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Cold Hole Expansion Process for Stress Analysis and Evaluation of Fatigue Properties

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ABSTRACT: *Cold expansion of fastener holes has been successfully used for many years to impart beneficial compressive residual stresses. These residual stresses serve to extend crack initiation lives and to slow down growth of small cracks. In this paper stress analysis in open holes in Aluminium alloys 7050 series have been carried out with FEM approach. The Split-Sleeve process has been used wherein expansion of the hole is accomplished by putting tapered mandrel prefitted with a lubricated split sleeve through the hole. The mandrel and the sleeve are designed to generate a prescribed amount of plastic deformation around the hole that in turn creates a state of biaxial residual compressive stress in that area. A typical development of plastic deformation in terms of Von Mises stresses in 7050 Al plates were examined. Tests were carried out using plates containing plain holes and cold expanded holes in aluminium. Residual stress measurements have been done after cold expansion and after various loading conditions. Results were obtained from the FE simulation for radial and tangential residual stress through the thickness of the plate as a function of the radial position. This investigation conclusively show that a significant fatigue life extension can be obtained from a hole that is reworked using a split sleeve cold expansion after a period of constant amplitude or flight spectrum loading. The degree of improvement increases if the hole was also cold expanded during the expansion.*

Key words: *Fatigue, Cold hole expansion, residual stresses, split sleeve process*

I. INTRODUCTION

With the need for higher strength to weight ratio of engineering components, fatigue has become a very important phenomenon specially in automobiles, aircrafts, gas turbines which are subject to repeated loading and vibration. Considerable interest in the influence of residual stresses on fatigue behaviour of components exists in the aircraft industry [1]. These compressive residual stresses are highly effective in preventing premature fatigue failure under conditions of cyclic loading [2, 3, 13]. An ideal solution would be to build in fatigue resistance into the critical assemblies themselves providing increased safety and fatigue life. One of these methods, which were used in this, is to form a controlled compressive residual stress field around the fastener hole [4]. The technology of cold hole expansion is used to impart a favorable residual compressible stress on surfaces subjected to highly alternating stress and thus increases fatigue life [5]. The change of cold expansion residual stresses due to static compressive loading was studied by Stefanescu et al [8] using an experimental approach.

The highest incidence of aircraft structural fatigue has been associated with holes in fastens joints and other holes in the structure. Manufacturing and other defects are very common at holes. The majority of civil aircraft components are designed using the damage-tolerant approach. Within this approach the emphasis is on the control of the crack growth rates and on effective periodic inspection, with the requirement for the crack detection techniques to be able to identify flaws of a certain size. [6]. During aircraft operation the adverse effects of these flows or defects is magnified by the high stress concentration factors associated with holes, which lead to fatigue, cracks. Modern manufacturing technologies and closer attention to detailed design and analysis of fatigue sensitive joints have substantially reduced the occurrences of severe structural fatigue damage at holes. Nevertheless the challenges of the aerospace industry remain to produce larger, lighter, more efficient, less costly and considerably more durable and damage tolerant airframes. These goals coupled with the growing need to extend the operational lives of exiting aircraft will require use of all tools available to maximize the fatigue lives of holes and other stress concentrations. Fatigue crack growth may be significantly delayed or even arrested by the compressive cold expansion residual stresses [5, 7].
Generation of permanent compressive stresses near holes has long been recognized as a means to extend fatigue life by retarding crack initiation and growth. Methods commonly used to induce compressive stress around holes include shot penning, rolls burnishing mendrelising and coining. However, these techniques produce only

relatively shallow residual compression zones, which are sensitive to manufacturing variables and other operator proficiency. Consequently these hole treatments have only a limited ability to effectively prolong fatigue life.

One of the best techniques is the split sleeve cold expansion system, which generates beneficial residual stress around the hole by permanently enlarging the hole. Cold expansion process has become commercially viable process within the last few years with the design, construction and operation becoming comparable with a manufacturing environment in size and capability. There have also been demonstrations of large improvements in fatigue strength in various metals and alloys. Typical application includes turbine blades and disks, rotating shafts, gears, reciprocating parts, connecting rods and prosthetic devices. In the United Kingdom, split sleeve cold expansion is used primarily during manufacture by the civil aircraft industry and for refurbishment and repair by the military aircraft industry. In the latter case, extra care has to be taken to ensure that the correct degree of expansion is achieved, since the holes are usually damaged from service as a result of wear, corrosion, scoring, cracking etc, It is common practice to remove damage by reaming, or drilling and reaming, prior to cold expansion. Nevertheless, it is always possible that cracks are still present even after such operations [9].

Split sleeve cold expansion system is a cost effective solution to problems associated with fatigue cracks and holes in metal structures. Split sleeve cold expansion is accomplished by pulling a tapered mandrel, pre-fitted with a lubricated split sleeve through a hole in aluminium, steel or titanium. The function of the disposable split sleeve is to reduce mandrel pull force, ensure correct radial expansion of the hole, preclude damage to the hole and allow one-sided processing. The process works by imparting beneficial compressive residual stress around the hole.

II.FIGURES AND TALBES

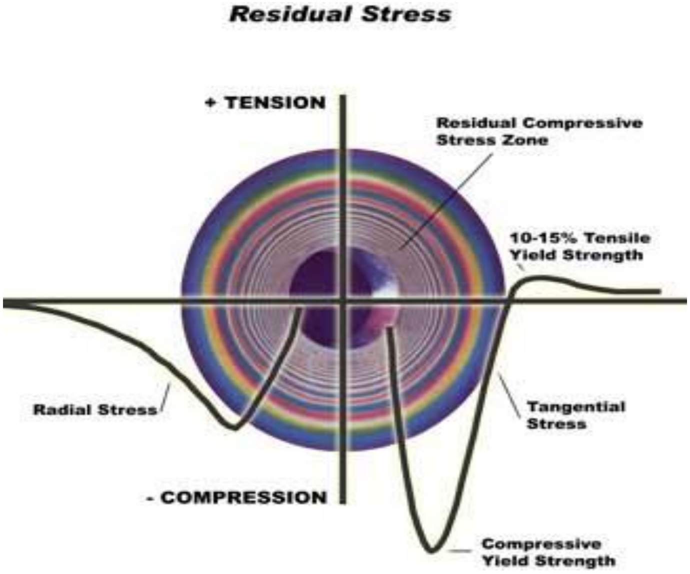


Figure 1: Stress distribution around a cold expanded hole

Sleeve allows for one-sided processing and shields the hole from frictional forces generated by the high interference of the expansion mandrel. The residual stresses created by cold expansion significantly increase fatigue life by reducing the stress intensity factor and crack growth by reducing the applied stress ratio at the hole. The magnitude of the peak residual compressive circumferential stress is about equal to the compressive yield stress for the material. The compressive stress zone spans one radius to one diameter from the edge of the hole for diameters up to 12.5mm for most materials.

The split sleeve cold expansion process involves the following stages:

Stage 1: After verifying the starting hole size slip the pre lubricated split sleeve onto the mandrel, which is attached to hydraulic

Stage 2: Insert the mandrel and sleeve through the hole with the nose cap held firmly against the workplace.

Stage 3: Activate the puller unit. The mandrel is drawn through the sleeve and the hole.

Stage 4: Remove and discard sleeve

Stage 5:- Ream hole to final size. Use pin end of combination gage to confirm size**.**

Although fatigue prevention is a goal that is not unique to the aerospace industry, metal fatigue prevention and control plays a major role in the design of aircraft structures. Repeated cyclic loads such as those caused by the flexing of the aircraft wing can lead its fatigue cracks. The *fatigue* life benefit associated with the cold expansion process has been validated numerous times by both experimental testing and in-service. The challenge is to predict the fatigue life benefit without extensive testing. The most common method used today is a two-dimensional (2-D) stress intensity factor (K) solution using linear superposition associated with cold expansion (Cx). This method can be summarized in Eqn. 1.

$$K_{\text{non cold expanded}} + K_{\text{residual stress}} = K_{\text{effective}} \qquad (1)$$

Past studies by various authors have shown varying levels of success in predicting the overall fatigue life [10-12]. Many researchers [14-17] were concentrated on test programs with the purpose to individuate the effects of various significant parameters (i.e. material, stress level, expansion level) on the fatigue life improvement.

III.EXPERIMENTAL PROCEDURE:

Alloy	E (GPa)	γ	ρ (gm/cc)
Al 7075	72	0.3	2.7
Thickness	4mm and 6mm plates		

The present work aims at finding the tensile strength characteristics of cold worked specimen. The first step includes the cold hole expansion of aluminium specimen (with centrally drilled hole) under constant pressure condition and varying mandrel velocity. The second deals with the tension tests performed on a universal testing machine for evaluation of tensile properties.

Test Specimens
Aluminium 7050 series
Ultimate Strength of the Specimen: 1500Kg

1. Circular Holes of diameter 13.5mm are drilled in the aluminium plates of 6mm thickness at a cutting speed of 350 rpm.
2. The holes are reamed to exact diameter of 14mm using a straight reamer at a speed of 120 rpm. The test specimens are prestressed.

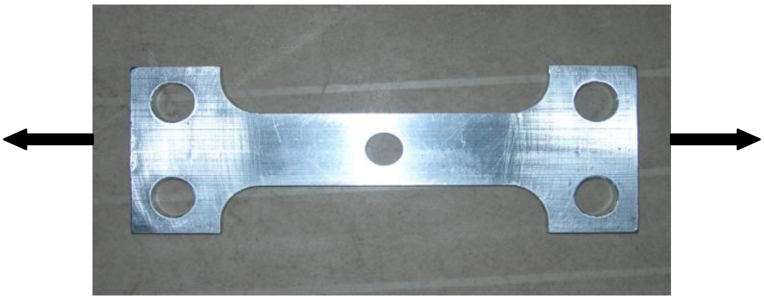
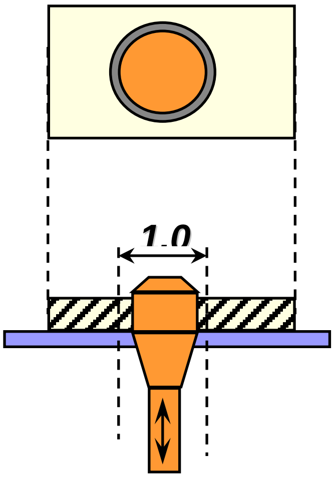


Figure 2: Aluminium Test Specimen



Split sleeve - stainless steel

Expanded hole diameter = 10.4 mm
Ream the hole to = 10.5 mm

Figure 3: Split sleeve process

IV.ANALYSIS

The specification for the cold-hole expansion process has three steps that are useful to the residual stress model development

1. Hole expansion by the expansion of the collet in the hole (Application of load).
2. Recovery in the expanded hole on removal of the load
3. Removal of very thin layer of material around the hole

V.FEA STEPS

1) Uniform displacements are added on the nodes at the hole edge to simulate 2-8% cold expansion
2) The removal of the mandrel and the corresponding unloading process is simulated by the removal of the boundary condition at the hole-edge.
3) Removal of the material surrounding the hole to bring the hole to the final size is simulated by the powerful function of element removal in *ANSYS.*

VI.MESHING

For cold hole expansion process of hole without cracks, because of the symmetry, one half of the hole is representative of the entire hole. The size of the specimen analyzed is 100 mm x 100 mm x 4 mm in length, width and thickness, respectively. The initial and final hole diameters are 14 mm and 14.84 mm respectively. These values follow the experimental specifications. The 20-node 3-D solid element has been adopted for the analysis. The analysis model contains 8020 elements and 9324 nodes. The mesh used is shown in Fig.4 (a).

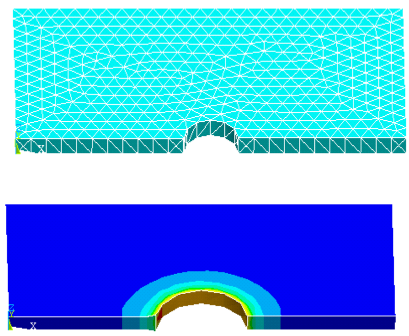


Fig. 4(a) Cold hole expansion of hole without a

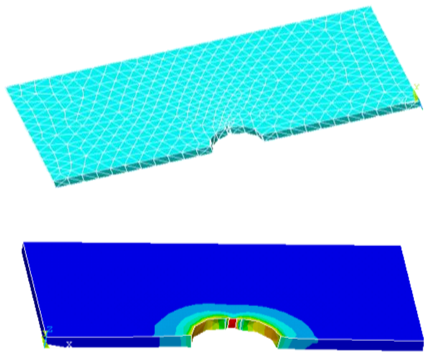
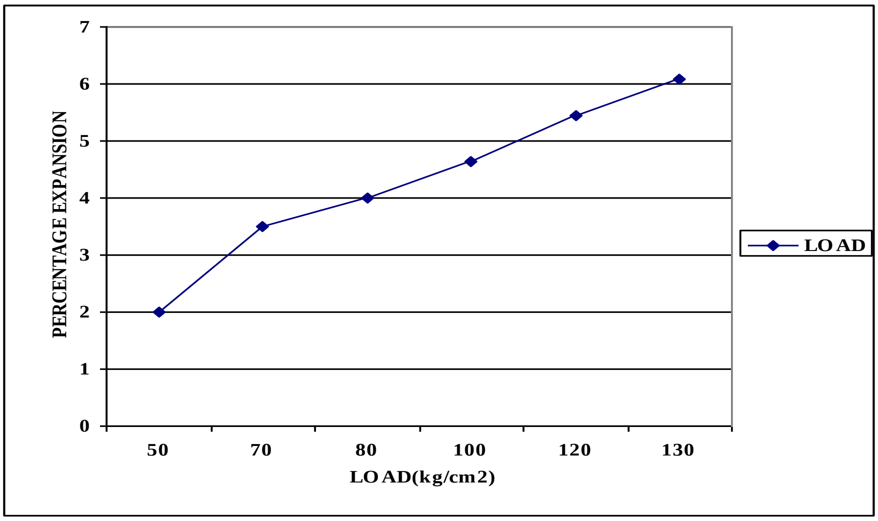


Fig. 4 (b) Cold expansion of hole with a corner crack A/C =1, C/T = 0.6

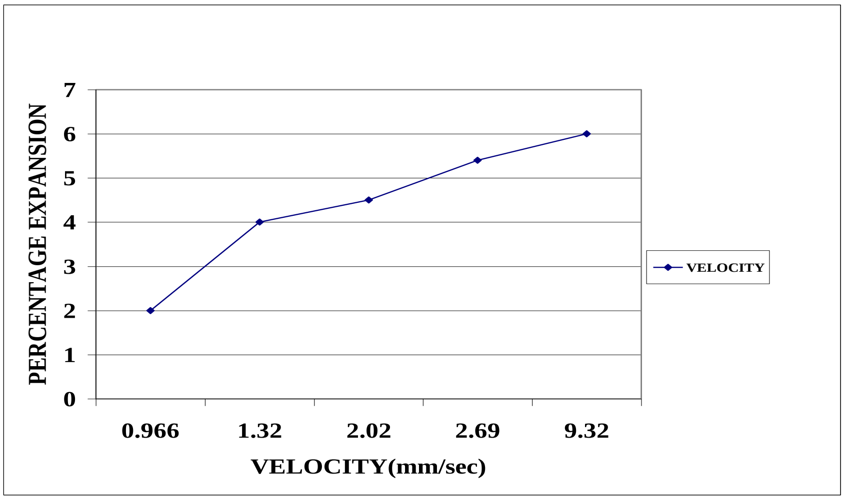
TABLE. CALIBRATION OF HYDROTHRUST WITH VELOCITY CONSTANT AND VARYING LOAD

Specimen No.	Thickness mm	Load (kg/cm^2)	Velocity (mm/sec)	Initial Diameter	Final Diameter	% Expansion
1	6	50	1.117	14.1	14.38	2%
2	6	70	1.117	14.1	14.59	3.5%
3	6	80	1.107	14.1	14.67	4.01%
4	6	100	1.107	14.1	14.75	4.64%
5	6	120	1.100	14.1	14.87	5.44%
6	6	130	1.100	14.1	14.96	6.07%



Graph 1: At constant velocity and carrying load
With the increase of the applied load the percentage expansion increases. With the increase of load the curve is linear.
TABLE.CALIBRATION OF THE HYDROTHRUST WITH CONSTANT LOAD AND VARYING VELOCITY

Specimen No.	Thickness mm	Load(kg/cm^2)	Velocity (mm/sec)	Initial Diameter	Final Diameter	% Expansion
1	4	100	0.996	14.1	14.38	2%
2	4	100	1.320	14.1	14.67	4%
3	4	100	2.020	14.1	14.73	4.5%
4	4	100	2.690	14.1	14.87	5.4%
5	4	100	9.320	14.1	14.96	6%



Graph 2: At constant load and varying velocity

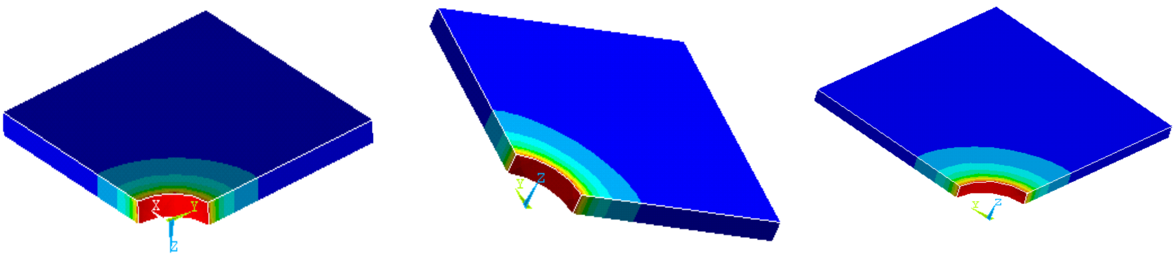
Graph 2 indicates with the increase of percentage expansion the velocity required increases.

VII.RESULTS AND DISCUSSIONS

A typical development of plastic deformation in terms of Von Mises stresses in 7050 Al is shown in Figure 5. Plastic deformation is given after each of the three process steps: expansion, release and reaming. The materials analyzed revealed the maximum stress values and distribution of the residual stresses at the surface and the mid-section. For comparison purposes, the ratio of residual stress to yielding stress of the materials is introduced. Maximum stresses are concentrated at the edge of the hole. Residual stress distribution in different sections surrounding the expanded hole can be visualized in the model easily.

Results were obtained from the FE simulation for radial and tangential residual stress through the thickness of the plate as a function of the radial position. The radial position is also at the hole edge. The obvious feature of the radial residual stress is the high tensile stress at the entrance face close to the hole edge. The tensile stress however, occurs only in a thin layer about 50-100 μm thick. The residual radial stress is compressive through the rest of the plate expect around the exit face near the hole edge where normalized stresses of up to 0.2 may observed.

Tensile tangential residual stresses are also found, particularly, at the entrance face slightly away from the hole edge. Again these tensile residual stress regions exist only in thin layer. The residual stress results this behaviour: the stresses differ in the vicinity of the hole where reverse plasticity occurs but are similar throughout the rest of the plate



(a) Expanded hole **(b) Released hole** **(c) Reamed hole**

Fig.5 FEM analysis of cold hole expansion in Al7075

VIII.FATIGUE RESULTS

1. For all stresses tested, the log average total fatigue lives and fatigue lives after rework was considerably longer than the log average baseline Cx fatigue lives.

2. At the low maximum stress levels, rework cold expansion prevented failures at the holes. At these stresses, despite the presence of fatigue cracks at many of the holes, the cracks did not resulting failures.
3. The minimum fatigue lives after rework of specimens initially cold expanded were comparable to or greater than the corresponding Cx baseline lives. The improvement in fatigue life afforded by Cx rework can be explained primarily by the removal of most of the initially fatigue damage during reaming and the high compressive residual stress created by clod expansion.
4. In general, plastic deformation produces atomic level dislocations. In a strain hardening material, further plastic deformation is made difficult by the increase in the effective yield stress of the material as plastic deformation increases. With strain hardening, cold expansion rework of previously cold expanded or otherwise overstrained hole can produce higher residual stress than cold expansion of untreated hole.

IX.CONCLUSIONS

This investigation conclusively show that a significant fatigue life extension can be obtained from a hole that is reworked using a split sleeve cold expansion after a period of constant amplitude or flight spectrum loading. The degree of improvement increases if the hole was also cold expanded during the expansion. The resultant fatigue lives after reworks are complete to or exceed the lives of initially cold expanded but not reworked holes. The cold expansion rework process performs well even when cracks (up to 1.25 mm, for the conditions evaluated here) are present. Although the tests were conducted using an open-hole specimen configuration, the level to a full fastener oversize and the stress (relative to, e.g., a filled holes configuration) make these results a conservative assessment of cold expansion system effectiveness.

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