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REVIEW ARTICLE

Cold expansion technology of connection holes in aircraft structures: A review and prospect

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Abstract As one kind of key anti-fatigue manufacture approaches with simplicity and effectiveness, the hole cold expansion technology satisfies the increasing needs for light weight and durability of aircraft structures. It can improve the fatigue life by several times at no additional weight conditions. The hole cold expansion technology has been widely used in manufacturing and repairing of both fighters and commercial aircraft, and has become a research hotspot in the strengthening technology. In recent years, hole cold expansion process methods, residual stress around expanded holes, the behavior of fatigue crack initiation and propagation, and fatigue lives after cold expansion are researched extensively through lots of experiments and finite element simulations. A review on the hole cold expansion technology research status in the last twenty years is presented in this paper. Via the analysis of the current characteristics and defects of the hole cold expansion technology, combined with the actual needs in design and manufacture of new-generation aircraft, development trends and novel research directions are presented for realizing precise and high-efficiency anti-fatigue manufacture.

1. Introduction

Light weight and durability have become the common goals of design and manufacturing engineers, for both advanced fighter and modern commercial aircraft. Fatigue loading may lead to failures of structures and components even when the load level is much lower than the ultimate strengths of materials, causing serious consequences.[1] Fatigue failure becomes one of the most important failure modes in aircraft structures.[2] In order to improve the fatigue life of aircraft structures, a lot of research on two aspects, that is, advanced materials and manufacturing processes, has been done by scholars and aviation manufacturing enterprises. On one hand, novel titanium alloys and composites as representatives of advanced materials are widely used in modern aircraft structures, reducing the overall weights of aircraft structures and improving the fatigue resistance performances of structures during service periods. On the other hand, using structure optimization and different anti-fatigue manufacturing process methods, the fatigue life of aircraft is improved and the service time is prolonged effectively.

In aircraft structures, three types of joints are used, namely, mechanically fastened joints, adhesively bonded joints, and

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welded joints. With the special requirements on safety and durability, mechanical connection including bolted and riveted is still the dominant connection mechanism in primary aircraft structural components.[3] However, implementing riveted or bolted joints needs the components to be drilled to create fastener holes, which causes geometrical discontinuities and entail local stress (or strain) concentration during loading.[4] Investigations showed that there were a number of accidents caused by fatigue failures initiating from fastened joints. According to statistics, fatigue fractures of fasten holes account for 50%–90% of fractures of aging planes.[5,6]

In order to countervail the unfavorable effect of holes on the fatigue life of notched components, various techniques for improving fatigue life have been proposed, such as laser shock, shot peening, cold expansion, and interference fitting.[7,8] The appropriate interference fit is an effective process method for improving the fatigue life of bolted joints. However, the interference degree is difficult to precisely control. The large amount of interference is easy to damage the hole surface, and the protuberance produced in installation is harmful to the strength of joints.[9,10] It not only affects the normal assembly process but also reduces the connection strength. The shot peening process basically modifies a surface and the characterizing parameters of the near surface substrate including principally elastic residual stress distribution, increased surface hardness, higher near-surface dislocation density, and alternated surface topography.[11] Nevertheless, over high surface roughness caused by shot peening offsets the contribution to prolong the fatigue life by residual stress, and reduces the assembly stiffness of an aircraft structure. Laser shock processing is a competitive technology as a kind of green method of imparting compressive residual stresses to improve fatigue and corrosion properties.[12,13] Unfortunately, costly high power laser, high operation cost, and instability of the production process limit the application of laser shock processing in aircraft assembly.

A widely used technique for cold expansion fastener holes has been developed by Boeing Company in the early 1970s and was firstly used in F/A-18 and other aircraft structure components.[14] In the cold expansion technique (the term "coldworking" was used by the inventor and early investigators), an oversized tapered mandrel goes through a hole. During this process, elastic–plastic deformation is generated and then compressive residual stress is produced around the hole. This residual stress can reduce the concentration stress and delay the initiation and propagation of fatigue cracks. It is highly effective in preventing premature fatigue failure undergoing cyclic loading.[15] The technique has been applied to critical holes in highly loaded zones of structures, such as landing gears and engine mounting regions. The cold expansion technique can be not only used for new aircraft designing, but also applied to repairing of in-service aircraft. With further studies of the cold expansion technology, a lot of improvements on the cold expansion process have been made in the aviation industry, and novel cold expansion approaches have been proposed and researched in recent years.

It is well known that aluminium alloys have been used as the primary material for structural components of aircraft for more than 80 years,[16] and the current research of cold expansion still focuses on these aviation aluminium alloys. For the "one generation material one generation aircraft" aviation manufacturing industry, the hole expansion anti-fatigue manufacture technology is relatively backward. Especially since entering the new century, new materials have been widely used in aircraft structures, such as new titanium alloys, aluminum lithium alloys, and composite materials. It needs to carry out cold expansion research about various materials in order to maximize the fatigue life. In addition, current studies are limited to single-plate strengthening. Research for the cold expansion technology of multi-plate assembly structure has not been publicly reported. Because of the great influence of external environment on the strengthening effect, it is necessary that the hole cold expansion technology in different external loading conditions should be researched extensively. Furthermore, the development of the cold expansion technology is promoted by the major projects of large aircraft.

In this paper, a review is given on the current status of cold expansion processes, containing process methods, strengthening mechanisms, reinforcement results, and influence factors. Base on that, some disadvantages of current research are analyzed and then corresponding solution countermeasures are pointed out. In light of the current demands of light weight and durability for modern aircraft with complex structures and new materials, the development trends and difficulties urgently needed to be solved for the cold expansion technology are addressed. Finally, five novel research directions of the cold expansion technology are presented and prospected.

2. Application of the cold expansion technology in the aviation industry

Generally, fatigue failure is the most prevalent mode of failure in aircraft structures. While there are many fatigue critical locations and components of aircraft, one common aircraft fatigue location is the fastener hole, especially in the main bearing component, for example, the connection holes of a wing and a fuselage. The cold expansion technology, a kind of simple and effective anti-fatigue manufacturing technology, has been widely used in key fastening holes of various aircraft. Table 1 lists the application of the cold expansion process in

Table 1 Application of the cold expansion process in some aircraft types.[8]

Strengthening method	Aircraft type	Strengthening position
Cold expansion process	F-16, F-18, B-707, B-747, B-757, B-767, MD-82, F-15, Kfir, etc.	Main bearing components
Cold expansion process and interference fit bolting	J-5, DC-9, DC-10, etc.	Lower surface of central wing, etc.
Cold expansion process and interference fit riveting	B-707, etc.	Connection of stiffening profile and skin in the wing box spanner torque wall. Connection of stringer and skin in the lower wing panel. Connection of fuselage frame and skin

some early aircraft types.[8] At the same time, cold expansion were applied in the girder holes of MIG aircraft in Soviet aviation industry, such as MiG-17, MiG-19, MiG-21, etc. The damage tolerance design philosophy has been used in modern aircraft, and the fatigue life of components has been paid more attention in the aviation industry. The cold expansion technology is not only used in manufacturing and repairing for traditional aircraft structures, but also applied in durability design of new model aircraft.

3. Investigation of the cold expansion process

Over the past decades, the cold expansion technology has been used extensively in the aircraft industry to improve the fatigue life of mechanical connections structures with fastener holes. Many cold expansion approaches have been developed and investigated according to the diverse expansion tools. The most widely used methods in practice are four cold expansion techniques: hole edge expansion, direct mandrel expansion (without sleeve), ball expansion, and split sleeve expansion processes.

3.1. Hole edge expansion

The hole edge expansion process is carried out by means of a high-hardness tapered indenter or a rigid ball to extrude or hammer the hole edge under the action of axial force *F*. This process method is shown in Fig. 1. During the hole edge expansion process, plastic deformation occurs in the material near the hole edge, and then a zone of compressive residual stress is generated around the hole edge. However, due to the middle part of the hole wall is not directly strengthened, the fatigue gain effect brought by this approach is limited. Therefore, the hole edge expansion process is not suitable for thick-plate connecting holes, and only used for strengthening of holes in sheet metal parts. In order to enhance the fatigue strength of parts, it usually needs to carry out multiple expansions for holes.[17] Liu et al.[18] investigated the effect of the hammer peening process on the fatigue behavior of holes in aluminium alloy 2A12-T4, and found that the fatigue life of these hammer-peened holes was significantly prolonged fivefold compared to non-treated holes. For skin parts, considering the aerodynamic requirements of aircraft, the dimple treatment is necessary for assembly holes. The experiment and analysis results show that the hole edge expansion process is better for sheet metal with holes effectively.

3.2. Direct mandrel expansion

The direct mandrel expansion process is one of the earliest developed methods of anti-fatigue manufacture in the aviation industry, for example, Douglas Company. In this way, the cold expansion process consists of pushing a pre-lubricated tapered mandrel through the hole from the entrance side of a specimen and removing it from the other side. Fig. 2 illustrates the mandrel direct expansion method. The hole is expanded to an extent sufficient enough to cause permanent plastic deformation. Upon the removal of the mandrel, the surrounding elastic material attempts to return to its undeformed state, producing a proper distribution of compressive residual stresses around the fastener hole. This residual stress can delay the initiation and propagation of fatigue cracks, and contribute to improving fatigue life. Furthermore, due to the direct contact between the mandrel and the hole surface, this method has advantages of burnishing and smoothing the hole surface.

The strengthening mechanisms and strengthening effects were researched extensively.[19–23] Because the direct mandrel expansion method is easy in operation, it has been widely used in the anti-fatigue manufacture of aircraft structural parts.

3.3. Ball expansion

The ball expansion process is carried out by inserting a pre-lubricated and oversized hard steel ball from one side of the holed plate, and then followed by the removal of the ball from the other side.[24,25] The expansion process is depicted in Fig. 3. Due to producing a localized interference ring between the steel ball and the hole surface, the friction is smaller in comparison with the mandrel expansion method. Therefore, this method may be used in anti-fatigue manufacture of small holes on alloy steel plates.

Due to producing a localized residual tensile ring at the entry side of the hole, the beneficial effect on fatigue life from this method is smaller in comparison with other expansion methods. In order to overcome this problem, a double ball expansion process is investigated. In addition, the area of the compressive residual stress zone is larger in the hole surface, in the sense that the hole drilling followed by double expansion can give rise to a significant increase in the number of cycles

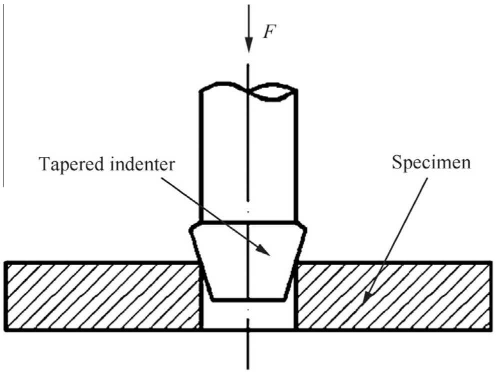

Fig. 1 Hole edge expansion process.

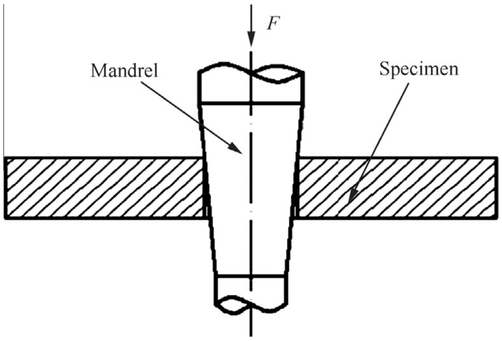

Fig. 2 Direct mandrel expansion process.

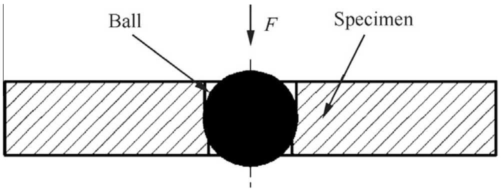

Fig. 3 Ball expansion process.

for the initiation of fatigue cracks, in comparison with a single ball expansion.[26]

3.4. Split sleeve expansion

A major impediment to the use of a ball or a mandrel in the cold hole expansion of fasteners is the surface damage introduced at the interface during the cold expansion process. To overcome this difficulty, the split sleeve expansion process is used. A schematic drawing of this process is shown in Fig. 4. In this technique, a solid tapered mandrel and an internally lubricated stainless steel split sleeve are utilized. The split sleeve is placed over the mandrel, and the mandrel/sleeve assembly is then inserted into an accurately sized hole. Plastic deformation of the material is generated when the part of the mandrel with a larger diameter moves through the sleeve. When the mandrel is withdrawn from the sleeve, some elastic recovery can take place, and the split sleeve is removed from the hole after cold expansion, leaving a permanent enlargement of the hole and a desired compressive residual stress.[27] Because of the existence of the split in the sleeve, a small raised pip is formed on the bore of the hole surface. A reaming operation to size the hole accurately is carried out after cold working which removes the pip and also avoids the occurrence of cracks near the pip.[28]

This expansion method has the advantages of good adaptability, high production efficiency, and small damage around the hole surface after expansion. Comparing with other existing cold expansion techniques, the split sleeve cold expansion method has been more widely used in the aerospace industry[29–31], especially in the bad openness connection of aircraft assembly.

4. Residual stress investigation

The local plastic deformation strengthening process is one of the strengthening methods of active application of residual stress. The cold expansion technology just utilizes this residual stress caused by plastic deformation to achieve anti-fatigue manufacture. The strengthening effect is affected by the size and distribution of residual stress. Therefore, the investigation of the residual stress field is the focus of attention for the cold expansion strengthening technology.

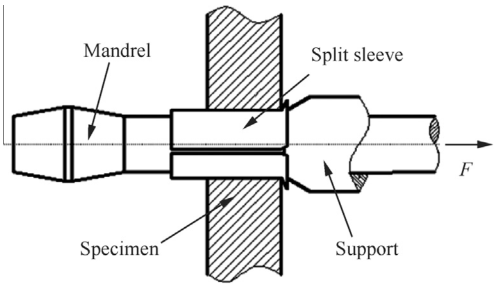

Fig. 4 Split sleeve expansion process.

4.1. Residual stress measurement method

Since it is the compressive residual stress field produced by cold expansion which is responsible for the amelioration of stress concentration at faster holes, accurate measurement of these fields has been the focus of many experimental programs. In the early studies, researchers have made a careful analysis of the residual stress around an expansion hole, starting with material deformation and springback in the theory of elastoplasticity.[32,33] It is important to note, however, that due to the limitation of measurement techniques, stress was not directly measureable in the initial researches. With the progress of means of measurement, various test methods are used to study the residual stress after cold expansion. According to the measurement area, it may be divided into two types, namely, point measurement and face measurement. Point measurement methods, for example, the strain gage method,[31] the hole-drilling method, the X-ray diffraction method,[34–36] single beam laser speckle interferometry,[37] etc., have been widely applied in the measurement of the residual stress in an annular region adjacent to the hole. As a distinguishing feature of these methods, the residual stress field is fitted with some point stress by repeated measurement. Nevertheless, it should be pointed out that the residual stress cannot be accurately obtained at a point in the region close to the hole since the experimental measurements are averaged over a 1 mm × 1 mm area. To overcome this problem, face measurement methods such as moiré interferometry[38,39] and the photoelastic coating method[40–42] are utilized. Although the mechanism and accuracy of these measurement methods are different from each other, the typical distribution of residual stress measured by various methods around a cold expanded hole is basically similar. The typical distribution of tangential residual stresses σ_θ around a cold expanded circular hole is shown in Fig. 5.

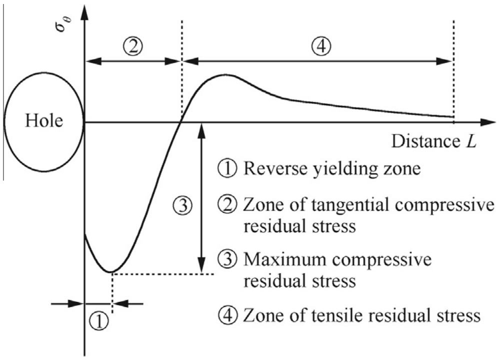

Fig. 5 Typical tangential residual stress distribution around an expanded hole.

4.2. Residual stress simulation research

Although many analytical models and experimental techniques viz. X-ray diffraction, single-beam laser speckle interferometry, photoelastic coating, etc., have been employed and developed to predict the residual stresses field, it is still difficult to capture the three-dimensional distribution of the residual stress near the hole wall surface, due to inherent limitations of different experimental methods. The elastic–plastic deformation zone of a metal material is only a small part around the cold expanded hole, so the compressive residual stress is limited to a certain small areas around the hole. Because of the limitations of measurement range and accuracy of existing test methods, the residual stress field with a large gradient variation still cannot be measured accurately. In other words, it is difficult to measure the stress field of the internal material near the hole wall. With the development of computers, finite element simulation can be widely applied to study the residual stress generated by the cold expansion process. Through the rational designs of meshes, material properties, contact conditions, boundary conditions, etc., accurate residual stress distributions can be obtained from numerical simulation.

Various analytical models and numerical simulations have been tried and used to investigate the residual stress. In the early 1990s, two-dimensional axisymmetric finite element (FE) approximation models have been designed for the cold expansion of a fastener hole.[28,35] The tangential and radial residual stresses are obtained around the cold expanded hole. It is shown that there is good agreement between simulation and experimental results. Although some limited numerical works have been carried out to consider the residual stress along the thickness of a sheet metal, the two-dimensional finite element simulation models of cold expansion are not adequate to accurately estimate the residual stress field resulted from the cold expansion process, due to the asymmetry of the residual stress field through the thickness of the plate induced by the cold working process.[43]

In recent years, three-dimensional finite element simulation models have been utilized to research cold expansion.[44,45] A simplified 3-D finite element simulation of the cold expansion of a fastener hole has been developed by employing a new approach by Mahendra et al.[46] and this approach is capable of capturing the variation of residual stresses at various sections along the thickness. In order to obtain a more accurate residual stress distribution around the hole, it would be good to set out the prerequisites for the creation of an adequate FE model. It has been proven that there are two key moments in the building of an adequate finite element model: the first is modeling of a realistic contact mandrel-workpiece with or without a mediator and a workpiece-support, and the second is a suitable constitutive model of the workpiece material.[47] Finite element analysis results show that, during the hole cold expansion process, the residual compressive stress of the hole edge exhibits grades across the thickness, with the least amount of residual compressive stress at the tool entrance face, the largest amount of residual compressive stress in the mid-bore, and good residual compressive stress at the tool exit face. The simulation results were consistent with those of experiments by the X-ray diffraction method.[34] Artificial neural networks (ANN) simulation modeling was built and trained to simulate the stress topography surrounding an expanded hole by Toktas and Özdemir,[48] and the result showed that diffraction methods and current ANN predictions were overlaid and similarities in residual stress distributions perceived to valid only at regions where the strain gradient was not changing precipitously.

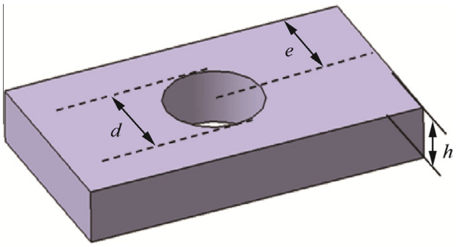

Fig. 6 Main dimensions of a part with a hole.

4.3. Influencing factors of residual stress

The stress fields near a connection hole have a great influence on fatigue life under alternate loads. In order to improve the fatigue life, it is necessary that the factors affecting residual stress should be researched after hole cold expansion. It has been found that predicted residual stresses are sensitive to the details of the process, particularly the expansion degree and the geometry relation.

A variety of methods mentioned above can generate the residual stress around the cold expansion hole. Research shows that the reaming of the material around the hole has a slight effect on the maximum value and distribution of residual stresses.[45] Process parameters have great influences on the residual stress, such as mandrel speed,[49] lubrication, expansion degree, etc. From the experimental and simulation results, it is understood that the residual stress increased with the expansion degree.[50,51] Because of the different material properties, the correlation between process parameters and the expansion degree is not the same. The geometry relation is a crucial factor in the design of aircraft strength. The main dimensions of a part with a hole is shown in Fig. 6, including h (thickness), d (hole diameter), e (the distance from the hole center to the specimen boundary along the width direction), and then the edge distance ratio is e/d. The effects of key processing and design parameters have been systematically studied.[52–56] A small e/d results in a change of the residual stress distribution around a cold expanded hole, and it influences the fatigue life.[57] When e/d is more than 3, it has no effect on the residual stress field.[54]

5. Fatigue crack investigation

The fatigue fracture process is divided into three stages, including fatigue crack initiation, propagation, and fracture.[58] Through the investigation of the behaviors of crack initiation and propagation of a hole with cold expansion strengthening treatment, the internal relationship between fatigue life and residual stress can be established. Furthermore, the fatigue strengthening mechanism of cold expansion can be revealed.

5.1. Fatigue crack source

Fatigue damage often occurs in a stress concentration position, for example, the specimen surface or defect, or a hole.

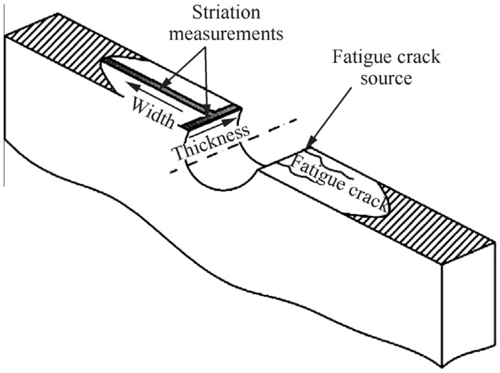

Fig. 7 Fractography analysis of a metal fatigue specimen.[59]

Results suggest that all specimens with a hole broke at the plane of the smallest cross section, as shown in Fig. 7.[59]

As mentioned previously, the maximum compressive tangential residual stress occurs at the hole edge near the mid-plane, whereas the smallest compressive residual stress occurs at the entrance face.[46] SEM studies indicate that, in cold expanded fatigue specimens, fatigue cracks initiated and propagated at the mandrel entrance face around the hole edge, and in unexpanded specimens, fatigue cracks initiated at the corner of the hole and the surface of the hole bore, respectively; the former have only a single fatigue source while the latter have multiple sources.[60–64] In cold expanded holes, the propagation speed of fatigue cracks along the transverse direction is faster than that along the axial direction.[65] The distribution of residual stress and the regulations of fatigue crack initiation and propagation are in good agreement.

5.2. Fatigue crack propagation

Crack morphology reflects the whole process of fatigue crack initiation and propagation. In the fatigue life, the crack propagation life is longer than the crack initiation life. In order to increase the fatigue life effectively, it needs to extend the crack propagation time as long as possible using anti-fatigue manufacture approaches. Studies on crack propagation mainly include the size of the crack propagation area, crack propagation rate, stress intensity factor, etc.

Under the same condition of the crack propagation rate, enlarging the size of the crack propagation area can prolong the fatigue propagation life. Because of the differences of cold expansion processes and mechanical properties, the size of the fatigue crack propagation area is different from each other after hole cold expansion. Studies suggest that the size of the crack propagation area increases with the increasing of the expansion degree.[66] The fatigue striation which is perpendicular to the crack propagation direction can be seen clearly in the fracture surface. The rates of fatigue crack propagation are determined by the measurement of striation spacing.[67,68] It has been found that the cowrie pattern spacing resulted from cold expanded holes is always smaller than that resulted from "as drilled" holes, which indicates that the cold expansion process retards the crack propagation rate.[62] In order to research the fatigue crack growth rate, the stress intensity factor must be known and it has been widely studied recently.[69–72] Due to the complexity of residual stress distributions around holes, the stress intensity factor is difficult to be used directly for description of the fatigue life. The superposition principle has been used to account for the presence of residual stresses near cold expanded holes. In fact, the effect of residual stress may be explained using a fatigue crack closure model in which compressive residual stress reduces the effective stress intensity factor, consequently reducing the crack growth rate.[73,74] The effective stress intensity factor (K_{eff}) is equal to the residual stress intensity factor (K_{res}) plus the stress intensity factor caused by the external applied load (K_{app}). In order to estimate the residual stress intensity factor along the crack plane, the closure-based method and the weight function technique are used.[75] The effective stress intensity factor can easily solve the problem of crack propagation, and a certain relationship between the fatigue life and the residual stress field is established via this factor. It is helpful to the study of the fatigue life which is strengthened by the cold expansion technology.

6. Fatigue life investigation

6.1. Anti-fatigue effect

Anti-fatigue manufacture is the fundamental purpose of the hole expansion process. The fatigue gain effect has been studied extensively in recent years. According to the differences of materials and expansion process methods and parameters, the gain coefficient is also different from each other. In general, the fatigue lives of aluminium alloys are increased more than those of other metals, because they have good ductility. Research results show that the fatigue life of 7050 high-strength aluminium alloy can be increased 6 times using the hole cold expansion process, while that of 7B50-T7451 can be increased 28 times.[16,76,77] However, the gain coefficients of low-plasticity metal materials are relatively smaller, for example, the fatigue lives of Ti6Al4V and 30CrMnSiNi2A can be increased 2.8 times and 1.7 times.[61,62] In addition, stress levels also affect the gain coefficient. For example, in the same conditions, the fatigue life improvement factor is about 3.2 and 1.5 for a degree of cold expansion of 5.58% when applying nominal stresses of 191 MPa and 300 MPa, respectively.[78]

6.2. Fatigue life prediction

Fatigue life usually consists of the initiation life and the propagation life of a fatigue crack. Fatigue crack initiation and propagation life estimations have been investigated extensively and the total estimated fatigue lives have been compared with available experimental fatigue test results. The cold expansion process can generate compressive residual stress near the expanded holes. The superposition of the mean stress between the residual stress and the external stress is used to analyze fatigue crack initiation. The ε-N method is implemented to predict the fatigue crack initiation life.[79] Another method is put forward to predict the fatigue crack initiation life of LY12CZ alloy after hole cold expansion under variable amplitude loadings and has been substantiated by a fatigue test under a flight-to-flight spectrum.[80] Based on fatigue experiments, fracture analysis, and residual stress computed by elasto-plastic finite element simulation for cold expanded fastener holes, an engineering approach is used to predict fatigue life, and the result is well agreed with that of the experiment.[81] A reliability analysis method is presented and used to analyze the effects of different tolerances and strengthening parameters on the fatigue life distributions.[82] Fatigue life estimation can be used to determine the optimum degree of cold expansion avoiding long-time fatigue tests.

7. Development conception of cold expansion technology

With the tireless efforts of researchers and engineers, cold expansion technology has been applied in the vast majority of military and commercial aircraft. It makes sense in reducing the stress concentration around fastener holes, and also improving the fatigue lives of aircraft components. However, the high request to the manufacturing and design of aircraft is put forward in recent years. On one hand, a large number of new materials are used for the primary structure in the fourth-generation fighters and civil commercial aircraft. The current cold expansion process cannot be implemented directly in the new materials and structures of aircraft. It is necessary to carry out research of a novel cold expansion technology so as to meet the requirement in practice. On the other hand, the beneficial effect of the cold expansion process is the focus of attention for aircraft designers. In order to accurately predict the fatigue life, the influence of environmental factors on cold expanded components should be researched in the aircraft service conditions. Unfortunately, research on this aspect is not carried out extensively. Numerical simulation has been carried out in cold expansion researches; however, it is still confined to the residual stress around expanded holes. The study on life estimation for cold expanded structures should be developed by synthesis simulation technology. According to the above analysis, five research directions of cold expansion technology are proposed as shown in Fig. 8.

7.1. Synthesis simulation technology

Finite element simulation has been widely applied in research of hole cold expansion technology, especially analysis of the residual stress around expanded holes. In view of the different cold expansion process approaches, such as direct mandrel expansion and split sleeve cold expansion, various residual stress fields are obtained via finite element simulation. Experiment results demonstrate that the accuracy of the residual stress field can be improved through optimizing the geometric model, boundary conditions and mesh, etc. Researches of the residual stress and the crack propagation factor reveal the strengthening mechanism of hole cold expansion technology.

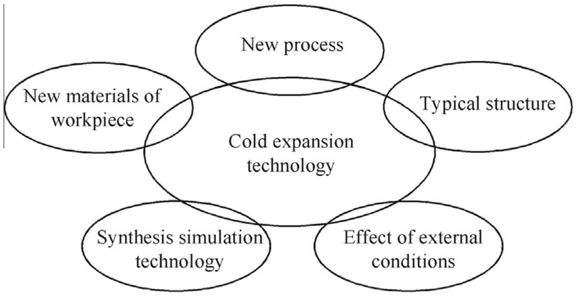

Fig. 8 Research directions of cold expansion technology.

In current studies, however, the simulations of fatigue crack initiation and propagation are not carried out, and the relationship between the fatigue life and the cold expansion process is not established by finite element simulation. It is necessary to carry out synthesis simulation technology which includes the residual stress, the fatigue properties of materials, and the load spectrum, as shown in Fig. 9. First of all, the relationship between the residual stress and the fatigue crack should be established by researching on the mechanism of crack initiation and propagation near the expanded holes, which is a key step towards the cold expansion fatigue life simulation. Via fatigue analyses about the fatigue properties of materials, the load spectrum, and the simulation results of the residual stress, the fatigue life can be estimated with specific cold expansion process and environmental conditions.

7.2. New process

Despite the cold expansion technology has been widely used in the assembly and repair of aircraft, the conventional approaches usually have certain limitations.[83] On one hand, cold expansion without sleeves is easy to cause hole surface and mandrel damages, and it is difficult to carry out a large degree of cold expansion. On the other hand, the disadvantage faced by the split sleeve expansion process is necessary reaming operation; moreover, each split sleeve can only be used for processing one hole. It not only causes the complexity of the technology, but also increases the cost of production.

To further improve the performance of cold expansion, new advanced processes have attracted more focus currently. Double cold expansion (ball cold expansion method) can realize relatively large expansion degrees, and the second expansion is carried out in the opposite direction of the first expansion employing a second ball with a larger diameter.[26] A method which allows the calculation of the optimal radial interference and the optimal mandrel shape on a cold-expanded bushing is introduced in order to obtain the desired values of the residual stresses on the hole surface.[84] The surface upset is an undesirable effect which accompanies all mandrel expansion methods; however, the fretting fatigue phenomenon is strongly provoked by the surface upset. With the purpose of reducing the surface upset, Maximov et al.[85,86] presented a symmetric cold expansion method and tool (shown in Fig. 10) ensuring "pure" radial cold hole expansion –

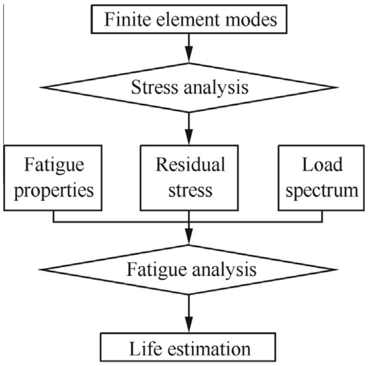

Fig. 9 Synthesis finite element simulation for fatigue life estimation of cold expanded specimens.

introducing nearly uniform residual hoop stresses around the hole along its axis having a minimized and symmetric gradient with respect to the plate middle plane, and another advantage of the method is that it ensures one-sided processes like the split sleeve and split mandrel. In addition, according to the actual impact factors including material, geometric dimension, application environment, etc., it is necessary to design suitable cold expansion process approaches and parameters to maximize the fatigue lives of components.

7.3. New materials of workpiece

The development of the aviation industry is always accompanied by the development of new materials. The hole cold expansion techniques applied to the new materials need to be researched and developed according to their physical and mechanical properties respectively.

7.3.1. New metals

Titanium alloys are widely used in the new-generation large aircraft, both military transports and commercial airliners, as shown in Fig. 11.[87] According to different positions, there are various titanium alloys with different properties, especially in the main load-bearing components, for example, engine, keel beam, wing, fin, etc. Compared with aluminium alloys, titanium alloys have high strength and toughness, but poor cold expansion shaping. As an available anti-fatigue manufacture process, however, the cold expansion technology of titanium alloys is barely referred in current documents.[57,62]

In addition to titanium alloys, other new alloy materials have been widely used in aircraft. The high hot strength and significant resistance to heat and fatigue of nickel-based superalloy lead to its wide application in turbine sections of jet engines.[88] However, the excellent performance also results in its poor deformation ability, especially the cold expansion deformation of structural parts. According to experimental results, it is shown that the alloy GH169 has a strengthened layer with a nearly 3-mm depth from the hole edge.[89] In the aspect of light alloy with low density, the third-generation Al–Li alloys and Al–Mg alloys have been developed and applied in modern airplane structures.[16,90,91]

According to public documents, hole cold expansion still focuses on the traditional materials – various types of aluminium alloys. Because of the different material properties, the cold expansion process for aluminium alloy holes cannot be directly applied to strengthening treatment of new metal materials. Combined with the application conditions and the physical and mechanical properties of metal materials respectively, cold expansion strengthening and anti-fatigue manufacture should be further investigated.

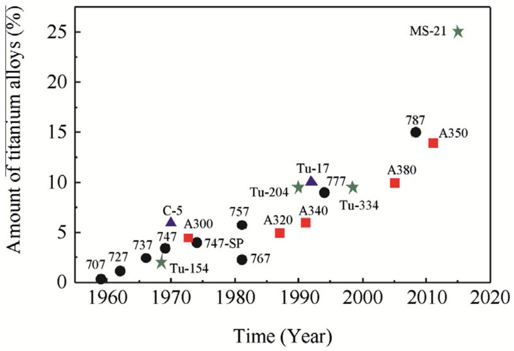

Fig. 11 Change of titanium application in large airliners and military transports.[87]

7.3.2. Composite

Due to their low weights and high mechanical properties, nearly for a decade, composite materials have been more widely used in aeronautical and aerospace structures for the fuselage and the wing as well as other structural parts (shown in Fig. 12[87]). The amount of fiber composites applied in commercial airplanes becomes an important index to evaluate the advanced technology of the aviation industry.

Anti-fatigue connection technology of composite materials has become an important research topic in aircraft manufacturing. In general, three types of joints are used in composite structures, namely, mechanically fastened joints, adhesively bonded joints, and hybrid mechanically fastened/adhesively bonded joints.[92] Mechanical connection is the main connection way for aircraft parts. Bolted joints are still the dominant fastening mechanisms used in jointing of primary structural parts.[93] Sometimes, as many as 55,000 holes are generally required to be drilled in the complete single unit production of an Airbus A350 aircraft.[94] However, the presence of connection holes compromises the structure integrity, and causes a local stress or strain rise in aircraft parts. On the other hand, drilling composite joint components, to make bolt holes, may create fiber pullouts or delamination in the hole surface. The stress concentration and damage around holes reduce the connection strength, and decrease the fatigue lives of

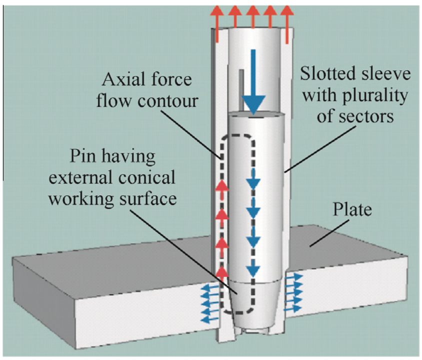

Fig. 10 Scheme of symmetric cold expansion.[85]

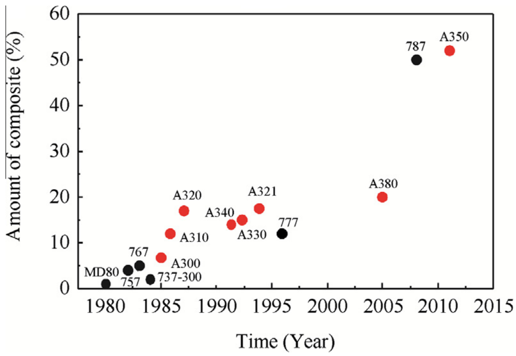

Fig. 12 Change of composite application in large airliners.[87]

aircraft parts under the action of alternating loads. Compared with metallic material structures, fastener holes are the weak link in composite material structures. The fatigue fractures of fastener holes account for 60%–80% of structure fractures of aircraft.[95]

From the cold expansion technology of metal holes, Fatigue Technologies Incorporated (FTI) has developed a cold expansion process with a metal sleeve for composite holes in aircraft assembly structures (shown in Fig. 13). However, the specific information of this approach is still a secret. In order to improve the fatigue lives of composite material structures, the cold expansion technology for composite holes has become an urgent requirement of aircraft manufacturing enterprises. Therefore, the strengthening mechanism, process, and effect of cold expansion composite holes need further analysis and reveal through a large number of experimental researches.

7.4. Typical structure

Although cold expansion technology has been studied for decades, it still focuses on the hole strengthening of a single plate. Actually, various components are assembled through multi-hole connection in the aircraft manufacture. The service life of aircraft is determined by assembly structures. Therefore, it is very necessary to research the cold expansion of typical structures for improving the fatigue life of aircraft.

7.4.1. Multi-hole structure

In a mechanical connection structure, the load-bearing components are assembled by numerous fasteners. Particularly in aircraft, there exist a lot of fastener holes at regular intervals. A typical part is shown in Fig. 14. Due to the complexity of the structure, the research of stress distribution and fatigue damage about these holes is relatively difficult. In that case, the residual stress variation might be influenced by the adjacent holes if cold-expanded.[96]

In early studies, the effect of the geometry of two adjacent cold expanded holes upon the resulting three-dimensional residual stress fields has been preliminarily examined considering both simultaneous and sequential cold expansion of the two holes.[15,22] These researches focus only on simulation of the residual stress around cold expanded holes. Amazingly, however, extensive search of the literatures indicates that no attempt has been made to experiment the cold expansion of numerous holes. Especially, the initiation and propagation mechanisms of fatigue cracks for the cold expanded adjacent holes need to be widely researched. It needs to do a lot of researches for improving the fatigue life of the adjacent holes part with cold expansion technology.

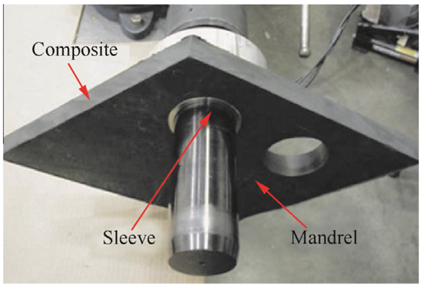

Fig. 13 Cold expansion process for a composite hole.

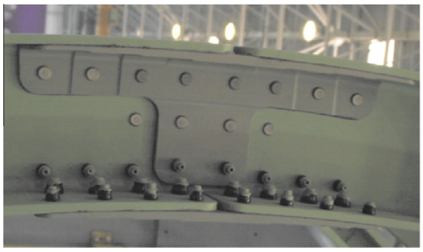

Fig. 14 Multi-hole connection component in aircraft structures.

7.4.2. Sandwich structure

The aircraft structure is composed of two or more parts connected together with assembly holes and fasteners. In order to improve the fatigue life of aircraft, it is essential for engineers to carry out anti-fatigue manufacture of assembly units. The current research of the cold expansion strengthening technology of holes is only limited to the single board, and it is not involved in the assembly structure. However, it is the key point to improve the fatigue life of the aircraft structure.

The cold expansion process for a multi-plate structure is required to complete expanding all holes of plates at one time, as shown in Fig. 15. Due to the differences of material properties and physical sandwich plates, different interferences should be used in the assembly units, especially for different materials. Consequently, the traditional cold expansion process of a single plate cannot be directly applied in sandwich plates. Experiments and simulation should be carried out to research the cold expansion technology of sandwich structures.

7.5. Effects of external conditions

Cold expansion process has an obvious beneficial effect on the fatigue life of components with holes. However, the effect of cold expansion on the fatigue life is subjected by external conditions including bolt clamping, external stress, and working temperature. It should be pointed out that the researches of cold expansion strengthening technology have not been widely involved in the effects of external conditions on fatigue gain. In order to improve the fatigue life of a component under working conditions, it is necessary to carry out the initiation and propagation mechanisms of fatigue cracks and expansion process researches for connecting holes under certain environment.

7.5.1. Bolt clamping

Among the most important connection structures in aircraft are mechanical joints, especially bolted joints. When a nut

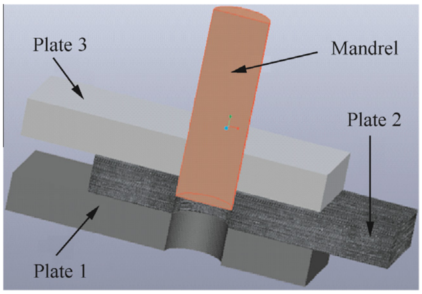

Fig. 15 Cold expansion process for sandwich structure holes.

and a bolt are used to join mechanical members together, the nut is tightened by applying a torque, thus causing the bolt to axially stretch.[97] The result is that the bolt is left in tension and the mechanical members are compressed together. It is well known that the bolt clamping effect can decrease the stress concentration at the bolted hole region and thus increase the tensile and fatigue strengths of the joint.[98]

There are many researches about cold expansion and bolt clamping separately in the past decade. Nevertheless, studies about the combined effects of cold expansion and clamping torque in joints have not been carried out extensively. In fact, because a bolt is installed in a cold expanded hole, the compressive stress field of bolt clamping superimposes to the primary residual compressive stress field, and the result is that it can significantly affect the fatigue behavior of the cold expanded specimen. Moreover, the frictional contact between the washer of the bolt assembly and the specimen can bring further changes in the fatigue behavior.[99] Investigations of fatigue tests and numerical simulations should be conducted to study the combined effects of cold expansion and bolt clamping on fatigue life and failure mode.

7.5.2. External stress

Fatigue failure is the most common failure mode of aircraft structural components. Fastener holes as natural stress concentrators are a basic factor for the fatigue strengths of these components.[45] Research shows that the cold expansion process always improve fatigue life compared to that of "as drilled" holes in all stress levels.[62,78] In a cold expansion process, residual stresses are those stresses existing in the structural components without an applied external load, and they form a self equilibrated system of internal forces.[100] However, the external cyclic stress is the main factor affecting the fatigue lives of components.[101] Residual stress relaxation occurs around cold expanded holes under cyclic tension. That is to say, the beneficial anti-fatigue effect from the cold expansion process is influenced by external cyclic stress.[102] In spite of the extensive researches of the cold expansion process, the effect of stress levels on fatigue life after cold expansion has not been researched extensively. To efficiently improve fatigue life, the optimization of process parameters should be studied according to the load spectrum of aircraft in service.

7.5.3. Working temperature

High temperatures can be generated near engine components as well as in the structure of an aircraft sitting idle on blacktop runways in the sun, and additionally, frictional heating may occur during supersonic flight.[103] When the speed of a supersonic aircraft reaches 2.4 Mach, temperatures arising from aerodynamic heating are anticipated to be 160 °C and higher.[104] Residual stresses are generated by the cold expansion process around expanded holes. However, there is a concern that the residual stresses may be subjected to relaxation under elevated temperature conditions and can therefore significantly affect the fatigue life.

One of the most important reasons for residual stress relaxation is metal material creep in service. The relaxation is caused not by external reasons, but by the natural property of non-ferrous alloys to change their internal equilibrium at room temperature.[105] The creep behavior of aluminium alloys is typical for high temperatures and its effect on residual stress relaxation is studied.[106–108] In current studies, cold expansion technology is employed usually in components which are exposed only to service conditions at room temperature. With regard to the problem that temperature fluctuations affect the fatigue resistance of a cold expanded hole, only a few papers have been published. Consequently, it is important to research whether fatigue life improvement from cold expansion is still retained at elevated temperatures.

8. Conclusions

(1) Cold expansion has been one key anti-fatigue manufacturing technology for light-weight, high-strength, and durable components in aviation industries. The fatigue lives of 7B50-T7451, 7050 aluminium alloy, and Ti6Al4V can be increased 28, 6, and 2.8 times, respectively, using hole cold expansion processes. These approaches including hole edge expansion, direct mandrel expansion, ball expansion, and split sleeve expansion have been introduced and analyzed respectively. New cold expansion approaches have been put forward, through the analysis of the disadvantages existing in the current processes.

(2) Experimental investigations and finite element simulations have been made for better understanding of the anti-fatigue behavior with cold expansion technology. Residual stress and fatigue cracks are the key areas of current cold expansion research. On the basis of an analysis of the factors affecting the residual stress and the initiation and propagation of fatigue cracks, the current urgent demands for development of cold expansion have been described. Thus, studies of cold expansion technology should be carried out extensively according to structural characteristics and working conditions.

(3) With the development of aviation manufacturing technology, numerous new materials are widely utilized for commercial and military aircraft, including Al-Li alloys, titanium, composites, etc. Because of the differences of material properties, the traditional methods and process parameters of hole cold expansion are not applicable for them. Therefore, referencing current strengthening methods, novel methods and tools of hole cold expansion for new materials are designed necessarily according to the different material properties. The strengthening mechanism, parameter optimization, and effect of cold expansion need to be further studied and revealed through a large number of simulations and experimental researches.

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