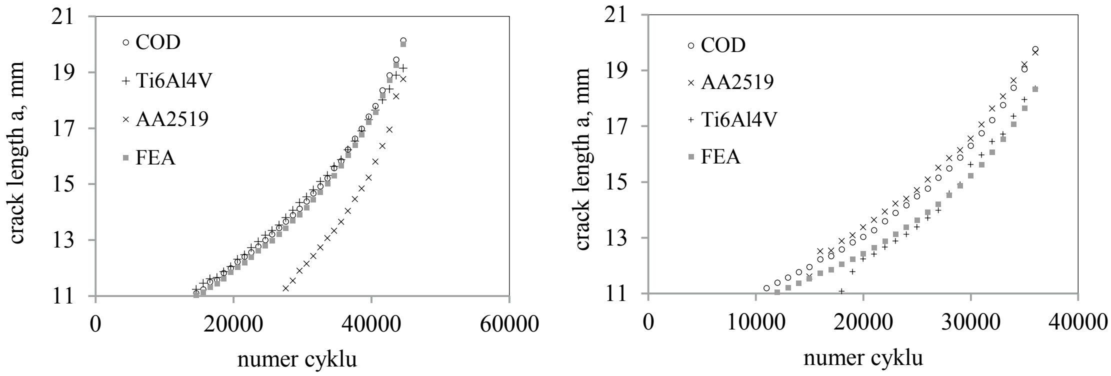

Fig. 6. Examples of measured and calculated crack length in CT specimens for: a) crack initiation in Ti6Al4V layer, b) crack initiation in AA2519 layer. 'Ti6Al4V' - crack length measured on the titanium alloy surface, 'AA2519' - crack length measured on the aluminum alloy surface, 'COD' - crack length determined by the compliance method, 'FEA' - crack length determined by the hybrid, experimental-numerical method

Analyzing the measurement results it can be noticed that the crack growth behavior is different in each layer, depending among others on where the crack was the first to initiate. However, differences in the crack length decreased along with an increase in their length. Such a crack growth behavior can be explained using an analysis of separate application of load onto the aluminum layer and the titanium layer. The structure of test specimens and the loading manner makes both layers of the laminate undergo the same displacements within the site of force application. Using a simplified specimen loading model shown in Figure 7 it can be said that the distribution of loading depends on relations of Young modulus and the cross-section dimensions. This means that for different mechanical properties and different dimensions of momentary cross-section of the layer dimensions, the forces acting on both layers will be different. Thus the range of stress intensity coefficient for the aluminum and titanium layer will have a different value. It is illustrated on the basis of two specimens in which the first crack initiated in the aluminum layer and in the second case a crack initiated first in the titanium alloy.

Assuming that a load line displacement is the same for the aluminum layer and titanium layer, the following system of equations can be can be written:

$$\begin{cases} P_{CT} = P_{Al} + P_{Ti} \\ \frac{P_{Al}}{S_{Al} \cdot E_{Al}} = \frac{P_{Ti}}{S_{Ti} \cdot E_{Ti}} \end{cases} \tag{1}$$

where:
S_{Al} - aluminum layer cross-section,
S_{Ti} - titanium layer cross-section,
E - Young modulus,
P_{Al} - forces acting on the aluminum layer,
P_{Ti} - forces acting on the titanium layer,
P_{CT} - total force.

On the basis of dependences 1 it is possible to determine the values of forces P_{Al} and P_{Ti} as well as momentary values of the stress intensity coefficients range for both layers, calculated according to dependence:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \cdot \frac{(2+\alpha)}{(1-\alpha)^{\frac{3}{2}}} \cdot (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \tag{2}$$

where:
$\alpha = a/W$,

B - specimen (layer) thickness,
W – specimen width.

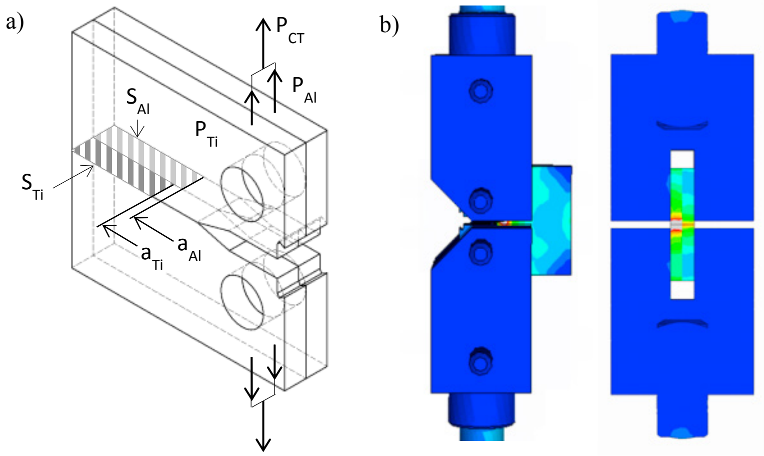

Fig. 7. Simplified model of specimen loading (a) and FEA analysis of loading system (b)

Figure 8 shows changes in ΔK value for both considered cases which were compared with the changes in ΔK determined for the whole specimen. An analysis of diagrams shown in Figure 6 and 8 indicates mutual influence of the layers on their crack growth behavior. The layer with a longer crack is partly relieved at the cost of the other layer. This means that the value of stress intensity coefficient increases in the layer with shorter crack length. In effect, the lengths of cracks gradually equalize.

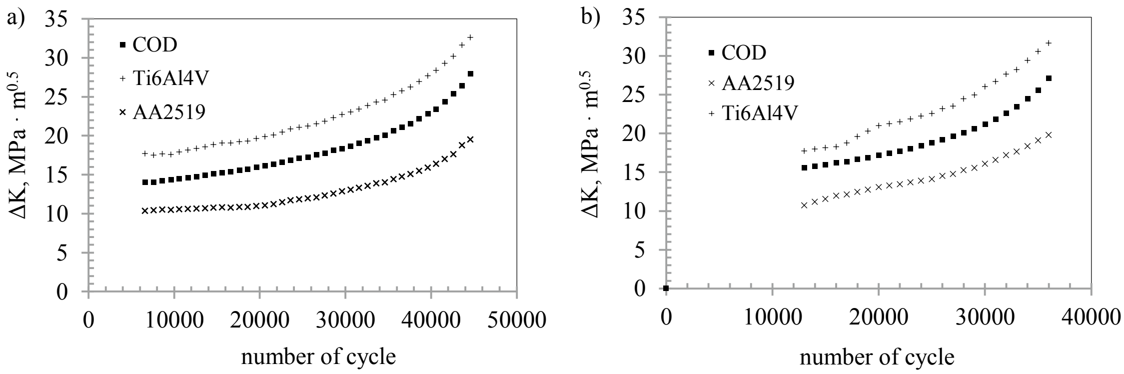

Fig. 8. Changes in ΔK value for both layers (Ti6Al4V, AA2519) and whole specimen (COD) for: a) crack initiation in Ti6Al4V layer, b) crack initiation in AA2519 layer.

The crack length for the entire specimen was analyzed by the compliance method on the basis of COD crack opening displacement measurement and by the hybrid method with the use of numerical calibration [24]. The method of finite elements was used for determination of the crack length in which a given crack opening is obtained for a given value of a force. The compliance method and the hybrid method were used for both conditions of testing, that is, ambient temperature and cryogenic conditions.

Figure 9 presents a comparison of crack length change histories in CT specimens for the same load amplitudes, determined by both methods. A comparison of tests results indicates only a slight influence of cryogenic conditions on the crack growth. However, an analysis of the specimen fracture topography (Fig.10) shows a different character of cracking depending on the temperature. No layer delamination was found in specimens tested in ambient conditions, subsequently no cohesion loss of a layered material was reported in the zone of cracking. Whereas, numerous delamination were found in the specimens tested under cryogenic conditions and they were reported practically right from the first loading cycles. A more thorough analysis of the fractures revealed that delamination occurred both between the layers of AA1050 aluminum alloy and Ti6Al4V titanium alloy (Fig.11a), as well as the layer of AA1050 alloy and AA2519 alloy (Fig.11b).

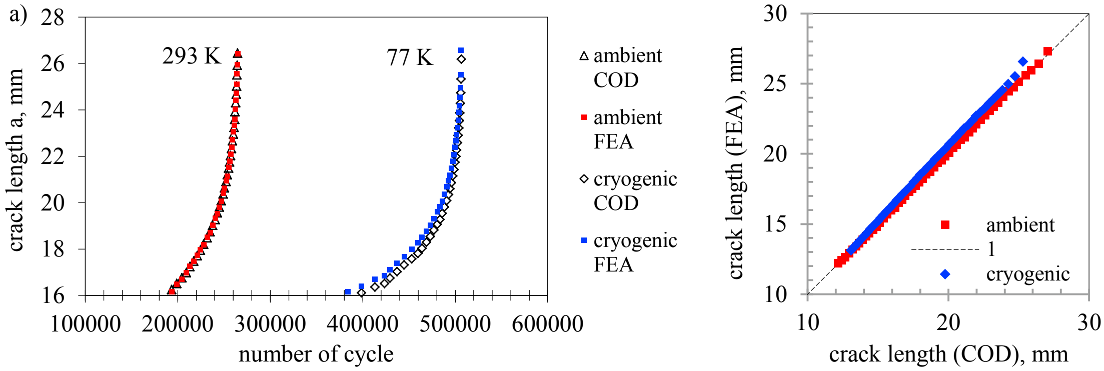

Fig. 9. Crack length for ambient (293 K) and cryogenic (77 K) conditions (a). Comparison of crack length determined for the same number of cycle by the compliance method (COD) and the hybrid method (FEA) (b).

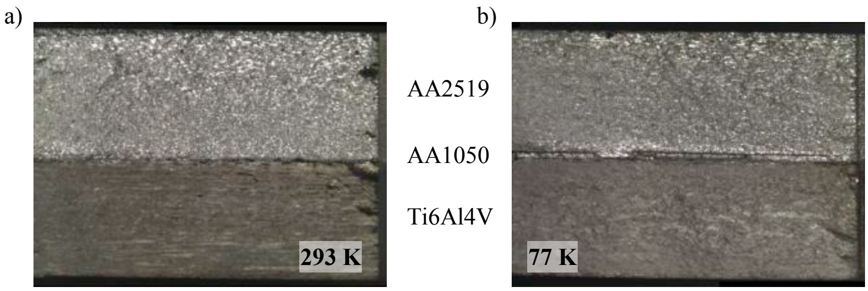

Fig. 10. Images of fracture surface: a) for ambient conditions, b) for cryogenic conditions.

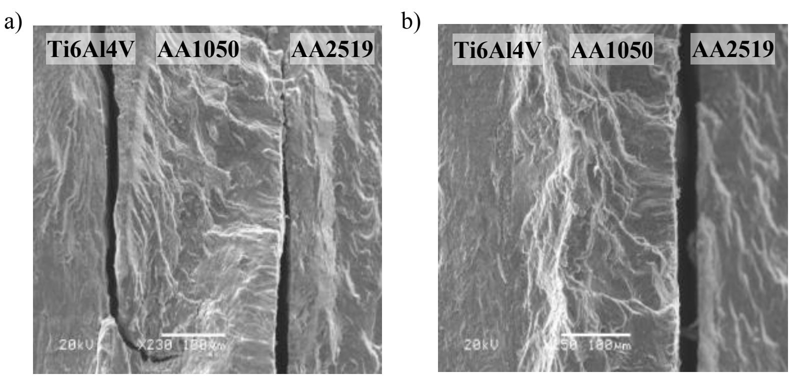

Fig. 11. Examples of layers delaminations under cryogenic conditions: a) delamination between the AA1050 and Ti6Al4V, b) AA1050 and AA2519

4. Conclusions

A comparative analysis of crack growth behavior for AA2519-AA1050-Ti6Al4V layered material has been made for two aspects: differences in crack growth rate of aluminum alloy and titanium alloy as well as the influence of cryogenic conditions on the crack growth behavior of CT specimens according to a global approach, that is, without taking in to consideration differences in the crack growth behavior of particular layers.

The following conclusions can be drawn on the basis of a tests results analysis:

1. In the initial phase, a crack growth of particular layers of AA2519-AA1050-Ti6Al4V laminate depends on which layer is the first for a crack to occur first.
2. Crack length of layers equalizes along with an increase in the crack length.
3. For the same loading conditions, cryogenic environment has only a slight effect on the crack length growth.
4. Fracture topography of the specimens tested under cryogenic conditions indicates that there is a possibility of occurrence of delamination in the crack zone which was not observed for ambient conditions.

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