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AN INVESTIGATION ON THE GROWTH OF FATIGUE CRACK BETWEEN SEQUENTIALLY COLD EXPANDED ADJACENT CIRCULAR HOLES IN Al 7075 - T651 ALLOY

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Abstract. Critical structural holes located in close proximities are sequentially cold expanded one after the other in series to enhance their fatigue strengths by inducing beneficial residual stresses around hole regions. In some instances, where, several holes are closely located, the cold expansion–induced beneficial residual stress fields in the regions between the holes are considerably different in comparison to the case of cold expansion of a single hole that is free from a proximity hole. Therefore, an attempt is made in the present work to investigate the crack growth behavior in the residual stress field induced by the sequential cold expansion of closely spaced adjacent holes in typical aircraft-grade Al 7075-T651 alloy. In the present work, initially, Finite Element (FE) simulation on the sequential cold expansion of two adjacent holes in thin Al 7075-T651plate is carried out for 4% expansion level and resulting compressive residual stress fields around hole regions are predicted. Further, an experimental investigation on sequential cold expansion process is carried out using indigenously developed tooling set-up and Fatigue Crack Growth (FCG) behavior between cold expanded holes is measured through testing. The FCG measurement results indicate that crack propagation rate is higher between the cold expanded holes in comparison to the case of non-cold expanded holes.

Keywords: adjacent circular holes, aluminium alloy, sequential cold expansion, beneficial residual stresses, fatigue crack growth

1. Introduction

Numerous fastener holes separated by certain distances are inevitably provided in aircraft and aero-engine structural members for the purpose of mechanical connections. Under in-service tensile fluctuating loads, the regions around fastener holes are highly vulnerable to fatigue failures due to localized stress concentration effects. To countervail the problems of pre-mature fatigue crack initiations or failures, the cold expansion process is routinely employed around critical aero-structural holes in practice [1-3].

Typically, the cold expansion process involves forcing the hardened and oversized pre-lubricated mandrel into a hole of starting size from one side of the hole followed by the ejection of the mandrel from the other side of the hole. During the sliding of mandrel over the material on hole thickness direction, the material surrounding the hole edge undergoes elastic-plastic expansion. Further, the expanded material undergoes elastic-plastic recovery (spring-back effect) upon the ejection of the mandrel. As a consequence, an annular zone of localized

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compressive residual stresses around the hole regions is induced. Although compressive residual stresses are developed in radial, tangential and thickness directions, tangential residual stresses are found to be highly effective in reducing the stress concentration effects and retarding fatigue crack initiations/propagations around hole regions. Therefore, the cold expansion–induced tangential compressive residual stresses are considered as beneficial residual stresses [2,4]. The size of the compressive residual stress zone and magnitude of compressive residual stress around the hole region depends on the process parameter such as applied expansion level (I_a). The applied expansion level (I_a) is usually defined as Eq. (1)

$$I_a = \frac{D_m - D}{D} \times 100, \tag{1}$$

where D_m is the major diameter of the mandrel and D is the starting hole diameter [4]. In practice, 2% to 6% expansion levels are typical for the fastener holes which range from 5 mm to 40 mm in diameter [4-5].

The guidelines for selecting the cold expansion process parameter such as applied expansion level (I_a) is clearly established and standardized for the given geometrical parameters (hole size, edge margin, and hole thickness), material parameters (type of aircraft-grade metallic material, yield strength of the material, strain hardening behavior of the material, etc.) and loading conditions [5]. Whereas, the actual aircraft structural members consist series of fastener holes separated by certain distances and cold expansion of holes is carried out sequentially one after the other. The separation of holes is usually defined by the ratio of hole center-to-center distance (C) to hole diameter (D). Although the significant number of studies have been devoted to investigating the cold expansion process for the single hole which is free from the influence of proximity hole, very few studies have attempted to study the influence of proximity hole on the cold expansion process [1,3-4,6-7]. It is identified from those studies [1,3-4,6-7] that cold expansion of one hole is influenced by the proximity hole when 5 < C/D> 3 and therefore holes are considered as closely spaced if 5 < C/D> 3 condition prevails. For the condition of (C/D) ratio greater than five, the cold expansion of one hole is not influenced by the proximity hole. Whereas, if C/D ratio is lesser than three, the cold expansion of adjacent holes is found to be failed because of insufficient material between the holes [4,8]. In accomplishing the actual cold expansion process for closely spaced adjacent circular holes, the process parameter viz. applied expansion level is selected from the process specification guidelines reported in Ref. [5]. These guidelines are derived for the case of the single hole which is free from the influence of proximity hole. While, if the process parameter is directly selected from the available process specification guidelines during the cold expansion of closely spaced adjacent holes (5 < C/D > 3), the cold expansion–induced residual stress fields around and in-between the closely spaced holes are considerably different from the expected residual stress fields from single hole cold expansion [4,8]. A thorough review of literature in the field of cold expansion process around closely spaced adjacent holes has revealed that very limited studies [9,10] have attempted to evaluate the growth of fatigue cracks in cold expansion–induced residual stress fields around a single hole which is free from the influence of adjacent hole. On the other hand, it is identified that not even a few studies have attempted to study the growth of fatigue cracks between residual stress fields induced by sequential cold expansion of closely spaced adjacent holes. Therefore, the present study attempts to investigate the growth behavior of fatigue crack in residual stress fields between two closely spaced adjacent holes, which are sequentially cold expanded in typical aircraft-grade Al 7075-T651 alloy.

2. Finite element simulation on the sequential cold expansion of two adjacent holes

The mechanics of sequential cold expansion of two closely spaced adjacent holes in Al 7075-T651 alloy material is thoroughly understood by carrying out FE simulation. For the purpose of simulation, the plate specimen (84.5 mm × 60 mm × 6.35 mm) made of Al 7075-T651 alloy representing the typical aircraft fastener hole configuration is considered. The plate specimen consists of two adjacent holes with a diameter (D) of 6 mm each separated by center-to-center distance (C) of three times hole diameter (C/D =3). Owing to the symmetry in plate geometry and loading conditions, the only upper-half portion is modeled in the commercial FEA tool (ANSYS) as shown in Fig. 1. The model is developed using 46512 numbers of 8 noded, solid 185 element type after ensuring mesh independence. In simulating the sequential cold expansion process, the right side hole is cold expanded first, and then the left side hole is cold expanded by choosing the nominal level of expansion (I_a) viz. 4%. During each hole, cold expansion simulation, a simplified and realistic FE simulation framework described in the author's previous studies is employed [2,4,8]. This FE simulation framework is capable of realistically simulating the layer-by-layer expansion of the material on the hole thickness surface (during mandrel sliding through-hole) followed by the elastic-plastic recovery of expanded material (during ejection of the mandrel) as happens in the actual cold expansion process. For the simulation, the complete stress-strain curve for Al 7075-T651 alloy material is modeled through the bilinear stress-strain curve reported in Ref. [8]. The values of mechanical properties used for bilinear stress-strain curve modelling includes elastic modulus = 72 GPa, Poison's ratio = 0.28, yield strength = 506 MPa and tangent modulus = 100 MPa. From the complete FE simulation, the cold expansion–induced beneficial residual stresses around and along the thickness direction of both the holes are predicted and analyzed. The predicted benefits form the basis for carrying out experimental investigations on the sequential cold expansion process for adjacent holes.

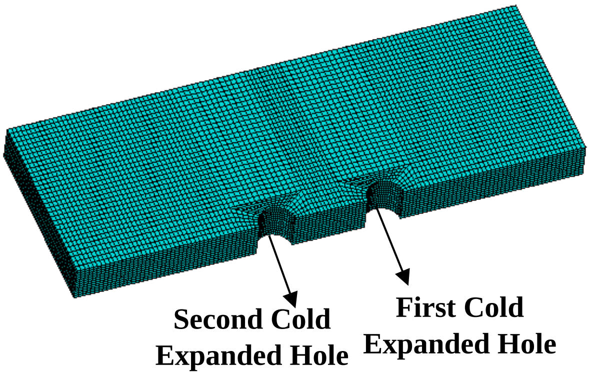

Fig. 1. FE model of plate specimen having two adjacent holes

3. Experimental procedure

Set-up for sequential cold expansion of adjacent holes. To carry out experimental investigations on the sequential cold expansion of closely spaced adjacent holes, the cold expansion tooling system is indigenously developed as shown in Fig. 2. The developed tooling system utilizes BISS make 150 kN Universal Testing Machine. The set-up consists mandrel of major diameter 6.24 mm made from High Carbon High Chromium (HCHCR) steel. For the experiments, the specimens are cut to the dimensions shown in Fig. 3 from 'as-received' Al 7075-T651 alloy samples. The specimen contains two pinholes which are provided for the purpose of connection to FCG testing machine further to cold expansion operation. The complete cold expansion operation is accomplished in two stages. In the first stage, the mandrel of major diameter 6.24 mm is forced into the right side hole of 6 mm diameter causing 4% expansion of the right side hole first. In the second stage, the same mandrel is again forced into the left side hole of 6 mm diameter to cause 4 % expansion of the left side hole. As a consequence of the sequential cold expansion of two adjacent holes one after the other, both the holes are in a cold expanded state at the end of the operation.

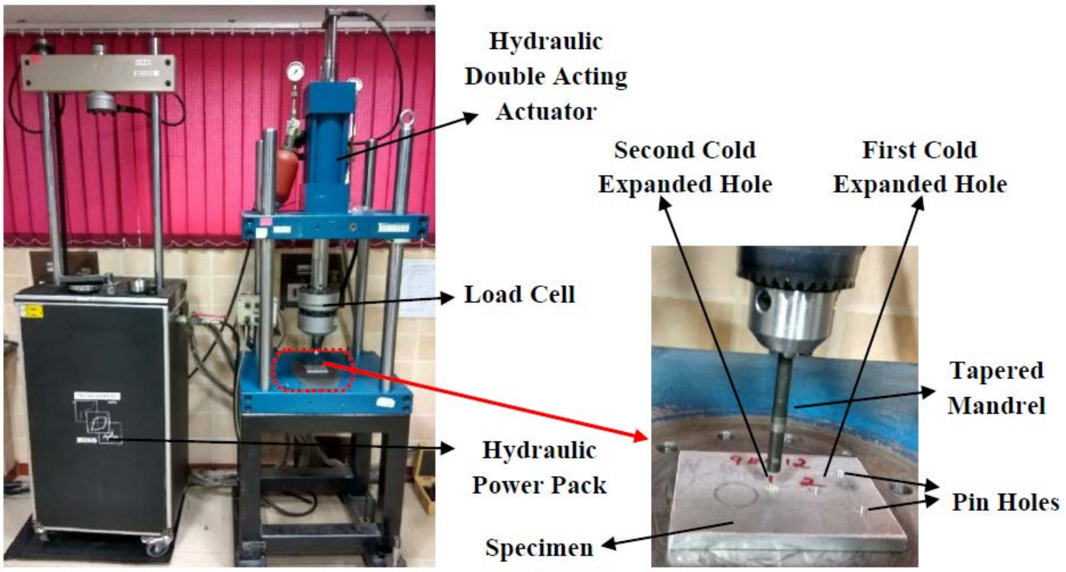

Fig. 2. Cold expansion tooling set-up

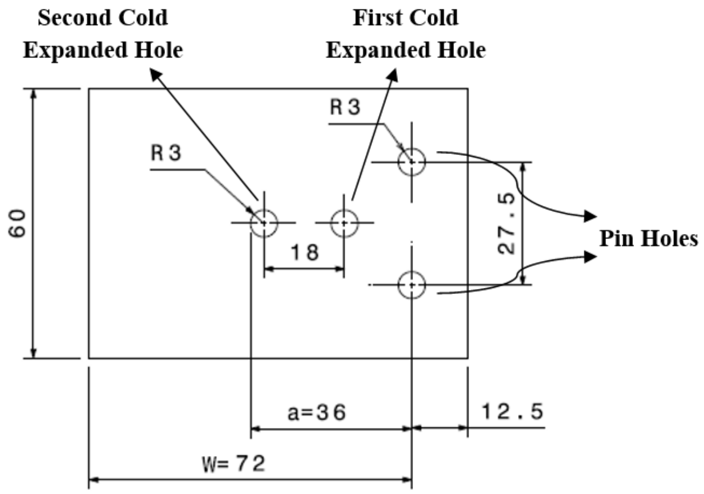

Fig. 3. Dimensions (mm) of the specimen used for the sequential cold expansion process

Measurement of fatigue crack growth between cold expanded adjacent holes. The present FE simulation predictions (Fig. 6) reveal that induced residual stress fields due to the sequential cold expansion of adjacent holes are considerably different from the usual residual stress fields induced due to cold expansion of a single hole. Therefore, in order to investigate the influence of induced residual stress fields on FCG behaviors around sequentially cold expanded adjacent holes, FCG testing is carried out using BISS make 25 kN nano type dynamic testing machine.

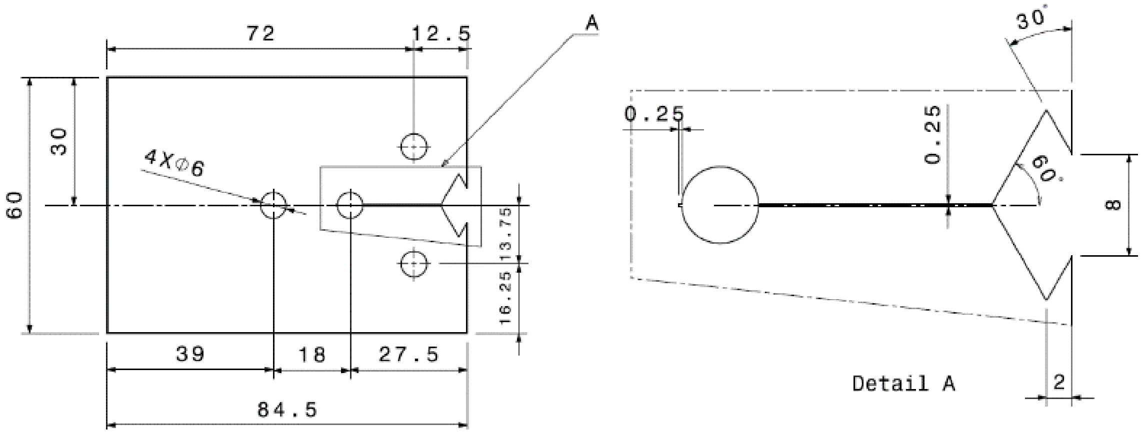

Fig. 4. Dimensions (mm) of the specimen used for FCG testing

For the purpose of FCG testing, the specimen is cut to the dimensions shown in Fig. 4 after sequential cold expansion of adjacent holes (Fig. 2). Also, the sharp crack of 0.25 mm length is cut on the critical location of the first cold expanded hole using the wire machining process. The orientation of crack is chosen in such a way that Mode I (opening) loading prevails during testing as shown in Fig. 5. For the FCG testing, the constant-amplitude remote fluctuating loads varying from 5.1 kN to 0.5 kN with a stress ratio of 0.1 at 10 Hertz frequency are considered. The value of maximum load (5.1 kN) is determined as 55% of the material's K_{IC} value (31.6 MPa·√m). During the testing, the steady growth of fatigue crack (stage II) between sequentially cold expanded adjacent holes and non-cold expanded adjacent holes under the application of fluctuating loads is measured using the compliance method. The measured FCG rates are expressed in terms of changes in crack length over a number of elapsed fluctuating load cycles.

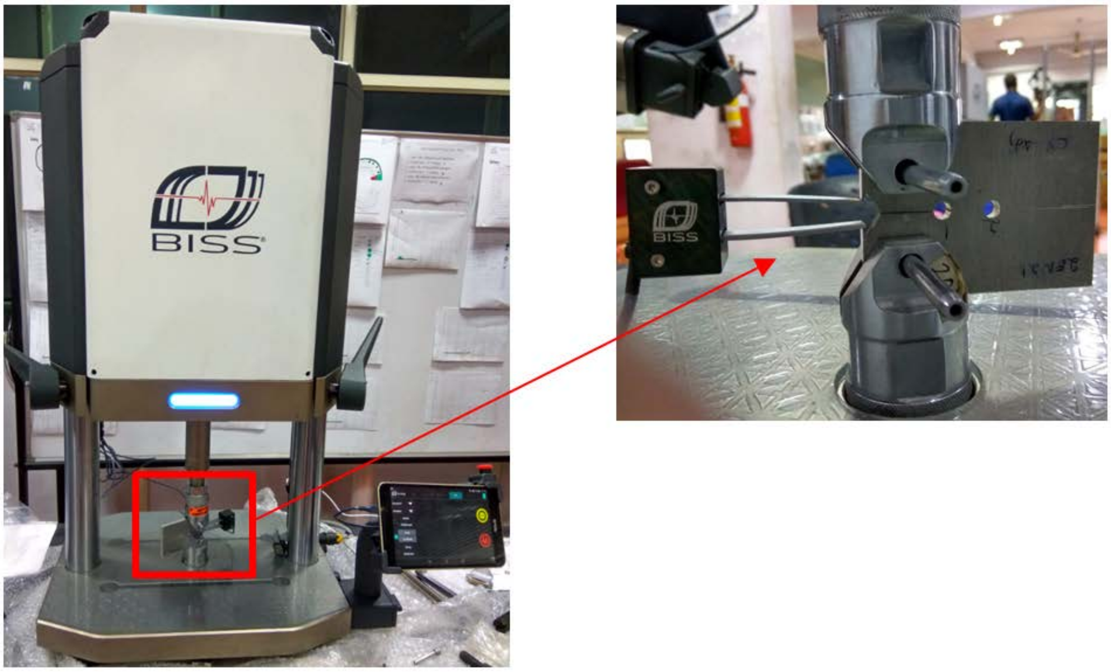

Fig. 5. FCG measurement set-up

4. Results and Discussions

Beneficial residual stress predictions. The efficacy of the cold expansion process in enhancing the fatigue life of holes can be quantified from the extent of beneficial residual stresses induced around hole regions. As a result of FE simulation on the sequential cold expansion of two adjacent holes in the present work, induced beneficial residual stresses around the hole regions are predicted as shown in Fig. 6.

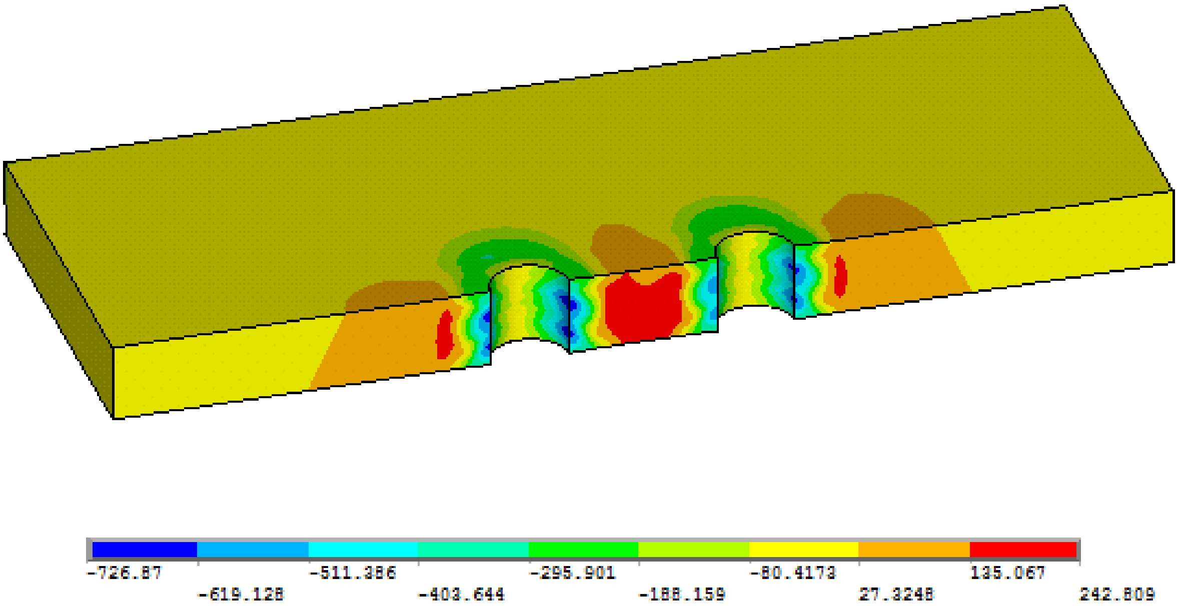

Fig. 6. Beneficial residual stress distributions around cold expanded holes

It can be observed from Fig. 6 that induced beneficial residual stresses are compressive at both hole edges. Also, these compressive stresses vary significantly from the top face (mandrel entry side) to the bottom face (mandrel exit side) of the plate by attaining a maximum value (726 MPa, compressive) at a 5 mm distance from the top face. The presence of such a significant amount of beneficial residual stresses (up to 1.43 times the yield strength of the material) on the hole thickness directions can lead to an appreciable amount of fatigue life extension around hole regions. Whereas, due to the low C/D ratio and influence of proximity hole during the cold expansion of each hole, a considerable amount of equilibrating tensile residual stresses (up to 0.47 times the yield strength of the material) are developed between the holes. On the contrasting side, if there is no adjacent hole, the equilibrating tensile residual stresses could be typically around 0.1 to 0.2 times the yield strength of the material. These observations indicate that cold expansion-induced equilibrating tensile residual stresses between the closely spaced adjacent holes are quite higher than the single hole cold expansion case. Therefore, it is aimed to investigate the effect of such higher amounts of equilibrating tensile residual stresses on FCG behaviors between the cold expanded holes through experiments.

Fatigue crack growth measurement. In order to investigate the influence of cold expansion-induced residual stress fields on FCG behaviors between cold expanded adjacent holes, FCG testing on cold expanded and non-cold expanded specimens is carried out. During testing, the growth of the initial crack (0.25 mm size) from the first cold expanded (right side) hole towards the second cold expanded (left side) hole is measured in cold expanded and non-cold expanded specimens. The averaged results of FCG testing for one cold expanded and non-cold expanded specimen are presented in Fig. 7.

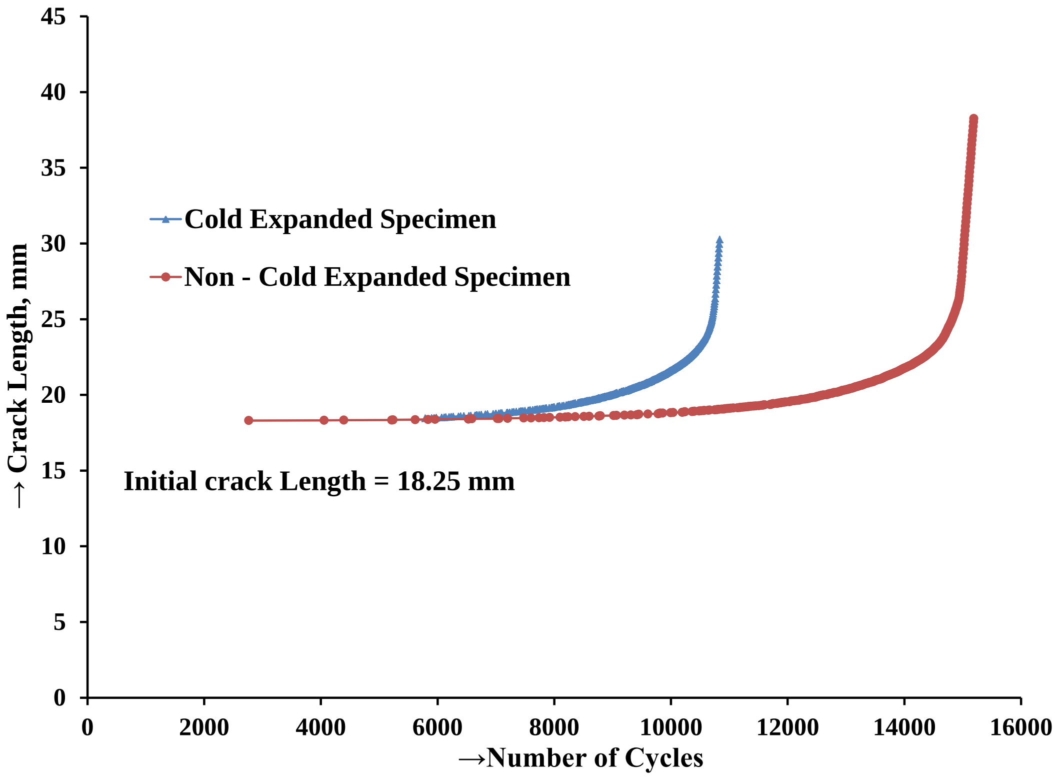

Fig. 7. Crack size versus number of cycles curve

It is evident from Fig. 7 that number of load cycles taken for the initiation of crack growth is higher in the cold expanded specimen in comparison with the non-cold expanded specimen. The reason for the delay in initiation of crack growth from the cold expanded hole (right side) is due to the resistance offered by induced beneficial residual stresses around hole regions. Whereas, after initiation of crack growth from the right side hole, the crack growth rate between the adjacent holes is found to be higher for the cold expanded specimen in comparison with the non-cold expanded specimen. The reason for such higher crack growth between the holes is due to the large equilibrating tensile residual stresses induced as an effect of the sequential cold expansion of adjacent holes and least spacing between holes.

5. Conclusions

The induced residual stress fields due to sequential cold expansion of two closely spaced adjacent holes are considerably different from the residual stress fields induced due to cold expansion of a single hole. As a consequence of the sequential cold expansion of two adjacent holes and least hole spacing, a large amount of tensile equilibrating residual stresses are induced between the holes. Whereas, in the regions around both the holes, a significant amount of beneficial compressive residual stresses are induced due to cold expansion of holes as expected. Experimental measurement of crack growth in the residual stress fields between two adjacent holes reveals that the presence of equilibrating tensile residual stresses enhances the crack growth rate between holes. Therefore, during the cold expansion of closely spaced adjacent holes, it is required to carefully consider the effects of equilibrating tensile residual stresses between the hole regions. Otherwise, if cold expansion is implemented to closely spaced adjacent holes, it is suggested to thoroughly conduct periodic inspections so as to observe any crack growth problems between the holes and to initiate corrective actions.

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